Transformer Modelling Guide

Confidential/Internal

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Teshmont

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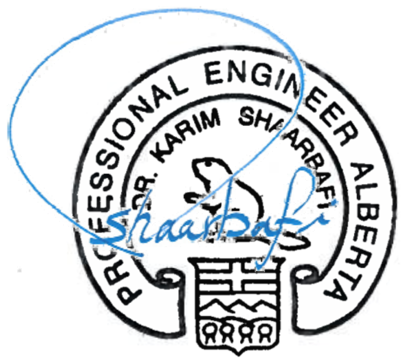

The intent of this document is to provide a general guide for the purpose of assisting AESO and other authorized parties with modelling of transformers in the electrical network of Alberta. All authorized parties may use this guide only for the purpose for which it is intended and at their own risk.

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1 Basic Concepts of Power Transformers

1.1 Introduction

Transformers are static devices that induce mutual coupling between circuits to transfer energy from one circuit to another. There are many types of transformers, and they are used in many types of applications. This guide deals exclusively with power transformers used in power transmission and distribution systems.

A transformer usually consists of two or more coupled windings on a magnetic iron core. Each phase of a power transformer normally has a pair of windings (the primary and secondary) linked by a magnetic circuit or core. The windings of ordinary transformers can have effective resistances of a fraction of an ohm to several ohms. The transformer core is made of a high-magnetic-permeability iron that makes high magnetic-flux density with minimal magneto-motive force possible. Because the flux density in the core has to be limited to about 1.7 Tesla, there is a limit to the minimum size of the core. Shipping limitations may determine the maximum transformer size. Transformers are usually the largest, heaviest, and often the costliest, components in power transmission systems.

This guide discusses certain technical and practical aspects of all types of transformers in power systems including the purpose of their application, the equivalent electrical circuit and modelling techniques currently utilized for power systems studies, and the determination of transformer parameters. Its purpose is to facilitate the modelling and analysis of transformers using different power systems software. For consistency and ease of understanding, this guide uses SI units.

To make this guide accessible to a wide range of users, it begins with a review of basic concepts and key technical points.

1.2 Basic Transformer Theory

Transformers are used for different purposes; however, the fundamental theories and concepts of all transformers are same. A transformer works on the principle of electromagnetic induction. Figure 1-1 shows a single-phase power transformer with a magnetic core and two windings (the primary and the secondary) wound around the core on opposite core legs. The transformer is in the no-load condition with the primary winding connected to an ac source. The windings are linked by a mutual flux φ_m.

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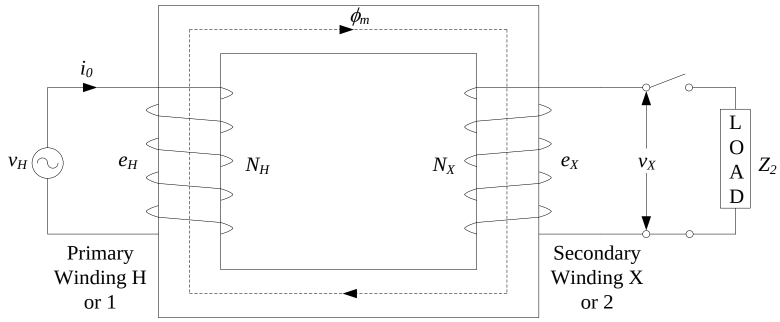

Figure 1-1- Ideal transformer with a primary and secondary winding

1.2.1 Ideal Transformer

A way to make understanding transformer operation easier is to consider a transformer as an ideal device.

An ideal transformer has the following features:

- The windings have perfect conductivity. Therefore, copper losses in either the primary coil or the secondary coil are zero.
- The energy dissipation from hysteresis and eddy currents in the magnet core is zero.
- The magnetic permeability in the core is perfect and constant (reluctance or magnetic resistance are zero; therefore, the leakage inductance is zero).
- No magnetizing current is needed to set up the magnetic flux.
- The core exhibits linear magnetic characteristics because of constant permeability.

According to these assumptions, an ideal transformer is a no-loss device able to transform even dc voltage.

The relationship between the induced voltage and the flux is given by Faraday's law as follows:

$$e_{turn}(t) = \frac{d\varphi(t)}{dt}$$

where $e_{turn}(t)$ is instantaneous induced voltage in a single turn or volts per turn, and $\varphi(t)$ is the linkage flux. Assuming the transformer is excited by an ac voltage with frequency f, $\varphi(t)$, it will be sinusoidal. Therefore, the effective volts per turn value (the rms value) will be:

$$e = \frac{2\pi}{\sqrt{2}}\, \emptyset_{max}\, f$$

where f is the operating frequency and $\emptyset_{max}$ is the amplitude of linkage sinusoidal flux. For design purposes, this expression is shown as:

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$$e = \frac{E}{N} = 4.44\, B_m\, A\, f$$

where E is the induced voltage and N is the number of turns. A is the effective cross-section of the core and B_m is the maximum value of flux density in the core. This equation is the EMF equation of a transformer. For a given frequency and number of turns, the flux (and flux density) in a core is determined by the applied voltage. In practice, B_m is set by the core material selected by the designer and by the operating conditions of the transformer. Because the same linkage flux induces voltage in the primary and secondary windings, the volts per turn is the same for both windings:

$$e = \frac{E_H}{N_H} = \frac{E_X}{N_X}$$

The total voltage induced in each of the windings must, therefore, be proportional to the number of turns:

$$\frac{E_H}{E_X} = \frac{N_H}{N_X}$$

where E is the induced voltage and N is the number of turns in the winding identified by the appropriate subscript. If a load is attached to the secondary winding of an ideal transformer, the current will flow in the secondary and hence in the primary. From the point of view of the magnetic circuit, the ampere-turns in both windings are balanced thus:

$$I_H N_H = I_X N_X$$

Therefore:

$$\frac{E_H}{E_X} = \frac{N_H}{N_X} = \frac{I_X}{I_H}$$

This is the basic equation for all types of transformers.

1.2.2 Practical Transformer

The assumptions and analysis presented for an ideal transformer are helpful when explaining the fundamentals of transformer operation. However, some ideal assumptions made for an ideal transformer are not applicable in a real-world practical transformer.

a) Magnetizing Current

In practice, the magnetic resistance of a practical transformer is not zero (as in an ideal transformer). This means that not all flux produced by the primary is contained in the core. The flux not contained in the core is the leakage flux, which occurs external to the core “air”. The

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primary winding draws a small excitation current, I_M , from the source and sets up an alternating MMF and, therefore, an alternating flux in the core. This current is the magnetizing current (the excitation current). Depending on the magnetic reluctance of the core, a large part of the flux will flow in the core and link both windings and induce an EMF in each winding. The induced EMF in the primary is the back EMF and opposes with the primary applied voltage as per Lenz's law. In the secondary winding, the induced voltage is open-circuit voltage. If the secondary circuit is open circuited, the transformer will behave like an inductor with a high-permeability closed iron core. It will, therefore, have high inductance. However, a small amount of current will still flow in the primary winding and will excite the magnetic circuit and generate the primary voltage or back EMF. If a load is connected to the secondary, the induced voltage will result in the flow of a current in the load and the secondary winding. This current creates demagnetizing MMF and destroys the balance between the applied voltage and the back EMF. To restore the balance, the drawn current in the primary winding from the supply is increased to provide an exactly equivalent MMF. The balance is established when this additional primary current creates the same ampere turns as those the secondary ampere turns create.

b) Leakage and Mutual Inductances

As noted, the magnetic permeability of an iron core in a real transformer is not infinite. Therefore, not all the flux produced by the primary winding links the secondary winding. A small part of the flux linking each winding, the leakage flux of that winding, does not link to another winding or windings and is closed through the air, so the transformer can be said to possess leakage reactance in each winding. When transformers were first being used, leakage reactance was seen as a shortcoming to be minimized as much as possible, subject to cost constraints. With the growth of power distribution and transmission systems, it came to be recognized that the transformer leakage reactance (total transformer impedance) has a large role in the limitation of fault current in power systems. At the present time, using high impedance transformers is one of the approaches utilized to limit the fault current beyond the maximum value in power systems. The two-winding transformer model shown in Figure 1-1 can now be developed into the lossless and linear model of the unsaturated transformer shown in Figure 1-2.

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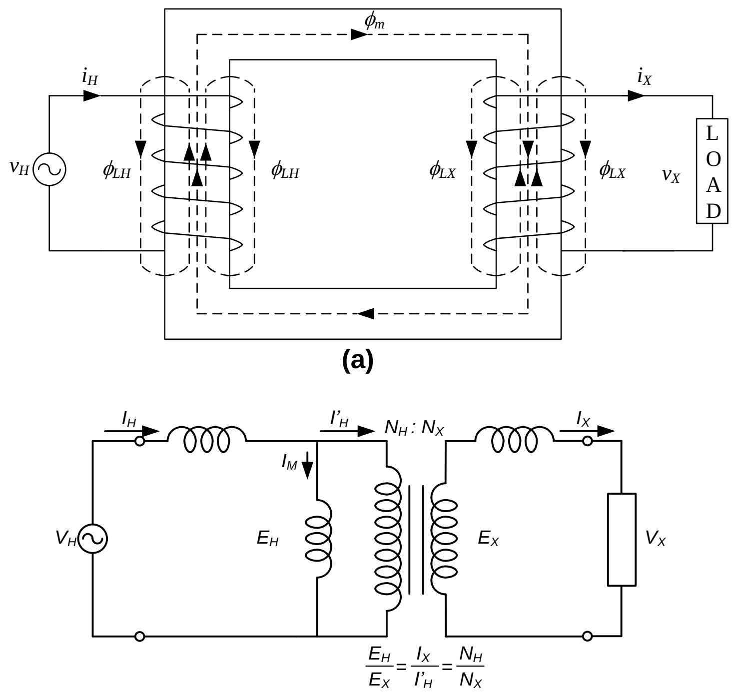

(b)

Figure 1-2- Lossless linear model of a two-winding transformer with an equivalent circuit of a transformer including magnetizing and leakage inductances

The leakage flux φ_{LH} shown in Figure 1-2 is produced by the current i_H in winding H and only links winding H. The leakage flux φ_{LX} is produced by the current i_X in winding X, which only links winding X. The primary and secondary leakage inductances are, respectively:

$$L_H = \frac{N_H^2}{\mathcal{R}_H}$$

$$L_X = \frac{N_X^2}{\mathcal{R}_X}$$

If the magnetic reluctance offered to the path of the linkage flux or the mutual flux is denoted by $\mathcal{R}_\mathrm{m}$, the mutual inductance can be defined by:

$$M = M_{HX} = M_{XH} = \frac{N_H N_X}{\mathcal{R}_m}$$

Substituting these equations gives:

$$M = k\sqrt{L_H L_X}$$

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in which k is the coupling coefficient and is between 0 and 1. For an ideal transformer, the windings said to have perfect coupling with no leakage flux, k is 1.

c) Core Losses (No Load Losses)

In a power transformer the eddy current and hysteresis losses cannot be ignored. In practice, whenever a magnetic material undergoes an alternative magnetization two types of losses occur in it: eddy current loss and hysteresis loss. Eddy and hysteresis losses together constitute no load losses in the transformer. For the purposes of this guide, it is enough to state that eddy loss, P_e , occurs because of eddy currents circulating within the core steel produced due to induced voltage in the core iron in response to the flow of alternative magnetic flux geometrically normal to the width of the core. Hysteresis loss, P_h , is caused by the successive reversal of flux in the magnetic circuit and is proportional to the area of the hysteresis loop in the B-H curve.

$$P_h = k_h f B_{mp}^n$$

It is proportional to the square of thickness of the laminations, the square of the frequency, and the square of the effective value of the flux density as given by:

$$P_e = k_e f^2 t^2 B_{rms}^2$$

where k_h and P_e are constants depending on the materials, B_{mp} is the actual peak value of the flux density, B_{rms} is the rated effective flux density corresponding to the actual rms voltage, t is the thickness of the individual laminations, and n is the Steinmetz constant having a value of 1.6 to 2.0 for hot-rolled laminations and a value of more than 2.0 for cold-rolled laminations due to the use of higher operating flux density in them. Cold-rolled steel has been used in nearly all power transformers since the 1960s.

Both eddy current loss and hysteresis losses can be reduced by using thinner steel laminations, but this increases the cost. A compromise is to use a lamination thicknesses of between 0.23 and 0.27 mm.

Eddy current losses and hysteresis losses are exponentially increased with flux, and consequently, with voltage. The voltage, and therefore the core losses, cannot be allowed to exceed the limit at which the temperature of the hot spot in the transformer rises above the point that will result in a decrease in the life of the insulation. This limit is practically expressed in transformer voltage ratings by the ratio of N_H/N_X . Therefore, a transformer is typically described by its rated voltages V_H and V_X, which gives both the limits and the turns ratio.

Core losses can be modelled as a conductance in parallel with the magnetizing branch; however, it is nonlinear and frequency-dependent. The transformer model presented in Figure 1-2 can now be developed to the transformer in Figure 1-3, which includes a core losses model.

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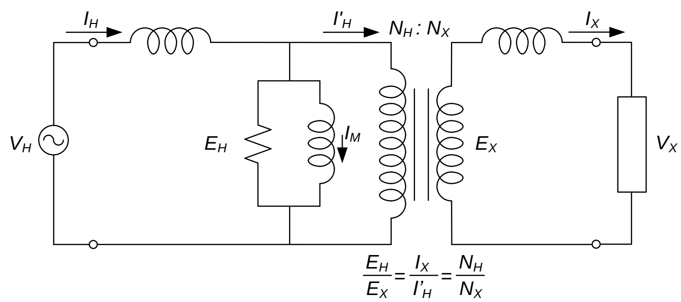

Figure 1-3- Load losses transformer equivalent circuit

d) Load Losses (Conductor Losses)

The term load losses (conductor losses) represents the losses in the transformer that result from the flow of load current in the windings. It comprises the dc resistance losses, the eddy current losses caused by the leakage flux, and the stray losses in the windings and elsewhere in the transformer tank.

Resistance losses (dc resistance losses) are caused by the current flowing through the resistance of the conductors and leads. It is proportional to the conductor length divided by the conductor cross-sectional area. This is true for dc currents. However, taking only resistance losses as load losses is actually an oversimplification for ac currents. In practice, additional conductor losses that affect the transformer design must be taken into account to some extent.

The first additional conductor loss is eddy current loss caused by the leakage flux. As discussed previously, eddy currents induced due to the alternating magnetic field generate local RI^2 losses even if the conductor itself is not carrying any net electrical current. When a transformer is heavily loaded, large amounts of leakage flux can occur. The magnetic fields associated with this leakage flux not only penetrate the winding conductors, but can involve other metallic parts of a transformer such as the transformer trunk and the transformer frame. The eddy currents induced by these fields are proportional to the leakage flux, which in turn is proportional to the load currents. Therefore, the eddy current can be modelled as an additional resistance since it is related to the load current.

Additional stray losses are those losses are associated with the winding and core clamping structure and with the transformer tank [2],[6].

Besides the stray losses, skin effect increases the effective resistance of the conductor. It concentrates current toward the edge in the conductor due to the nature of the alternative load current in the windings, and consequently, it reduces the effective area of the conductor that actually carries the current [2].

The total conductor losses in a transformer, including the eddy-losses component and the skin-effect component, can be represented as an ac resistance given by:

$$R_{AC} = R_{DC} + R_e + R_{Stray} + R_S$$

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where R_{AC} is the ac resistance of the conductor and R_{DC} is its dc resistance, R_e is the eddy current loss equivalent resistance, R_{Stray} is the stray loss equivalent resistance, and R_S is the skin effect equivalent resistance. The load losses are modelled as equivalent to placing a lumped resistance in series with the winding terminal.

Conductor losses increase the transformer temperature, and this temperature is limited in accordance with the standards. Therefore, it is important to reduce the conductor losses, i, which in turn reduces the ac resistance of the windings.

To reduce conductor losses it is not sufficient to reduce conductor dc resistance by shortening the length of the conductor and increasing the cross-section of the conductor because the eddy losses in the conductor will increase faster than the heating losses will decrease. Instead, the conductor is subdivided into a number of small parallel strands insulated from each other to break up the eddy current paths; this can reduce eddy-current and skin effect losses. The strands are joined at the end of the core and make parallel components to carry the current. The parallel components might be involved in circulating current due to different induced EMFs in the strands caused by different loops of strands linking with leakage flux. To avoid this circulating current and further loss, each conductor element is arranged to occupy every possible position in the array of strands so that all elements have the same resistance and the same induced EMF [6].

1.3 Low-Frequency and Switching-Transient Equivalent Circuit

The transformer model developed in the previous sections is the linear model of a transformer in the operating frequency. In this model the core losses and load losses have been taken into account. In practice, the magnetic behavior of a transformer is nonlinear; however, in power system analysis it is assumed to be a linear component. Figure 1-4 shows the equivalent circuit of a single-phase two-winding transformer at the operating frequency. This model is known as the transformer T-equivalent circuit and has been successfully used for many years in steady-state studies and some low-frequency transient studies. Most textbooks and literature use this model to describe the transformer behavior in which R_H and R_L are the series resistances including the conductor losses of each winding and L_H and L_L are the leakage inductances of the windings. The R_m and L_m in the shunt branch represent the core behavior including nonlinearity, saturation and hysteresis, and eddy current phenomena.

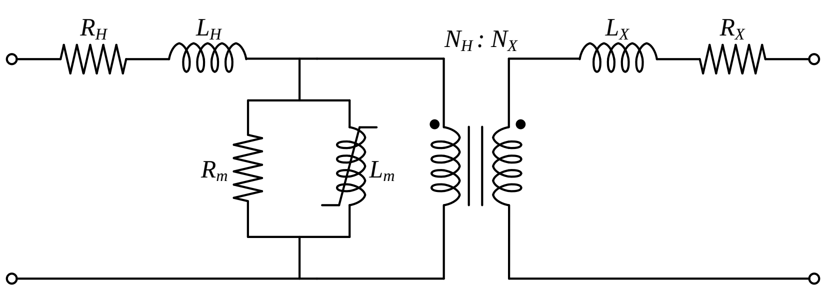

Figure 1-4- Equivalent circuit of a real transformer (T-Model)

The T-model is relatively easy to implement, but except for the winding resistance, in a topological sense other parameters do not have a relationship with the physical components of the

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transformer. The main disadvantage of this model is arbitrarily dividing the series leakage reactance into two series reactances for each side. Another equivalent circuit which is known transformer π-model is shown in Figure 1-5. In this model the internal elements represent physically the magnetic circuit. It has only one leakage inductance in the middle and two magnetizing branches.

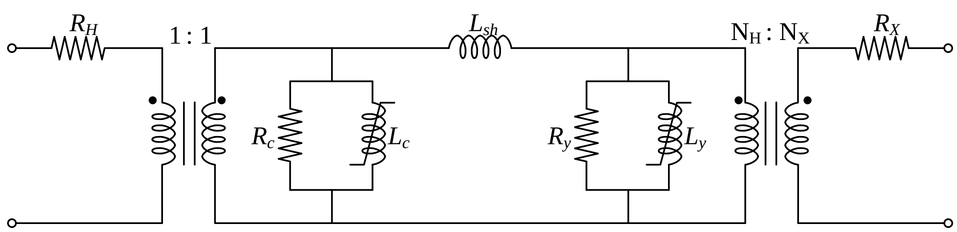

Figure 1-5- Equivalent circuit of a real transformer (π-Model)

1.4 Representation of Transformers in Power Systems

The transformer model in Figure 1-4 is an accurate model of a transformer, but it is not a very useful model. To analyze practical circuits containing transformers it is usually necessary to have the equivalent circuit at a single voltage level; therefore, the equivalent circuit can be referred to either the transformer's primary side or its secondary side. Figure 1-6 shows the transformer equivalent circuits referred to (a) the primary side and (b) the secondary side. Aside from converting the equivalent circuit parameters to one side of the transformer, the model is still more complex than necessary for practical engineering applications. Because the magnetizing branch adds another node to the circuit being analyzed, it increases the complexity of the circuit solution more than is necessary.

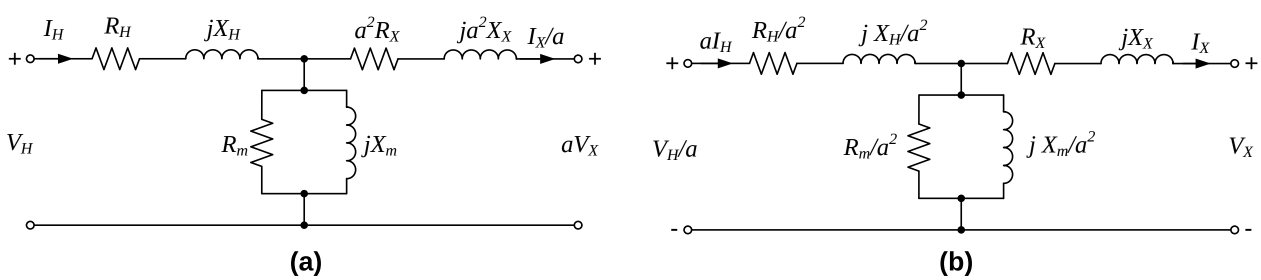

Figure 1-6- Transformer equivalent circuit referred to: a) The primary side b) The secondary side

Under rated conditions (i.e., maximum current and voltage) in large transformers the exciting current is less than 1% of the full load current. Therefore, the exciting current effect on the voltage drop on the leakage inductance and winding resistance is negligible. Under maximum rated current the total voltage drop on the winding resistances and on the leakage inductances does not exceed 6% of the rating voltage in a typical transformer [7]. Therefore, the effects of the winding current and voltage across the winding resistance and leakage inductance on the magnetizing branch voltage in Figure 1-6 are small, and their effects on the magnetizing current can be ignored. These considerations allow the core shunt branch to be moved to the one terminal in the transformer equivalent circuit. The obtained approximated equivalent circuit presented in Figure

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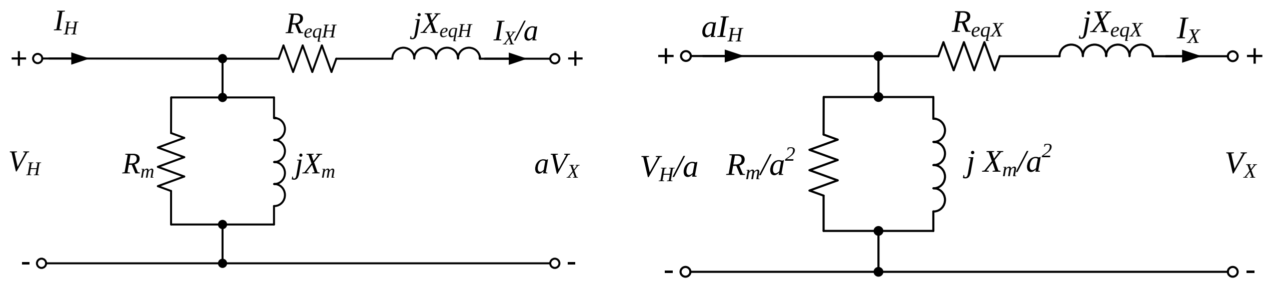
1-7 is called the simplified transformer equivalent circuit. It is accurate enough for modelling purposes and useful in power systems studies. This approximation can be improved by adding the winding resistance and leakage reactance to the core's resistance and reactance, but that is not often done.



$R_{eqH} = R_H + a^2 R_X$ and $X_{eqH} = X_H + a^2 X_X$

(a)

$R_{eqX} = \frac{R_H}{a^2} + R_X$ and $X_{eqX} = \frac{X_H}{a^2} + X_X$

(b)

Figure 1-7- Simplified transformer model used in power system analysis referred to: a) The primary side b) The secondary side

Normally in power system study the system parameters are expressed in per unit of a base value calculated using a selected voltage and power base. For example, in a transformer at the high-voltage side the nominal high voltage is the base voltage, and at the low-voltage side the base voltage is the nominal voltage at the low side. Therefore, in per unit terms voltage at both sides of the transformer is 1.0 pu. Using the per-unit values removes the need for the ideal transformer in the analysis, and the transformer model becomes that given in Figure 1-8.

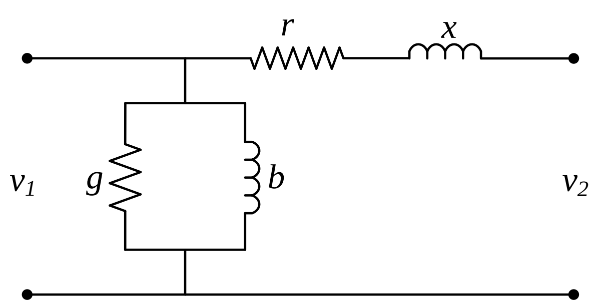


Figure 1-8- Simplified equivalent circuit of a two-winding transformer in per unit

In some applications, the magnetizing branch may be neglected entirely without causing a serious error. In this case, the equivalent circuit of the transformer is reduced to a simple series impedance of Z_{eqH} , as shown in Figure 1-9. There is no need to obtain no-load losses test results. It is a good approximation in most cases, unless the core is saturated [7], [13].

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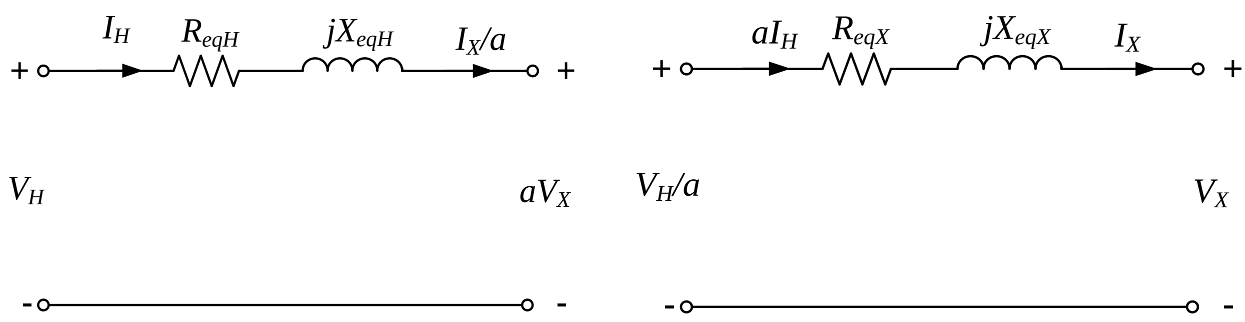

Figure 1-9- Simplified transformer model referred to: a) The primary side b) The secondary side

This simplification is sometimes used to express transformer series impedance. In this method, the impedance is expressed as a percentage voltage drop in the transformer at full load current [3], [4]. For example, an impedance of 7% means the voltage drop at full-load current is 7% of the open-circuit voltage, or, alternatively, with the secondary terminals short-circuited, 7% voltage will cause full load current to flow through the windings.

1.5 Parameters Determination in the Transformer Model

It is possible to technically determine all parameter values in the transformer model presented in Figure 1-4 by carrying out experiments. As mentioned in the previous section, the simplified model shown in Figure 1-7 is an adequate approximation of a transformer model. The parameters of this model can be determined by open-circuit (no load) and short-circuit (load) tests.

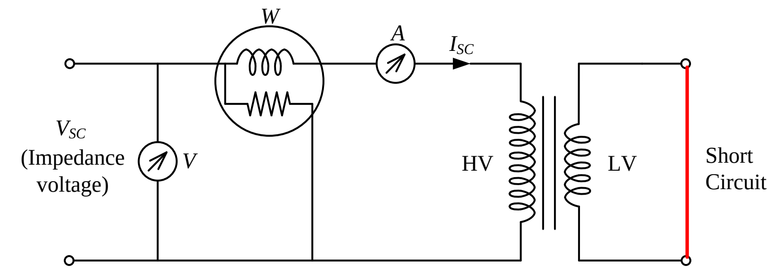

Figure 1-10- Short-circuit test diagram

$$R_{eqH} = \frac{P_{SC}}{I_{SC}^2}$$

$$X_{eqH} = \frac{\sqrt{(V_{SC} I_{SC})^2 - P_{SC}^2}}{I_{SC}^2}$$

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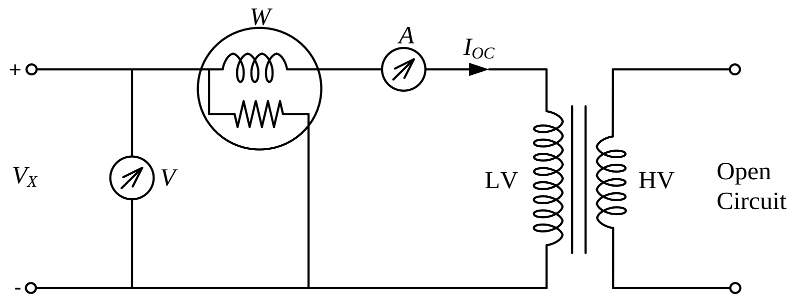

Figure 1-11- Open-circuit test diagram

$$\frac{R_m}{a^2} = \frac{V_{OC}^2}{P_{OC}}$$

$$\frac{X_m}{a^2} = \frac{V_{OC}^2}{\sqrt{(V_{OC} I_{OC})^2 - P_{OC}^2}}$$

R_{eqH} is the equivalent ac resistance referred to the high-voltage winding. As explained previously, it includes the dc resistance of the windings, the resistance equivalent for eddy losses in the windings, the skin effect, and the stray losses in structural parts. It is not practical to apportion parts of stray losses to the two windings. Therefore, if the resistance parameter is required for each winding it is usually assumed that:

$$R_H = R'_X = a^2 R_X = \frac{R_{eqH}}{2}$$

Similarly, it is assumed that:

$$L_H = L'_X = a^2 L_X = \frac{L_{eqH}}{2}$$

although there are some concerns regarding its applicability. [7].

Practically, percentage reactance (% X) might be taken to be the same as percentage impedance (% Z) because R is much smaller than X. This approximation may not be true for very small distribution transformers.

1.6 Transformer's T-Model and π-Model

The transformer T-model in Figure 1-4 is a well-known model that has been used for power system studies for many years. However, it still has the series impedance separation disadvantage. Another disadvantage is it adds an extra bus to the power system study model for the magnetizing branch of the model. The π-model presented in Figure 1-5 does not add an extra bus; however, an issue with this model is dividing the magnetizing branch.

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Theoretically, a two-winding transformer can be considered as a two-port network. In Appendix C two-port network analysis and deriving a π-model from a T-model are described. For the purpose of simplification, a transformer equivalent circuit transferred to the high-voltage side, as shown in Figure 1-12, is considered to be a two-port network. Assuming the series impedance is not greater than 7% and the magnetizing current is not greater than 3%, the measured magnetizing parameters can be doubled to build the π-model magnetizing branches. However, the π-model series impedance can be obtained from load losses, as described earlier. Figure 1-13 shows the transformer π-model and equivalent two-port network.

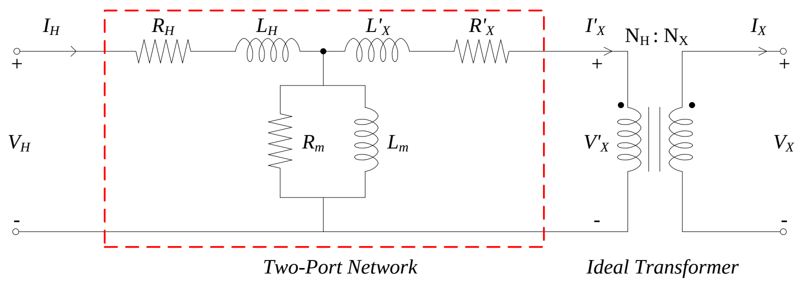

Figure 1-12- Transformer T-model as a two-port network

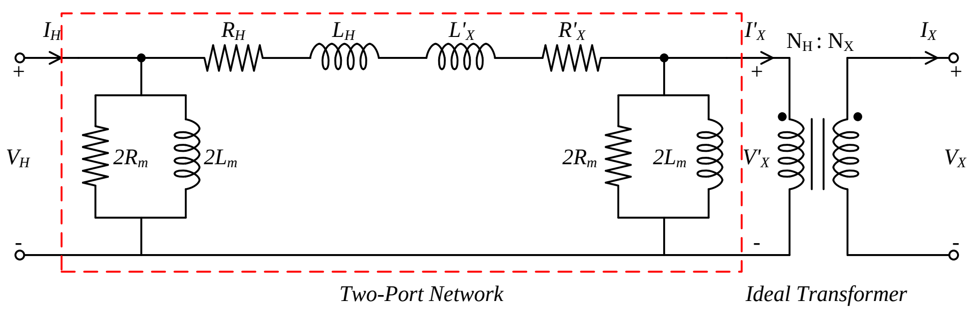

Figure 1-13- Transformer π-model as a two-port network

1.7 Assumptions, Terms, and Designations

The following assumptions have been applied when preparing this guide, unless stated otherwise:

- There is positive sequence phase rotation and all the configuration diagrams were built on positive sequence phase rotation.
- An attempt has been made to analyze the internal connections to the transformer, and what occurs behind the bushing that is not changeable by the end user is described. However, diagrams may represent external phase connections and their shift. The connection diagrams usually show the high-voltage winding above and the low-voltage winding below. Therefore, the direction of induced voltages at each winding set is on the upper part of the windings, as indicated by a bold point on each winding in Figure 1-14.
- There is no difference between the windings in a winding set. However, practically, the magnetic coupling between the windings in a winding set is dependent on the physical parameters, such as position in magnetic core, but in this consideration it is very difficult to take that into account. It is also outside of scope of this modelling guide.

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- The load losses or short-circuit test is performed from the high-voltage side, which means the low-voltage high-current side is short-circuited.
- The open-circuit test is performed from the low-voltage side, which means the transformer is excited by low voltage and the high-voltage side is left open.

The winding connections in this guide are designated as follows:

- High Voltage: always capital letters
- Neutral brought out: N
- Delta: D
- Star: Y
- Zigzag: Z
- Low Voltage: always small letters
- Neutral brought out: n
- Delta: d
- Star: y
- Zigzag: z

This guide describes transformers used in the North American network, and particularly, transformers used in the Alberta network, so the phases A, B, and C and the bushing names H and X will be used generally.

Winding: In this guide a “winding” denotes a single continuous coil of wire on a single-core leg; a “winding set” denotes the set of three windings that constitute the three phases in a three-phase transformer, each on different core legs with a terminal at one voltage level (for example, H1, H2, and H3); and a “phase set” refers to the two or more windings that are found on the same core leg, as shown in Figure 1-14. The windings in the transformer figures are given the terms W1-W9. The winding sets associated with the various voltage levels, each on a different core leg, are assumed to be the following:

- Winding Set 1: W1, W2, and W3
- Winding Set 2: W4, W5, and W6
- Winding Set 3: W7, W8, and W9 (seen in three-winding and zigzag transformers).

In four-winding transformers the windings are given the proper terms accordingly. Eventually, the windings that share a common core leg are the following:

- Core Leg 1: W1, W4, W7, and W10
- Core Leg 2: W2, W5, W8, and W11
- Core Leg 3: W3, W6, W9, and W12

It is difficult to classify the terms of the zigzag windings among three core legs because they cross-connect core legs. Generally, it does not matter which winding is given which number, but it is important when the second set of windings is connected to the various bushings because this operation shifts phase angles in positive and negative sequences across the transformer.

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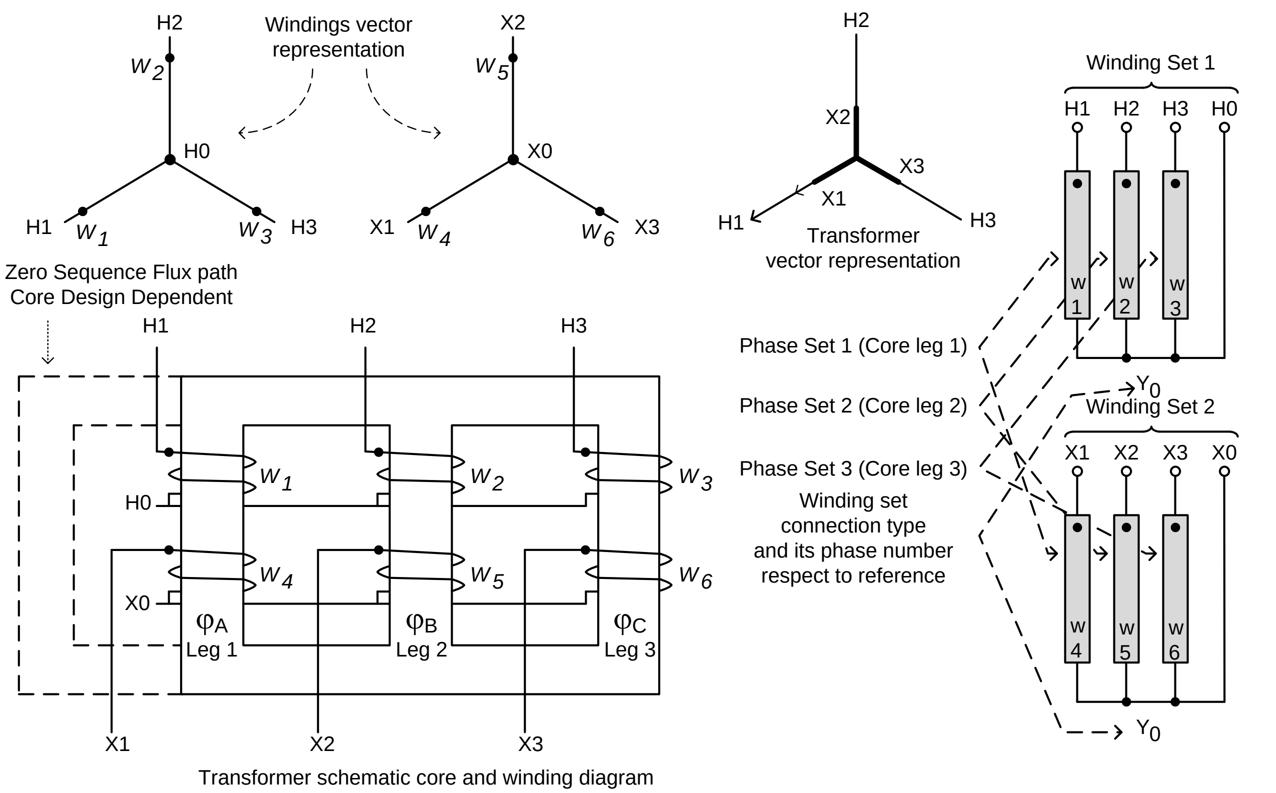

Figure 1-14- Basic transformer representation

1.8 Single-Phase Transformers

The physical structure of a single-phase transformer is simpler than that of a three-phase transformer. A single-phase transformer is a primary winding and a secondary winding wound around the same magnetic core (shell type) or around two legs of a core-type magnet core (core type). They can be used in single-phase circuits or in three-phase systems as a set of three transformers in which the primary and secondary winding set of each phase is wound around separate core legs. The primary winding of a single-phase transformer can be connected between a phase conductor and ground or between two phase conductors of an ac system. A single-phase transformer may have two windings, three windings, or more than three windings, as three-phase transformers do. Figure 1-15 shows a termination bushing of a single-phase transformer.

According to the symmetrical operation of power systems, single-phase transformers are to be used at the end points of a distribution network as distribution transformers. In high-power transmission systems, three single-phase transformers are used as a set to make three-phase station transformers.

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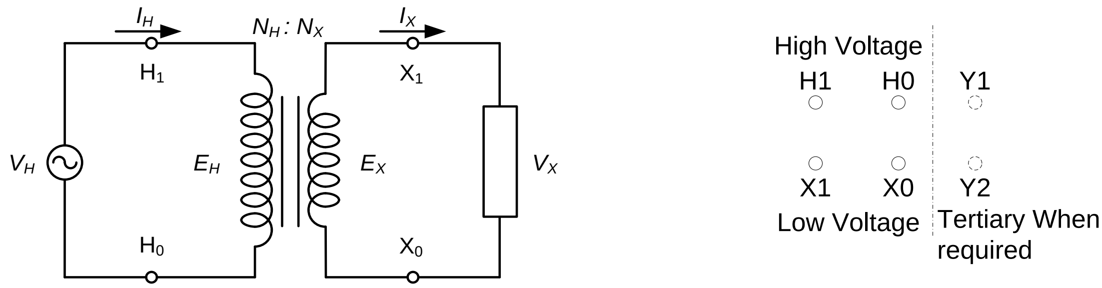

a) Electrical Diagram **b) Bushing Termination**

Figure 1-15- Single-phase transformer bushing termination

1.9 Three-Phase Transformers

Transformers used in three-phase systems are usually three-phase transformers with the windings on a three-leg magnetic core. A bank of three single-phase transformers might be used instead of a single three-phase transformer; however, a three-phase transformer has a number of important advantages compared to three single-phase units: it is more efficient, lighter, smaller, and less expensive. A three-phase transformer requires less floor space and has significantly less external wiring. However, a bank of three single-phase transformers offers the advantage of flexibility: if there is an unbalanced load for a long period of time, one or more transformers in the bank can be replaced by a transformer with a larger or smaller kVA rating. A malfunctioning single-phase transformer in a bank of three transformers can be easily replaced; but the entire common-core three-phase transformer would have to be replaced in the event of malfunction. However, except in special cases such as the upper end of the size range, the use of three single-phase transformers is not common, and most three-phase power transformers are three-phase with windings on a single multi-leg core.

Three-phase transformers are categorized into two types according to their winding/core configuration: shell type and core type. Most large transformer manufacturers make core-type transformers. In a shell-type transformer the flux return path of the core is closed out of the windings, and its magnetic circuit is very similar to three single-phase transformers. In a core-type transformer the first three legs are surrounded concentrically by the windings of the three phases. Figure 1-16 shows the winding structure of different types of three-phase transformers. As shown in the figure, a core-type transformer may have three, four, or five legs. In this guide, the term three-phase transformer is applied only to a three-legged core-type transformer because that is the type most widely used in power systems for economic reasons. If the transformer is not a three-legged core-type transformer, the transformer type will be clearly stated.

In a three-legged core-type three-phase transformer the magnetic circuit of each phase is mutually connected in that the flux of one phase must return through the other two phases. Therefore, in the normal operation condition the total instantaneous magnetic flux in each core section due to the fundamental excitation current is expected to be zero.

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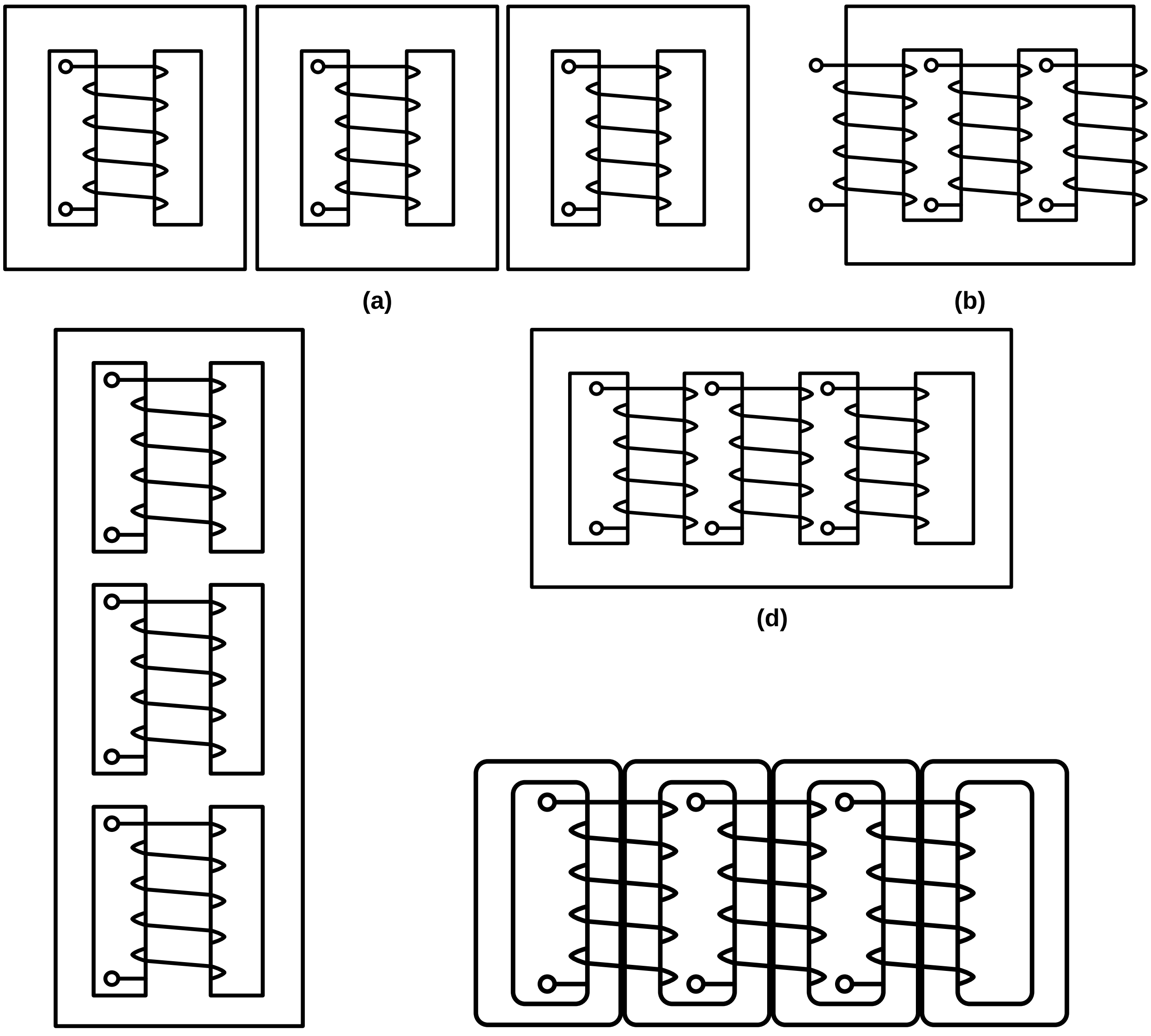

Figure 1-16- Schematic winding structures of three-phase transformers: a) Bank of three single-phase or triplex core, b) Three-legged stacked core, c) Shell core, d) Five-legged stacked core, and e) Five-legged wound core

Figure 1-17 shows different terminations and the nomenclature of single three-phase transformers used in standards, studies, sales documents, books, and papers.

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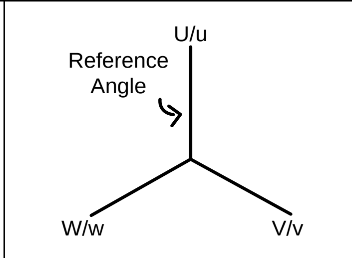
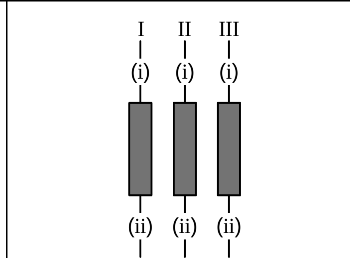
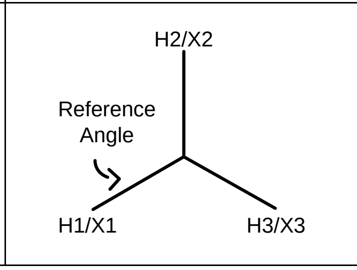
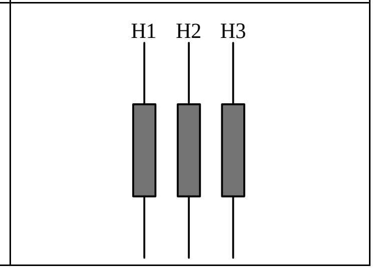
	Phases and Bushing Names	Transformer Phasors	Winding Terminology
IEC 60076-1	High Voltage H0 U V W X0 u v w Low Voltage		
IEEE C57.12.10	High Voltage H0 H1 H2 H3 X0 X1 X2 X3 Low Voltage		

Figure 1-17- Terminations and nomenclature of single three-phase transformers

Whether the three-phase winding is or is not connected to ground depends on the application; it does not matter what type of magnetic structure a transformer has. Transformers designed to be grounded on the neutral end of the primary usually have only one neutral bushing to connect to the system ground. This connection must always be closed. If the neutral end of the primary winding is always grounded it is possible to grade the high-voltage insulation and have less insulation at the neutral end of the winding. The primary-voltage designation on the nameplate of a graded insulation transformer will include the letters “GRDY” as in “12470 GRDY/7200”, which indicates it must be connected phase-to-ground on a grounded wye system.

1.9.1 Three-Phase Winding Configurations

Most three-phase power transformers have a wye and/or a delta winding connection; however, occasionally a zigzag connection is used in situations in which a high zero-sequence impedance is required. Within these three configurations, the three-phase winding configuration can be created in a number of ways, but only a few versions of each method normally occur in practice.

An autotransformer has a winding configuration that is different from the three configurations already discussed. It is described separately.

1.9.2 Angular Phase Shift Across Three-Phase Transformers

Angular displacement in three-phase transformers is defined as the phase angle in degrees between the line-to-neutral voltage of the reference-identified high-voltage terminal and the line-to-neutral voltage of the corresponding identified low-voltage terminal. The angle is positive when the low-voltage terminal lags the high-voltage terminal. The convention for the direction of rotation of the voltage phasors in transformers is always anti-clockwise. The 12 hours “clock” indicator is used to indicate the phase displacement angle, and each hour represents 30°. The minute hand

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is set on 8 o'clock (instead of 12 o'clock according IEC standards). It replaces the line-to-neutral voltage of the high voltage winding as a reference. This position is always the reference point shown, as can be seen in Figure 1-17. Because the rotation is anti-clockwise, 9 = 30° lagging (low voltage lags high voltage with 30°) and 7=330° lagging or 30° leading (low voltage leads high voltage with 30°). According to the IEC standard 1 = 30°, 2= 60°, 3 = 90°, 5 = 150°, 6 = 180°, 11 = 330°, and 12 = 0° or 360° [IEC 600-71].

1.9.3 Wye-Winding Configuration

In the Y connection, the low-voltage ends of all three windings are connected to a common point, which may or may not be grounded. The line current flows directly into the winding. Regardless of what type the configuration of the other windings is, if there is balanced loading of the transformer no current will flow to the ground from the common point, even if this point is grounded. In practice, there are six ways to interconnect a winding set and the bushings of a transformer, as shown in Figure 1-18, which also shows the vector diagram of each interconnection. As mentioned, it does not matter which term is given to the specific winding; however, in order to know the positive phase sequence from one winding set to another set across the transformer it is necessary to know which winding core is connected to which bushing.

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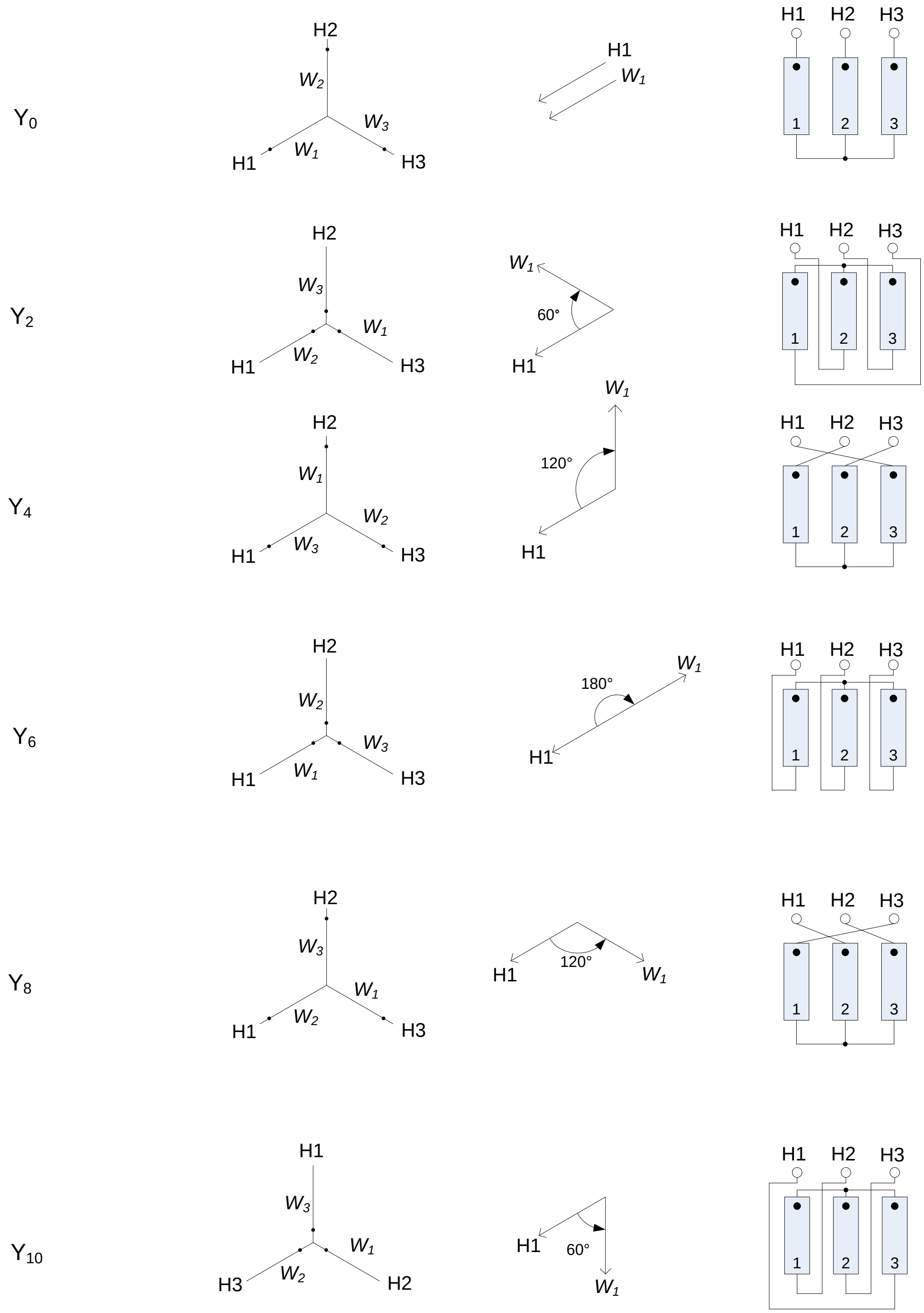

Figure 1-18- Six ways to connect a wye winding

There is a disadvantage to grounding the neutral point of a Y connection in transformers. The grounded neutral point in the transformer serves as a return path for the current when one of the lines or all three of the lines on the Y-connection side is short-circuited to the ground. These fault currents are high, and if not cleared within a fraction of a second they can create a significant

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system disturbance. The ground fault currents have a high third harmonic component that can disrupt local telecommunication networks and can cause pilot relaying in the power system.

1.9.4 Delta Winding Configuration

In practice, there are two different ways to interconnect a delta winding to the bushings of the transformer: with a vector of D1 or with a vector of D11, as shown in Figure 1-19. Four other arrangements are possible, but they involve rotating the phases, and are therefore rarely used.

The delta connection offers low impedance to third harmonics and traps the ground fault current in the delta. If a ground fault occurs in the delta-connected side of the transformer, the fault current will be lower (and mathematically it will be zero) because there is no return path for the current to complete the circuit in that transformer. In such a case, the protection devices may not work due to the lower current than they have anticipated. Another issue in the delta-connected side of the transformer during an unbalanced ground fault is the voltage shifting problem. Depending on the fault type and location, voltage on the un-faulted phases may be shifted and exceed the maximum rated voltage during the fault. These are two reasons that grounding at least one side of the transformer is required in the system.

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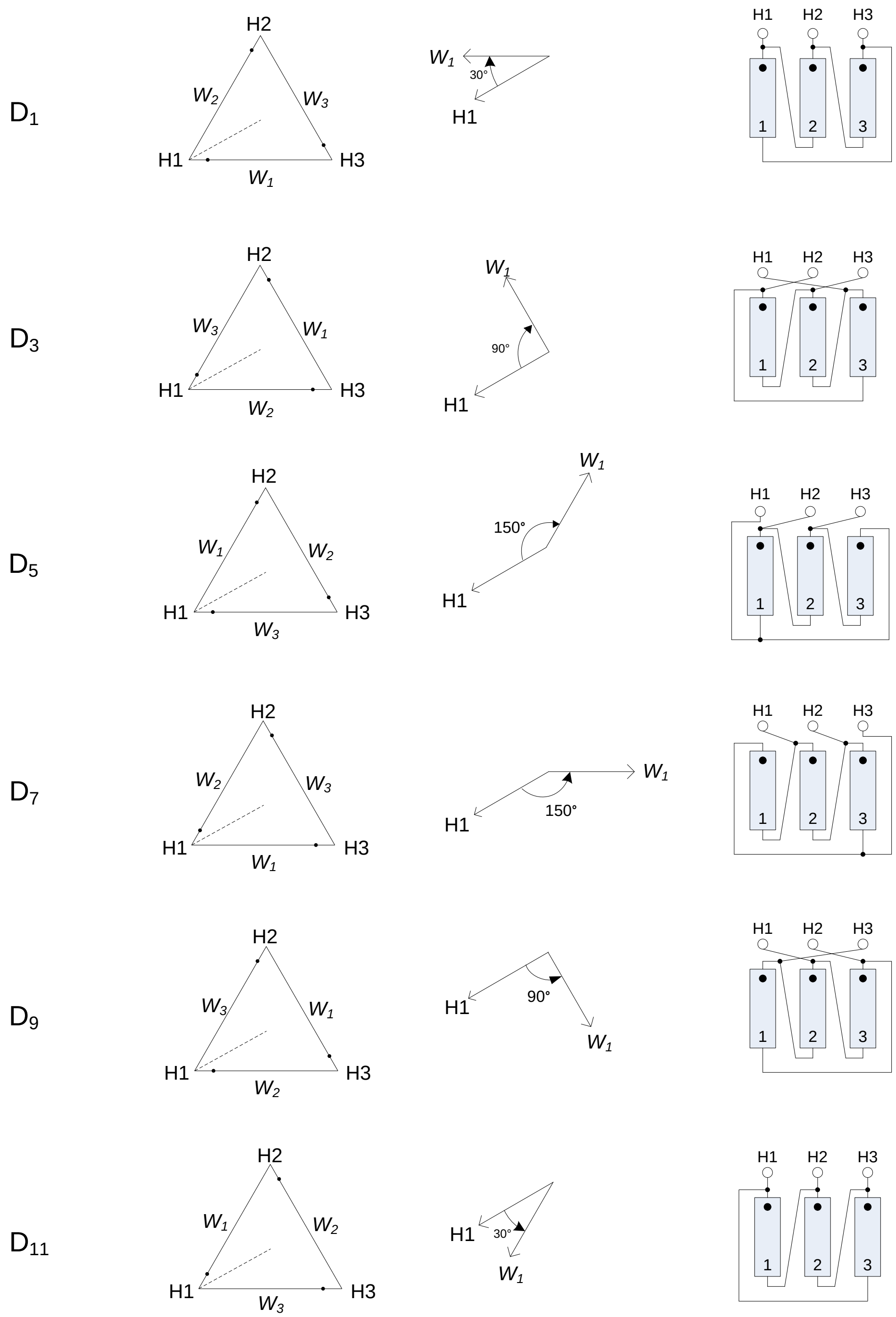

Figure 1-19- Six ways to connect a delta winding

1.9.5 Zigzag (Interconnected Star) Winding Configurations

A zigzag connection (interconnected star connection) has some of the features of the wye and delta connections and combines the advantages of both. It is not commonly used where these features and advantages are not needed. In a zigzag connection on one side of a transformer each phase winding has two equal sections of winding connected in series on two core legs. In a manner similar to that used in an autotransformer, the lower-voltage-level windings are connected in wye, +30º or -30º. These arrangements are shown In Figure 1-20.

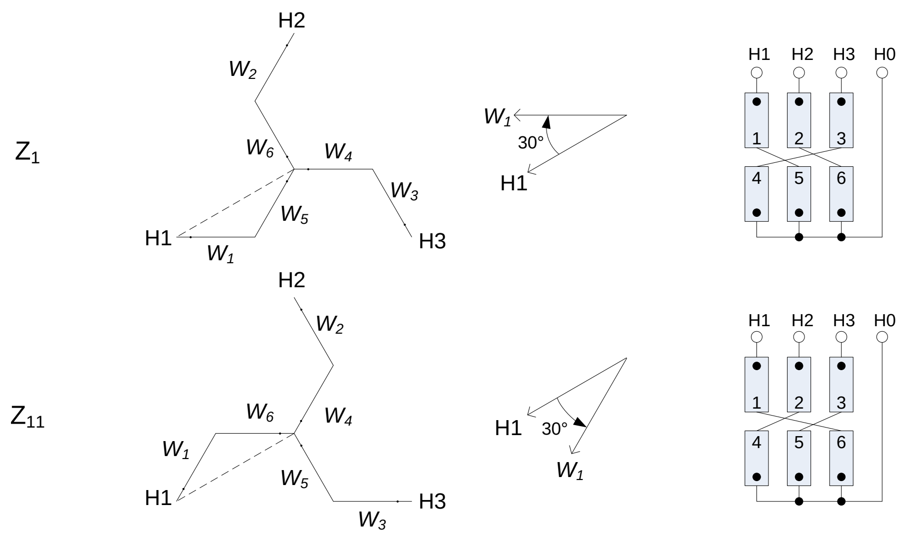

Figure 1-20- Two practical zigzag connections of four possible configurations

1.9.6 Autotransformer Winding Configurations

Autotransformers are exclusively used to interconnect high-voltage systems. It is economically advantageous to share the common section of the high-voltage winding with the low-voltage winding. An autotransformer has common windings between the low-voltage terminals and the neutral, and a series windings between the low-voltage terminals and the corresponding high-voltage terminals. As shown in Figure 1-21, each winding has two ends and one terminal in the middle of the winding that serves as the tap terminal. Three-phase autotransformers are Y-y-connected although sometimes a delta-connected tertiary winding is provided. The tertiary may have its terminals brought out to supply local load, or it may be "buried" and not have any external connections. Therefore, the system to which autotransformers connect must be (usually solidly) grounded. In theory, an autotransformer is a two-winding transformer with $N_{Ser} + N_{Com}$ turns in the primary winding and N_{Com} turns in the secondary winding as shown in Figure 1-21.

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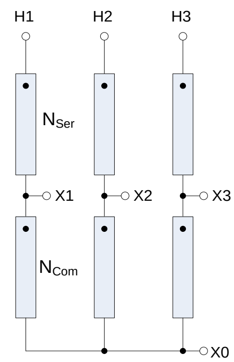

Figure 1-21 - An autotransformer winding

An autotransformer winding is connected in only one way. There is no phase shift in the autotransformer between the high-voltage and lower-voltage winding connections. Any phase shift to the tertiary winding is the same as that of a wye/delta transformer.

1.10 Autotransformers Equivalent Circuit

An autotransformer is smaller than a transformer with the same features. Its core size is determined using the largest ratio tap position, as follows:

$$MVA_{Core} = \frac{V_H - V_X}{V_H}\, MVA_{Autotransformer}$$

An autotransformer has smaller iron losses than a conventional transformer, and it has less copper loss because the common winding only carries the difference between the low-voltage and high-voltage windings. The closer the low-voltage and high-voltage winding voltages are, the greater the advantage of using an autotransformer is. In practice, this ratio is approximately 2.

The circuit model of the two-winding autotransformer in Figure 1-22 can be presented using separate windings. If the magnetizing current is not taken into account, the transformation equation can be given as:

$$a_T = \frac{N_H - N_X}{N_X} = \frac{E_1}{E_2} = \frac{I_X - I_H}{I_H} = \frac{N_H}{N_X} - 1$$

In autotransformers a ratio called a co-ratio is usually used. It is defined as:

$$R = \frac{N_H - N_X}{N_H} = \frac{V_H - V_X}{V_H}$$

The voltage equations from the primary and secondary side can be written as, respectively:

$$V_H = E_1 + Z_1 I_H + V_X$$
$$V_X = E_2 - Z_2(I_X - I_H)$$

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Multiplying the previous equation by a_T and substituting in two other equations gives:

$$V_H = Z_1 I_H + {a_T}^2 Z_2 I_H + (a_T + 1) V_X$$
$$V_H = Z_1 I_H + \left(\frac{N_H}{N_X} - 1\right)^2 Z_2 I_H + \frac{N_H}{N_X} V_X$$

These equations show that the leakage impedance of an autotransformer is similar to the leakage impedance of a regular two-winding transformer with the same windings not auto-connected. Therefore, in an autotransformer the equivalent series resistance and reactance are:

$$R_{eq\ H} = R_1 + \left(\frac{N_H}{N_X} - 1\right)^2 R_2$$
$$X_{eq\ H} = X_1 + \left(\frac{N_H}{N_X} - 1\right)^2 X_2$$

To model the parameters in the secondary side it can be found that:

$$V_X = \frac{V_H}{a_T + 1} - \frac{Z_1}{(a_T + 1)^2} I_X - \left(\frac{a_T}{a_T + 1}\right)^2 Z_2 I_X$$
$$V_X = \frac{N_X}{N_H} V_H - \left(\frac{N_X}{N_H}\right)^2 Z_1 I_X - \left(\frac{N_H - N_X}{N_H}\right)^2 Z_2 I_X$$

and consequently:

$$R_{eq\ X} = \left(\frac{N_X}{N_H}\right)^2 R_1 + \left(\frac{N_H - N_X}{N_H}\right)^2 R_2$$
$$X_{eq\ X} = \left(\frac{N_X}{N_H}\right)^2 X_1 + \left(\frac{N_H - N_X}{N_H}\right)^2 X_2$$

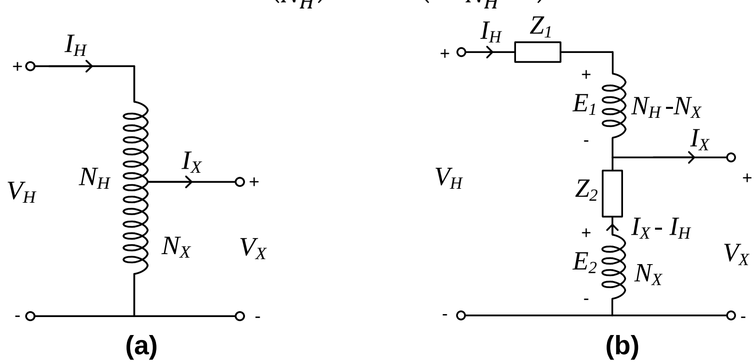

Figure 1-22- Two-winding autotransformer: a) The schematic diagram, b) The circuit model based on a separate windings circuit model

For completeness, the magnetization branch can now be taken into account. Therefore, the equivalent circuit of the autotransformer can be shown as in Figure 1-7, in which the parameters

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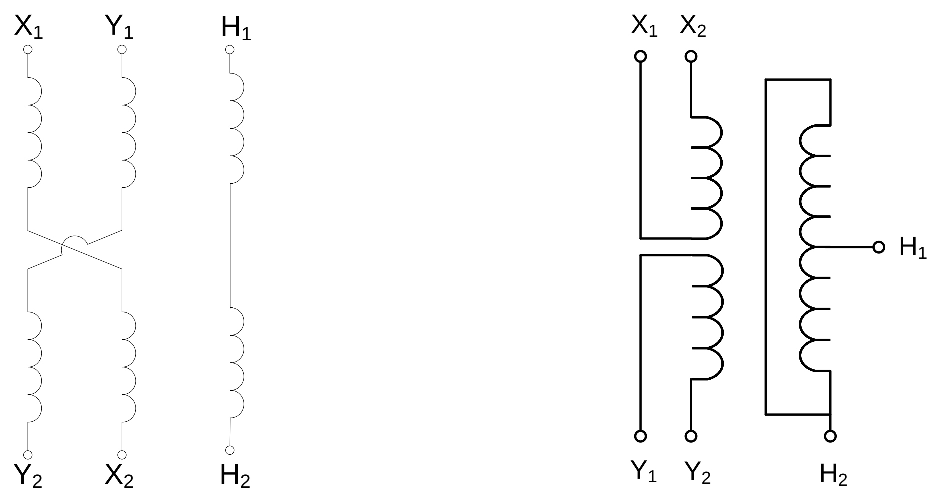
are as proposed in the previous equations. This model is valid for both step-up and step-down autotransformers. In a manner similar to that used with the other types of transformers, the autotransformer's leakage impedance can be obtained through test measurements with the low-voltage terminal short-circuited [10]. The magnetization branch parameters can also be determined through a no-load test. The procedure to determine the equivalent circuit parameters for an autotransformer is the same as the procedure for a regular transformer. In an autotransformer connection the short-circuit impedance is lower than that of a regular transformer with similar specifications, which is sometimes considered to be a disadvantage of the autotransformer connection.

1.11 Multi-Winding Transformers

1.11.1 Double Secondary Transformer [3]

A double secondary transformer is a special type of transformer that is sometimes used for generator transformers in applications in which each low-voltage winding is supplied from one generator. When designing a double -secondary transformer it is necessary that both low-voltage windings be disposed symmetrically with respect to the high-voltage winding so both have be identical impedances to the high-voltage winding. This can be done with either of the arrangements shown in Figure 1-23. In Figure 1-23-a there is a crossover between the two low-voltage windings halfway up the limb. In practice, the arrangement shown in Figure 1-23-b (a "Jones" connection) would be used.



a) Closely coupled **b) Practical double-secondary transformer**

Figure 1-23- Double-Secondary transformer winding arrangements

1.11.2 Three-Winding Transformer

Another type of transformer is the three-winding transformer, which is a subset of the multi-winding transformers. In addition to the usual primary and secondary windings, a third winding (tertiary winding) is added to each phase. Having three windings can serve several purposes:

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- Three windings allow the connection of three systems with different operating voltages.
- Three windings provide electrical isolation between dual input circuits or dual output circuits having the same operating voltage.
- If the third winding is delta-connected, this can stabilize voltages, supply third harmonic currents to magnetize the transformer core, filter third harmonics from the system, and provide grounding bank action when the primary and secondary windings are both wye-connected. In practice, this third winding is called the tertiary winding. It will circulate third harmonic currents. This arrangement is used in many transformers, including autotransformers where the high-voltage winding and the low-voltage winding are wye-connected and the tertiary is delta-connected.

The standard labels for the third-winding bushings in a single-phase transformer, are Y1 and Y2, and in a three-phase transformers they are (Y0), Y1, Y2, and Y3, as shown in Figure 1-24.

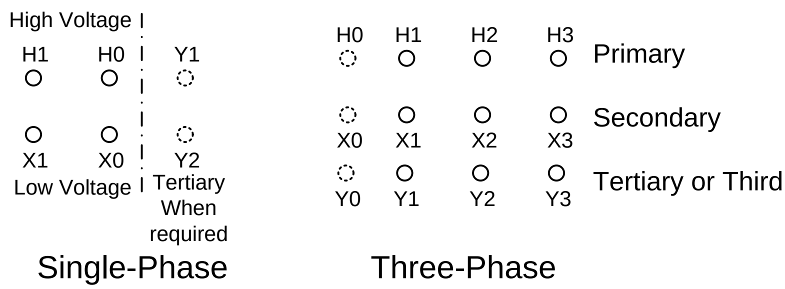

Figure 1-24- Third winding (tertiary) with terminals brought out to bushings

The third winding may serve several functions at the same time. It helps stabilize the primary and secondary voltages, it provides a grounding bank action to partially shield the primary circuit from secondary ground currents, and it supplies voltage to the other components or transformers. For example, a 13.8 kV delta-connected tertiary winding serves these functions and may supply voltage to the station service auxiliary transformer.

Sometimes the delta-connected tertiary winding is not required for an external load and is only intended to magnetically interact with the primary and secondary windings; therefore, it will not have any external terminal connections. In such cases the tertiary winding is referred to as an "embedded" or "buried" tertiary. Sometimes one corner is brought out and grounded internally to ensure the winding reference voltage is unable to drift.

The positive-sequence equivalent circuit of a transformer with a buried delta-connected winding is usually derived without considering the delta-connected winding. Even if that winding has been modelled, it is not taken into consideration because there is no load on it. In zero-sequence, the series impedance of the delta-connected winding appears in parallel with the magnetizing branch of the transformer. Therefore, a buried delta winding in the transformer does not change the configuration of the zero-sequence equivalent circuit of the transformer that does not have a buried winding. Normally, the test report of a transformer with a buried delta-connected winding

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does not include any load-losses test results for this winding. However, a manufacturer might test this winding before closing the tank but not report it in the summary test report issued on the transformer. For example, the test report of a Y-Y-connected transformer with a buried tertiary winding would include load losses test results of the primary and secondary windings and the zero-sequence equivalent circuit parameters of the Y-Y-connected transformer.

1.12 Tap Changers

The primary role of a transformer is to convert electrical energy at one voltage level to another voltage level. In practice, power transformers, in power systems, with tap changer capabilities are used to control the voltage, the phase angle, or both in a regulated circuit. For each transformer installed in a network, there is an ideal (optimal) voltage ratio for optimal operation of the system. In practice, this optimal voltage ratio varies depending on the operating conditions of the total network. For power systems to operate satisfactorily, transformer voltage ratios need to be adjustable (this can be achieved by interrupting or not interrupting the flow of energy during adjustment). A tap changer performs this function in a transformer. The tap changer may be on-load or off-circuit.

1.12.1 Off-Circuit Switch or De-Energized Tap Changer (DETC)

As the name implies, this type of tap changer can only be operated with the transformer disconnected from the network. It has a limited range of operation, commonly providing a range of ± 2.5 to ± 5.0 %.

Off-Circuit switches are often used on transformers that have an on-load tap changer. The use of both increase the size and cost of the transformer significantly.

The tap position on this DETC-type tap changer is changed infrequently. It is essential that the switch is only operated when the transformer is completely disconnected from the system. If there is any power voltage on between the taps, attempting to operate the switch will probably result in a three-phase short on the switch and the destruction of the transformer.

1.12.2 On-Load Tap Changer

An on-load tap changer capable of changing the turns ratio of a transformer while online is called a load tap changer (LTC) or an on load tap changer (OLTC). There are two basic types of LTC, “Reactor” and “Resistor”.

- Reactor-Type LTC tap changer: In a reactor-type tap changer there is a small mid-point autotransformer (MPA) in each phase. Before changing tap, the two ends of the MPA are connected to the tap winding positions and the midpoint is connected to position “S” as in Figure 1-25. During the tap change one of the MPA ends is opened and then connected to the next tap in sequence. At this stage the position “S” will be at a voltage midway between the two tap positions, and a controlled current will flow between the two taps. The other end of the MPA is opened and then it is also connected to the next tap. This completes the tap sequence, which takes a fraction of a second.

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- Resistor-Type LTC tap changer: The resistor-type tap changer sequence is similar to that of the reactor-type, except that two resistors are used to control the circulating current that will flow between the two taps. The tap sequence is quicker than that of the reactor type

Because of the inductance inherent in the MPA, the contacts in the reactor-type tap changer tend to wear more quickly.

Figure 1-25 shows the schematic circuit of an LTC-type tap changer. The LTC-type tap changer must follow a special “make-before-break” switching sequence. It must not create a short circuit between any two taps of the winding at any time. Use and placement of the tap windings varies with the application and among manufacturers. Since the transformer model’s parameters depend on the tap position, it is necessary for the transformer modeller to know how tap position affects the parameters. Therefore, a transformer tap changer is explained briefly in Appendix B. For more information refer to [13]. Examination of tap changer techniques is beyond the scope of this guideline due to the amount of detail required.

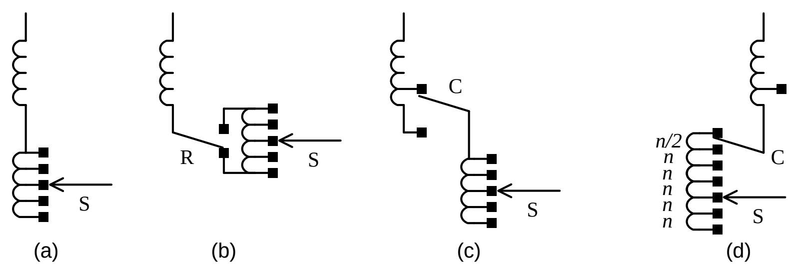
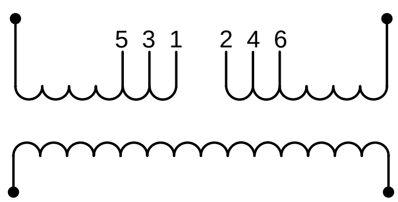


Figure 1-25- Schematic diagrams of LTC-type tap changers: a) Linear, b) Reversing, c) Corse/Fine, d) Linear, neutral end

The transformer name plate will contain the transformer winding schematic and tap changer connection diagrams. Figure 1-26 shows an example of the winding schematic and connection diagram of a transformer that has a DETC-type tap changer on the 138 kV side.



Volts L-L	DETC Position	Leads Connected
144900	A	1 - 2
141450	B	2 - 3
138000	C	3 - 4
134550	D	4 - 5
131100	E	5 - 6

Figure 1-26- A typical winding schematic and connection diagram

Figure 1-27 shows the same transformer with the addition of an LTC-type tap changer on the low-voltage side. It also shows a sample schematic in which an auxiliary transformer is used between the main winding and the LTC to limit the current through the LTC.

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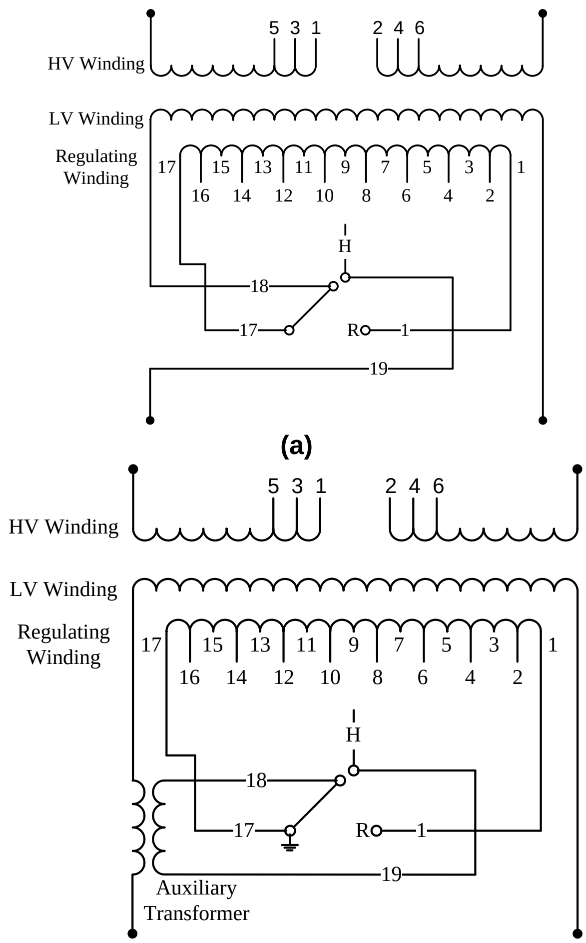

(b)

Volts L-L	LTC Positions	R Connects at Direction		H Connects
		Raise	Lower	
14520	16R	18 - 1	18 - 1	17 - 19
14438	15R	18 - 1	18 - 1	16 - 19
14355	14R	18 - 1	18 - 1	15 - 19
14272	13R	18 - 1	18 - 1	14 - 19
14190	12R	18 - 1	18 - 1	13 - 19
14108	11R	18 - 1	18 - 1	12 - 19
14025	10R	18 - 1	18 - 1	11 - 19
13943	9R	18 - 1	18 - 1	10 - 19
13860	8R	18 - 1	18 - 1	9 - 19
13778	7R	18 - 1	18 - 1	8 - 19
13695	6R	18 - 1	18 - 1	7 - 19
13613	5R	18 - 1	18 - 1	6 - 19
13530	4R	18 - 1	18 - 1	5 - 19
13447	3R	18 - 1	18 - 1	4 - 19
13365	2R	18 - 1	18 - 1	3 - 19
13283	1R	18 - 1	18 - 1	2 - 19
13200	RN	18 - 1	18 - 1	1 - 19
13200	N	18-17	18-17	18 - 19
13200	LN	18-17	18-17	17 - 19
13118	1L	18-17	18-17	16 - 19
13035	2L	18-17	18-17	15 - 19
12953	3L	18-17	18-17	14 - 19
12870	4L	18-17	18-17	13 – 19
12788	5L	18-17	18-17	12 - 19
12705	6L	18-17	18-17	11 - 19
12623	7L	18-17	18-17	10 - 19
12540	8L	18-17	18-17	9 - 19
12458	9L	18-17	18-17	8 - 19
12375	10L	18-17	18-17	7 - 19
12293	11L	18-17	18-17	6 - 19
12210	12L	18-17	18-17	5 - 19
12128	13L	18-17	18-17	4 - 19
12045	14L	18-17	18-17	3 - 19
11963	15L	18-17	18-17	2 - 19
11880	16L	18-17	18-17	1 - 19

(c)

Figure 1-27- A tap-changer schematic diagram obtained from a transformer nameplate: a) LTC-type tap changer in low voltage side without auxiliary transformer, b) With auxiliary transformer, c) Tap voltages

Autotransformers with tap changers present special challenges to transformer designers. There are three ways of connecting a tap changer in an autotransformer without using an auxiliary transformer; these are shown in Figure 1-28 [10].

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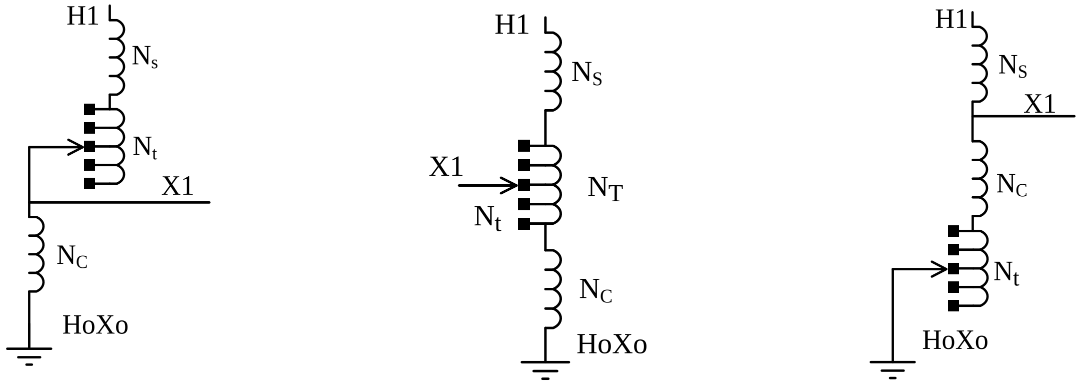

(a) (b) (c)

Figure 1-28- Connecting tap changer in an autotransformer without an auxiliary transformer: a) Line end, with HV variation, b) Line end, with LV variation, c) Neutral end

The connection in Figure 1-28-a is used when the high voltage of the transformer will vary while the low voltage is constant. The flux in the core is constant. The voltage at the high-voltage terminal varies linearly with the number of total turns as expressed in the equation below. In this case, the tap changer and tap winding must be rated for the voltage level of the low-voltage terminal plus the voltage across the tapped section at the high-voltage winding current.

$$\frac{V_H}{V_X} = \frac{N_S + N_C + N_t}{N_C}$$

The connection shown in Figure 1-28-b is used when the low voltage of the transformer will vary while the high voltage will be kept constant. In this case, the flux in the core is constant, as in the previous case. The voltage at the low-voltage terminal varies linearly with the number of total turns as expressed in the equation below. In this case, the tap changer and tap winding must be rated for the voltage level of the low-voltage terminal plus the voltage across the tapped section at the low-voltage winding current.

$$\frac{V_H}{V_X} = \frac{N_S + N_C + N_T}{N_C + N_t}$$

With both connections extra caution should be taken at the design stage because the tap winding is directly exposed to any voltage surge coming through the low-voltage terminal. Also, in a three-phase autotransformer the tap changer must have a full insulation level between phases. However, the volts per turn is constant in both cases, but the tap changer and winding do not carry the minimum current that flows in the common winding in the transformer. Practically, the Jansen-type tap changer is used for transformers in which the low voltage is above 138 kV [10]] (See Appendix B).

Three-phase transformers with a wye-connected tap changer at the neutral point benefit from the use of a low-insulation-level tap changer. For a single-phase transformer the connection shown in Figure 1-28-c can be used. However, if the high-voltage side of the transformer is of fixed voltage

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as the tap position is varied the volt per turn, and therefore the flux in the core, will be variable. As mentioned, this connection type has the disadvantage that the voltage of any tertiary winding will vary. However, there is a cost to obtaining the benefits. In this connection type the low voltage can vary and the high voltage can be kept constant and vice versa. They can be adjusted by the following equation:

$$\frac{V_H}{V_X} = \frac{N_S + N_C + N_t}{N_C + N_t}$$

1.13 Off-Nominal Turns Ratio

As mentioned in Section 1.12, in order to keep voltage levels at neighbouring buses within acceptable limits power transformers with tap-changer capabilities are used. When the adjusted turns ratio N is equal to the ratio of the system-rated voltages, the ratio is called nominal, and the transformer is omitted from the single-line diagram in a per-unit system. When the adjusted turns ratio N is not equal to the ratio of the system rated voltages, it is said the transformer has an off-nominal turns ratio. It should be noted that the off-nominal turns ratio is a definition used for modelling, and it is not to be confused with the physical transformer nominal ratio that may appear on the nameplate of the transformer. The off-nominal turns ratio can be a real number or a complex number. If it is a complex number, the transformer is called a phase-shifting transformer. In such a case, the voltages on the two sides of the transformer differ in phase as well as in magnitude.

In cases in which the off-nominal turns ratio is a real number, for modelling purposes an ideal transformer is put in series with the transformer terminal where the tap changer is located. The ideal transformer allows for the difference in the voltages. The off-nominal turns ratio is represented by the turns ratios of the ideal transformer, which would be around unity. With the transformer ratio being normalized as $t_1{:}1$, the non-unity side is called the tap side. The transformer equivalent circuit is connected to the unity side. Figure 1-29 shows the equivalent circuit for this situation.

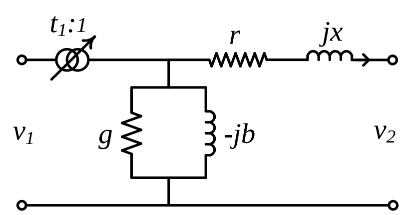

Figure 1-29- The transformer equivalent circuit in a per-unit system with an off-nominal turn ratio

In reality, the series impedance of the transformer is changed when the tap position is changed; however, due to the complexity of the model, it is usually assumed to be unchanged in most power system study software. These changes can be modelled using an impedance correction table.

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The tap changer mechanism is usually designed for placement on the high-voltage side of transformers, as described in Section 1.12. Therefore, the ideal transformer representing the off-nominal turns ratio is considered only at the high-voltage side. For an autotransformer, the ideal transformer representing the off-nominal turns ratio is located at the low-voltage side because the tap changer is positioned at the mid-point terminal of the autotransformer and, in practice, step-down autotransformers are normally used in the network. Figure 1-30 shows the equivalent circuit in a per-unit system of an autotransformer with an off-nominal tap ratio ideal transformer at the secondary side.

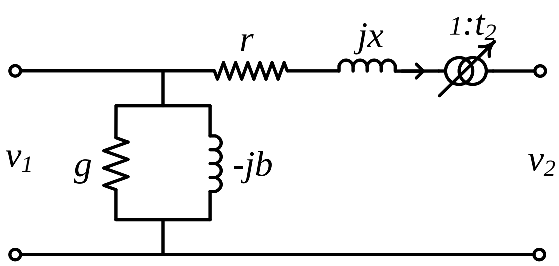

Figure 1-30 - The step-down autotransformer equivalent circuit in a per-unit system with off-nominal tap ratio

1.14 Transformer Data: Nameplate and Test Results

Power transformers usually have a printed or stamped metal nameplate attached to the tank that provides the basic information about the transformer. IEEE C57.12.00 details the information that must be shown on a transformer nameplate depending on the type and kVA rating of transformer. Transformers may be rated based on output power or input power, generally specified in MVA. Transformers are rated based on the power output delivered continuously at a specified rated voltage and frequency under the usual operating condition without exceeding the internal transformer temperature defined in IEEE C57.12.00 [6]:.

- For air cooling, air not to exceed 40 ºC, average temperature in any 24 hour period not to exceed 30 ºC.
- Top oil temperature during operation not to be less than -20 ºC.
- For water cooling, water not to exceed 30 ºC, average temperature in any 24 hour period not to exceed 25 ºC. The minimum water temperature shall not to be less than 1 ºC, unless antifreeze is included to allow operation down to -20 ºC.
- Maximum altitude 1000 m.
- Supply voltage approximately sinusoidal.
- Load current approximately sinusoidal, harmonic factor not to exceed 0.05 percent.
- Secondary voltage not to exceed 105% rated value.
- Load power factor 80% or higher.
- Frequency at least 95% rated value.
- Suitable for outdoor operation.
- Suitable for step-down operation.
- Generator transformers must be designed for step-up operation.

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- Autotransformers shall be designed for either step-up or step-down operation if so required.

Under certain conditions, a transformer can be operated beyond its rating, but such operation decreases the normal operating life of the transformer.

According to the IEEE standard, a transformer nameplate should have the following information:

- Serial Number, Month/Year, name, and location of manufacture
- Number of phases, frequency, MVA rating, voltage ratings, tap voltages, polarity for single-phase transformers or vector diagram for multi-phase transformers, percent impedance, conductor material, winding connection diagram
- Cooling class, temperature rise, type of insulation liquid, liquid volume or tank volume, pressure and liquid data
- Instruction for installation and operation, total weight, and basic impulse insulation level (BIL)
- It should be noted whether the equipment is a transformer or an autotransformer

Figure 1-31 shows a typical transformer nameplate of a two-winding transformer.

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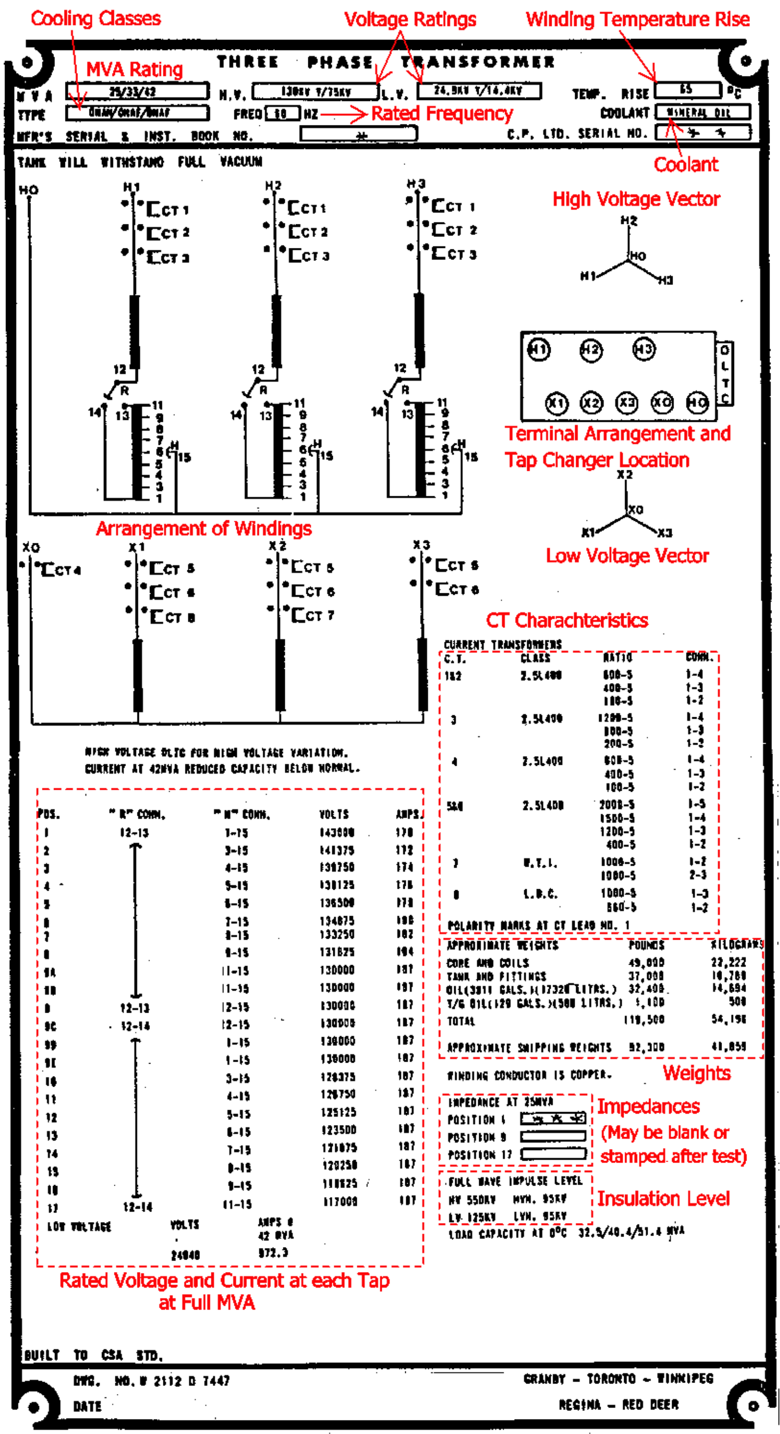

Figure 1-31- Typical nameplate of a two-winding transformer

The manufacturer must provide the test report for the transformer. Figure 1-32 shows the summary page of a typical transformer test report. The format will vary among manufacturers and will depend on the client and the year the transformer was built. The results of the no-load and load-loss tests will be given in the test report and on the nameplate. The following transformer parameters are presented in the test report:

- No-load loss (open circuit) test results.

  As described in Section 1.5, the transformer no-load losses and the excitation current are measured through the no-load losses test. The losses are reported in watts or kilowatts and the excitation current is reported in per unit on specified MVA ratings or in percent of the rated line current of the winding in which it is measured. According to IEEE C57.12.90, when the cooling class of the transformer involves more than one MVA rating, the lowest MVA rating is used to determine the base current. If an open-circuit test is done on two different voltages, both are reported. For nominal voltage, the manufacturer usually guarantees a maximum limit for the loss, which will be given in the report.
- Load loss (short-circuit) test results.

  The loss will be given in watts or kilowatts and the impedance and reactance will be reported in per unit on a specified MVA rating. The manufacturer normally guarantees a maximum limit for the loss, which is stated in the report.
- Zero-sequence test results.

  The format and reported parameters in zero-sequence test reports vary significantly from one transformer to another.

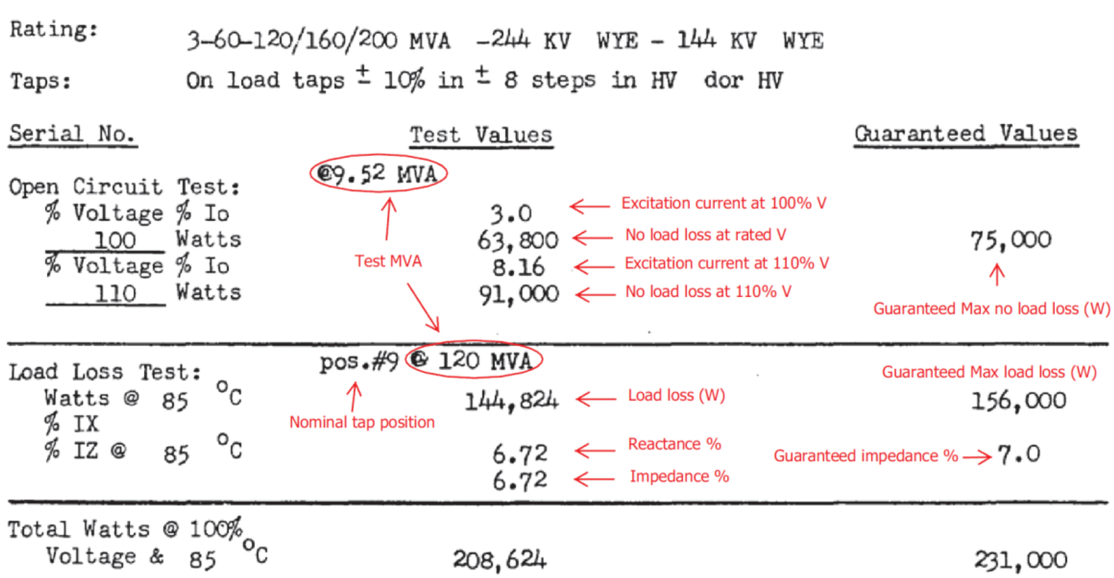

Figure 1-32- Typical test report of a two-winding transformer

1.15 Transformer Standard Tests

Power transformers are usually custom units, so numerous pre-production prototype tests cannot be carried out to ensure a transformer meets the specified requirements and limits and is fit for service. However, it is necessary to determine whether the transformer will be suitable for 30 or more years of service. Quality control procedures are used throughout the design and manufacturing process for each individual unit. It is logical that some testing should be carried out during manufacture as part of the quality assurance process. The quality assurance tests include

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the following: core loss measurement, core plate checks, core frame insulation resistance, winding copper check, and tank pressure test.

After manufacturing, the transformer shall be subject to testing as described in IEEE C57.12.90, These tests are classified in routine, design, conformance, and other tests defined in C57.12.80. The following tests are required by IEEE C57.12.90.

- Winding Resistance
- Polarity
- Ratio
- No Load Loss
- Excitation Current
- Load Loss Impedance
- Zero-Sequence Impedance *
- Dielectric Tests:
- Impulse Voltage
- Switching Impulse*
- Induced Voltage
- Partial Discharge*
- Insulation Resistance & Power Factor
- Temperature Rise, (normally only carried out on the first transformer)*
- Sound Level *

  * These tests are not mandatory on all units.

Tests are required to demonstrate that the transformer meets the specifications, including the guarantees, with the expectation that it will be suitable for 30 years of service. Two types of tests are carried out on transformers:

- Routine tests carried out on all units
- Type tests carried out on the first unit of a design (in addition to the routine tests)

Only some routine tests, such as the core-losses test, the load-losses test, and the zero-phase-sequence test, are considered in this guide. These tests are necessary to determine the transformer parameters. They can be estimated from transformer geometry and typical data available in the literature, but it is practically impossible to calculate the no-load current by estimating the ampere-turns required in different parts of the core to establish a given flux density. This guide describes only the test measurement approaches.

The procedures in this guide assume that the measurement test results discussed previously and the usual nameplate data are available. Table 1-1 shows the list of transformer data required to calculate the parameters of the equivalent circuit. However, for many transformers information such as the zero-sequence test results is not available; therefore, several assumptions are introduced in this guideline to allow the parameters to be estimated.

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Table 1-1- Information Required for Modelling a Transformer

Item	Transformer Parameter	Symbol	Example
General			
1	Transformer ONAN Ratings [1]	MVA_{ONAN}	25 MVA
2	Winding Voltages (primary, secondary, …)	V_H, V_X,… V_P, V_S, … V_1, V_2, …	130 kV / 25 kV
3	Connection type [1]	-	wye-wye
4	Tap range [1]	t_1, t_2, …	± 10%
5	Number of tap steps [1]	-	17
6	Winding with an adjustable tap [1]	-	Primary (high) side
7	Phase angle of windings	θ_1, θ_2, …	0°
No Load Loss Test Results			
8	No-load loss test MVA	$MVA_{NL\ Test}$	42 MVA
9	No-load loss	P_{NL}	28500 W
10	Excitation current	I_{exc}	0.4 %
11	Tap setting for no-load loss test	t_{NL}	Nominal
Load Loss Test Results			
12	Load loss test MVA [1]	$MVA_{SC\ Test}$, …	25 MVA
13	Load loss [1]	P_{SC}, P_{LL_HX}, …	86000 W
14	Impedance Voltage(%) or Test Voltage [1]	I_{Z_HX}, or Z_{HX}, V_{Test}…	7.88 %
15	Reactance [1]	I_X, or X_{HX}, …	7.87 %
16	Tap setting for load loss test [1]	t_{SC}	Nominal
Zero-Sequence Test Results			
17	Zero-sequence open circuit test results	Z_1, Z_2	8%, 7.02%
18	Zero-sequence short circuit test results	Z_3	
19	Zero-sequence T-model parameters	Z_{H0}, Z'_{X0} Z_{M0} for the T-model	
20	Grounding configuration	Windings' neutral points grounding status: Solidly grounded or grounded through an impedance	
21	Grounding Impedance	Z_{GH}, Z_{GX}, …	

[1] In the case of a transformer with more than two windings, these parameters should be given for each winding or each pair of windings, depending on the parameter.

The procedure to determine the positive and negative sequence parameters in three-phase transformers is similar to that used for single-phase transformers; it does not matter what the type of the primary and secondary connections are or what the core type of the transformer is. However, the zero-sequence parameter must be determined in three-phase transformers. As described in Section 1.5 , the positive and negative sequence parameters are determined through no-load (core) and load-losses test measurements. Some of the parameters, such as transformer

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MVA, connection type, and grounding impedance, listed in Table 1-1, must be provided in the test report and/or in the nameplate data for the calculation of the equivalent circuit. This way, no assumptions can be made for these parameters. However, some data are missing, and when this is the case acceptable assumptions must be made regarding some of the variables. Table 1-3 and Table 1-4 in the section that follows list of assumptions for the missing data.

1.15.1 No-Load Losses Test

The purpose of the no-load losses test is to measure no-load losses at a specified excitation voltage and frequency. Figure 1-33 shows the schematic diagram of the test setup and the equivalent circuit of a three-phase transformer for a no-load losses test. More details can be found in IEEE C57.12.90, Section 8. In this test, the rated voltage and frequency are applied to one winding, usually the low-voltage winding (or sometimes a tap winding) while the other winding(s) are left open. The transformer is energized to give 100% peak volts per turn, which results in 100% flux in the core. The rms voltage is noted to confirm that the voltage form factor is acceptable. The real power (no-load losses) and the excitation current are measured. The expected excitation current at the nominal voltage is below 1% of the rated current at the base rating of the transformer. In modern transformer designs the excitation current can be as low as 0.6%.

The standard CSA C88, clause 16.3-k states that a one hour excitation run at 110% of rated voltage after the completion of all dielectric tests on all transformers with a voltage classification at or above 123 kV. At the completion of this one hour test, the excitation current and no-load loss shall be measured at rated voltage and 110% of rated voltage. These measurements shall be the official values for exciting current and excitation loss. Therefore, if the excitation current and no-load loss measurements after one hour dielectric test have been provided in the test report, these are the no-load losses test results that should be used in modelling.

No-load losses measurements are normally referred to the nominal tap position in regular transformers and autotransformers. According to IEEE C57.15, no-load losses in step-voltage regulator transformers is the average of no-load losses in the neutral and the next adjacent boost position with rated voltage applied to the shunt or series winding for voltage regulators that do not include a series transformer.

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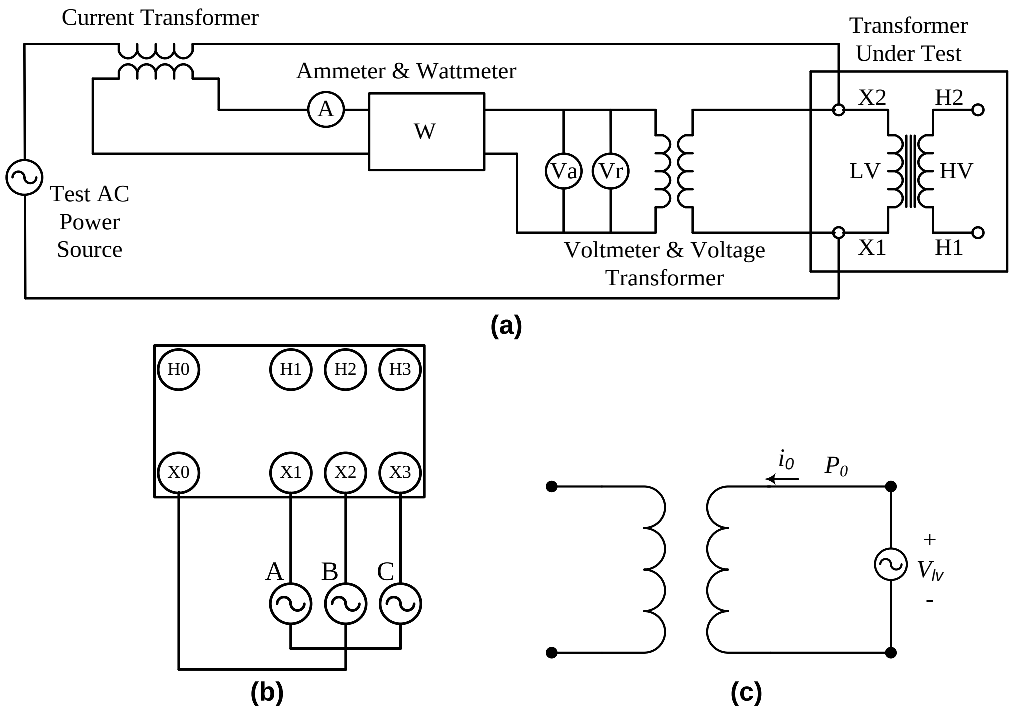

Figure 1-33- Schematic diagram of the no-load losses test: a) Test setup, b) Bushings connection, c) Equivalent circuit

This test is repeated at the 110% voltage level, a requirement of the standards; however, most utilities ask for the no-load losses and the excitation current to be measured for 90% of the rated voltage, and then with the voltage increasing to 110% in 5% increments. Some manufacturers do this even though it is not included in the customer specification. The extra measurements are for information purposes and can be used to determine the characteristics of the core steel.

The core temperature causes variation in the no-load losses, as does the excitation voltage. Therefore, a reference temperature is required when stating no-load losses. According to IEEE C57.12.00, the standard reference temperature T_r for transformer no-load losses is specified as 20 ºC.

The no-load losses test is usually conducted by energizing the low-voltage side of transformer. It is possible to supply the high-voltage winding and leave the low-voltage winding open. The reason this is not usually done is due to the voltage limitations of the test equipment. In a few cases, even the rated voltage of the low-voltage winding is higher than the capabilities of the voltage generator. For these cases, if a tap winding exists and is located in the neutral of a wye-connected winding in the transformer under test it can be used to excite the transformer. If this is not an option, a test winding must be added. The problem of the low voltage exceeding the voltage generator capabilities is not encountered in generator step-up (GSU) transformers due to the voltage limitations of the generators.

Manufacturers normally provide a guaranteed maximum value for the no-load losses. The designer will normally design the transformer so the actual no-load losses will be close to the

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guaranteed value. If this is not the case, there is a problem with the unit or with the calculation, and a monetary penalty can be applied if the tested no-load losses exceed the guaranteed value.

1.15.2 Load Losses Test

The load losses test is carried out to determine not only the losses in the transformer under load, but also the impedance of the unit. The losses and the impedance are usually subject to a guarantee. Because the losses represent a cost to the user due to the power they consume, and there may be a financial penalty. The series impedance of a transformer determines the amount of fault current flowing in the windings when a short circuit occurs during the operation of the transformer.

The load losses test is normally conducted by supplying the high-voltage winding while short-circuiting the low-voltage winding and increasing the voltage until the rated current circulates in both windings. If the transformer has more than two low-voltage windings, the test will be repeated with each low voltage shorted in turn. In addition a similar test is performed supplying one low-voltage and shorting the terminals of the other low voltage.

By definition, the supply voltage of the load losses test is equal to the impedance voltage of the windings under consideration. The excitation current is normally less than one percent at the rated voltage; therefore, the shunt branch can be neglected. The supply voltage, input current, and power are then measured. Figure 1-34 shows the load-losses test diagram of a single-phase transformer. The load-losses test for three-phase transformers is performed in the same manner except that all connections, the test setup, and the measurements are three-phase, and a balanced three-phase power source is used.

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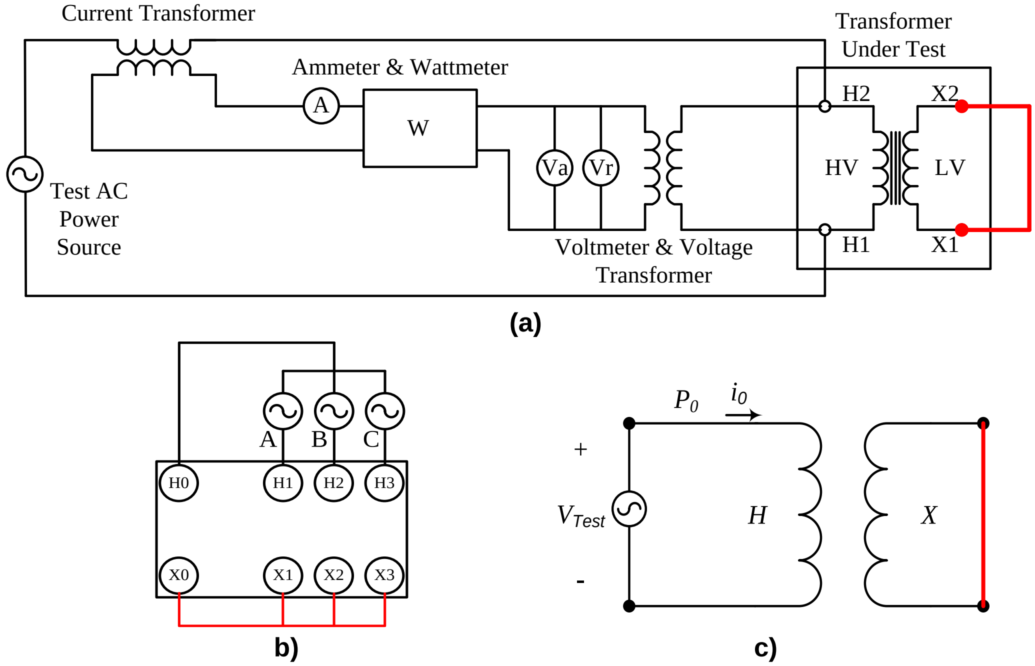

Figure 1-34- Schematic diagram of the load-losses test: a) Test setup, b) Bushings connection, c) Equivalent circuit

Load losses of transformers are very low, which means the power factor in the load-losses test is very low, ranging from 5% to 1%. Consequently, the phase-angle between the voltage and the current is close to 90°, and the active power measurement at the low-power-factor circuits is very sensitive to the phase angle between the current and the voltage.

As is the case with other experimental measurements, the load losses test measurements are subject to measurement errors; these include phase-angle error in the wattmeter and any associated CTs and PTs. Therefore, the load-losses measurements have to be corrected as per IEEE PC57.123. When using load-loss information from test reports, check the base (MVA) at which the test was carried out, and if necessary make a correction (load losses increase by the square of the current). At the same time, check that the current reflects the full-load current condition of the winding concerned.

The measured losses in the load-losses test is the sum of losses in the primary and the secondary. The reactive power consumed is also that absorbed by the leakage reactance of the two windings. If the exact equivalent circuit as illustrated in Figure 1-4 is needed, then R_H and R'_X and also X_H and X'_X should be separated from the total calculated resistance and reactance, respectively. As described in Section 1.3, the separation series impedance between two windings is the main disadvantage of a T-model equivalent circuit. However, the winding dc resistances measured by the dc test are smaller than the resistances determined from the load-losses test. As mentioned in Section 1.5, if the impedance parameters are required for each winding then the total impedance is divided equally between the two windings. (One idea from the dc test is to divide the total resistance between the two windings with the same ratio as that obtained from dc test. But it is not considered in this guide.) As for the separation of X_H and X'_X, they are assumed to be equal. This is a fairly valid assumption for many types of transformer windings because the leakage flux paths are through air and are similar. If the approximate equivalent circuit, as illustrated in Figure 1-7, is required, there is no need to separate the total calculated resistance and reactance from the test between the two windings.

Because the rated current flows in the transformer windings, the current increases the temperature of the windings and therefore increases the losses in the windings during the load-loss test measurement. To minimize the magnitude of this effect, manufacturers keep the test time as short as possible. In practice, the test only takes a short time, and the oil temperature is taken before and after the test; the mean temperature is used; and then the necessary temperature correction made. Measuring load losses in three-phase transformers can be carried out using different methods. The three-wattmeter method is widely used in routine testing of transformers.

The load-losses test is usually carried out at room temperature. ANSI standards require the results be reported in the specified reference temperatures on the test report. Therefore, the losses should be corrected to either 75 °C for 55° rise units or 85 °C for 65° rise units, the specified reference temperatures. According to IEEE C57.12.00, the standard reference temperature T_r for transformer load losses is specified as 85 ºC. This temperature is the winding temperature and is defined as:

$$T_r = Ambient\ Temperature + Temperature\ raise$$

According to IEEE C57.12.90, load losses should be measured at a load current equal to the rated current for the corresponding tapping position. The calculated impedance is usually expressed as the percentage ratio of applied voltage to rated voltage. Under the rated-current load-losses test, the impedance voltage is the per-unit impedance of the transformer. In this case, the test MVA rating must be expressed in the test report as well. If the test current is not exactly equal to the rated current, the measured load loss value will need to be corrected by the square of the ratio of the rated current to the test current (average of the measured phase current in three-phase transformers) as follows. In the circumstances, the test measurements might be reported instead of impedance voltage in the test report.

$$P_{LL\ @\ I_{Rated}} = P_{LL\ @\ I_{Test}} \frac{{I_{Rated}}^2}{{I_{Test}}^2}$$

Because:

$$\frac{P_{LL\ @\ I_{Test}}}{{I_{Test}}^2} = \frac{P_{LL\ @\ I_{Rated}}}{{I_{Rated}}^2} = \begin{cases} R \text{ for single} - \text{phase} \\ 3R \text{ for three} - \text{phase} \end{cases}$$

Load-losses test measurements are made on maximum, normal, mean, and minimum tap positions. In autotransformers, they are usually made on the normal tap position. In step-voltage regulators, according to IEEE C57.15, the load losses test measurements are made on four positions including the maximum and adjacent-to-maximum buck positions and the maximum and adjacent-to-maximum boost positions with rated current in the windings. In the test report, the

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average value of these four measurements may be reported. However, the measurements might be made on the minimum and maximum tap position and the average value has been reported in the test report.

1.15.3 Zero Phase Sequence Test

The zero-sequence impedance in three-phase transformers is measured at the rated frequency between the line terminals of a Y-connected or zigzag-connected winding connected together and its neutral, and it is expressed in ohms per phase. The zero-sequence equivalent circuit of three-phase transformers varies depending on the type of winding connections and the core construction. Its topology depends on the path available for the flow of zero-sequence current and the MMF balancing within the transformer magnetic circuit. A three-legged two-winding three-phase core-type transformer and a four-legged two-winding three-phase core-type transformer are shown in Figure 1-35-a and Figure 1-35-b, respectively. The primary winding is excited by zero phase sequence voltages, and its connection is a wye-grounded connection at both transformers. The secondary winding in both transformers, regardless of its connection type, is left open circuit. The magnetic flux due to the zero-sequence excitation is enclosed through the path shown by the dotted line at each transformer.

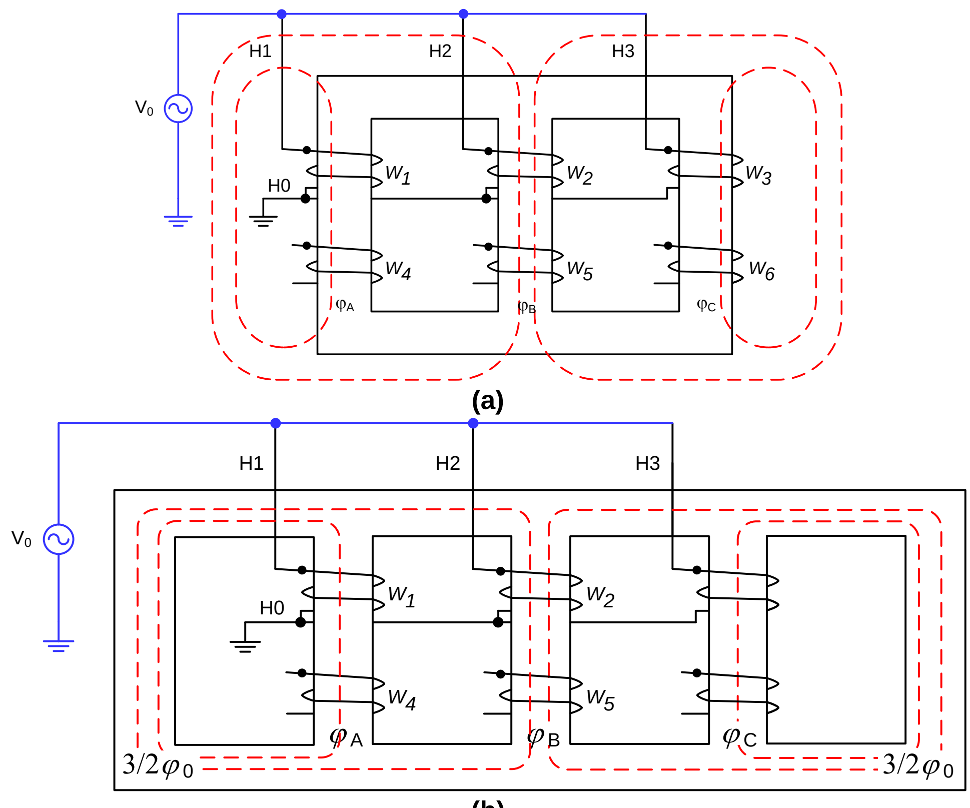

Figure 1-35- Schematic diagrams of core type transformers with wye-grounded connection in primary excited by a zero-sequence voltage: a) Three-legged magnetic core, b) Five-legged magnetic core

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In a three-legged magnetic core transformer, such as the one in Figure 1-35-a, there is no physical low-magnetic-reluctance return path from the top to the bottom core yoke for the zero-sequence flux. Therefore, it has to go through the high magnetic reluctance, the air gap, the structural steel, and the tank. In consequence, the magnetic reluctance for zero-sequence flux is relatively high and dependent on the transformer's physical structure and the tank’s steel type rather than on the type and structure of the magnetic core. Therefore, the magnetic impedance, which is inversely proportional to the magnetic reluctance, is very low.

To overcome the shortcomings of a three-legged transformer in zero-sequence excitation, a fourth or even a fifth leg is added to the transformer core structure, and the fourth and/or fifth leg provides a magnetic low-reactance return path for the zero-sequence flux in the transformer's magnetic core physical structure. Figure 1-35-b shows the zero-sequence flux counters in a five-legged core transformer. However, this magnetic path is not designed to return the total flux produced under a zero-sequence rated voltage that is three times the rated flux flowing through each leg, as shown in Figure 1-35-b. The zero-sequence returned flux in a five-legged core- and shell-type transformer is 1.5 times the flux flowing at each leg the winding is wound around. As a result, assuming that the return path of the zero-sequence flux in the transformer magnetic core remains in the linear area and does not saturate, it is expected that the magnetic impedance approximately equals the positive or negative sequence magnetic impedance. But, the additional legs in the transformer magnetic core structure never remain in the linear area while carrying flux higher than the rated flux. They are designed to carry the rated flux of one phase and are sized similarly to the other legs. Therefore, in a four-legged core-type transformer when the zero-sequence voltage approaches 33% of the rated voltage the fourth leg’s core begins to saturate. This value in a five-legged transformer and in a shell-type transformer is 66.67%. In a case in which the voltage exceeds these values, the magnetic impedance begins to drop dramatically.

The zero-sequence equivalent circuits of three-phase transformers for various types of winding connections are listed in Table 1-2. As this table shows, the zero-sequence current needs a grounded wye connection to flow; otherwise, it faces an open circuit and does not flow. Consequently, the overall zero-sequence impedance is effectively increased by any impedance in the connection between the neutral point of the wye connection and the ground point. It can be considered as one of advantages of the grounded wye connection that it limits the magnitude of the ground fault current under fault conditions.

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Table 1-2- Zero-Sequence Equivalent Circuits and Impedances for all Types of Two-Winding and Three-Winding Transformers including all Core-Type and Shell-Type Transformers

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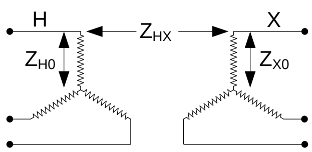
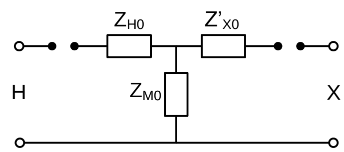
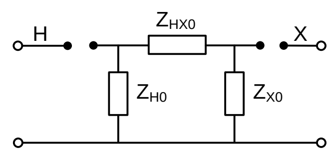
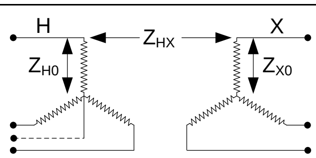
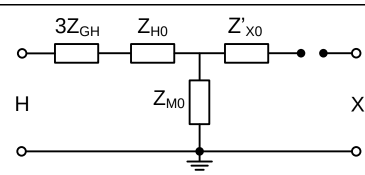
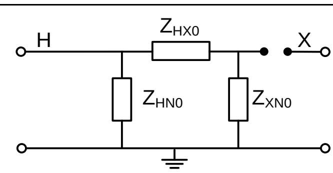
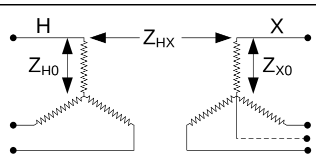
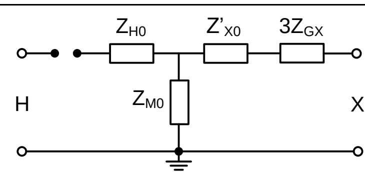
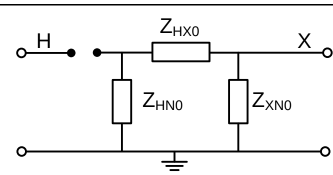
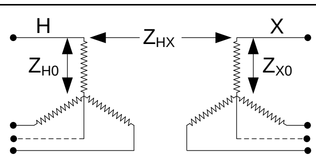
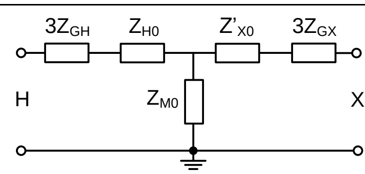
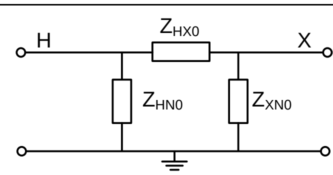
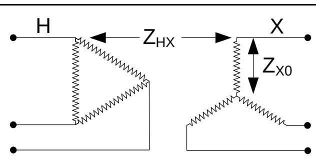
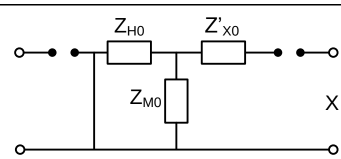
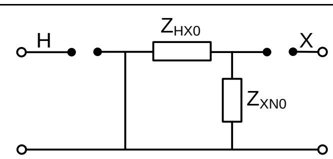
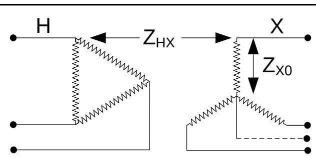
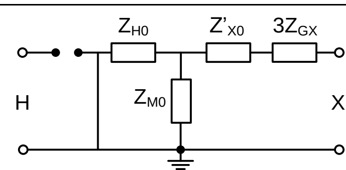
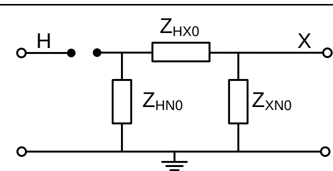
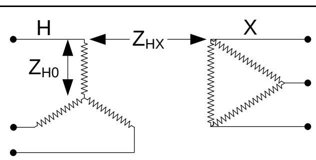
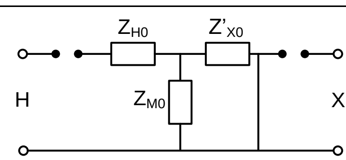
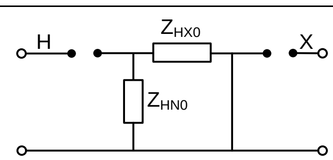
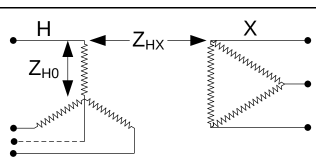
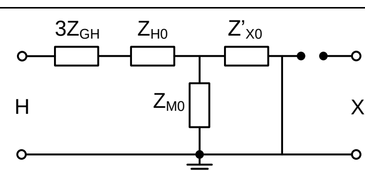
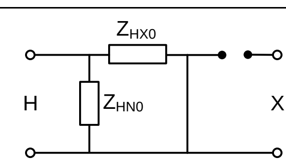
1			
2			
3			
4			
5			
6			
7			
8			

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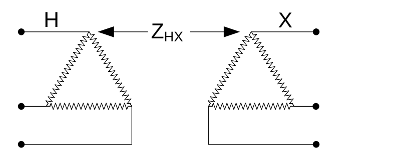
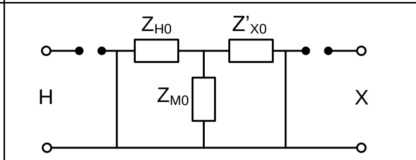
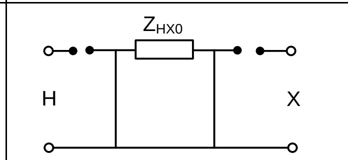
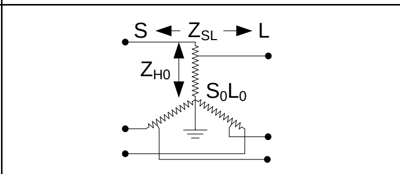
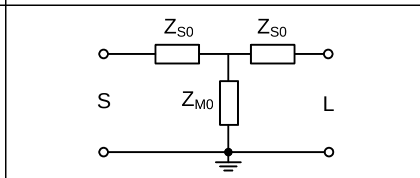
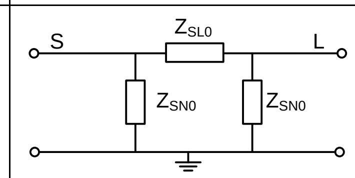
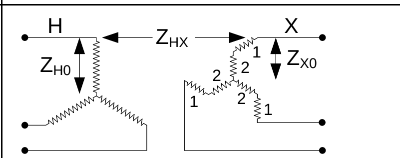
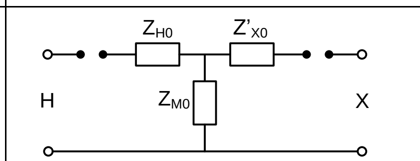
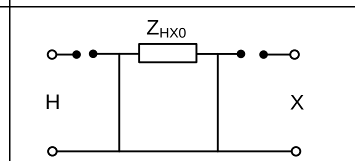
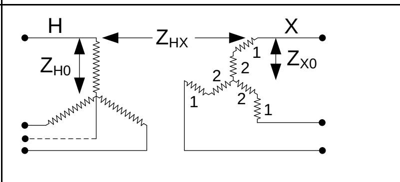
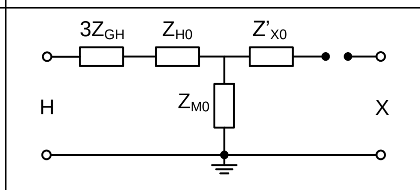
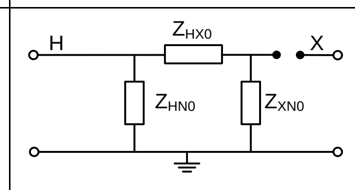
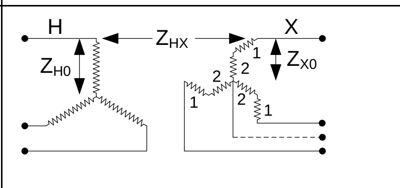
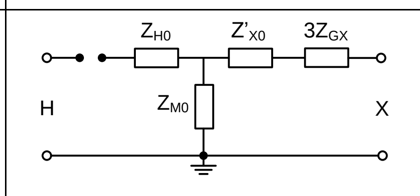
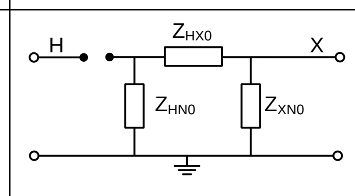
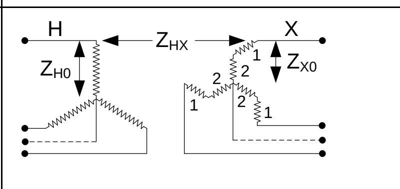
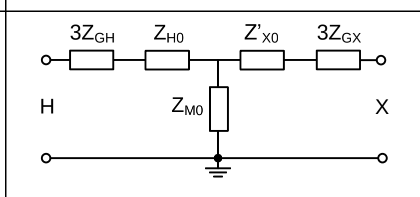
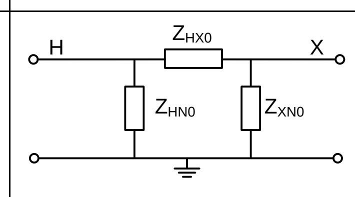
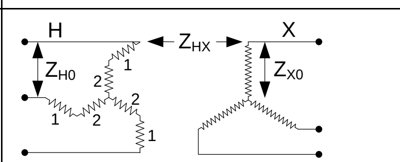
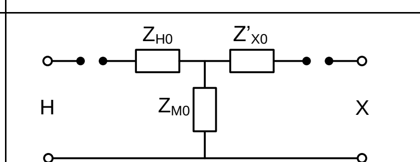
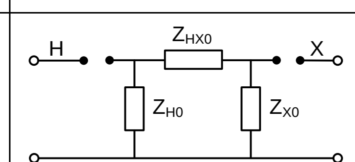
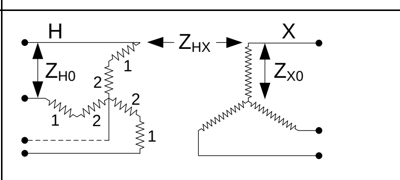
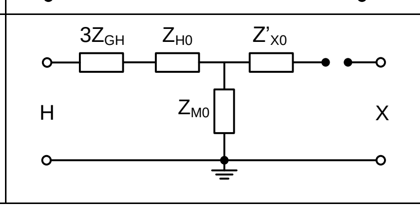
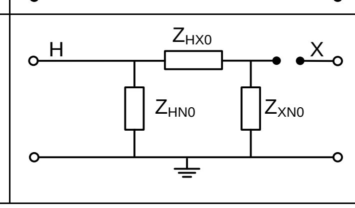
9			
10			
11			
12			
13			
14			
15			
16			

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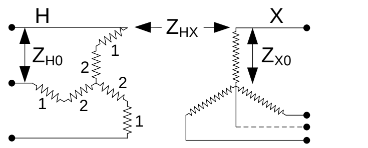
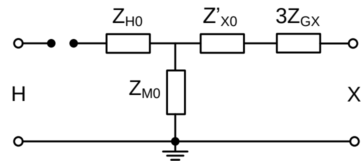
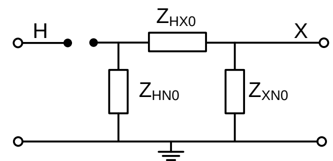
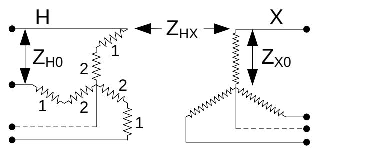
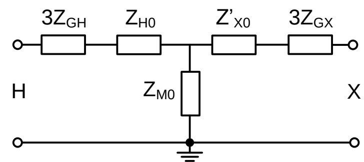
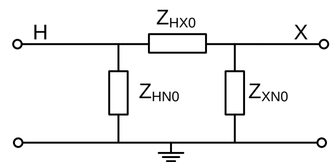
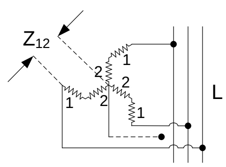
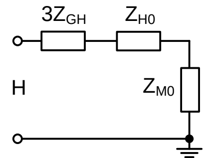
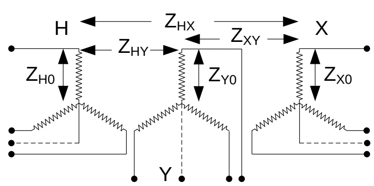
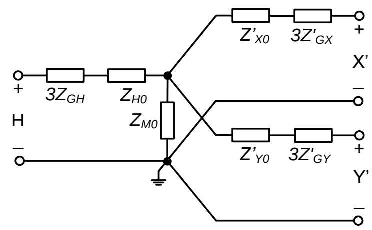
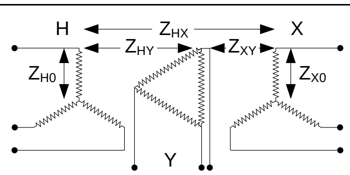
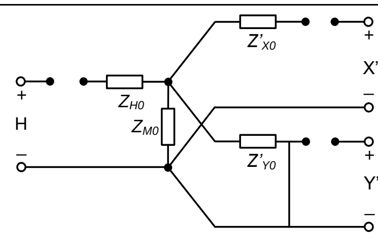
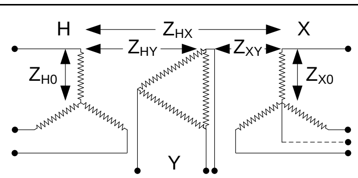
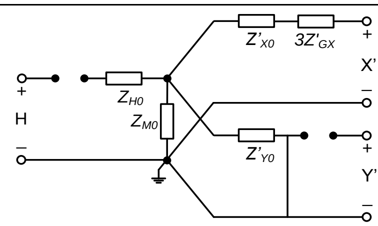
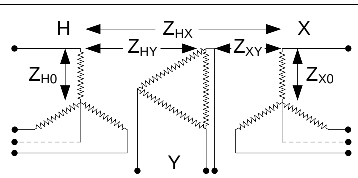
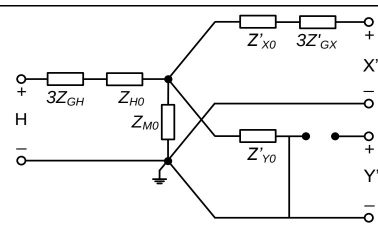
	Connection Type	T-Model	π-Model
17			
18			
19			-
20			-
21			-
22			-
23			-

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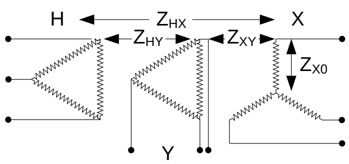
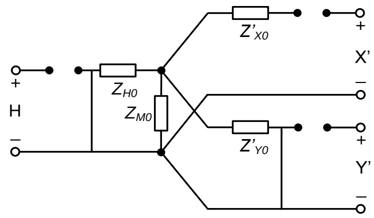
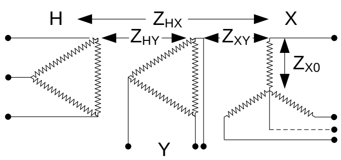
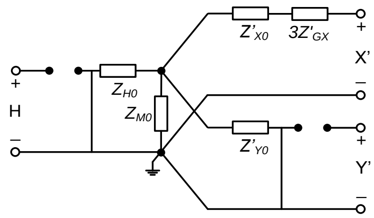
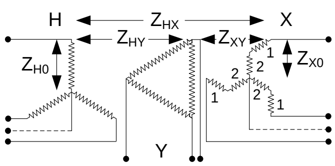
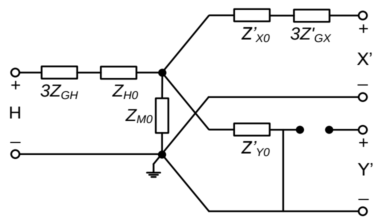
	Connection Type	T-Model	π-Model
24			-
25			-
26			-

The zero-phase-sequence equivalent circuit of a two-winding solid grounded Yg-Yg transformer (shown in Figure 1-36) consists of series impedance elements between the primary and secondary winding and a shunt impedance, which is similar to the positive-sequence and negative-sequence equivalent circuits of a three-phase transformer. The series impedance elements represent the losses and leakage reactance of the primary and secondary windings. In practice, there is no difference between the series impedance elements of the zero-sequence and those of a positive-sequence or negative-sequence. Shunt impedance represents the magnetizing current and core losses due to zero-sequence excitation. The shunt impedance of the zero-sequence is expected to be less than the positive-sequence or negative-sequence equivalent circuit shunt impedance in three-legged core-type transformers because of the increased likelihood of core saturation under zero-sequence excitation. Figure 1-36-a shows a T-model zero-sequence equivalent circuit in which elements in the low-voltage side have been transferred to the high-voltage side; and, in a manner similar to that used for a transformer general equivalent circuit, the π-model can be derived from a T-model through two-port network formulas, as described in Sections 1.3 and 1.4.

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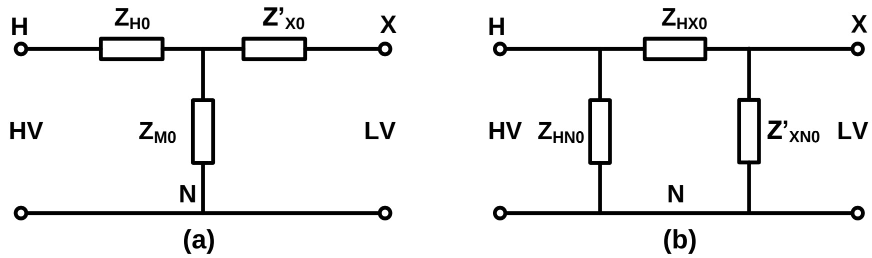

Figure 1-36- Zero-sequence equivalent circuit of a two-winding solid grounded YY transformer referred to the high voltage side: a) T-model, b) π-model

If the neutral point is grounded through a Z_G , this grounding impedance appears tripled in a zero-sequence equivalent circuit, as shown in Figure 1-37, in which Z_{GH} and Z_{GX} are the neutral-point impedance to ground at the high-voltage side and the low-voltage side, respectively. Z'_{GX} is the transferred value of Z_{GX} to the high-voltage side.

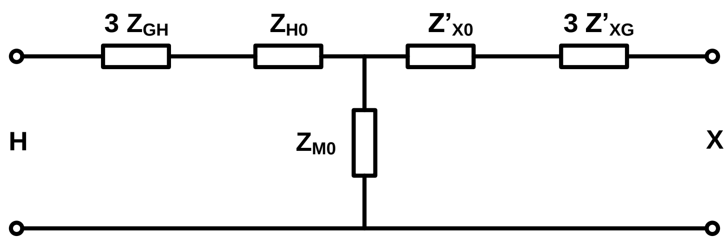

Figure 1-37- Zero-sequence equivalent circuit of a two-winding YY transformer grounded through individual impedance, referred to the high-voltage side

For all types of transformers except the three-legged-core type with at least one grounded Y connection, shunt impedance is very large. It assumed to be similar to positive- or negative-sequence shunt impedance of about 100 pu. But, for the three-legged core type, in addition to the high-reluctance zero-sequence flux path, relatively high eddy current losses in the tank are expected because the zero-sequence flux is enclosed by the transformer tank wall. However, some improvements in tank steel have been achieved recently, and these improvements decrease the eddy current losses in the transformer tank wall. Because of this, to keep the zero flux return path operating in the linear area the excitation voltage should not exceed 30% of the rated line-to-neutral voltage of the winding, which is energized when the other winding set connection is not a delta connection. If the other winding set connection is a delta connection, the excitation voltage should be low enough that it does not exceed the circulating current beyond the rated phase current of any delta winding. These excitation conditions can be found in IEEE C57.12.90, Section 9.5.

The zero-sequence parameters of the equivalent circuit of a three-phase transformer can be found by performing open-circuit and short-circuit tests with zero-sequence voltages applied. These tests are called zero-phase sequence impedance tests and are applied only to transformers having one or more windings with a physical neutral brought out of the transformer for external connections. One such winding is excited with a single voltage source at a rated frequency between the neutral point and the three terminals connected together; but another

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winding set may have a Y or a delta connection. According to IEC 76-1, the zero-sequence impedance tests are subject to agreement between the manufacturer and the purchaser. Manufacturers should provide the zero-sequence parameters on the transformer specification or the nameplate, particularly for special transformers. As listed in Table 1-2, all connection types for two-winding transformers can be considered in the following four categories:

a) Zero-Sequence Equivalent Circuit Parameters for Delta-Delta-Connected Transformers

Zero-sequence impedance tests can be carried out on transformers in which the winding connection consists of a grounded wye connection. Zero-phase sequence impedance tests for delta-delta-connected transformers are meaningless.

b) Zero-Sequence Equivalent Circuit Parameters for Grounded Y-Delta Connected Transformers

For the purposes of explanation, it is assumed that the connection of the primary winding set is a wye-grounded connection excited by a zero-sequence voltage source, as shown in Figure 1-38. If the secondary winding is connected in delta, it does not matter that the terminals of these windings are open or short circuited; they always contribute to zero-sequence excitation because the delta connection operates as a closed loop circuit for possible induced voltages to these windings due to the zero-phase magnetizing flux. However, no voltage appears on the terminal of the secondary windings.

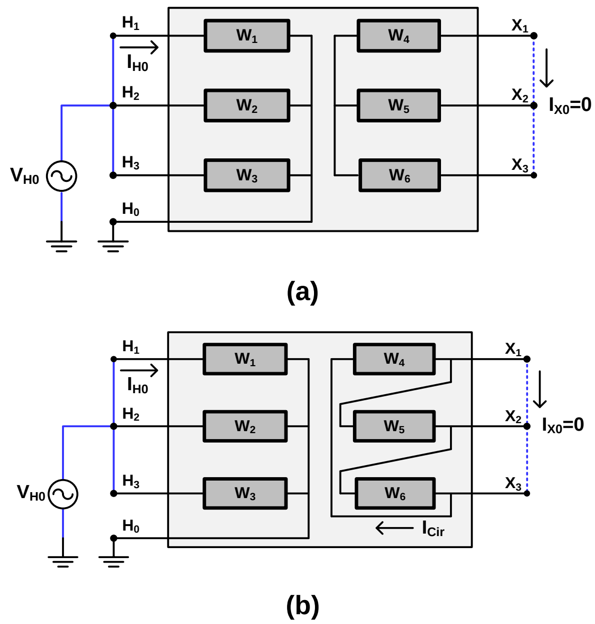

Figure 1-38- Zero-sequence impedance test of a two-winding transformer with: a) Yg-Y connection, b) Yg-delta connection

The zero-sequence equivalent circuit of a grounded Y-delta transformer through ground impedance is shown in Figure 1-39.

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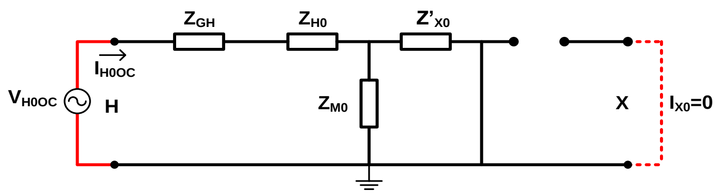

Figure 1-39- The zero-sequence equivalent circuit of a grounded Y-delta transformer through ground impedance

As shown in this figure, the zero-sequence impedance from the high-voltage side is:

$$Z_{0OC} = 3Z_{GH} + Z_{H0} + Z_{M0}||Z'_{X0}$$

Since the secondary delta connection appears open circuit under the zero-sequence condition, having an open circuit or a short circuit in the delta connection terminals does not change the circuit. Therefore, Z_{0OC} can be determined trough the zero-sequence (open circuit or short circuit) test measurements, as follows:

$$Z_{0\,OC} = \frac{V_{H0}}{I_{H0}}$$

$$R_{0\,OC} = \frac{P_{0\,OC}}{3{I_{H0}}^2}$$

$$X_{0\,OC} = \sqrt{{Z_{0\,OC}}^2 - {R_{0\,OC}}^2}$$

It is important to note that V_{H0} is not the phase-rated voltage for the abovementioned reasons. The per-unit value can then be calculated from the base impedance at the given base power.

c) Zero-Sequence Equivalent Circuit Parameters for Y-Y Connected Transformers

In this case, it is also assumed that the connection of the primary winding set is a wye-grounded connection excited by a zero-sequence voltage source, as shown in Figure 1-40. If the secondary winding is connected in Y form and the neutral point is not connected to ground, it does not matter that the terminals of these windings have been left open or are short-circuited. In either case they do not contribute to zero-sequence excitation because the neutral point of the wye connection is open-circuited.

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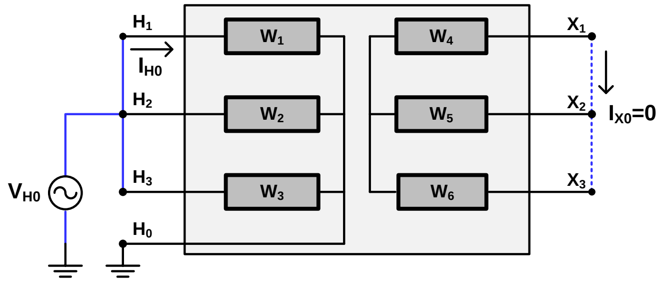

Figure 1-40- Zero-sequence impedance test for a two-winding transformer with a Yg-Y connection

In consequence, the zero-sequence impedance for a Yg-Y transformer through ground impedance at the primary winding is:

$$Z_{0\ OC} = 3Z_{GH} + Z_{H0} + Z_{M0}$$

which can be found from zero-sequence open circuit test measurements whereas Z_{GH} is zero.

To determine zero-sequence parameters both neutral points in a YY transformer have been connected to ground (Yg-Yg).Three tests, one open circuit test from each side and one short-circuit test (preferably from the high-voltage side) are recommended in IEEE C57.12.90, Section 9.5.3 , as discussed below:

1) Open circuit test from the high-voltage side: Short-circuit H1, H2, and H3, and leave X1, X2, and X3 open, as shown in Figure 1-41-a. Apply voltage to the high-voltage side terminals and measure voltage, current, and active power at the transformer terminal. Calculate Z_1 as indicated in Figure 1-41- b and the equations that follow.

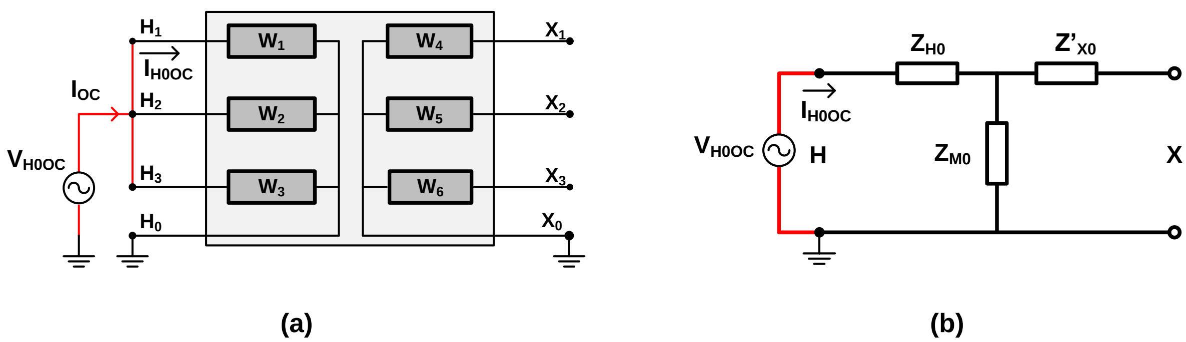

Figure 1-41- Zero-sequence impedance test: Open Circuit test from the high voltage side, a) Terminals connection, b) Equivalent circuit

$$Z_1 = Z_{H0} + Z_{M0} = R_1 + jX_1$$

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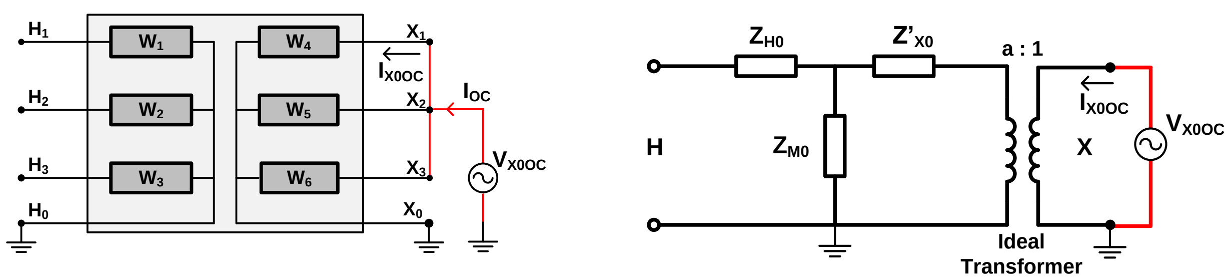
$$R_1 = \frac{P_{H0\ OC}}{3{I_{H0\ OC}}^2}$$

$$X_1 = \sqrt{\left(\frac{V_{H0\ OC}}{I_{H0\ OV}}\right)^2 - {R_1}^2}$$

2) Open-circuit test from the low-voltage side: Leave H1, H2, and H3 open, and short-circuit X1, X2, and X3, as shown in Figure 1-42-a. Apply voltage to the low-voltage terminals and measure voltage, current, and active power at the transformer terminal. Calculate Z_2 as indicated in Figure 1-42-b and the equations that follow.



(a) (b)

Figure 1-42- Zero-sequence impedance test: Open Circuit test from low voltage side, a) Terminals connection, b) Equivalent circuit

$$Z_2 = R_2 + jX_2$$

$$R_2 = \frac{P_{X0\ OC}}{3{I_{X0\ OC}}^2}$$

$$\mathrm{X}_2 = \sqrt{\left(\frac{V_{X0\ OC}}{I_{X0\ OC}}\right)^2 - {R_2}^2}$$

$$Z'_2 = a^2 Z_2 = Z'_{X0} + Z_{M0} = R'_2 + jX'_2$$

3) Short-circuit test from the high-voltage side: Short-circuit H1, H2, and H3, and short-circuit X1, X2, and X3, and also X0, as shown in Figure 1-43-a. Apply voltage to the high-voltage terminals and measure voltage, current, and active power at the transformer terminal. Calculate Z_3, as indicated in Figure 1-43- b and the equations that follow.

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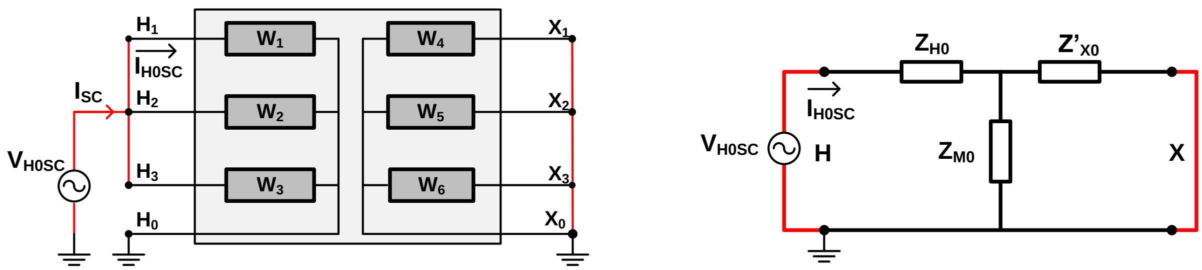

(a) (b)

Figure 1-43- Zero-sequence impedance test: Short-Circuit test from the high-voltage side, a) Terminals connection, b) Equivalent circuit

$$Z_3 = Z_{H0} + Z_{M0}||Z'_{X0} = R_3 + jX_3$$

$$R_3 = \frac{P_{H0\,SC}}{3I_{H0\,SC}{}^2}$$

$$X_3 = \sqrt{(\frac{V_{H0\,SC}}{I_{H0\,SC}})^2 - R_1{}^2}$$

Now, the zero-sequence equivalent circuit parameters can be found from these values as follows [12]:

$$Z_{H0} = Z_1 - \sqrt{Z'_2(Z_1 - Z_3)}$$
$$Z'_{X0} = Z'_2 - \sqrt{Z'_2(Z_1 - Z_3)}$$
$$Z_{M0} = \sqrt{Z'_2(Z_1 - Z_3)}$$

In practice, zero-sequence parameters have the following interesting characteristics:

1) The open-circuit impedances as measured from the high-voltage and low-voltage sides differ more than might be expected due to the physical arrangement of the high-voltage and low-voltage windings in a stacked three-legged core transformer. In a positive sequence or a negative sequence for a well-designed transformer they are expected to be equal.
2) The sum of the zero-sequence series impedances is approximately equal to the positive sequence or negative sequence series impedance. But, one of these impedances may have negative value.
3) The shunt impedance is considerably resistive in comparison to the positive sequence or the negative sequence shunt impedances due to the eddy current losses in the tank walls.

d) Zero-Sequence π- Model Equivalent Circuit for a Grounded YY Transformer

Figure 1-37 shows the zero-sequence T-model equivalent circuit of a Yy grounded transformer in which the primary and secondary neutral points have been grounded through Z_{GH} and Z_{GX}, respectively. If a neutral point is solidly grounded, the associate ground impedance is assumed to be zero in this model, as are the equations.

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The zero-sequence π-model equivalent circuit can be derived from the T-model using two-port network analysis, as described in Appendix C. In a zero-sequence π-model equivalent circuit, the π-model parameters should be calculated from the proposed equation, which is not the method used for a positive- or negative-sequence equivalent circuit. This is because the proposed approach to determine the π-model parameters from a T-model for a positive- or negative-sequence equivalent circuit is valid under specific conditions. These conditions are not valid for the zero-sequence T-model equivalent circuit.

1.16 Estimation of Transformer Parameters When Information is Not Available

Table 1-3- Assumptions Made for Missing Data for Two-Winding Transformers and Autotransformers

Data Missing	Assumptions
Core type/Shell type	All 3-phase transformers are 3-limb core type
No-load test results	g+jb=0+j0 (magnetizing branch is ignored)
Load-loss test results are not available	r+jx = 0+j7% (load-loss is assumed to be zero)
Zero-sequence test results are not available	Refer to Table 1-4 for assumptions
Zero-sequence test report does not specify what MVA base is used	The MVA base for the load-loss test will be used
MVA is not given for a test	ONAN rating will be used
No-load and load-loss tests are conducted on different MVAs	They should be converted to ONAN ratings
Impedances are provided in ohms Currents are provided in amps Voltage are provided in volts	They should be converted to per-unit
The values of no-load tests or load-loss tests for a bank of three single-phase transformers installed as a three-phase transformer are not equal	The average of per-unit values should be used
Tap position for the test is not given	Nominal tap is assumed
Voltage regulator impedance data are not available	The series reactance (x) is assumed to be equal to the range of the voltage regulator (10%) times the typical power transformer impedance (7%). So, for example, x=0.007 pu will be used for a voltage regulator with a voltage control range of ±10%. The series resistance (r) is calculated from load-loss test.
Voltage regulator output range and/or number of tap steps are not given	±10% output range and 17 tap steps are assumed
Voltage regulator impedance data are given both for highest tap and lowest tap	The impedance obtained from the lowest tap test is used in the model

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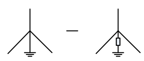
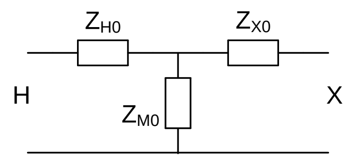
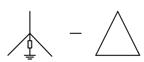
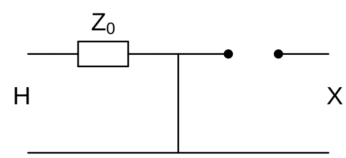
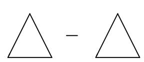
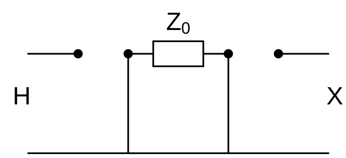
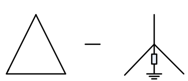
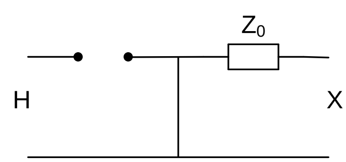
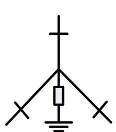
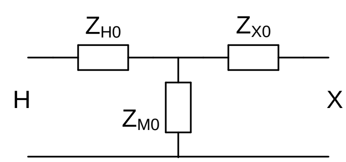
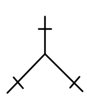
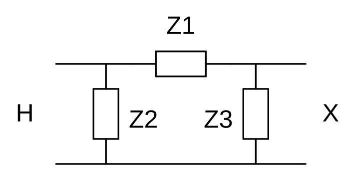
Table 1-4- Assumptions for a Zero-Sequence Model of Two-Winding Transformers and Autotransformers

Circuit Diagram	Approximate Zero-Sequence Model	
	$Z_{H0} = 0.1 \cdot Z_{HX}$ $Z_{X0} = 0.9 \cdot Z_{HX} + 3 \cdot Z_{GX}$ $Z_{M0} = 5 \cdot Z_{HX}$ Z_{HX}: Positive sequence impedance	
	$Z_0 = 0.85 \cdot Z_{HX} + 3 \cdot Z_{GH}$	
	$Z_0 = 0.85 \cdot Z_{HX}$	
	$Z_0 = 0.85 \cdot Z_{HX} + 3 \cdot Z_{GX}$	
	$Z_{XO} = 0.1 \cdot Z_{HX} + 3\left(\frac{N-1}{N}\right)\frac{Z_{G(\Omega)}}{Z_{base}}$ For $Z_{HO} = 0.9 \cdot Z_{HX} - 3\left(\frac{N-1}{N^2}\right)\frac{Z_{G(\Omega)}}{Z_{base}}$ $Z_{MO} = 5 \cdot Z_{HX} + \frac{3}{N}\frac{Z_{G(\Omega)}}{Z_{base}}$ $N = \frac{V_H}{V_L}$, $Z_{base} = \frac{\left(V_{L(kV)}\right)^2}{MVA}$ voltage regulators VL is the voltage at the minimum tap	
	$Z1 = (N-1) \cdot Z_{0SE}$ $Z2 = (-N) \cdot Z_{0SE}$ $Z3 = Z_{0SE}$ $N = \frac{V_H}{V_L}$ $Z_{OSE} = 6 \times Z_{HX}$ is assumed based on [8]	

IEC-60076-8-1997, Section 4, page 41, proposes typical zero-sequence impedance values for transformers with different connection types.

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1.17 Interpreting Transformer Test Reports

The information in Table 1-5- should be provided in a transformer test report so the transformer parameters can be determined from it. This information is not always reported. In such cases, the required data and/or the transformer parameters should be estimated according to the Standard as described in Table 1-3. However, all these data do not have to be reported in a test report. For example, the reactance per unit, $\%I_X$, is not usually reported. Since the load losses are dependent on the transformer temperature, it is necessary that the test report clearly states the transformer test temperature, which is called the reference temperature and denoted by $\mathrm{T_r}$. As described in Section 1.15.1, according to IEEE C57.12.00, the reference temperature for power transformers is 85 °C. This standard clarifies that as long as the following two conditions are met, the variation of temperature encountered from performing the test will not affect the load losses:

1) The average oil temperature is within ±10 °C of T_r .
2) The difference between the top and bottom oil temperature does not exceed 5 °C.

If the tests have been conducted at a temperature other than 85 °C and one of these two conditions is not met, the measured no-load losses should be corrected using the method that has been proposed in IEEE C57. 12.90, Section 8.4.

Table 1-5- List of Information Required to Determine Transformer Parameters

Quantity	Name in Report	Unit	Measurement Process	Symbol
No load exciting current	$\%I_o$ or %Exciting current	% as unit	Open-circuit test measured at 100% rated voltage	I_{OC}
No load losses	No-Load (kW)	kW	Open-circuit test measured at 100% rated voltage	P_{OC}
DC resistance	Resistance or Resistance per phase	Ω	DC test on each winding (set of windings in three-phase transformers)	$R_{DC\,H}$ and $R_{DC\,X}$
Test base power	MVA test	MVA	Both open-circuit test and short-circuit test	MVA_{NL} and MVA_{FL}
Short-Circuit test voltage	$\%I_Z$ or Impedance voltage	% as unit	Short-circuit test measured at 100% rated current	$\%I_{Z\,HX}$
Load losses	Load Losses	kW	Short-circuit test measured at 100% rated current	P_{SC}
Series reactance per-unit	$\%I_X$	% as unit	Short-circuit test measured at 100% rated current	

1.18 X/R Ratio in Power Transformers

In power systems, the X/R ratios are higher for generating units and transformers and lower for transmission lines. Typically, the lower the voltage, the lower the X/R ratio. A substation's X/R ratio may vary considerably, but it will always be less than the transformer X/R ratio because much of the short-circuit contribution comes over transmission lines that have a lower X/R ratio than a transformer. Generally, in a generation station or a substation with many transformers the X/R ratio is fairly high.

The X/R ratio for power transformers can be between about 15 and 125, lower for smaller transformers and low-voltage transformers and higher for larger transformers and high-power transformers. ANSI/IEEE C37.010-1979, page 42, recommends the typical range of the X/R ratio

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for a power transformer, but because of the higher loss evaluations currently used, the X/R ratios, particularly for larger units, can be considerably higher than this recommendation.

Based on a review of the X/R ratios of over 900 transformers in the Alberta power system, the maximum ratio may be taken as suggested in Figure 1-44. The IEEE curve shown in this figure is the maximum range recommended in IEEE C37.010.

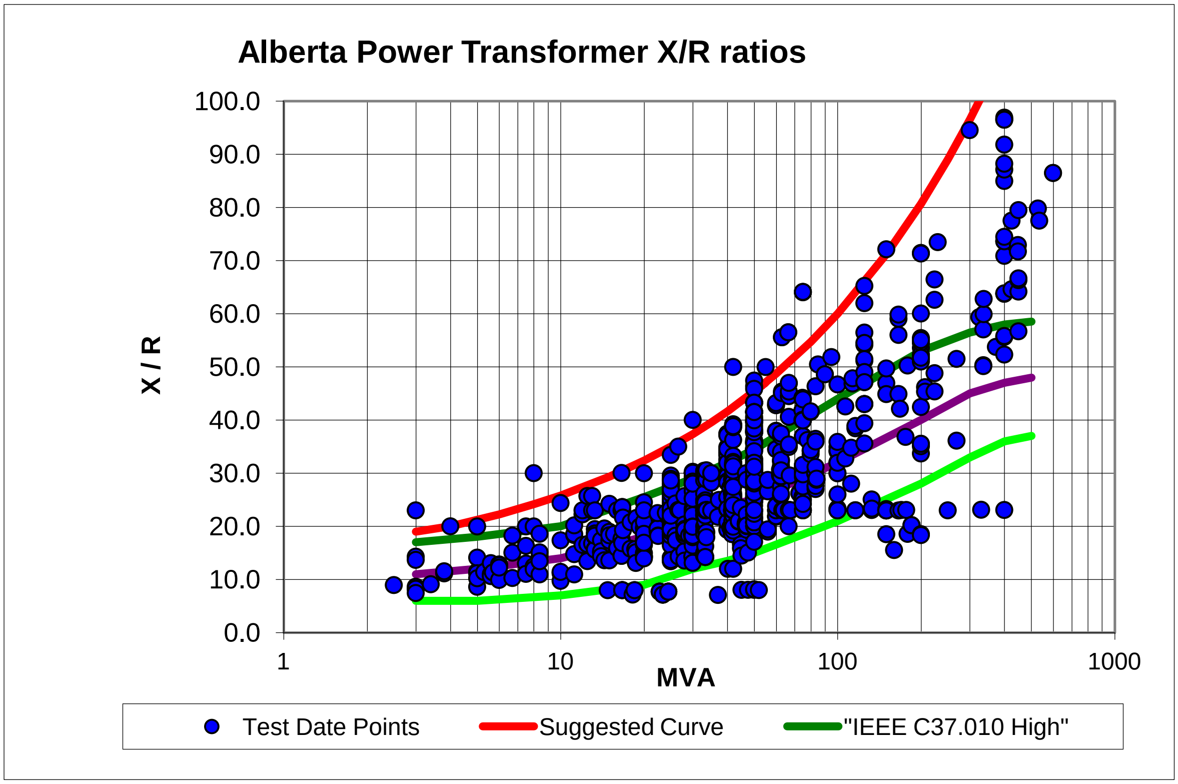

Figure 1-44- The recommended X/R ratios

1.19 Other Types of Transformer Applications

Transformers can be classified according their location, their general function in power systems, and/or their specific application. Following are different types of transformers according to their function and application. (Technical information and analysis regarding each type of transformer can be found in [6].) In this guide, transformers are classified according to their number of phases and windings, for example, single-phase, three-phase, two-winding, three-winding, etc.

1.19.1 Generator Transformers

Generator transformers are connected directly to the source supplying power and can be high-loss transformers. The power generated at power plants or generation stations is in the range of 11 to 25 kV, and for transmission the level of the voltage should be stepped up to a few hundred kilovolts by generator transformers. Generator transformers are frequently provided with off-circuit tap changers for small infrequent variations in the voltage. On-load tap changers may not be

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required because the voltage can be controlled by the generator filed excitation. If required, an on-load tap changer can be used to provide reactive power control for the power system. The low voltage winding is usually delta-connected because the circuit is grounded through the generator neutral. On the high-voltage side this type of transformer is generally wye-connected because this circuit is grounded in some way. The design of generator transformers has to allow for any over-excitation that may occur during operation.

1.19.2 Unit Auxiliary Transformers

Unit auxiliary transformers are required to supply various loads associated with each generator. The step-down transformer is connected directly to the generator circuit and provides power. The secondary voltage depends on the design used, but it is typically 6.9 kV or thereabouts. The rated kVA of unit auxiliary transformers is approximately 15% of the generating rating. They are usually oil-filled, and because of the danger of fire if there is a failure, they are generally located outdoors.

Auxiliary transformers supply various types of auxiliary equipment in power stations. They are step-down transformers connected directly to the generator and provide station service supply (typically 6.9 kV). The rated kVA of unit auxiliary transformers is approximately 15% of the generating rating. These transformers are usually outdoor transformers and one unit auxiliary transformer is present for every generating unit.

1.19.3 Distribution Transformers

Distribution transformers play an important role in reducing voltage. A distribution transformer reduces the voltage to 120/240 volts single-phase for residential customers and to 480/277 or 208Y/120 volts for commercial or light industry customers. Distribution transformers can vary in size; most are in the 5 kVA single-phase to 2500 kVA range. They come in single-phase and three-phase configurations and can be pad-mounted or pole-mounted, the most common application. Three-phase pad-mounted transformers are used with an underground primary circuit. Three single-phase pole-mounted transformers for overhead service are usually installed in an underground vault in large cities or in large concentrations of businesses. Power is then sent via underground cables to each customer.

Most distribution transformers are built in a shell form. They usually have two, three, or four secondary bushings, and the most common voltage ratings are 240 V and 480 V, with or without a mid-tap connection. Figure 1-45 shows various single-phase secondary connections [6]. A transformer with two bushings can supply only a single voltage to the load; a transformer with three bushings can supply a single voltage with a tap at the voltage midpoint. This type of transformer is widely used to supply three-wire residential systems in North America. As can be seen in Figure 1-45, the 120/240 secondary can supply load at either 120 V or 240 V. The secondary voltage for pad-mounted transformers is usually 240/120 V or 480/240 V. Some transformers may have a secondary with four bushings that can be connected together to provide a mid-tap connection with one or two bushings in common. The four-bushing secondary may be designated as 120/240 V or 240/480 V.

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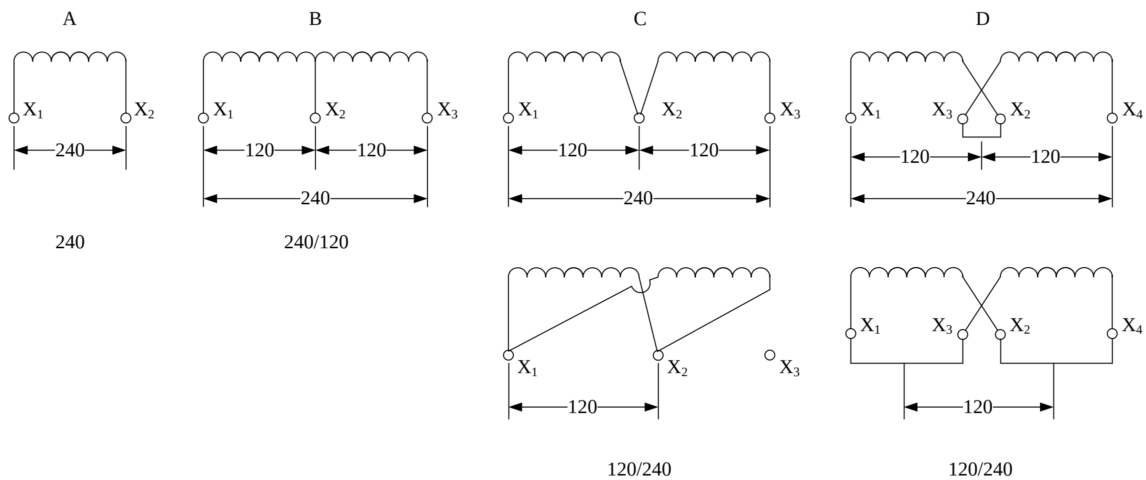

Figure 1-45- Single-phase secondary connections

Distribution transformers use either copper or aluminum conductors and may be either dry-type or liquid-type. Dry-type transformers are usually smaller, do not generate much heat, and can be located in a confined space at a customer's location. They are used as auxiliaries in generating stations and in industrial applications. Liquid-type transformers usually have oil that surrounds the transformer core and the conductors to cool and electrically insulate the transformer. They are usually larger than dry-type transformers and need more than air to prevent overheating. One of the main advantages of distribution transformers is that they can usually withstand overloads.

1.19.4 Distribution Source Substation Transformers

Distribution source substation (receiving station) transformers are basically step-down transformers that reduce transmission or sub-transmission voltage to the primary feeder level (e.g., 25 kV). Some may directly supply industrial plants. Loads on these transformers vary over wider limits, and their losses are expensive. Automatic tap changing on load is usually necessary, and their tapping range is high to account for the wide variation in voltage.

1.19.5 Phase-Shifting Transformers

Phase-shifting transformers help control the real power flow over transmission lines and systems interties by varying the phase angle between the input and output voltages of the transformer. Through a proper tap change the output voltage can be made to either lead or lag the input voltage. The amount of phase shift required directly affects the rating and size of the transformer.

Phase-shifting transformers are used in networks where intensive power-wheeling takes place due to deregulation. These transformers are available with non-symmetrical direct or indirect regulation and with symmetrical direct or indirect regulation. A phase-shifting transformer consists of two transformers, one associated with the line terminals and other with the tap changer.

There are two types of designs for phase-shifting transformers: single-core and two-core. The single-core design is used for small phase shifts and small MVA/voltage ratings. The two-core

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design is used for bulk power transfers with large MVA/voltage ratings. Product scope depends on technical specifications and requirements. However, technical specifications and transport restrictions determine whether the transformer selected for an application is a single-tank, double-tank, or triple-tank design.

1.19.6 Interconnecting Transformers

Interconnecting transformers connect two grids or systems of different voltage classes (e.g., 240 kV and 500 kV). They are autotransformers that provide the necessary voltage conversion and voltage control. Interconnecting transformers are normally found in transmission and sub-transmission systems (500 kV 240 kV 138 kV and 69 kV voltage classes)

In autotransformers there is no electrical isolation between the primary and secondary windings; therefore, autotransformers become more economical as the ratio of secondary voltage to primary voltage approaches unity. When used as interconnecting transformers, they are characterized by a wide tapping range and an additional tertiary winding that may be loaded or unloaded. The unloaded tertiary acts as a stabilizing winding by providing a path for the third harmonic currents.

1.19.7 Earthing (Grounding) Transformers

Earthing (grounding) transformers are used to provide a ground path to either an ungrounded "Y" or a delta-connected system to facilitate grounding and detection of an earth fault. They are typically used to do the following:

1) Provide a relatively low impedance path to ground, thereby maintaining the system neutral at or near ground potential
2) Limit the magnitude of transient overvoltages when re-striking ground faults occur
3) Provide a source of ground fault current during line-to-ground faults
4) Permit the connection of phase-to-neutral loads when desired

Grounding transformers are normally constructed with either a zigzag (Zn)-connected winding with or without an auxiliary winding or as a wye (Ynd)-connected winding with a delta-connected secondary that may or may not be used to supply auxiliary power. The zigzag connection helps to eliminate third harmonic voltages in the line. It can be used without a delta-connected winding or the 5-leg core design normally used for this purpose in distribution transformers and power transformers. Eliminating the need for a secondary winding can make this option less expensive and smaller than a comparable two-winding grounding transformer. Use of a zigzag transformer provides grounding with a smaller unit than a two-winding wye-delta transformer providing the same zero-sequence impedance does.

Wye-Connected grounding transformers require either a delta-connected secondary or the application of 4- or 5-leg core construction to provide a return flux path for the unbalanced loading associated with this primary connection. Since it is often desirable to provide auxiliary power from the grounding transformer secondary winding, this benefit can lead the end user to specify a two-winding grounding transformer in lieu of a zigzag connection. This connection is usually used in

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wind farms. Both zigzag and two-winding grounding transformers can have the ability to provide auxiliary power, and this can be either a wye- or delta-connected load.

In practice, the Scott-T-style transformer can provide a neutral point, but it is not cost-effective in comparison to the abovementioned methods. Using a zigzag transformer is typically the least costly method. It can be ordered as a three-phase unit or as three individual single-phase units.

1.19.8 Converter Transformers

a) Rectifier Transformers

Rectifier transformers are used in applications in which the secondary voltage must be varied over a wide range at a dc constant current value, such as aluminum smelters and chemical plants in electrolytic industries. Recently, they have been combined with a diode or thyristor rectifier designs. Manufacturing of rectifier transformers poses challenges due to special characteristics of this type of transformer, such as complex winding arrangements, high current and associated stray field effects, additional losses and heating effects due to harmonics, and the necessity of maintaining constant direct current.

Rectifier transformers may have two secondary windings with only one turn at each. Accordingly, the tap windings are on the primary winding because of the very low number of turns and the high current value at the secondary windings. The tap windings may be either on the primary winding or on a separate autotransformer that can be located at the same tank. Various circuit arrangements can be used to regulate the secondary voltage [7].

b) HVDC Converter Transformers

HVDC converter transformers are a special type of transformer built in accordance with IEEE C57.129. The detailed requirements for HVDC converter transformers are specified by the HVDC supplier, and are beyond the scope of this document. In principle they are similar to other multi-winding units, but they are subject to significant harmonic currents and losses.

HVDC converter transformers are a key component of the converter stations in HVDC transmission systems. HVDC transformers react as a coupling element between the connected ac grids and high-power rectifiers; therefore, they operate with the applied dc electric stress in addition to the ac stress, and because of this a special insulation design is necessary. The converter transformers typically have a leakage reactance of about 10-18% to limit the current during a short-circuit fault at the dc side. These transformers are also subjected to high levels of harmonics in the load current. Depending on voltage and transferred power, HVDC transformers are either built as single-phase or three-phase units and can have one or two valve windings per phase. Voltage variation is realized through the application of on-load tap changers.

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1.19.9 Other Types of Transformers

a) Furnace Duty Transformers

Furnace duty transformers are a special type of transformer that has an very high low-voltage current. They are used in the steel industry for smelting scrap iron and refining steel as ac or dc arc furnace transformers. They can be used in induction furnaces with different designs and duties. Furnace-duty transformers are characterized by a low secondary voltage (80 to 1000 V) and a high current, depending upon the transformer MVA rating. In these transformers non-magnetic steel is usually used for the tank, and low-voltage lead termination is usually used to eliminate hot spots and minimize stray losses. The high-current bus bars are interleaved to reduce the leakage reactance.

b) Locomotive Transformers

Locomotive transformers are mounted in the engine compartment of locomotives. The primary is supplied from an overhead line, and this type of transformer steps down the voltage to an appropriate level for feeding a dc rectifier. The rectifier output dc voltage drives the locomotive.

c) Series Reactors

Series reactors are connected in series with transmission lines, feeders, or generators to limit fault currents. They should have linear magnetic characteristics under fault conditions. Series reactors are also used in HVDC transmission lines as smoothing reactors and are connected between the converter and the dc line. They are usually one-winding transformers.

d) Shunt Reactors

Shunt reactors are used to compensate the capacitive reactive power generated during the load condition or the switching operation in extra-high-voltage transmission lines, thereby maintaining the voltage profile at the desired level. They are also used in harmonic filter structures, particularly in converter stations of line-commutated converter HVDC technology. Shunt reactors can be of coreless (air-core) or gapped-core (magnetic circuit with non-magnetic gap) design. They are similar to series reactors in that they are usually one-winding gapped-core or air-core transformers. They are designed to have constant impedance characteristics, even up to 1.5 times the rated voltage, in order to operate in the linear area and minimize the harmonic current generated under overvoltage conditions.

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2 Determination of Low-Frequency Parameters of Two-Winding Transformers

2.1 Introduction

In the first section of this guide, the basic concepts of transformers were explained and the basic information needed to model a transformer in a power system was provided. In this section, the modelling of two-winding single-phase and three-phase power transformers is described.

A general description of a single-phase transformer was provided in the first section. In this section, a technical description is provided and a practical generic model that includes primary and secondary tap ratios is proposed. For each type of transformer the connection diagram is described; then, the generic equivalent circuit of the transformer, which will form the basis of the generic model for that transformer type, is presented. The procedure for how to calculate the parameters from test results for the generic model is given and practical transformer data for each type of transformer is provided. The pu system for generic models is defined based on the winding voltage base.

2.2 Single-Phase Transformers

A single-phase transformer comprises two-windings wound around a core. Modelling a transformer for non-transient power system studies is carried out to determine the parameters of the circuit depicted in Figure 2-1, in which t_1 and t_2 present the tap settings of the primary and secondary windings. Figure 2-1-a is the simplified model and Figure 2-1-b is the equivalent π-model of a single-phase two-winding power transformer in a per-unit system. The procedures to determine the parameters of both of these models are similar. The parameters are determined through short-circuit and open-circuit tests, as described in Section 1.5. Though the circuits look schematically different, the procedures utilized to determine the parameters are the same. In this guide, these two equivalent models are considered to be a basic generic model for all types of two-winding power transformers, including single-phase and three-phase transformers.

2.2.1 Single-Phase Two-Winding Transformer Generic Model

The generic model for single-phase transformers described earlier is presented in Figure 2-1.

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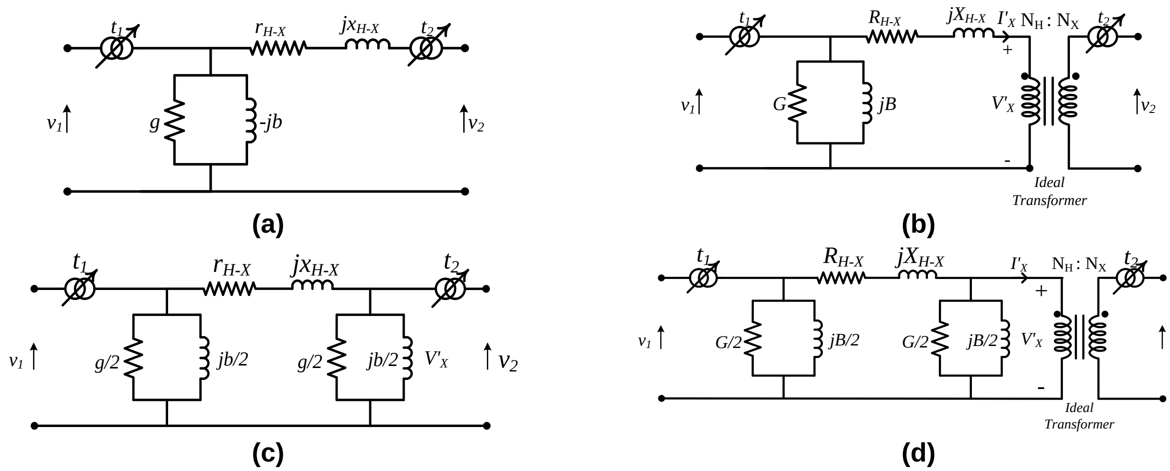

Figure 2-1- Two-winding power transformer generic models in a per-unit system: a) Simplified pu model b) Simplified real model, c) π -model in pu, d) π-model in real values

2.2.2 *Single-Phase Two-Winding Transformer Modelling Procedure*

To model a single-phase two-winding transformer, the following steps should be followed:

Step 1: The transformer data listed in Table 1-1 should be extracted from the available data, or assumptions should be made based on Table 1-3 and Table 1-4.

Step 2: The equivalent circuit parameters should be calculated using the formulas in Table 2-1.

2.3 Three-Phase Transformers

In practice, the majority of three-phase power transformers are three-legged core-type transformers, although on very large transformers a five-legged core may be required. In this guide, unless otherwise noted, the term three-phase two-winding transformer means a three-legged-core-type two-winding transformer. The formulas to calculate positive and negative sequence equivalent circuit parameters are similar to the single-phase formulas proposed in Table 2-1, except that the three-phase line voltages should be replaced properly in the formulas.

2.4 Two-Winding Transformers With Wye Primary and Wye Secondary

Wye primary and wye secondary is the most common connection of three-phase transformers in which the primary and secondary circuits are in phase; i.e., there are no phase-angle displacements introduced by this connection. Under a balanced system, each phase operates as a separate single-phase transformer. The neutral points at each side may be connected to ground. If the neutral point is connected to ground, the connection is designated by “GrdY”. In this case, as mentioned in Section 1.9, insulation close to the neutral point can be graded to lower the cost of the transformer. This is an advantage of Y-Y transformer application in high-voltage transmission systems. It should be noted that a winding in a GrdY connection must not be connected between two phases. This limitation is expressed as GRD in the transformer rating voltage on the nameplate; it means that windings must always be connected between phases-to-

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ground. Figure 2-2 shows the schematic transformer diagram, vector representation, vector diagram, and phase displacement vector diagram of a Yy connected transformer. The vector group of this connection is Yy0. The Yy connection can also be connected in a way in which there is a 60° phase-shift between the primary and secondary voltages. In this case, the vector group of this connection is Yy6. Figure 2-3 shows the schematic transformer diagram, vector representation, vector diagram, and phase-displacement vector diagram of a Yy0 transformer.

In practice, the problem associated with the Yy-connection core-type transformer is that the zero-sequence component cannot be readily eliminated. If a line-to-earth fault occurs, through transformer action the fault current will flow in the transformer tank. Installation of a delta-connected tertiary winding in the transformer structure eliminates this condition.

Table 2-1- Formulas to Calculate Generic Model Parameters of a Transformer from a Test Report

Type	Parameters in Per Unit (Winding Ratings Base)	Parameters in SI Units[1]
Windings' leakage impedance	$z = V_{SC\,[pu]} = \begin{cases} \%I_Z/100 \;\text{ if } \%I_Z \text{ given} \\ otherwise \;\; \dfrac{V_{SC}}{V_{H\,rated}} \end{cases}$ and $\%I_Z = V_{SC\,[pu]} \times 100$	$Z_{H-X} = \begin{cases} \dfrac{V_{SC}}{I_{SC}} & \text{Single} - \text{phase} \\ \dfrac{V_{SC}}{\sqrt{3}I_{SC}} & \text{Three} - \text{phase} \end{cases}$ $Z_{H-X} = \frac{V_{SC}}{I_{SC}} = \frac{\%I_Z}{100} \times Z_{H\,base} = \frac{\%I_Z}{100} \times \frac{{V_{H\,rated\,[kV]}}^2}{MVA_{Test\,[MVA]}}\,\Omega$ $Z_{H\,base}$ is at load losses MVA base
Load losses equivalent resistance	$r_{H-X} = \frac{P_{SC[kW]}}{MVA_{SC\,Test\,[MVA]} \times 1000}$ pu	$R_{H-X} = \begin{cases} \dfrac{P_{SC}}{{I_{SC}}^2} = \dfrac{P_{SC\,[kW]} \times 1000}{{I_{H\,rated}}^2} & Single - phase \\ \dfrac{P_{SC}/3}{{I_{SC}}^2} = \dfrac{P_{SC\,[kW]} \times 1000}{3\,{I_{H\,rated}}^2} & Three - phase \end{cases}$ $R_{H-X} = \frac{P_{SC[kW]} \times {V_{H\,rated\,[kV]}}^2}{{MVA_{SC\,Test\,[MVA]}}^2 \times 1000}\,\Omega$
Windings' leakage reactance	$x_{H-X} = \begin{cases} \%I_X/100 \text{ if given} \\ \text{otherwise } \sqrt{(\dfrac{\%I_Z}{100})^2 - r^2} \end{cases}$ pu	$X_{H-X} = \begin{cases} \%I_X/100 \times Z_{H\,base} \text{ if } \%I_X \text{ given} \\ \text{otherwise } \sqrt{{Z_{H-X}}^2 - {R_{H-X}}^2} \end{cases}\;\Omega$ $Z_{H\,base}$ is at load losses MVA base
Magnetizing branch admittance	$y = \lvert g + jb \rvert = \%I_{exc.}/100$ pu	$Y_X = \frac{I_{OC}}{V_{OC}} = \frac{\%I_{exc}/100}{Z_{X\,base}}$ ℧ or $Y_H = \frac{\%I_{exc}/100}{Z_{H\,base}}$ ℧ $Z_{X\&H\,base}$ are at no load MVA base
No Load losses equivalent conductance	$g = \frac{P_{NL[kW]}}{MVA_{NLTest[MVA]} \times 1000}$ pu	$G = \begin{cases} \dfrac{P_{OC[kW]}}{{V_{OC(phase)[kV]}}^2 \times 1000} & \text{Single - phase} \\ \dfrac{P_{OC[kW]}}{{V_{OC(line)[kV]}}^2 \times 1000} & \text{Three - phase} \end{cases}$ ℧

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Type	Parameters in Per Unit (Winding Ratings Base)	Parameters in SI Units[1]
		$G_X = \frac{P_{NL[kW]}}{V_{X\,rated[kV]}{}^2 \times 1000}$ ℧ or $G_H = \frac{P_{NL[kW]}}{V_{H\,rated[kV]}{}^2 \times 1000}$ ℧
Magnetizing branch susceptance	$b = -\sqrt{y^2 - g^2}$ pu	$B_X = -\sqrt{Y_X{}^2 - G_X{}^2}$ ℧ or $B_H = -\sqrt{Y_H{}^2 - G_H{}^2}$ ℧

1- Note that it is assumed the short-circuit test is performed from the high-voltage side and the no-load test is performed from the low-voltage side. This is usually not declared clearly because in test reports the measured exciting current and impedance voltage are usually reported in per unit.
For two-winding transformers, the parameters with subscripts $H-X$ are the same as the parameters with HX.

2.4.1 Two-Winding Y-Y Transformer: Positive and Negative Sequence Generic Model

The generic model of a three-phase two-winding Y-Y transformer for a positive and negative sequence is similar to that of a single-phase transformer, as presented in Figure 2-1. This generic model is applicable for all types of Y-Y connections as well as for the shell type for the 5-legged core type and for three banks of single-phase transformers, regardless of whether the neutral point is grounded or not.

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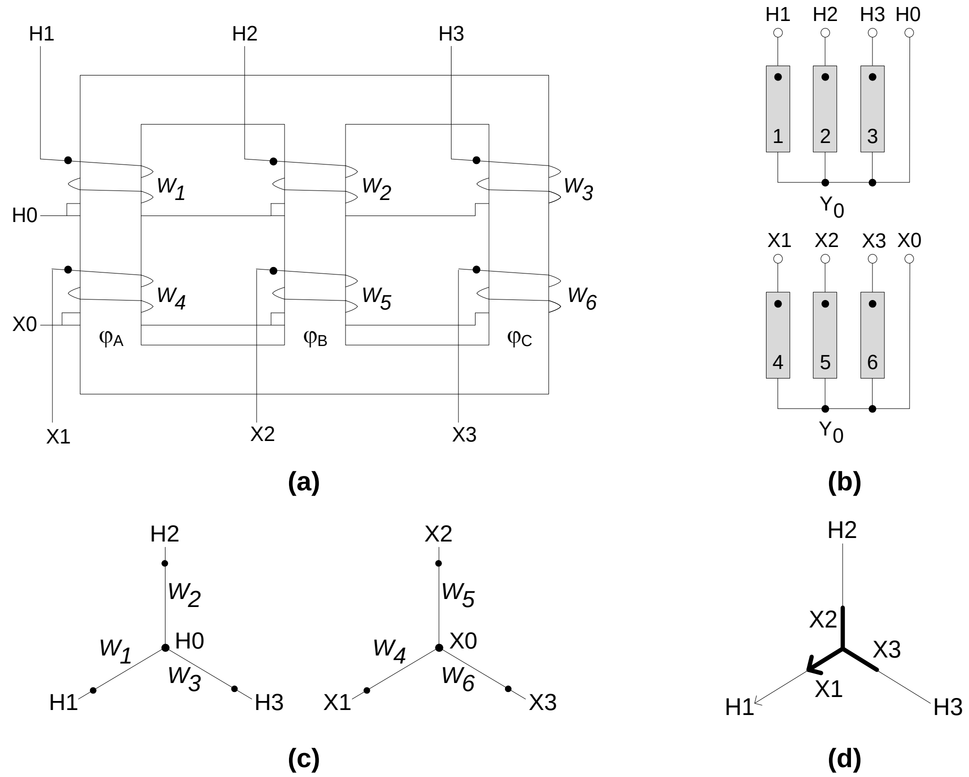

Figure 2-2- Two-winding Yy0 transformer with wye primary wye secondary: a) Schematic transformer diagram, b) Winding connection diagram, c) Vector diagram, d) Phase displacement vector diagram

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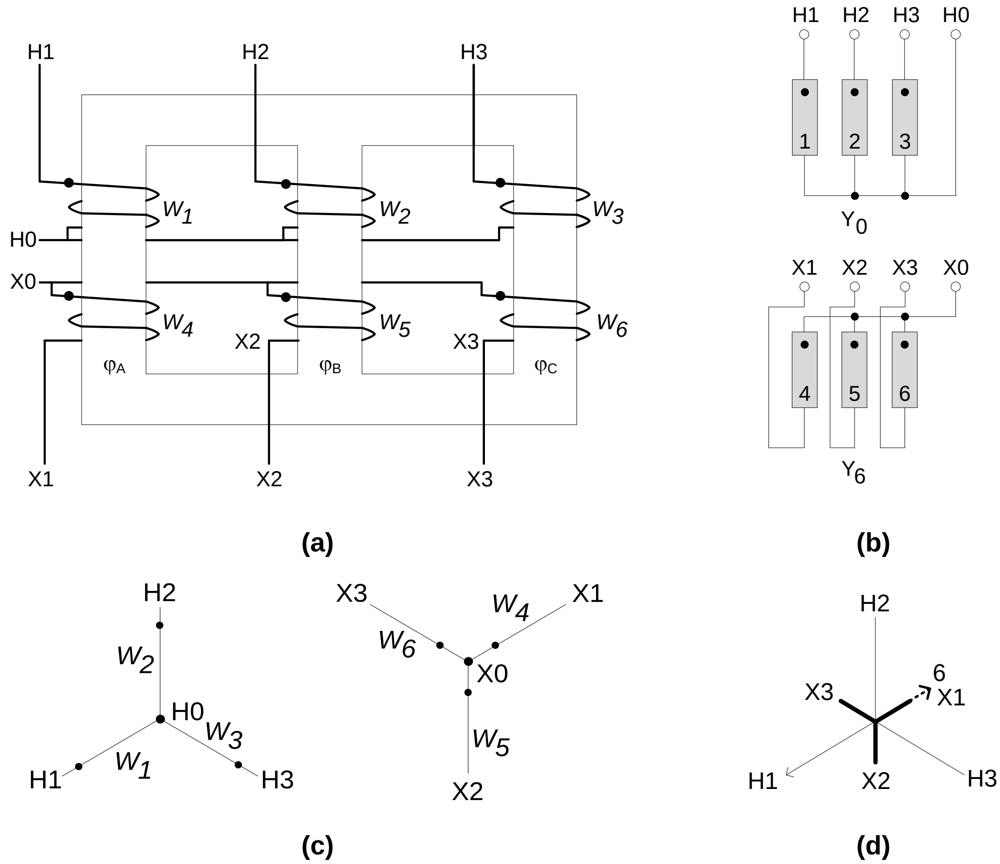

Figure 2-3- Two-winding Yy6 transformer with wye primary wye secondary: a) Schematic transformer diagram, b) Winding connection diagram, c) Vector diagram, d) Phase displacement vector diagram

2.4.2 Two-Winding Y-Y Transformer: Procedure to Determine Generic Model Parameters

To model a three-phase two-winding Y-Y transformer in positive or negative sequence, the following steps should be followed:

Step 1: The transformer data listed in Table 1-1 should be extracted from the available data, or assumptions should be made based on Table 1-3 and Table 1-4.

Step 2: The equivalent circuit parameters should be calculated using the formulas in Table 2-1.

Step 3: Zero-sequence parameters should be calculated as described in next section.

2.4.3 Two-Winding Y-Y Transformer: Zero-Sequence Equivalent Circuit

There are four types of Y-Y connection depending on whether the neutral point in both sides is connected to ground or not. Some may not be practical. The four types are listed in Table 2-2.

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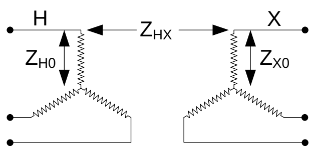
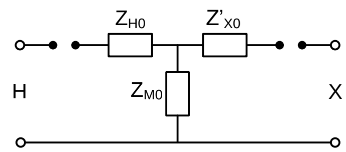
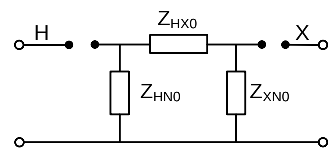
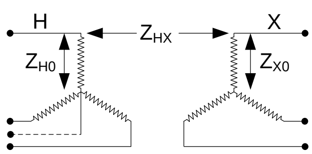
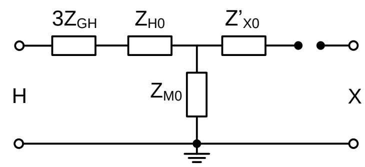
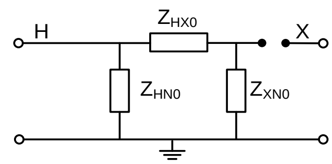
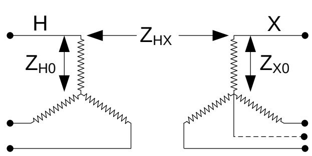
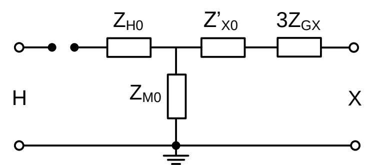
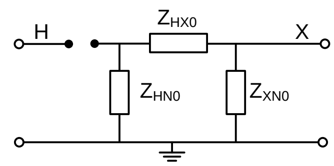
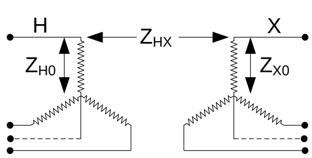
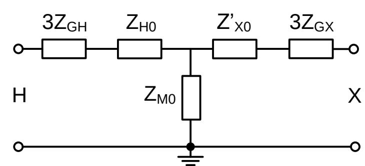
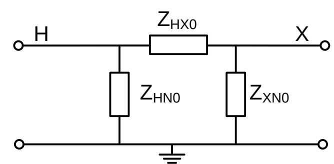
Table 2-2- Zero-Sequence Equivalent Circuits of Y-Y Transformers

	Connection Type	T-Model	π-Model	
1				Y-y
2				YN-y
3				Y-yn
4				YN-yn

2.4.4 Example 1: A Practical Two-Winding Yy0 Transformer

Figure 2-4 shows the nameplate information of a 138/26.5 kV, 15/20/25 MVA two-winding $Y_N y_n$-connected transformer. The schematic diagram and vector diagram of this type of transformer is shown in Figure 2-2. The nominal voltages of the primary and secondary windings are 138 kV and 26.5 kV, respectively. The winding insulation at both sides is graded; therefore, the neutral points must be grounded at both sides; if they are not, the winding insulation will not withstand the normal voltage during unbalanced operating conditions in the network. The two-page test report of the transformer is shown in Figure 2-21-a and Figure 2-21-b.

The report shows the load losses test has been conducted for three tap positions including nominal tap ratio and ±10% nominal voltages. Accordingly, dc resistances of the high-voltage and low-voltage windings have been measured and listed in the test report. To determine the transformer generic model parameters, only the nominal tap ratio test results are used. In this transformer, the nominal tap ratio is tap position 9.

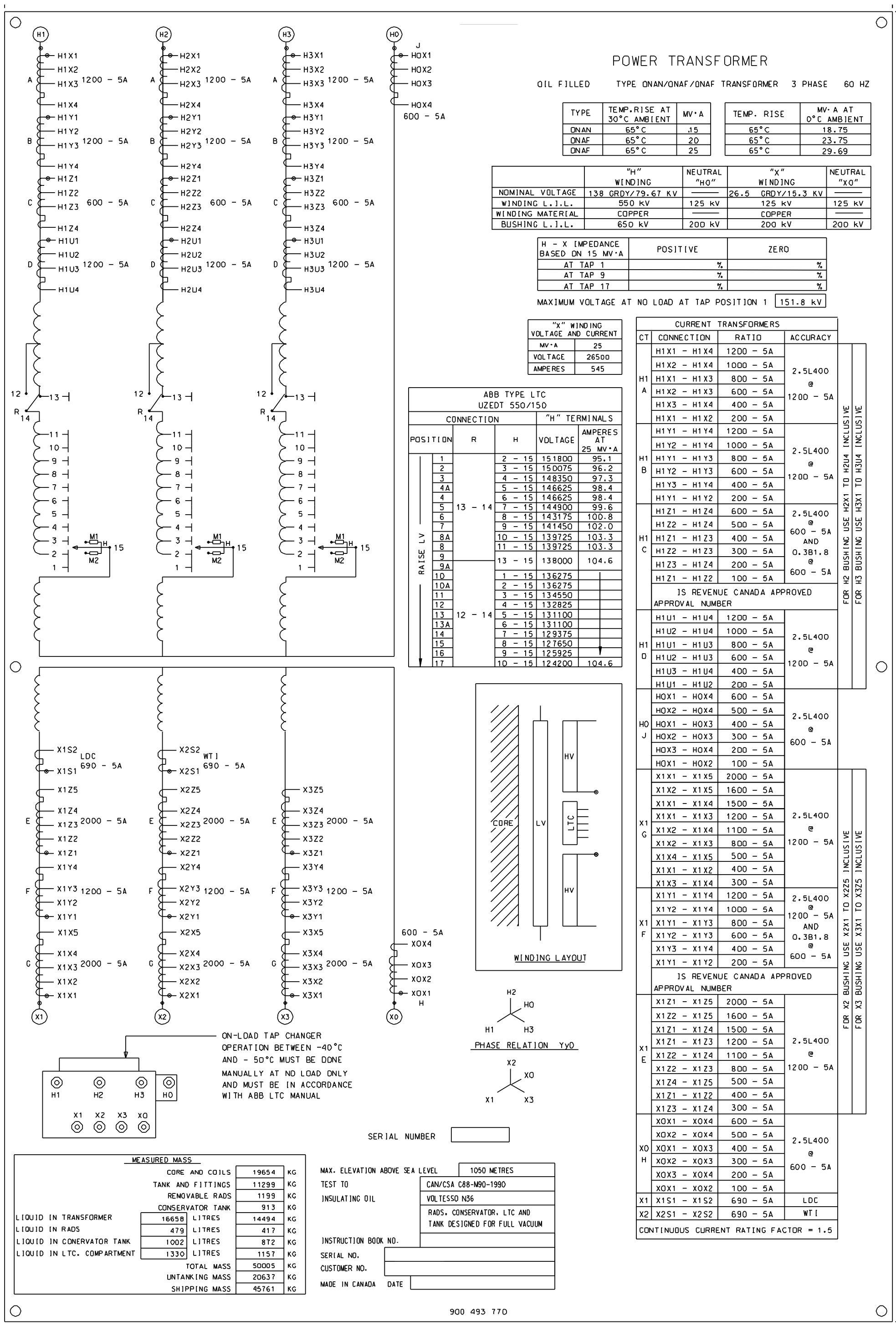


Figure 2-4- Example 1: Transformer nameplate, two-winding $Y_N y_n$ connected

Page 1 of 2

TRANSFORMER TESTS REPORT

Purchaser		Purchaser's Order #		Customer Spec #	
Date of Test	January 28, 2004	FP Order #		FP Serial #	
Type	ONAN/ONAF/ONAF	Phase		Cycles	60 Hz
Insulating Fluid	OIL	Temp Rise	65°C		
Winding	HV	Winding	LV	Winding	
MVA	15/20/25	MVA	15/20/25	MVA	
Voltage	138000Y/79670	Voltage	26500Y/15300	Voltage	
Taps	+/- 10% IN +/-8 STEPS RCBN	Taps	--	Taps	

Resistance, exciting current, losses and impedance

Losses and regulation are based on wattmeter measurements.

For three-phase transformers the resistances are the sum of the three phases in series.

Tap Voltage (kV) (HV/LV)	Tap Position (HV/LV)	Resistance (Ω) @ 85°C			% Exciting Current at 100/110% Rated Voltage @ Base MVA	No-load (kW) at 100/110% Rated Voltage @ 85°C	15 MVA HV/LV @ 85°C		13.5 MVA HV/LV @ 85°C		25 MVA HV/LV @ 85°C	
		HV	LV	---			Load Loss (kW)	%IZ	Load Loss (kW)	%IZ	Load Loss (kW)	%IZ
138/26.5	9/-	5.7152	0.11705		.119/.359	11.61*/16.00	41.66*	7.68*			114.832	11.61
151.8/26.5	1/-	6.2858	0.11705				39.952	7.50				
124.2/26.5	17/-	5.1471	0.11705						37.25	7.41		
				Guarantees		12.0*	41.5*	7.5*				

Note: * denotes guaranteed values

Regulation @ 15 MVA

%Leading PF @ TAPS: 9				%Lagging PF @ TAPS: 9			
100%	90%	80%		100%	90%	80%	
0.5710	-2.8408	-4.1748		0.5710	3.8172	4.9969	

Efficiency @ 85°C : 15 MVA

TAP POSITIONS : 9

1/4 load	2/4 load	3/4 load	4/4 load	5/4 load
99.622	99.707	99.689	99.646	99.593

Sound Level @ 1 P.U. Voltage

	15 MVA	25 MVA	
Measured (dB)	59.5	72.8	
Guarantee (dB)	72.0	75.0	

CM50011-101-01

Auxilary losses

	MVA
Measured (kW)	-
Guarantee (kW)	-

Summary The following tests sheets are attached:

- Ratio Test
- Impulse Log
- Doble Test
- Oil Tests (DGA, PCB)
- CT/Bushing Tests
- CT Ratio & Polarity Test
- Control Wiring Checklist

I hereby certify that this is a true report based on factory tests made in accordance with the latest transformer test code; and that the transformer withstood the above tests.

Prepared by ______ FP spec ______ Date ______ Approved ______

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Figure 2-5-a- Example 1: Transformer test report, Page 1

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TRANSFORMER TESTS REPORT

Purchaser ______ Purchaser's Order # ______ Customer Spec # ______
Date of Test January 28, 2004 FP Order # ______ FP Serial # ______
Type ONAN/ONAF/ONAF Phase ______ Cycles 60 Hz Insulating Fluid OIL Temp Rise 65°C

Winding	HV	LV	
MVA	15/20/25	15/20/25	
Voltage	138888Y/79670	26500Y/15300	
Taps	+/- 10% IN +/-8 STEPS RCBN	--	

Insulation Tests

Winding	Basic Impulse: Full Wave Level (kV)	Basic Impulse: Chopped Wave Level (kV)	Switching Impulse: Crest Wave Level (kV)	Applied Potential: Applied Voltage (kV)	Applied Potential: Duration (seconds)
H1,H2,H3	550	--		50	60
H0	125	--		50	60
X1,X2,X3	125	--		50	60
X0	125	--		50	60

Insulation Tests Continued

Induced Potential Tests

Tap	Enhanced Level: Times Rated Voltage	Enhanced Level: kV to Ground	Enhanced Level: Duration (cycles)	One-Hour level: Times Rated Voltage	One-Hour level: kV to Ground	One-Hour level: Duration (minutes)	Internal Partial Discharge Test: RIV in Phases A,B,C (µV)	Guarantee	AC in Phases A,B,C (pC)	Guarantee
#	1.700	149	7200	1.500	131.5	60	A = 70 B = 58 C = 45	<100	A = - B = - C = -	

Insulation Tests Continued

Reference Temperature	Winding Megger Test (GΩ) {values @ 1 minute}: Test kV	HV - (LV & GRD)	LV - (HV & GRD)			Core Megger Test (GΩ): Test kV	CORE MEGGER
20°C	1	5.25	3.22			1	2.6

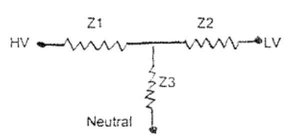
Temperature rises Average rise in °C, corrected to instant of shutdown, with windings connected and loaded as follows, until constant temperature rise was reached. (CM60011-101-01)

Winding	kV	MVA	Current	Rise of winding by resistance	Guarantee	Fluid rise: Average	Fluid rise: Top	Fluid rise: Bottom	Ambient Temp.
HV	138	15	62.8	51.4°C	65°C	40.5°C	47.5°C	33.5°C	29.9°C
LV	26.5	15	315	49.9°C	65°C				
HV	138	25	104.6	57.2°C	65°C	39.5°C	53.1°C	25.9°C	31.6°C
LV	26.5	25	545	54.9°C	65°C				

Remarks:

Zero Sequence Impedance:-

Tap *	Z1(%)	Z2(%)	Z3(%)
1	0.86	6.80	46.06
9	0.80	7.02	45.93
17	0.90	6.53	41.12



FORM-62-045-1-02/06/13

Figure 2-5-b- Example 1: Transformer test report, Page 2

According to the proposed procedure in Section 2.4.2, Step-1, the required parameters listed in Table 1-1 are extracted from the test report. These data are shown in Table 2-3 .

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Table 2-3- Information Required for Modelling the Transformer in Example 1

Item	Transformer Parameter	Symbol	Values
General			
1	Transformer ONAN Ratings	MVA_{ONAN}	15 MVA
2	Winding Voltages (primary, secondary, …)	V_H, V_X,… V_P, V_S, … V_1, V_2, …	138 kV / 26.5 kV
3	Connection type	-	wye-wye
4	Tap range	t_1, t_2, …	± 10%
5	Number of tap steps	-	17 (±8 steps)
6	Winding with an adjustable tap	-	Primary (high) side
7	Phase angle of windings	θ_1, θ_2, …	0°
No Load Loss Test Results			
8	No-load loss test MVA	$MVA_{NL\ Test}$	15 MVA
9	No-load loss	P_{NL}	11.610 kW
10	Excitation current	I_{exc}	0.119 %
11	Tap setting for no-load loss test	t_{NL}	Nominal
Load Loss Test Results			
12	Load loss test MVA	$MVA_{SC\ Test}$, …	15 MVA
13	Load loss	$P_{SC,}$ $P_{LL\_HX, \dots}$	41.660 kW
14	Impedance	I_Z, or Z_{HX}, …	7.68 %
15	Reactance	I_X, or X_{HX}, …	- Not reported
16	Tap setting for load loss test	t_{SC}	Nominal
Zero-Sequence Test Results			
17	Zero-sequence open-circuit test results	Z_1, Z_2	-
18	Zero-sequence short-circuit test results	Z_3	-
19	Zero-sequence T-model parameters (if these parameters have been provided instead of Zero-sequence open circuit test results)	Z_{H0}, Z'_{X0} , Z_{M0} for the T-model	0.80%, 7.02%, 45.93%
20	Grounding configuration	Winding 1 solidly grounded Winding 2 grounded through impedance	Both solidly grounded
21	Grounding Impedance	Z_{GH}, Z_{GX}, …	0, 0

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The T-model zero-sequence equivalent circuit of this transformer has been completely given in the test report, page two, for three different tap positions. The procedure provided in Appendix D can be followed to calculate the complete zero-sequence parameters. The calculated parameters are listed in Table 2-4. The transformer generic model is shown in Figure 2-6. The zero-sequence equivalent circuit is shown in Figure 2-7.

Table 2-4- Example 1: Generic Model Parameters of the Transformer

Type	Parameters in Per Unit	Parameters in SI Units
Windings' leakage impedance	$z = \%I_Z/100 = 0.0768$	$Z_{H-X} = \frac{V_{SC}}{I_{SC}} = 97.5053\Omega$
Load losses equivalent resistance	$r = \frac{P_{SC}}{MVA_{SCTest} \times 1000} = 0.002777$ pu	$R_{H-X} = \frac{P_{SC}}{I_{SC}^2} = \frac{P_{SC}}{3I_{H\,rated}^2} = 3.526\ \Omega$
Windings' leakage reactance	$x = \sqrt{(\%I_Z/100)^2 - r^2} = 0.07675$ pu	$X_{H-X} = \sqrt{Z_H^2 - R_H^2} = 97.44150\ \Omega$
Magnetizing branch admittance	$y = \%I_{exc.}/100 = 0.00119$ pu	$Y_X = \frac{I_{OC}}{V_{OC}} = \frac{\%I_{exc}/100}{Z_{X\,base}} = 0.00003\ \mho$ or $Y_H = \frac{\%I_{exc}/100}{Z_{H\,base}} = 9.373E-7\ \mho$
No Load losses equivalent conductance	$g = \frac{P_{NL}}{MVA_{NLTest} \times 1000} = 0.000774$ pu	$G_X = \frac{P_{OC}}{V_{OC}^2} = \frac{P_{NL}}{V_{X\,rated}^2} = 1.653E-5\ \mho$ or $G_H = \frac{P_{NL}}{V_{H\,rated}^2} = 6.0964E-7\ \mho$
Magnetizing branch susceptance	$b = -\sqrt{y^2 - g^2} = -0.00090$ pu	$B_X = -\sqrt{Y_X^2 - G_X^2} = -1.9307E-5\ \mho$ or $B_H = -\sqrt{Y_H^2 - G_H^2} = -7.1195\ E-7\ \mho$
Zero-sequence parameters	$Z_{H0} = 0.08$ $Z'_{X0} = 0.0702$ $Z_{M0} = 0.4593$	$Z_{GH} = 0$ $Z_{GX} = 0$ $Z_{H0} = 10.157\ \Omega$ $Z'_{X0} = 89.126\ \Omega$ $Z_{M0} = 583.127\ \Omega$ $Z_{HN0} = 659.737\Omega$ $Z'_{XN0} = 100.835\ \Omega$ $Z_{HX0} = 5789\ \Omega$

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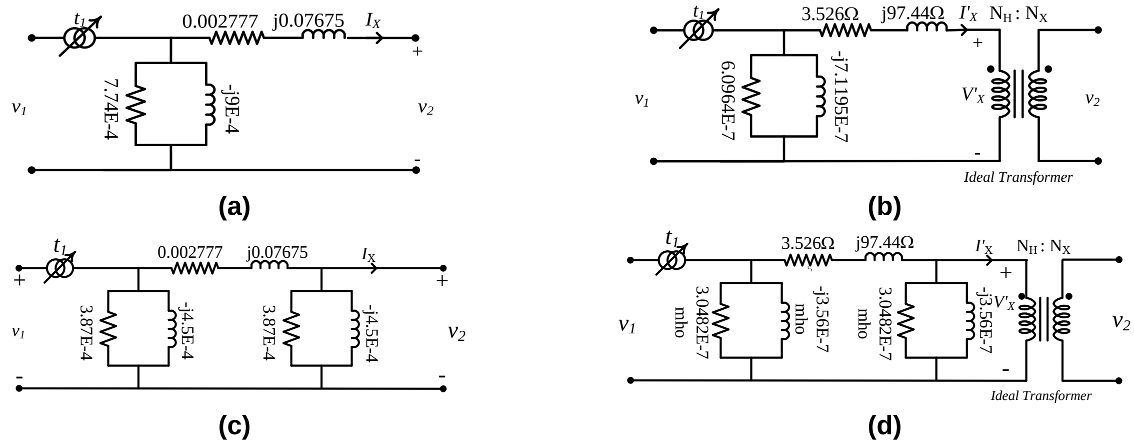

Figure 2-6- Example 1- Transformer generic models : a) Simplified pu model b) Simplified real model, c) π-model in pu system, d) π-model in real values

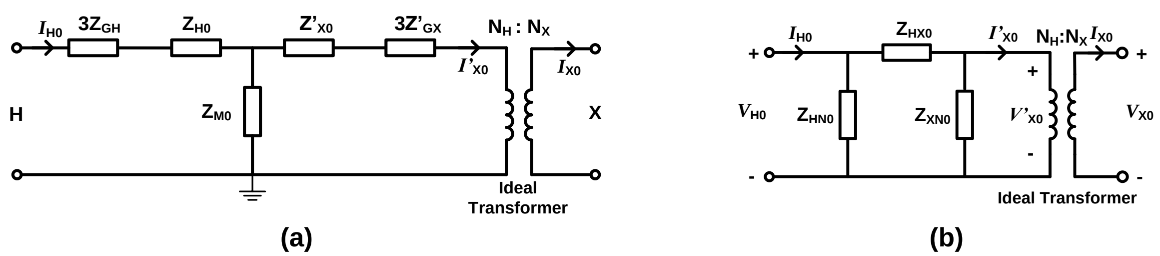

Figure 2-7- Example 1- Zero-sequence equivalent circuit: a) T-model, b) π-model

2.5 Two-Winding Transformers with Wye Primary Delta Secondary

Wye-Delta connections are generally used for large-ratio step-down transformers. The wye connection on the high-voltage side is used because of electrical and mechanical advantages such as the low insulation costs of the windings or low insulation tap changer mechanism. The neutral point can be grounded to be stable with respect to unbalanced loads. The delta-connected secondary prevents triplex harmonics from flowing on the load-side terminal. It provides an improved waveform to the load. Figure 2-8- shows the schematic transformer diagram, vector representation, vector diagram, and phase displacement vector diagram of a Y-delta-connection transformer. The vector group of this connection is called Yd7.

2.5.1 Two-Winding Y-delta Transformer: Positive and Negative Sequence Generic Model

The generic model of a three-phase two-winding Y-delta transformer for positive and negative sequence is similar to that of a Y-Y transformer or a single-phase transformer, as shown in Figure 2-1.

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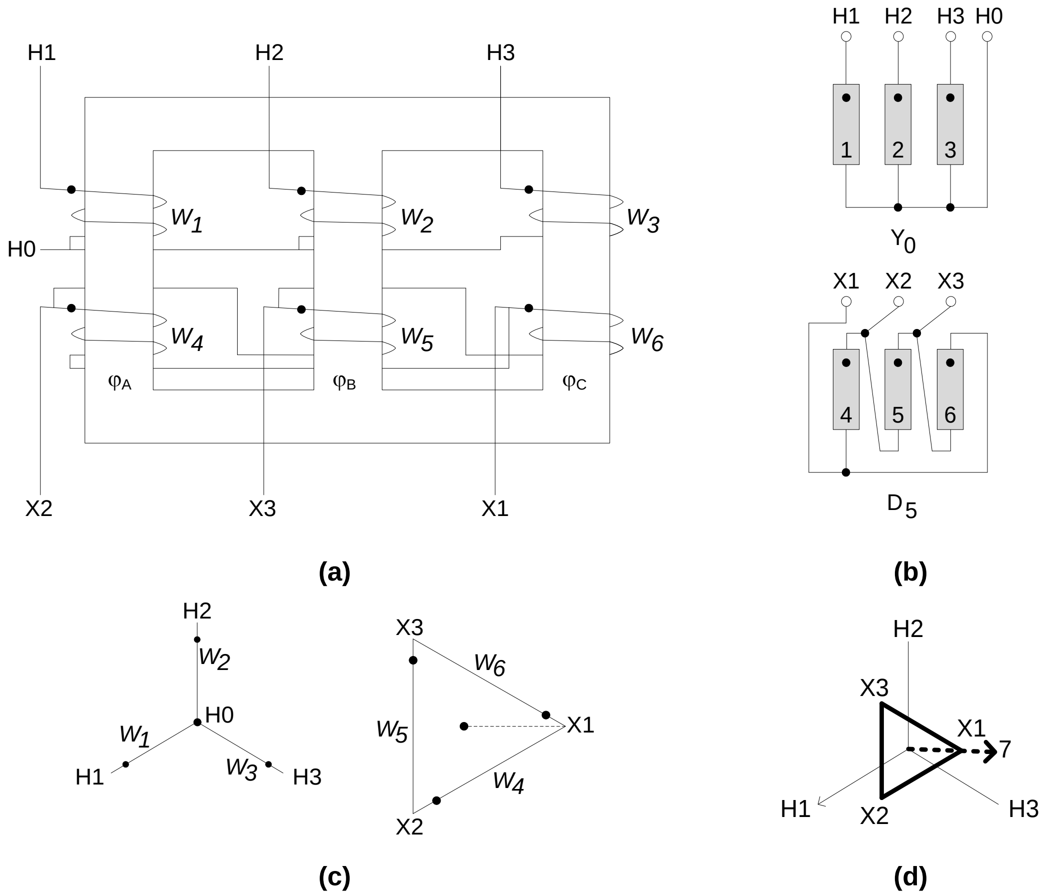

Figure 2-8- Two-Winding transformer with Y primary delta secondary: a) Schematic transformer diagram, b) Winding connection diagram, c) Vector diagram, d) Phase displacement vector diagram

2.5.2 Two-Winding Y-Delta Transformer: Procedure to Determine Generic Model Parameters

The procedure to model a three-phase two-winding Y-delta transformer in positive or negative sequence is the same as the Y-Y transformer procedure described in Section 2.4.2, except that the zero-sequence model is different. The next section describes how the zero-sequence equivalent circuit of a two-winding Y-delta transformer is modelled.

2.5.3 Two-Winding Y-Delta Transformer: Zero-Sequence Equivalent Circuit

There are two types of Y-delta connection, the difference between the two being whether the neutral point in the Y-connected side is connected to ground or not. Table 2-5 shows these two types of connection. The ungrounded Y-delta connection presents open circuit under zero-sequence excitation; therefore the zero-sequence current does not flow through the transformer. However, it does flow through a grounded Y-delta connected transformer. It is described in Section 1.15.3 b) that if the primary winding set is a grounded Y connection the zero-sequence current flows in the delta-connected secondary winding set; however, the total zero-sequence

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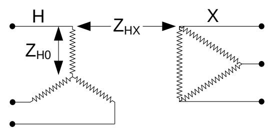
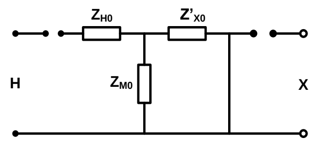
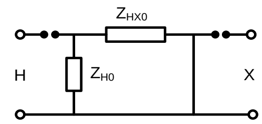
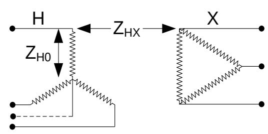
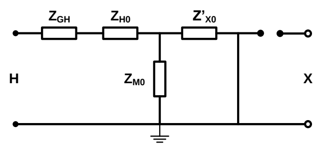
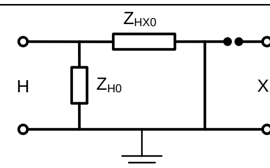
current flowing through the secondary terminals is zero and no zero-sequence voltage appears on the terminal of the secondary windings because the delta connection operates as a closed loop circuit for the possible induced voltages to these windings due to the zero-phase magnetizing flux. This is shown schematically in Figure 2-9.

Table 2-5- Zero-Sequence Equivalent Circuits of Y-Delta-Connected Transformers

	Connection Type	T-Model	π-Model	Symbol
1				Y-delta
2				YN-delta

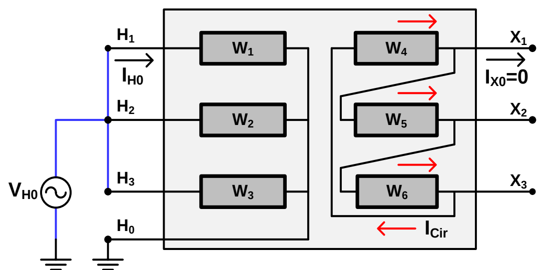


Figure 2-9- The Y-delta-connected transformer behavior under zero-sequence excitation

The zero-sequence impedance described in Section 1.15.3 b) can be calculated by only one test from the Y-connected side in which:

$$Z_0 = Z_{H0} + Z_{M0}||Z'_{X0} = Z_{H0}||Z_{HX0} = R_0 + jX_0$$

$$R_0 = \frac{P_{H0\ OC}}{3I_{H0\ OC}{}^2}$$

$$X_0 = \sqrt{\left(\frac{V_{H0\ OC}}{I_{H0\ OV}}\right)^2 - R_0{}^2}$$

2.5.4 Example 2: A Practical Two-Winding YNdelta1 Transformer

Figure 2-10-a and Figure 2-10-b show the nameplate information of a 72/13.8 kV, 50/66/83 MVA two-winding YNdelta-connected transformer. The schematic diagram and vector diagram of this type of transformer is shown in Figure 2-8. Nominal voltages of the primary and secondary windings are 72 kV and 13.8 kV, respectively. The nameplate does not show that the winding

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insulation at the high-voltage side is graded. Therefore, the neutral points of the high-voltage side may be or may be not grounded. In this example the neutral point is grounded through a 2 Ω reactance. The test results of this transformer are shown in Figure 2-11-a to Figure 2-11-j. In a similar manner to that in Example 1, the load losses test for this transformer has been conducted for three tap positions including the nominal tap ratio and ±10% nominal voltages. It has been clarified for this transformer that the nominal tap position is Position 9. To determine the transformer generic model parameters, only the nominal tap ratio test results are used. The zero-sequence test measurements have been proposed in Page 9 of the test report, Figure 2-11-i.

According to the proposed procedure in Section 2.4.2 Step 1, the required parameters listed in Table 1-1 are extracted from test report. This data are shown in Table 2-6.

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GENERATOR STEP-UP TRANSFORMER RP-8298

SERIAL NO.:			
TYPE NO.:	TM-0846		
NUMBER OF PHASE	3		
FREQUENCY	60	Hz	
WINDING	RATED CAPACITY	RATED VOLTAGE	
H.V	50 / 66 / 83 MVA	72	KV
L.V	50 / 66 / 83 MVA	13.8	KV
%IMPEDANCE AT 85deg.c ON 50MVA(ONAN) BASE			
MAX. TAP		%	
RATED TAP		%	
MIN. TAP		%	
CAPACITY AT 0deg.C AMBIENT TEMPERATURE			
H.V	62 / 78 / 98	MVA	
L.V	62 / 78 / 98	MVA	
MATERIAL OF CONDUCTOR	COPPER		
TANK WITHSTANDING PRESSURE	1.0 kg/cm^2		
YEAR OF MANUFACTURE	. .		

VECTOR GROUP SYMBOL	YNd1		
TYPE OF COOLING	ONAN / ONAF / ONAF		
STANDARD	CSA - C88-M90		
MAX. TEMP. RISE(WINDING/OIL)	65 /65	deg.C	
RATED CURRENT		B.I.L? (LINE/NEUTRAL)	
401/ 529 /666	A	350 / 125	KV
2092 / 2761 / 3473	A	125	KV
TYPE OF INSULATING OIL	VOLTESSO N36		
DYNAMIC EARTHQUAKE WITHSTAND	HORIZONTAL	0.3	G
	VERTICAL	0.24	G
SOUND LEVEL(AT 50 MVA BASE)		dB	
CORE AND COIL(UNTANKING)	55,000	kg	
TANK AND FITTINGS	22,000	kg	
TOTAL WEIGHT	100,400	kg	
QUANTITY OF OIL	23,400	kg	
TRANSPORTATION	69,000	kg	
REFERENCE TO INSTRUCTION MANUAL			

CONSERVATOR TANK AND OLTC TANK ARE WITHSTAND AT FULL VACUUM BY EQUALIZING METHOD.

Figure 2-10-a- Example 2: Transformer nameplate, Page 1

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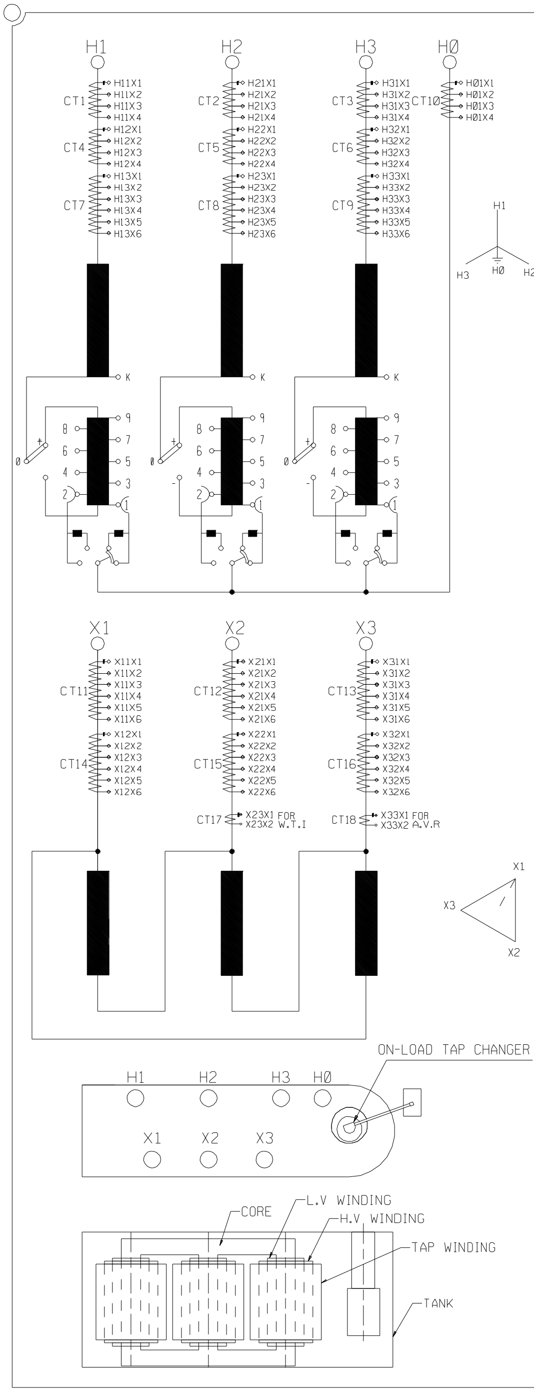

HIGH VOLTAGE SIDE						
TAP POS	VOLTAGE (V)	CURRENT (A) ONAN	ONAF	ONAF	SEL S/W	CHANGE OVER S/W
1	79200	364.5	481.1	605.1	1	
2	78300	368.7	486.7	612.0	2	
3	77400	373.0	492.3	619.1	3	
4	76500	377.4	498.1	626.4	4	Ø TO +
5	75600	381.8	504.0	633.9	5	
6	74700	386.4	510.1	641.5	6	
7	73800	391.2	516.3	649.3	7	
8	72900	396.0	522.7	657.3	8	
9a					9	
R 9b	72000	400.9	529.2	665.6	K	
9c					1	
10	71100	406.0	535.9	674.0	2	
11	70200	411.2	542.8	682.6	3	
12	69300	416.6	549.9	691.5	4	
13	68400	422.0	557.1	700.6	5	Ø TO −
14	67500	427.7	564.5	709.9	6	
15	66600	433.4	572.1	719.5	7	
16	65700	439.4	580.0	729.4	8	
17	64800	445.5	588.0	739.5	9	

LOW VOLTAGE SIDE			
VOLTAGE	CURRENT (A) ONAN	ONAF	ONAF
13800 V	2091.8	2761.2	3472.5

BUSHING CURRENT TRANSFORMER (B.C.T)				
TYPE	RATIO?	BURDEN?	CLASS	REMARK
CT1				
CT2	1200/5A MR	100 VA	2.5L400 @1200/5	FOR RELAYING
CT3				
CT4		100 VA	2.5L400 @1200/5	
CT5	1200/5A MR			FOR RELAYING & METERING
CT6		45 VA	0.3B1.8 @1200/5	
CT7				
CT8	2000/5A MR	100 VA	2.5L400 @1200/5	FOR RELAYING
CT9				
CT10	1200/5A MR	100 VA	2.5L400 @1200/5	FOR RELAYING
CT11				
CT12	4000/5A MR	100 VA	2.5L400 @4000/5	FOR RELAYING
CT13				
CT14		100 VA	2.5L400 @4000/5	
CT15	4000/5A MR			FOR RELAYING & METERING
CT16		45 VA	0.3B1.8 @4000/5	
CT17	4000/2A	12.5 VA	1.2	FOR W.T.I
CT18	4500/5A	12.5 VA	1.2	FOR A.V.R

Figure 2-10- b - Example 2: Transformer nameplate, Page 1

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INSPECTION & TEST REPORT

FOR

TRANSFORMER

Customer	:	
Project Name	:	
Applicable Standard	:	CSA C88−M90
Cooling Type	:	ONAN / ONAF1 / ONAF2
Phase	:	3
Frequency	:	60 Hz
Capacity	:	50 / 66 /
Primary voltage	:	72 kV
Tap Voltage	:	72 kV ±
Secondary Voltage	:	13.8 kV
Vector Group	:	YNd1
Quantity	:	1 set
Serial No.	:	

APPROVED BY : ____________ WITNESSED BY : ____________

CHECKED BY : ____________

TESTED BY :

Figure 2-11-a- Example 2: Transformer test results, Page 1

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GUARANTEE LIST				
Description	Unit	Guarantee Values	Tolerance	Measured values/result
1. Percent impedance at 85℃, on ONAN (50MVA) rating				
a) Highest tap(Tap No. 1)	%	12.5	±7.5%	12.24
b) Nominal tap(Tap No. 9)	%	12.0	±7.5%	11.64
c) Lowest tap(Tap No. 17)	%	11.4	±7.5%	11.18
2. Zero sequence impedance at ONAN (50MVA) rating – Nominal tap	%	Approx. 11.0	–	11.25
3. No load loss at rated voltage and rated frequency				
a) Before dielectric test	kW	40.0	–	34.467
b) After 1 hour excitation test	kW	40.0	–	34.414
4. Load loss at 85℃				
a) at ONAN(50MVA) rating	kW	97.0	–	96.014
b) at Maximum(83MVA) rating	kW	268.0	–	264.576
5. Auxiliary losses	kW	6.0	–	2.192
6. Voltage regulation at ONAN(50MVA) rating				
a) at 1.0 power factor	%	1.0	–	0.869
b) at 0.8 power factor	%	8.2	–	7.557
7. Sound level				
a) without cooling system(ONAN rating)	dB	75.0	–	65.57
b) with cooling system(Maximum rating)	dB	–	–	67.93
8. Temperature rise				
a) ONAN(50MVA) rating				
– Oil temperature	℃	65.0	–	45.50
– Winding temperature(HV)	℃	65.0	–	45.73
– Winding temperature(LV)	℃	65.0	–	48.89
b) ONAF2(83MVA) rating				
– Oil temperature	℃	65.0	–	61.00

Figure 2-11-b- Example 2: Transformer test results, Page 2

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No load loss and current

Test frequency at 60 Hz

(LV)side connection at rated voltage 13800 V , Based 50000 KVA

Rated voltage/$\sqrt{3}$			No load current			Average		No load losses(W)	
(%)	mean	rms	Ia	Ib	Ic	Io	%	Pm	Po
90	6456	7171	1.70	1.19	1.25	1.38	0.07	26035	26001
100	7173	7967	2.27	1.69	1.62	1.86	0.09	34512	34467
110	7891	8764	5.56	4.61	4.33	4.83	0.23	49304	49282
* mean = rms/($\pi/2\sqrt{2}$)									

$$Po = \frac{Pm}{\left(\frac{Ur}{Um \times (\pi/2\sqrt{2})}\right)^2 \times 0.5 + 0.5}$$

Pm : Measured value

Po : Corrected value

Um : (Ua mean + Ub mean + Uc mean) / 3

Ur : (Ua rms + Ub rms + Uc rms) / 3

Date of test : Tested by :

Figure 2-11-c- Example 2: Transformer test results, Page 3

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No load loss and current
(After 1hr Excitation test)

Test frequency at 60 Hz

(LV)side connection at rated voltage 13800 V , Based 50000 KVA

Rated voltage/√3			No load current			Average		No load losses(W)	
(%)	mean	rms	Ia	Ib	Ic	Io	%	Pm	Po
90	6456	7171	1.69	1.18	1.25	1.37	0.07	25878	25845
100	7173	7967	2.29	1.70	1.65	1.88	0.09	34425	34414
110	7891	8764	5.71	4.76	4.48	4.98	0.24	48973	49209
* mean = rms/(π /2√2)									

$$Po = \frac{Pm}{\left(\frac{Ur}{Um \times (\pi/2\sqrt{2})}\right)^2 \times 0.5 + 0.5}$$

Pm : Measured value

Po : Corrected value

Um : (Ua mean + Ub mean + Uc mean) / 3

Ur : (Ua rms + Ub rms + Uc rms) / 3

Date of test : Tested by :

Figure 2-11-d- Example 2: Transformer test results, Page 4

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Load loss and Impedance Measurement

Measurement on 50000 KVA Base at 25 ℃

(HV) side connection, (LV) side short circuit

Tap No	Rated		Impedance		Load losses(W)	
	Voltage(V)	Current(A)	Volt(V)	%(85 ℃)	at 25 ℃	at 85 ℃
1	79200	364.5	9693	12.24	91512	96465
9	72000	400.9	8378	11.64	89931	96014
17	64800	445.5	7244	11.18	100243	109942

Correction to 66000 KVA Base

Tap No.	Rated		Impedance		Load losses(W)
	Voltage(V)	Current(A)	Volt(V)	%(85 ℃)	at 85 ℃
1	79200	481.1	12795	16.16	168080
9	72000	529.2	11059	15.36	167295
17	64800	588.0	9562	14.76	191564

Correction to 83000 KVA Base

Tap No.	Rated		Impedance		Load losses(W)
	Voltage(V)	Current(A)	Volt(V)	%(85 ℃)	at 85 ℃
1	79200	605.1	16091	20.32	265818
9	72000	665.6	13907	19.32	264576
17	64800	739.5	12025	18.56	302957

Date of test : 1999. 5. 31. Tested by :

HHI A24-565-0

Figure 2-11-e- Example 2: Transformer test results, Page 5

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Load loss and Impedance Measurement

Measurement on 50000 KVA Base at 25 ℃

(HV) side connection, (LV) side short circuit

Tap No	Rated		Impedance		Load losses(W)	
	Voltage(V)	Current(A)	Volt(V)	%(85 ℃)	at 25 ℃	at 85 ℃
1	79200	364.5	9693	12.24	91512	96465
9	72000	400.9	8378	11.64	89931	96014
17	64800	445.5	7244	11.18	100243	109942

Correction to 66000 KVA Base

Tap No.	Rated		Impedance		Load losses(W)
	Voltage(V)	Current(A)	Volt(V)	%(85 ℃)	at 85 ℃
1	79200	481.1	12795	16.16	168080
9	72000	529.2	11059	15.36	167295
17	64800	588.0	9562	14.76	191564

Correction to 83000 KVA Base

Tap No.	Rated		Impedance		Load losses(W)
	Voltage(V)	Current(A)	Volt(V)	%(85 ℃)	at 85 ℃
1	79200	605.1	16091	20.32	265818
9	72000	665.6	13907	19.32	264576
17	64800	739.5	12025	18.56	302957

Date of test : 1999. 6. 31. Tested by :

HHI A24-565-0

Figure 2-11-f- Example 2: Transformer test results, Page 6

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TPR−01, Version No. 1−0−0

Calculation of 3 phase Two Winding Transformer Characteristics

Serial No : Tap No : 9

Input Data

Capacity (KVA)	:	50000		
Rated Voltage HV/LV(V)	:	72000	13800	
Rated Current of HV/LV(A)	:	400.9	2091.85	
Impedance Voltage (V)	:	8378		
No Load Loss (W)	:	34467		
Load Loss (W)	:	89931		
Load Loss at oil Temperature	:	25 (℃)		
Resistance of each winding at	:	23 (℃)		
HV Winding (ohm)	:	0.06741	0.06722	0.06734
LV Winding (ohm)	:	0.003343	0.003335	0.003347

Output Data

Copper Loss at	25 (℃)	:	54823.27	(W)	at 85 ℃	:	67499.2	(W)
Stray Loss at	25 (℃)	:	35107.73	(W)	at 85 ℃	:	28514.7	(W)
Load Loss at	85 (℃)	:	96013.90	(W)				

%Resistance voltage drop at	85 (℃)	:	0.192	%
%Reactance voltage drop at	85 (℃)	:	11.636	%
%Impedance voltage drop at	85 (℃)	:	11.637	%

Calculation of Efficiency

99.713 %	at	L.F(%) : 120,	99.770 %	at	L.F(%) : 60,
99.727 %	at	L.F(%) : 110,	99.767 %	at	L.F(%) : 50,
99.740 %	at	L.F(%) : 100,	99.751 %	at	L.F(%) : 40,
99.751 %	at	L.F(%) : 90,	99.713 %	at	L.F(%) : 30,
99.761 %	at	L.F(%) : 80,	99.677 %	at	L.F(%) : 25,
99.768 %	at	L.F(%) : 70,	99.618 %	at	L.F(%) : 20,

Calculation of Voltage Regulation

0.869 %	at P.F 1.00	8.764 %	at P.F : 0.70
4.420 %	at P.F 0.95	9.241 %	at P.F : 0.65
5.784 %	at P.F 0.90	9.656 %	at P.F : 0.60
6.771 %	at P.F 0.85	10.017 %	at P.F : 0.55
7.557 %	at P.F 0.80	10.332 %	at P.F : 0.50
8.209 %	at P.F 0.75		

Figure 2-11-g- Example 2: Transformer test results, Page 7

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TPR-01, Version No. 1-0-0

Calculation of 3 phase Two Winding Transformer Characteristics

Serial No :   Tap No : 17

Input Data

Capacity (KVA)	:	50000		
Rated Voltage HV/LV(V)	:	64800	13800	
Rated Current of HV/LV(A)	:	445.5	2091.85	
Impedance Voltage (V)	:	7244		
No Load Loss (W)	:	34467		
Load Loss (W)	:	100243		
Load Loss at oil Temperature	:	25 (℃)		
Resistance of each winding at	:	23 (℃)		
HV Winding(ohm)	:	0.07684	0.07652	0.0765
LV Winding(ohm)	:	0.003343	0.003335	0.003347

Output Data

Copper Loss at	25 (℃)	:	68076.1	(W)	at 85 ℃ :	83816.2	(W)
Stray Loss at	25 (℃)	:	32166.9	(W)	at 85 ℃ :	26126.2	(W)
Load Loss at	85 (℃)	:	109942.4	(W)			

%Resistance voltage drop at	85 (℃)	:	0.2199	%
%Reactance voltage drop at	85 (℃)	:	11.1790	%
%Impedance voltage drop at	85 (℃)	:	11.1810	%

Figure 2-11-h- Example 2: Transformer test results, Page 8

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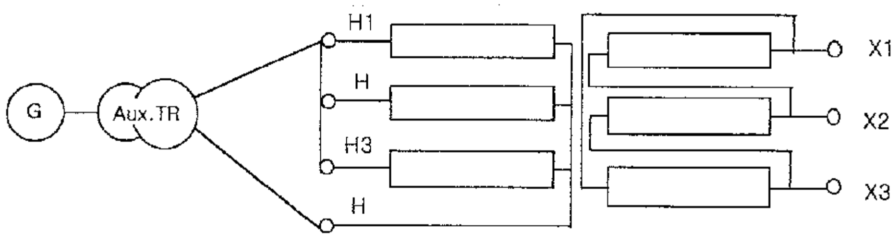
	Zero sequence impedance	

1. Test circuit : HV supply, LV open circuit (50 MVA Base)
(Tap No. : 9)



G : Generator (7500KVA, 6600V)
Aux.TR : 10MVA, (6600 / 63000V)

1) Rated current : 400.9 (A)
2) Rated voltage : 72000 (V)
3) Supply current : 150.4 (A)
4) Measured voltage : 584.6 (V)

2. Corrected zero sequence impedance voltage (V)

= Measured voltage × {(Rated current × 3) ÷ Supply current }
= 584.6 × {(400.9 × 3) ÷ 150.4 }
= 4675 (V)

3. Zero sequence impedance (%)

= {Measured voltage ÷ (Rated voltage ÷ $\sqrt{3}$)} × 100
= { 4675 ÷ (72000 ÷ $\sqrt{3}$)} × 100
= 11.25 %

Date of test : Tested by :

Figure 2-11-i- Example 2: Transformer test results, Page 9

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Table 2-6- Information Required for Modelling the Transformer of Example 2

Item	Transformer Parameter	Symbol	Values
General			
1	Transformer ONAN Ratings	MVA_{ONAN}	50 MVA
2	Winding Voltages (primary, secondary, …)	V_H, V_X,… V_P, V_S, … V_1, V_2, …	72 kV / 13.8 kV
3	Connection type	-	Wye-delta
4	Tap range	t_1, t_2, …	± 10%
5	Number of tap steps	-	17
6	Winding with an adjustable tap	-	Primary (high) side
7	Phase angle of windings	θ_1, θ_2, …	30°
No Load Loss Test Results			
8	No-load loss test MVA	$MVA_{NL\ Test}$	50 MVA
9	No-load loss	P_{NL}	34.467 kW
10	Excitation current	I_{exc}	0.09 %
11	Tap setting for no-load loss test	t_{NL}	Nominal
Load Loss Test Results			
12	Load loss test MVA	$MVA_{SC\ Test}$, …	50 MVA
13	Load loss	P_{SC}, P_{LL_HX}, …	96.014 kW
14	Impedance	I_Z, or Z_{HX}, …	11.64 %
15	Reactance	I_X, or X_{HX}, …	Not Reported
16	Tap setting for load loss test	t_{SC}	Nominal
Zero-Sequence Test Results			
17	Zero-sequence open circuit test results	$V_{0\ Test\ (Supply\ not\ RMS)}$ $I_{0\ Test\ (Suply\ for\ three\ phases)}$ Z_1, Z_2 (Calculated)	$V_{0\ Test} = 584.6V$ $I_{0\ Test} = 150.4\ A$ 11.25%, -
18	Zero-sequence short circuit test results	Z_3	-
19	Zero-sequence T-model parameters	Z_{H0}, Z'_{X0} Z_{M0} for the T-model	
20	Grounding configuration	Winding 1 grounded through impedance	
21	Grounding Impedance	Z_{GH}, Z_{GX}, …	j0.5Ω, -

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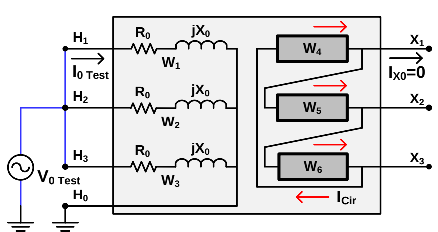
Table 2-7- Example 2: Generic Model Parameters of the Transformer

Type	Parameters in Per Unit	Parameters in SI Units
Windings' leakage impedance	$z = \%I_Z/100 = 0.1164$	$Z_{H-X} = \frac{V_{SC}}{I_{SC}} = 12.0684\Omega$
Load losses equivalent resistance	$r = \frac{P_{SC}}{MVA_{SCTest} \times 1000} = 0.0019203$ pu	$R_{H-X} = \frac{P_{SC}}{I_{SC}{}^2} = \frac{P_{SC}}{3I_{H\,rated}{}^2} = 0.199095\ \Omega$
Windings' leakage reactance	$x = \sqrt{(\%I_Z/100)^2 - r^2} = 0.1163842$ pu	$X_{H-X} = \sqrt{Z_{H-X}{}^2 - R_{H-X}{}^2} = 12.06671\ \Omega$
Magnetizing branch admittance	$y = \%I_{exc.}/100 = 0.00090$ pu	$Y_X = \frac{I_{OC}}{V_{OC}} = \frac{\%I_{exc}/100}{Z_{X\,base}} = 0.00024$ ℧ or $Y_H = \frac{\%I_{exc}/100}{Z_{H\,base}} = 8.6806E-6$ ℧
No load losses equivalent conductance	$g = \frac{P_{NL}}{MVA_{NLTest} \times 1000} = 6.9E-4$ pu	$G_X = \frac{P_{OC}}{V_{OC}{}^2} = \frac{P_{NL}}{V_{X\,rated}{}^2} = 0.000181$ ℧ or $G_H = \frac{P_{NL}}{V_{H\,rated}{}^2} = 6.6487E-6$ ℧
Magnetizing branch susceptance	$b = -\sqrt{y^2 - g^2} = -0.0005786$ pu	$B_X = -\sqrt{Y_X{}^2 - G_X{}^2} = -0.000152$ ℧ or $B_H = -\sqrt{Y_H{}^2 - G_H{}^2} = -5.58E-6$ ℧
Zero-sequence parameters	$Z_{base} = \frac{V_{H(kV)}{}^2}{MVA_{ONAN}} = \frac{72^2}{50} = 103.68\Omega$ $z_{pu} = \frac{Z_0}{Z_{base}} = \frac{11.66}{103.68} = 0.11247$ $z_{pu} = 11.25\%$ as reported $z_{H0} = z_1 = 0.1125$ pu  	$Z_{GH} = j2\Omega$ $Z_{GX} = -$ $V_{0\,Test} = 584.6V\ (Supply\ not\ RMS)$ $I_{0\,Test} = 150.4\ A\ (Suply\ for\ three\ phase)$ $X_0 = \frac{584.6}{150.4} \times 3 = 11.661\Omega$ * $Z_{H0} + Z_{M0} = jX_0 = j11.661\Omega$ $R_0 = 0$** $Z'_{X0} = -$ $Z_{HN0} = -$ $Z'_{XN0} = -$ $Z_{HX0} = -$ $Z_0 = 6 + j11.66\Omega$, $\|Z_0\| = 13.11\Omega$

* Three circuits are in parallel.

** $P_{0\,Losses}$ has not been given, so it is assumed that the high-voltage side resistance under zero-sequence excitation is zero.

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2.6 Two-Winding Transformers with Delta Primary Delta Secondary

The schematic transformer diagram, vector representation, vector diagram, and phase displacement vector diagram of two possible delta-delta-connected transformers are shown in Figure 2-12 and Figure 2-13. The vector groups of these connections are Dd0 and Dd2, respectively. In a delta-delta connection, if one winding fails the remaining windings can still provide three-phases services at a reduced capacity (57.7%). This would get the system back up and running even if there is a limit in delivered capacity. Using delta-delta-connected transformers is a practical solution for remote locations where transformer replacement services are not readily available. That is the main advantage of this type of connection. This is generally an advantage for three single-phase delta-delta connected transformers as well.

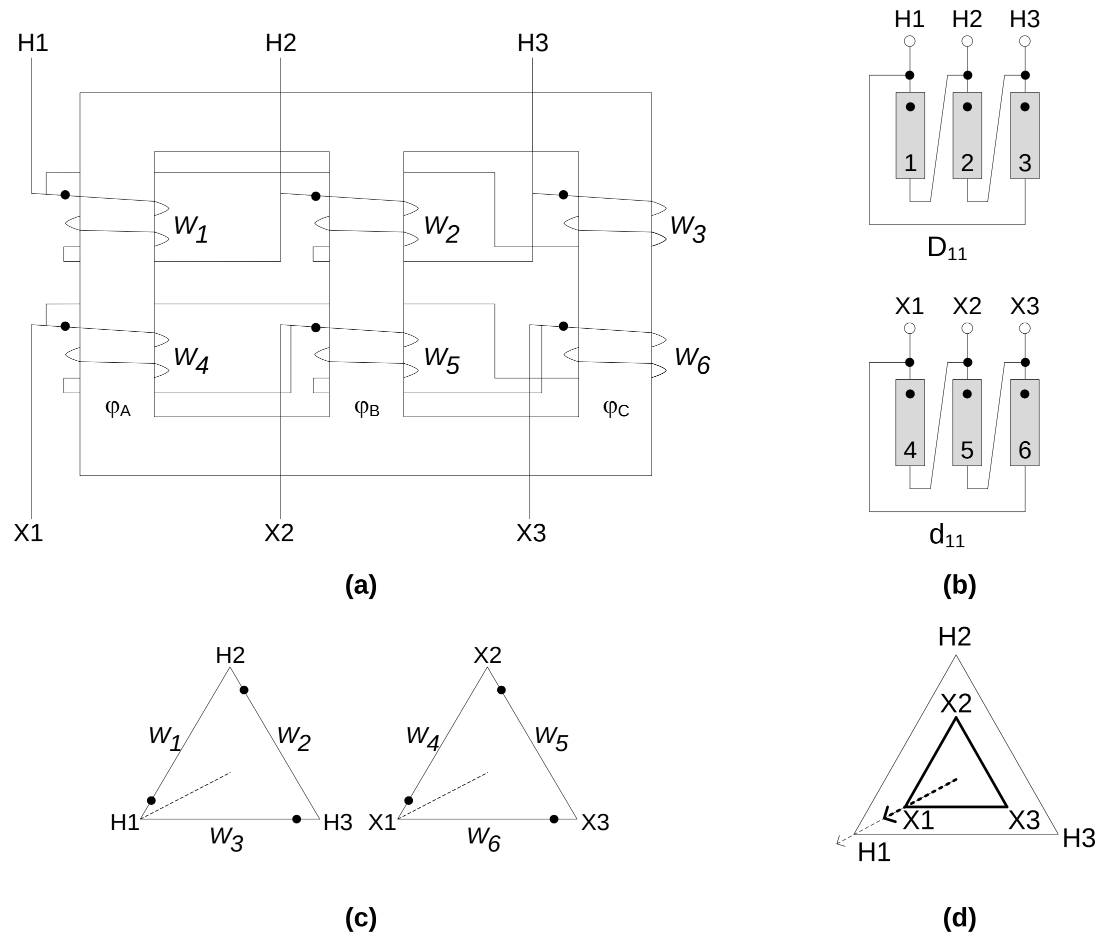

Figure 2-12- Two-Winding transformer with delta primary delta secondary: a) Schematic transformer diagram, b) Winding connection diagram, c) Vector diagram, d) Phase displacement vector diagram

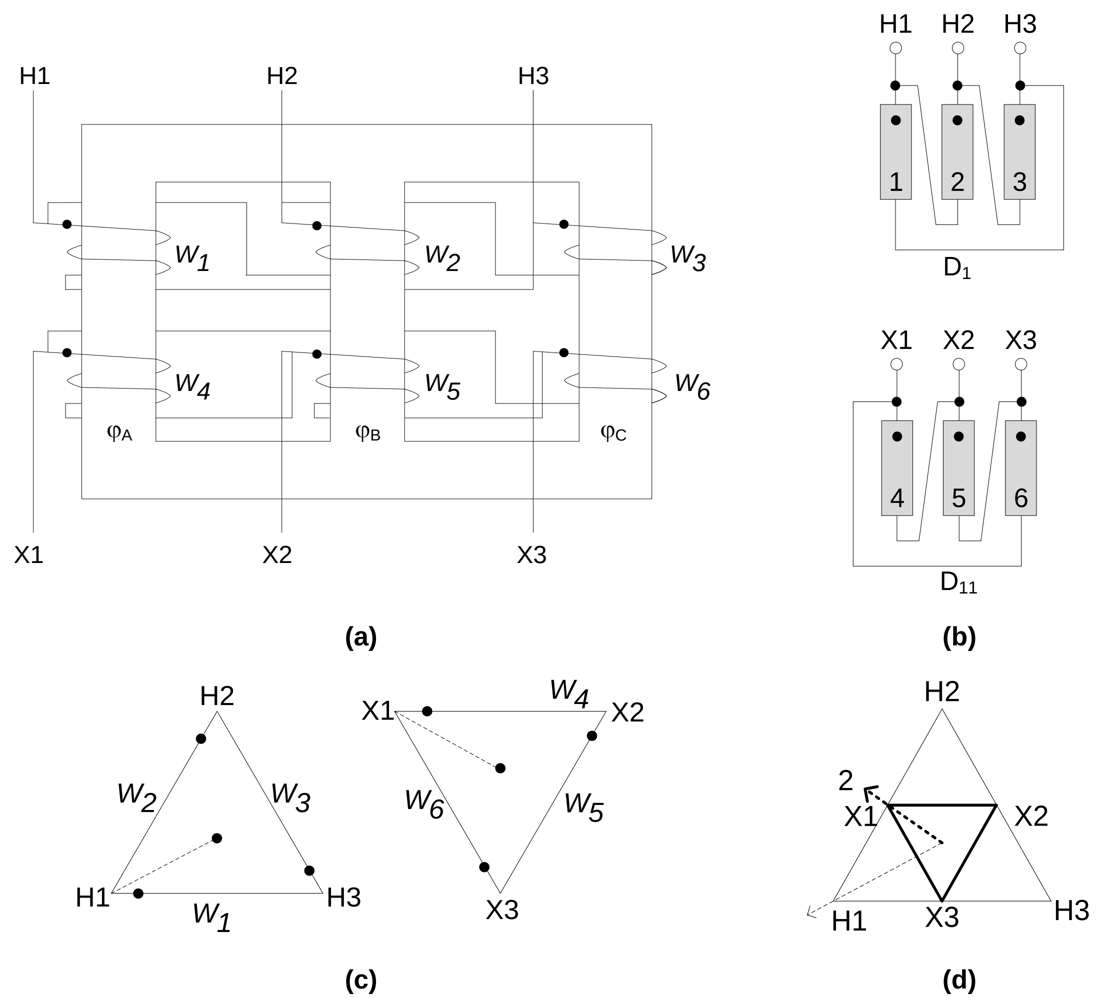

Figure 2-13- Two-Winding transformer with delta primary delta secondary: a) Schematic transformer diagram, b) Winding connection diagram, c) Vector diagram, d) Phase displacement vector diagram

2.6.1 Two-Winding Delta-Delta Transformer: Positive and Negative Sequence Generic Model

The generic model of a three-phase two-winding delta-delta transformer for positive and negative sequence is similar to that of a Y-Y transformer or single-phase transformer, as shown in Figure 2-1.

2.6.2 Two-Winding Delta-Delta Transformer: Procedure to Determine Generic Model Parameters

The procedure for modelling a three-phase two-winding delta-delta transformer in positive or negative sequence is same as the Y-Y transformer modelling procedure described in Section 2.4.2, except that the zero-sequence model for delta-delta-connected transformers is an open circuit from both sides of the transformer.

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2.6.3 Two-Winding Delta-Delta Transformer: Zero-Sequence Equivalent Circuit

The zero-sequence equivalent for a delta-delta-connected transformer is meaningless. It is theoretically shown as an open circuit from both sides, as shown in Figure 2-14.

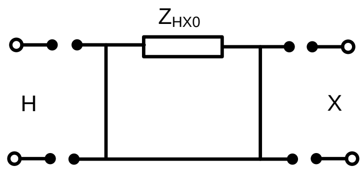

Figure 2-14- The zero-sequence equivalent circuit of a delta-delta connected transformer

2.6.4 Example 3: A Practical Two-Winding Dd0 Transformer

Figure 2-15 shows the nameplate information of a 66/2.4 kV, 7.5/8.4 MVA two-winding Dd0-connected transformer. The schematic diagram and vector diagram of this type transformer is shown in Figure 2-13. Nominal voltage of the primary is 66 kV and that of the secondary is 2.4 kV. It has five steps off-load tap changer in the high-voltage side; each step is 2.5%. The transformer test report is presented in Figure 2-16. It shows the load losses test has been conducted for the nominal tap position, which is position 3. The dc resistances of the high-voltage and low-voltage windings have been measured and are listed in the test report. To determine the transformer generic model parameters, only the nominal tap ratio test results are used.

The required information to determine the generic model parameters listed in Table 1-1 has been extracted from the test report. These data are shown in Table 2-8. The calculated parameters for the generic model are shown in Table 2-9.

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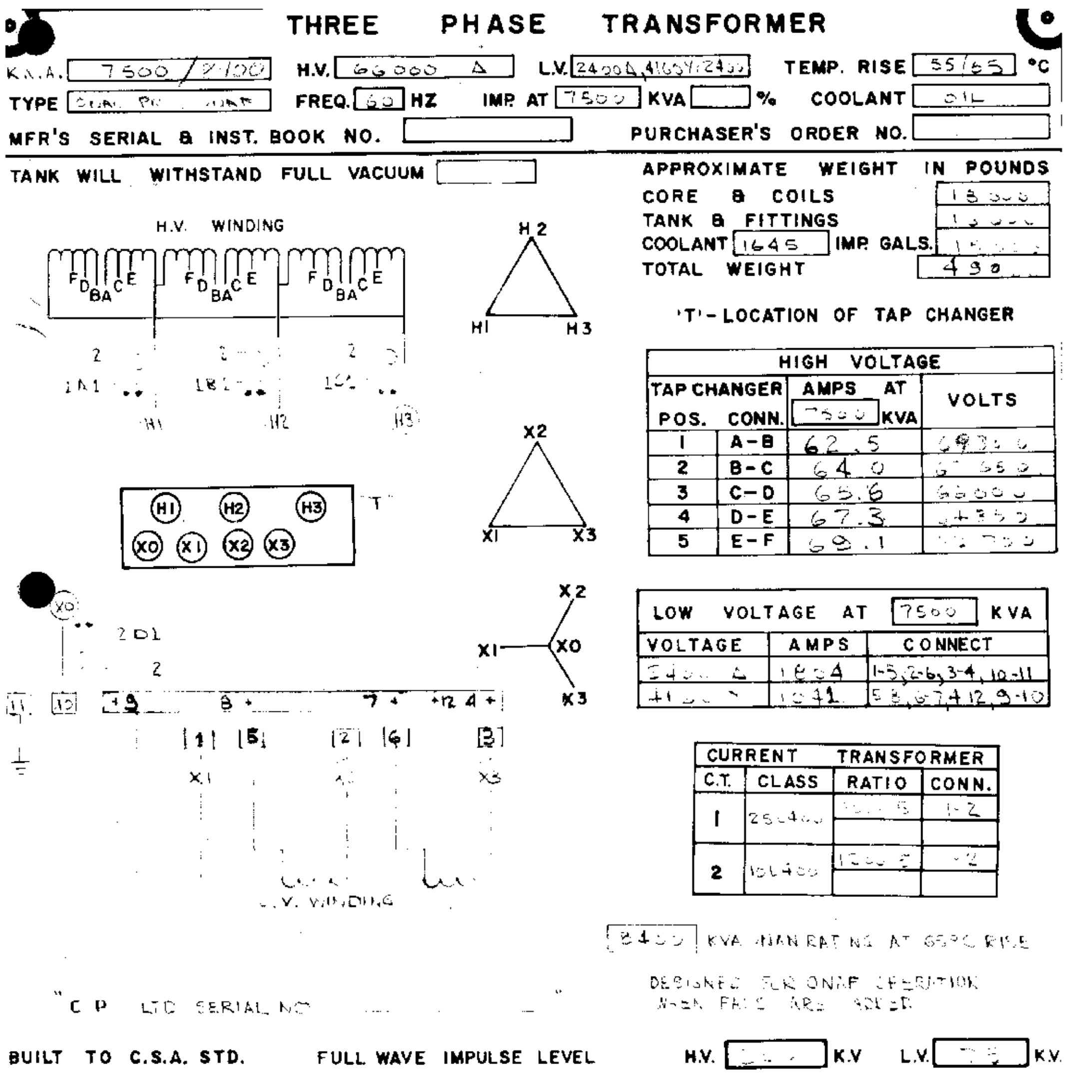

Figure 2-15- Example 3: Transformer nameplate

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TRANSFORMER TEST REPORT

DATE September 20, 1972

Customer:

Order No:

Rating: 3-60-7500 KVA 66000 Delta 2400 Delta 4160Y/2400

Taps: ±2½% ±5% in HV Off Load

Serial No.	Test Values	Guaranteed Values
WT 3288-1		
Open Circuit Test:		
% Voltage % Io	1.0	
100 Watts	12,350	12,000
% Voltage % Io	2.65	
110 Watts	18,800	
Load Loss Test:		
Watts @ 75 °C	41,110	42,000
% IX	6.92	
% IZ @ 75 °C	6.93	6.8
Total Watts @ 100% Voltage & 75 °C	53,460	54,000
Resistance Per Phase:		
Ohms @ 24 °C		
HV Position		
1	3.96	
2		
3	3.76	
4		
5	3.58	
L.V. Delta	.00391	
Heat Run Results:		
Oil Rise	39.3	55
H.V. Cu. Rise	47.1	
L.V. Cu. Rise	42.2	
Noise Level:		

Insulation Tests:

H.V. to L.V. and Ground 140 KV for 1 minute
L.V. to H.V. and Ground 19 KV for 1 minute
Induced Voltage at 2 times normal for 7200 cycles.

Figure 2-16- Example 3: Transformer test results

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Table 2-8- Information Required for Modelling the Transformer of Example 3

Item	Transformer Parameter	Symbol	Values
General			
1	Transformer ONAN Ratings	MVA_{ONAN}	7.5 MVA
2	Winding Voltages (primary, secondary, …)	V_H, V_X,… V_P, V_S, … V_1, V_2, …	66 kV / 2.4 kV
3	Connection type	-	delta-delta
4	Tap range	t_1, t_2, …	± 5%
5	Number of tap steps	-	5
6	Winding with an adjustable tap	-	Primary (high) side
7	Phase angle of windings	θ_1, θ_2, …	0°
No Load Loss Test Results			
8	No-load loss test MVA	$MVA_{NL\ Test}$	7.5 MVA
9	No-load loss	P_{NL}	12.350 kW
10	Excitation current	I_{exc}	1 %
11	Tap setting for no-load loss test	t_{NL}	Nominal
Load Loss Test Results			
12	Load loss test MVA	$MVA_{SC\ Test}$, …	7.5 MVA
13	Load loss	P_{SC}, $P_{LL\_HX, …}$	41.11 kW
14	Impedance	I_Z, or Z_{HX}, …	6.93 %
15	Reactance	I_X, or X_{HX}, …	6.92 %
16	Tap setting for load loss test	t_{SC}	Nominal
Zero-Sequence Test Results			
17	Zero-sequence open circuit test results	Z_1, Z_2	-
18	Zero-sequence short circuit test results	Z_3	-
19	Zero-sequence T-model parameters	Z_{H0}, Z'_{X0} Z_{M0} for the T-model	-
20	Grounding configuration	Winding 1 solidly grounded Winding 2 grounded through impedance	-
21	Grounding Impedance	Z_{GH}, Z_{GX}, …	-

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Table 2-9- Example 3: Generic Model Parameters of the Transformer

Type	Parameters in Per Unit	Parameters in SI Units
Windings' leakage impedance	$z = \%I_Z/100 = 0.0693$ pu	$Z_{H-X} = \frac{V_{SC}}{I_{SC}} = 40.25\Omega$
Load losses equivalent resistance	$r = \frac{P_{SC}}{MVA_{SCTest} \times 1000} = 0.00548$ pu	$R_{H-X} = \frac{P_{SC}}{I_{SC}^2} = \frac{P_{SC}}{3I_{H\,rated}^2} = 3.1836\ \Omega$
Windings' leakage reactance	$x = \%I_Z/100 = 0.0692$ pu	$X_{H-X} = \sqrt{Z_{H-X}^2 - R_{H-X}^2} = 40.1914\ \Omega$
Magnetizing branch admittance	$y = \%I_{exc.}/100 = 0.01$ pu	$Y_X = \frac{I_{OC}}{V_{OC}} = \frac{\%I_{exc}/100}{Z_{X\,base}} = 0.01302$ ℧ or $Y_H = \frac{\%I_{exc}/100}{Z_{H\,base}} = 1.7218E-5$ ℧
No load losses equivalent conductance	$g = \frac{P_{NL}}{MVA_{NLTest} \times 1000} = 0.0016467$ pu	$G_X = \frac{P_{OC}}{V_{OC}^2} = \frac{P_{NL}}{V_{X\,rated}^2} = 0.002144$ ℧ or $G_H = \frac{P_{NL}}{V_{H\,rated}^2} = 2.8352E-6$ ℧
Magnetizing branch susceptance	$b = -\sqrt{y^2 - g^2} = -0.009863$ pu	$B_X = -\sqrt{Y_X^2 - G_X^2} = -0.01284$ ℧ or $B_H = -\sqrt{Y_H^2 - G_H^2} = -1.70E-5$ ℧
Zero-sequence parameters	Open Circuit	Open Circuit

2.7 Two-Winding Transformers with Delta Primary Wye Secondary

A delta-Y transformer converts three-phase electrical power without a neutral wire into three-phase power with a neutral. This connection is commonly used in commercial, industrial, and high-density residential locations. The secondary can be used to provide a neutral point for supplying line-to-neutral power to serve single-phase loads. Also, the neutral point can be grounded for safety reasons. The delta connection in the secondary under a large amount of unbalanced load provides a better current balance for the primary. The delta primary traps third harmonics current to flow in the system. For these reasons the delta-Y-connected transformer is widely used in the distribution network. The schematic transformer diagram, vector representation, vector diagram, and phase displacement vector diagram of two possible delta-Y-connected transformers are shown in Figure 2-17 and Figure 2-18. The vector groups of these connections are Dy5 and Dy1, respectively.

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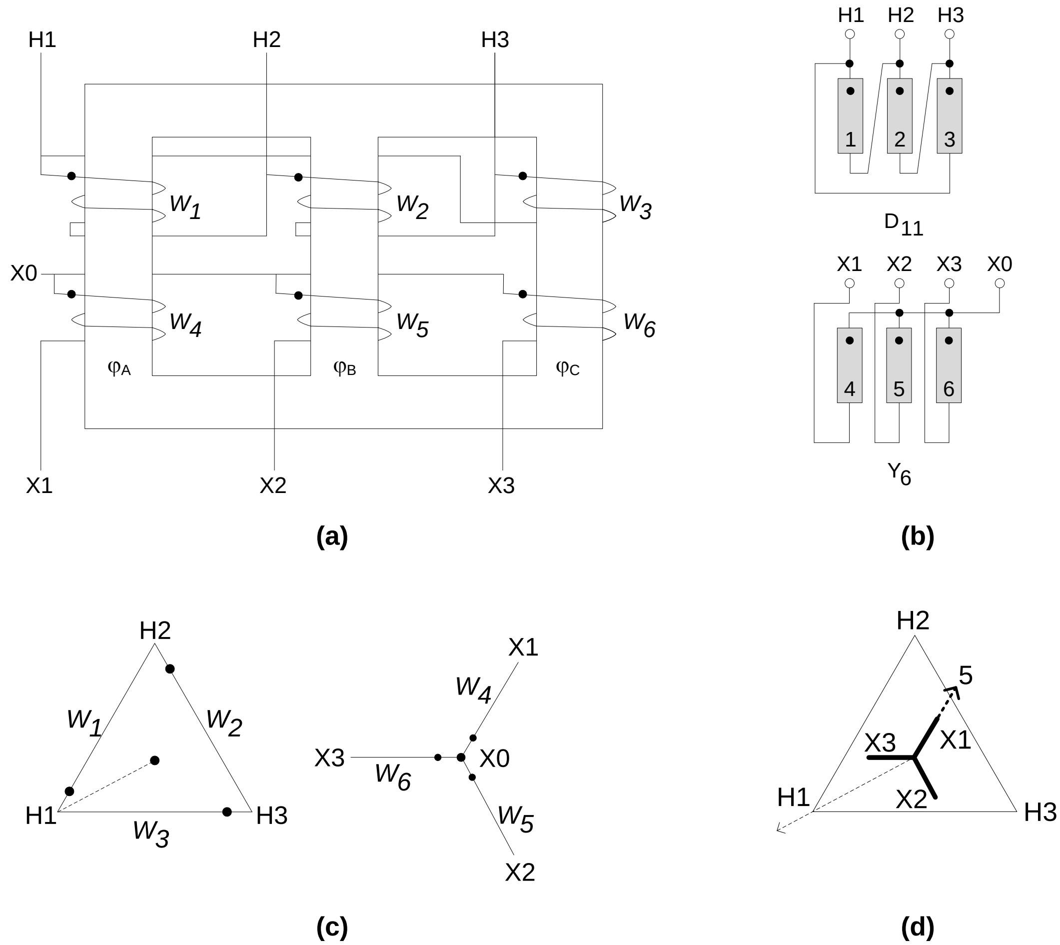

Figure 2-17- Two-Winding transformer with delta primary Y secondary: a) Schematic transformer diagram, b) Winding connection diagram, c) Vector diagram, d) Phase displacement vector diagram

2.7.1 Two-Winding Delta-Y Transformer: Positive and Negative Sequence Generic Model

The generic model of a three-phase two-winding delta-Y transformer for positive and negative sequence is similar to that of a Y-Y transformer or a single-phase transformer, as shown in Figure 2-1.

2.7.2 Two-Winding Delta-Y Transformer: Procedure to Determine Generic Model Parameters

The procedure to model a three-phase two-winding delta-Y transformer in positive or negative sequence is same as the Y-Y transformer modelling procedure described in Section 2.4.2, except that the zero-sequence model for delta-Y connected transformers is open circuit from the delta-connected side.

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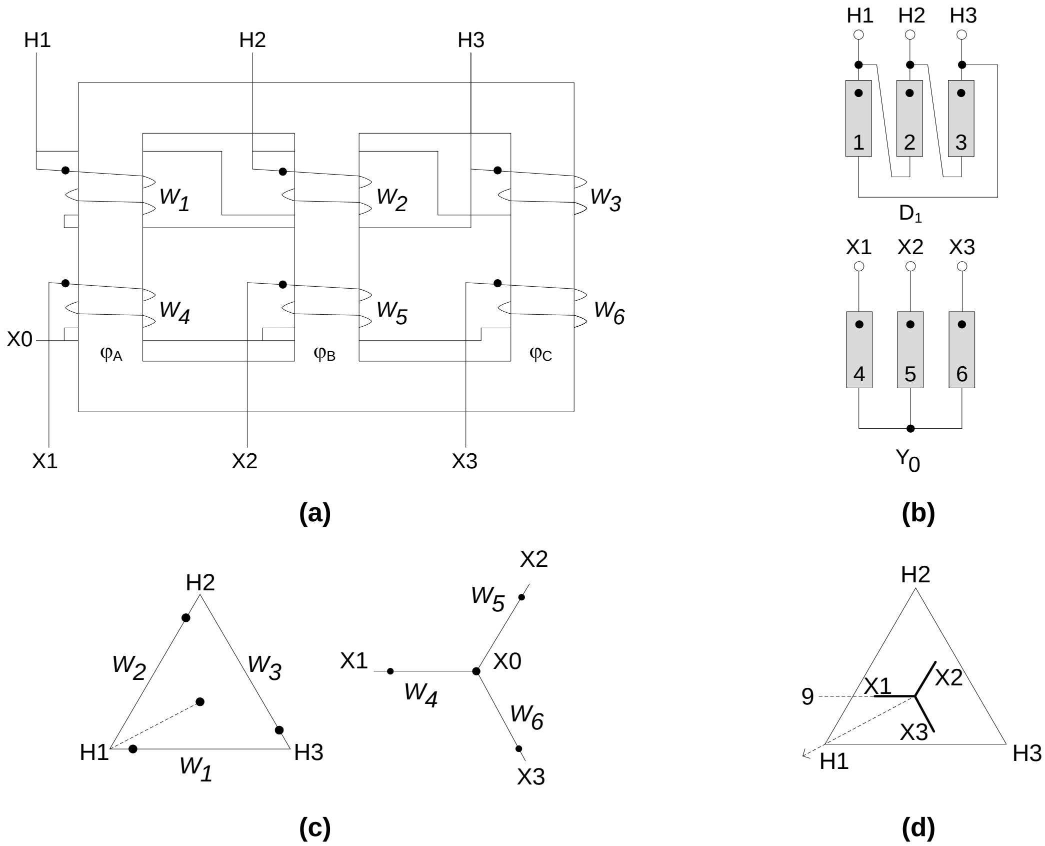

Figure 2-18- Two-Winding transformer with delta primary Y secondary: a) Schematic transformer diagram, b) Winding connection diagram, c) Vector diagram, d) Phase displacement vector diagram

2.7.3 Two-Winding Delta-Y Transformer: Zero-Sequence Equivalent Circuit

There are two types of Y-delta-connection transformer applications; the difference between the two types is whether the neutral point on the Y-connected side is connected to ground. Table 2-5 shows the two types of connection. The zero-sequence current does not flow through the transformer with an ungrounded Y-delta connection if the Y-connected side is connected to ground; in any case, the delta-connected secondary winding set always contributes to zero-sequence excitation; however, the total zero-sequence current flowing through the delta-connected terminals is zero and no zero-sequence voltage appears on these terminals because the delta connection operates as a closed-loop circuit for the possible induced voltages to these windings due to the zero-phase magnetizing flux. This is shown schematically in Figure 2-19.

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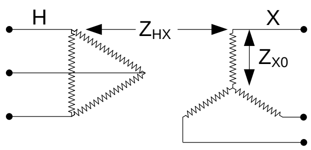
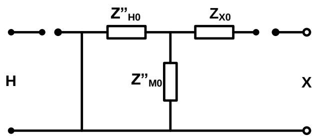
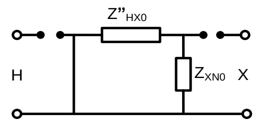
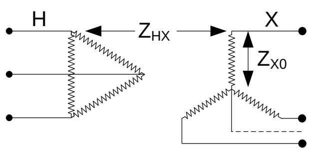
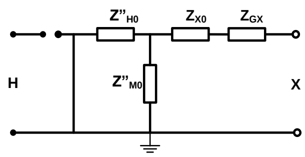
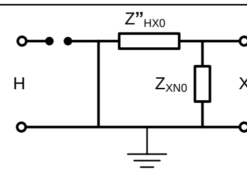
Table 2-10- Zero-Sequence Equivalent Circuits of Y-Delta-Connected Transformers

	Connection Type	T-Model	π-Model	Symbol
1				delta-y
2				delta-yn

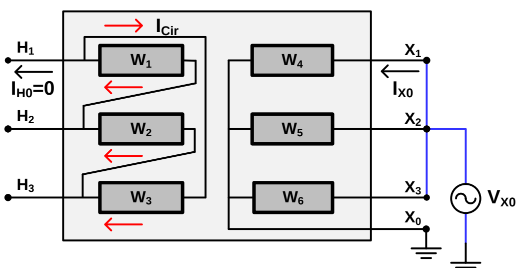


Figure 2-19- The delta-Y-grounded transformer behavior under zero-sequence excitation

The zero-sequence impedance described in Section 1.15.3 b) can be calculated through only one test from the Y-connected side. Therefore:

$$Z_0 = Z_{X0} + Z"_{M0}||Z"_{H0} = Z"_{HX0}||Z_{X0} = R_0 + jX_0$$

$$R_0 = \frac{P_{X0\,OC}}{3{I_{X0\,OC}}^2}$$

$$X_0 = \sqrt{\left(\frac{V_{X0\,OC}}{I_{X0\,OV}}\right)^2 - {R_0}^2}$$

in which Z_0 , R_0 , and X_0 are, respectively, zero-sequence impedance, resistance, and reactance at the low-voltage side, and $Z"_{M0}$, $Z"_{H0}$, and $Z"_{HX0}$ are zero-sequence parameters transferred to the low-voltage side.

2.7.4 Example 4: A Practical Two-Winding Delta-yn1 Transformer

Figure 2-20 shows the nameplate information of a 138/13.8 kV, 20/26.7/33.3 MVA two-winding Dyn-connected transformer; the neutral point is grounded through a 40 Ω resistance. The schematic diagram and vector diagram of this type of transformer is shown in Figure 2-17.

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Nominal voltage of the primary is 138 kV and that of the secondary is 13.8 kV. It has 17 steps on-load tap changer in the high-voltage side. The transformer test report is shown in Figure 2-21-a to Figure 2-21-e. It shows that the load losses test has been conducted for three tap positions including nominal tap ratio and ±10% nominal voltages. DC resistances of the low-voltage side and the high-voltage side for all tap positions have been measured and listed in the test report. To determine the transformer generic model parameters only the nominal tap ratio test results are used. The nominal tap position is position 9.

The load losses test is normally conducted from the high-voltage side with the low-voltage side is short-circuited. In the test report it is noted that the low-voltage winding has been excited for the load losses test. It is possible that this could be a typo because the test current, 87.5 A, which must be the rated current, is in the range of the high-voltage side rated current. Also, the load-losses test measurements have been reported in the test report instead of the impedance voltage. As mentioned in Section 1.15.2, the load-losses test current should be not exactly equal to the high-voltage-side rated current. Figure 2-21-c in Section 5.8 shows that the load-losses test has been conducted using a current 4.6% greater than the rated current. As explained in Section 1.15.2, the measured load-loss value should be corrected as follows:

$$P_{LL\,@\,I_{rated}} = P_{LL\,@\,I_{Test}} \times \frac{{I_{Rated}}^2}{{I_{Test}}^2}$$

$$P_{LL\,@\,I_{rated}} = 60.73 \times \left(\frac{83.67}{87.5}\right)^2 = 55.505\ kW$$

Accordingly, the supply voltage used to flow the rated current in the transformer during the load losses test is corrected as follows:

$$V_{LL\,@\,I_{rated}} = V_{LL\,@\,I_{Test}} \times \frac{I_{Rated}}{I_{Test}}$$

$$V_{LL\,@\,I_{rated}} = 9900 \times \frac{83.67}{87.5} = 9466.663$$

These calculations are valid only if the magnetic core remains linear under this over-excitation; therefore, it is assumed that this is so.

The information required to determine the generic model parameters listed in Table 1-1 is extracted from the test report. These data are shown in Table 2-11. The calculated parameters for the generic model are shown in Table 2-12.

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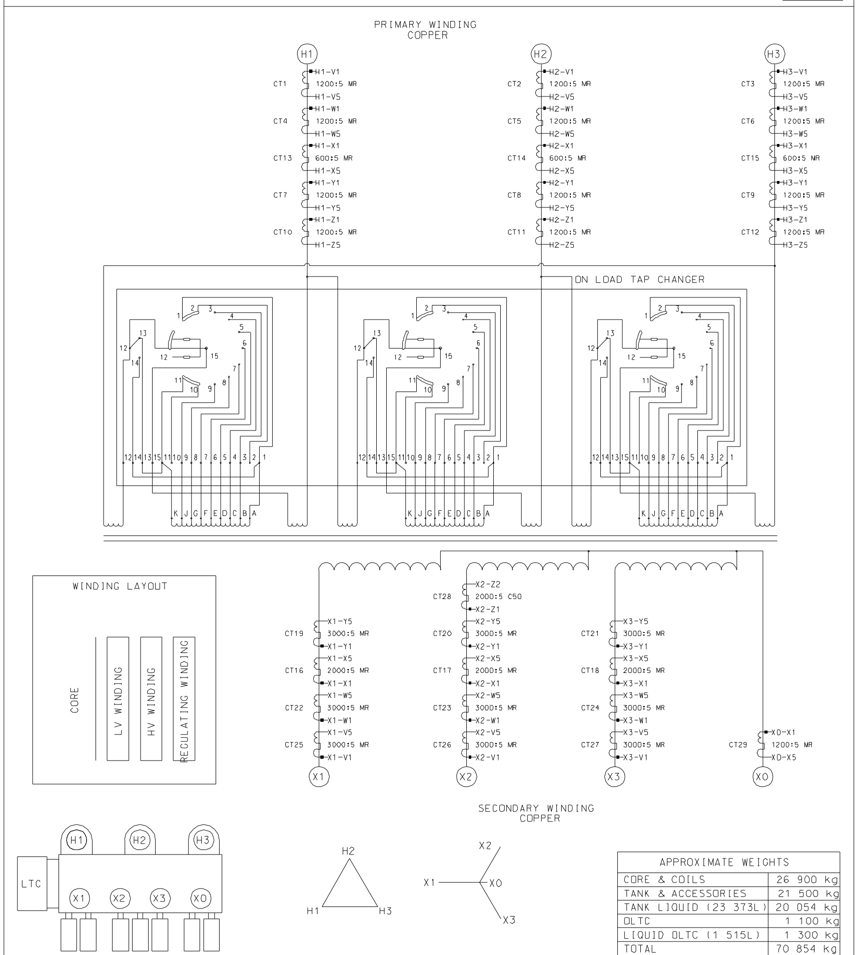
THREE PHASE OIL FILLED TRANSFORMER

RATING: 20/26.6/33.3 MVA | HV BIL: 550 kV | TEMPERATURE RISE: 65/65/65 33/64
HV: 138 kV | LV BIL: 110 kV | COOLING: ONAN/ONAF/ONAF
LV: 13.8 kV | IMPEDANCE @ 85 33/64 C & 20 MVA & POS 1-9-17: - - % | FREQUENCY: 60 Hz
LIQUID: VOLTESSO N36 (24 888L) | TANK & CONSERVATOR PRESSURE-VACUUM STRENGTH: +70, -100 kPA | CONNECTION: Dy1
LOAD CAPABILITY @ 0 33/64 C: 25/31.6/39.5 MVA | SUITABLE FOR 1050 m ELEVATION | DATE: NOVEMBER 2000
INSTRUCTION MANUAL NO.: M530 | SERIAL NO. | MEGATRAN SERIAL NO.:



APPROXIMATE WEIGHTS	
CORE & COILS	26 900 kg
TANK & ACCESSORIES	21 500 kg
TANK LIQUID (23 373L)	20 054 kg
OLTC	1 100 kg
LIQUID OLTC (1 515L)	1 300 kg
TOTAL	70 854 kg

ON LOAD TAP CHANGER (LTC) : ABB NO. UZERT 550/150

POSITION	REVERSING SWITCH	CONNECTION	HIGH VOLTAGE			
			VOLTS	AMPS ONAN	AMPS ONAF	AMPS ONAF
1	12-13	1-15	151800	76.1	101.2	126.7
2	12-13	3-15	150075	76.9	102.3	128.1
3	12-13	4-15	148350	77.8	103.5	129.6
4	12-13	5-15	146625	78.8	104.7	131.1
5	12-13	6-15	144900	79.7	106.0	132.7
6	12-13	7-15	143175	80.6	107.3	134.3
7	12-13	8-15	141450	81.6	108.6	135.9
8	12-13	9-15	139725	82.6	109.9	137.6
9	12-13	12-15	138000	83.7	111.3	139.3
10	12-14	3-15	136275	83.7	111.3	139.3
11	12-14	4-15	134550	83.7	111.3	139.3
12	12-14	5-15	132825	83.7	111.3	139.3
13	12-14	6-15	131100	83.7	111.3	139.3
14	12-14	7-15	129375	83.7	111.3	139.3
15	12-14	8-15	127650	83.7	111.3	139.3
16	12-14	9-15	125925	83.7	111.3	139.3
17	12-14	11-15	124200	83.7	111.3	139.3
LOW VOLTAGE			13800	836.7	1112.9	1393.2

CURRENT TRANSFORMERS

CT	CONN	RATIO	ACCURACY
CT1-12	1-5	1200:5	2.5L400 @ 1200:5
	1-4	800:5	
	1-3	300:5	
	1-2	200:5	
CT13-15	1-5	600:5	0.3B1.8 @ 600:5
	1-4	500:5	
	1-3	300:5	
	1-2	100:5	
CT16-18	1-5	2000:5	2.5L400; 0.3B1.8 @ 1200:5
	1-4	1500:5	
	1-3	1200:5	
	1-2	400:5	
CT19-27	1-5	3000:5	2.5L400
	1-4	2500:5	
	1-3	2200:5	
	1-2	1000:5	
CT28	1-2	2000:5	C50
CT29	1-5	1200:5	2.5L400
	1-4	800:5	
	1-3	300:5	
	1-2	200:5	

BUILT TO CSA C88

Figure 2-20- Example 4: Transformer nameplate

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5.1 MEGGER (core)

Resistance Megger: >	500	MΩ	Expected : >	50 MΩ

Meghommeter : Brunelle Instruments, model 1010-T, 1000 Volts

Tested by : ____________________ Date : 6 December 2000

5.2 RESISTANCE

Primary (Corrected to 20°C)				
Position	**Units**	**H1-H2**	**H2-H3**	**H3-H1**
1	Ω	2.95	2.96	2.96
2	Ω	2.92	2.93	2.92
3	Ω	2.89	2.90	2.89
4	Ω	2.86	2.88	2.86
5	Ω	2.83	2.85	2.83
6	Ω	2.81	2.82	2.80
7	Ω	2.78	2.79	2.77
8	Ω	2.75	2.76	2.74
9	Ω	2.72	2.73	2.72
10	Ω	2.75	2.76	2.75
11	Ω	2.78	2.79	2.77
12	Ω	2.81	2.82	2.80
13	Ω	2.84	2.84	2.83
14	Ω	2.86	2.87	2.86
15	Ω	2.89	2.90	2.89
16	Ω	2.92	2.93	2.92
17	Ω	2.95	2.96	2.94

Secondary (Corrected to 20°C)					
Connection	**Units**		**X1-X2**	**X2-X3**	**X3-X1**
NA	mΩ		14.75	14.75	14.76

Transformer Ohmmeter : Multi-Amp, model 830280

Tested by : ____________________ Date : 10 December 2000

Figure 2-21-a- Example 4: Transformer test results, Page 1

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5.3 RATIO TEST

TAP	Calculated	H1-H2 X1-X0	H2-H3 X2-X0	H3-H1 X3-X0	Polarity
1	19.054	19.074	19.074	19.074	N
2	18.837	18.854	18.854	18.854	N
3	18.620	18.640	18.640	18.640	N
4	18.402	18.420	18.420	18.420	N
5	18.185	18.202	18.202	18.202	N
6	17.967	17.982	17.982	17.982	N
7	17.750	17.764	17.764	17.764	N
8	17.533	17.550	17.550	17.550	N
9	17.315	17.330	17.330	17.330	N
10	17.098	17.112	17.112	17.112	N
11	16.880	16.892	16.892	16.892	N
12	16.663	16.674	16.674	16.674	N
13	16.446	16.460	16.460	16.460	N
14	16.228	16.242	16.242	16.242	N
15	16.011	16.022	16.022	16.022	N
16	15.793	15.804	15.804	15.804	N
17	15.576	15.590	15.590	15.590	N

Ratiometer : Multi-Amp, model TR-800

Tested by : ______________________ Date : 6 December 2000

5.4 APPLIED VOLTAGE TEST

(60 seconds)	Voltage (kV)	Leakage Current (mA)
H.V.	208	163
L.V.	34	55

H.V. A.C. source for hi-pot : Hipotronics, model 7200-40. 200 kV max

Tested by : ______________________ Date : 12/10 December 2000

5.5 APPLIED TEST (CT wiring and control wiring)

CT grounds were removed (terminals still shorted) and 2.5 kV was applied for 60 seconds. There was no sign of discharge or leakage current.

Control box wiring grounds were removed and 1.5 kV was applied for 60 seconds. There was no sign of discharge or leakage current.

Tested by : Date : 14 December 2000

Figure 2-21-b- Example 4: Transformer test results, Page 2

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5.6 DOUBLE INDUCED VOLTAGE TEST

2 x N (27600 kV) induced for 1 houre on L.V., at 120 Hz

Megatran 120 Hz A.C. source, with step up transformer.

Tested by : ______________________ Date : 14 December 2000

5.7 ZERO-SEQUENCE IMPEDANCE

Tap	Voltage (Volts)	Current (Amps)	Power (Watts)	Impedance (%)
9	72.46	264.1	15520	8.64

Test done with LV line terminals shorted together, voltage applied between lines and neutral.
ACE 2000 power meter

Tested by : ______________________ Date : 10 December 2000

5.8 LOAD LOSS, IMPEDANCE

ONAN

Tested @ 21.5 °C	VOLTS	AMPS	WATTS	Loss Corrected @ 85 °C
Tap 9	9900	87.5	55400	60703
Tap 1	10240	71.4	49570	58561
Tap 17	7915	85.7	53730	60452

Energised winding: LV, ACE 2000 power meter

IMPEDANCE @ 20 000 kVA & @ 85°C	6.9 %

5.9 NO-LOAD LOSS AND EXCITATION CURRENT

Series	VOLTS	AMPS	LOSS (W)	Corrected @ 20 °C (W)
(25.5 kW quoted)				
100 %, Tap C	13848	3.1	22777	22991
Excitation current	0.4 %			

Energised winding: LV
ACE 2000 power meter

Tested by : ______________________ Date : 10 December 2000

Figure 2-21-c- Example 4: Transformer test results, Page 3

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5.10 DISSIPATION FACTOR TEST

Setup				Readings	
H	L	Guard	Switch	Capacitance (pF)	Diss. (%)
HV	LV	GND	3-term	3974	0.289
HV	GND	LV	2-term	3317	0.233
LV	GND	HV	2-term	12220	0.319

Capacitance Bridge, Criterion Instrument Inc., model TCB-108

Tested by : ______________________ Date : 6 December 2000

5.11 ACCESSORIES TEST

All accessories: fan switches and contactors, door switch and light, thermostat and heater, outlet as well as auxiliaries contacts (temperature, level, pressure) were tested for proper operation.

Tested by : ______________________ Date : 6 December 2000

5.12 PRESSURE VACUUM TEST

Both tests were performed with all accessories mounted on the transformer.

Vacuum was pulled to 1mm of Hg. The vacuum pump was turned off, pressure then stabilised to 1.5mm. After 10 minutes the pressure was still 1.5mm, as well as after 13 minutes. (4-12-00)

Fine white powder was put on all joints and soldering.
A 35 kPa pressure was applied for 24 hours.
Careful examination did not show any displacement of powder.

Tested by : ______________________ Date : 11 December 2000

Figure 2-21-d- Example 4: Transformer test results, Page 4

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5.13 TEMPERATURE RISE TEST

Temperature Rise Test (Heat Run)
Megatran Job
Tested by:
Date: 7-8 December 2000

Unit Tested: Serial # 20011002
Tests and calculations performed as described in CSA-C88 Section 16.1

Starting Resistances @		20 °C
X2-X0	H2-H1	
14.75	2720	(mOhm)

Final Results		
33333 kVA Heat Run (Final ambient: 21 °C)		
	LV X2-X0	HV H2-H1
Final resistance:	17.7	3260
Time (s):	180	180
Temp (°C)	70.90	70.53
Correction for Current	0.00	0.00
Correction to Shutdown	+1.81	+3.18
Final Temp (°C)	72.71	73.71
Winding Rise (°C)	51.71	52.71

Figure 2-21-e- Example 4: Transformer test results, Page 5

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Table 2-11- Information Required for Modelling the Transformer of Example 4

Item	Transformer Parameter	Symbol	Values
General			
1	Transformer ONAN Ratings	MVA_{ONAN}	20 MVA
2	Windings Voltage (primary, secondary)	V_H, V_X,… or V_P, V_S, …	138 kV / 13.8 kV
3	Connection type	-	delta-Y
4	Tap range	t_1, t_2, …	± 10%
5	Number of tap steps	-	17
6	Winding with an adjustable tap	-	Primary (high) side
7	Phase angle of windings	θ_1, θ_2, …	30°
No Load Loss Test Results			
8	No-load loss test MVA	$MVA_{NL\ Test}$	20 MVA
9	No-load loss	P_{NL}	22.991 kW
10	Excitation current	I_{exc}	3.1 A (0.4 % *)
11	Tap setting for no-load loss test	t_{NL}	Nominal
Load Loss Test Results			
12	Load loss test MVA	$MVA_{SC\ Test}$, …	20 MVA
13	Load loss	P_{SC}, P_{LL_HX}, …	55.505 kW **
14	Impedance	I_Z, or Z_{HX}, …	6.9 % *
15	Load loss test Voltage	V_{Test}	9466.66 V **
16	Load loss test Current	I_{Test} **	83.67A
17	Reactance	I_X, or X_{HX}, …	Not reported
18	Tap setting for load loss test	t_{SC}	Nominal
Zero-Sequence Test Results			
19	Zero-sequence open circuit test results	Z_1, Z_2	-
20	Zero-sequence short circuit test results	V_{Test}, I_{Test}, P_{Test}, Z_{X0},	72.46V, 264.1 A, 15.52kW, 8.64% @ 20MVA
21	Zero-sequence T-model parameters	Z_{H0}, Z'_{X0} Z_{M0} for the T-model	-
22	Grounding configuration	Winding 2 grounded through resistance	40 Ohm
23	Grounding Impedance	Z_{GH}, Z_{GX}, …	-

* $I_Z = 6.9\%$ and $I_{exc} = 0.4\%$ are guaranteed values. Test values should have been corrected.
** Corrected values.

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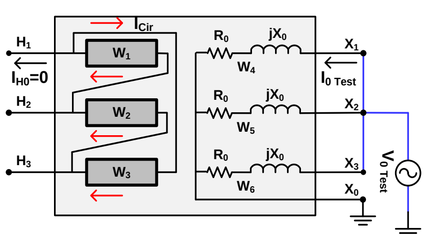
Table 2-12- Example 4: Generic Model Parameters of the Transformer

Type	Parameters in Per Unit	Parameters in SI Units
Windings' leakage impedance	$\%I_Z = \frac{V_{SC}}{V_H} = \frac{9466.66}{138000} \times 100 = 6.86$ $z = \%I_Z/100 = 0.0686$ pu	$Z_{H-X} = \frac{V_{SC}}{I_{SC}} = 65.32\Omega$
Load losses equivalent resistance	$r = \frac{P_{SC}}{MVA_{SCTest} \times 1000} = 0.002775$ pu	$R_{H-X} = \frac{P_{SC}}{I_{SC}^2} = \frac{P_{SC}}{3I_{H\,rated}^2} = 2.6428\ \Omega$
Windings' leakage reactance	$x = \%I_Z/100 = 0.0685$ pu	$X_{H-X} = \sqrt{Z_H^2 - R_H^2} = 65.27\ \Omega$
Magnetizing branch admittance	$y = \%I_{exc.}/100 = 0.0037$ pu	$Y_X = \frac{I_{OC}}{V_{OC}} = \frac{\%I_{exc}/100}{Z_{X\,base}} = 3.9\ E-4$ ℧ or $Y_H = \frac{\%I_{exc}/100}{Z_{H\,base}} = 3.886\ E-6$ ℧
No load losses equivalent conductance	$g = \frac{P_{NL}}{MVA_{NLTest} \times 1000} = 0.00115$ pu	$G_X = \frac{P_{OC}}{V_{OC}^2} = \frac{P_{NL}}{V_{X\,rated}^2} = 1.207E-4$ ℧ or $G_H = \frac{P_{NL}}{V_{H\,rated}^2} = 1.20726\ E-6$ ℧
Magnetizing branch susceptance	$b = -\sqrt{y^2 - g^2} = -0.00352$ pu	$B_X = -\sqrt{Y_X^2 - G_X^2} = -3.69\ E-4$ ℧ or $B_H = -\sqrt{Y_H^2 - G_H^2} = -0.0369$ ℧
Zero-sequence parameters	$Z_{X\,base} = \frac{V_{X(kV)}^2}{MVA_{ONAN}} = \frac{13.8^2}{20} = 9.522\Omega$ $z_{pu\,test} = \frac{Z_{0\,test}}{Z_{base}} = \frac{0.8231}{9.522} = 0.0864$ $z_{pu\,test} = 8.64$ % as reported $r_{0\,pu} = 12.67pu = 1267.4$ % pu $z_{0\,pu} \approx r_{0\,pu}$  	$Z_{GX} = 40\Omega$ $V_{0\,Test} = 72.46V\ (Supply\ not\ RMS)$ $I_{0\,Test} = 264.1\ A\ (Suply\ for\ three\ phase)$ $P_{0\,Losse} = 1552\ W\ (For\ three\ phase)$ $R_{0\,X\,Test} = R_{X0} + R"_{M0}$ $R_{0\,X\,Test} = \frac{P_{0\,Test}}{I_{0\,Test}^2} \times 3 = 0.66754\Omega$ $Z_{0\,X\,Test} = Z_{X0} + Z"_{M0} = \frac{V_{0\,Test}}{I_{0\,Test}} \times 3 = 0.8231\Omega$ $X_0 = \sqrt{Z_{0X\,Test}^2 - R_{0X}^2} = 0.45154\Omega$ $Z_{0X} = R_{0X\,Test} + 3 \times 40 + jX_0\ \Omega$ $Z_{0X} = 120.66754 + j0.45154 \approx 120.67\Omega$ $Z_{0X} = Z_{XN0} \| Z"_{HX0}$ All @ low-voltage side

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2.8 Two-Winding Autotransformers (Wye-Wye)

The schematic transformer diagram, vector representation, vector diagram, and phase displacement vector diagram of a two-winding autotransformer is shown in Figure 2-22. The vector group of two-winding autotransformers is Y_N-y_n. The neutral point is generally grounded.

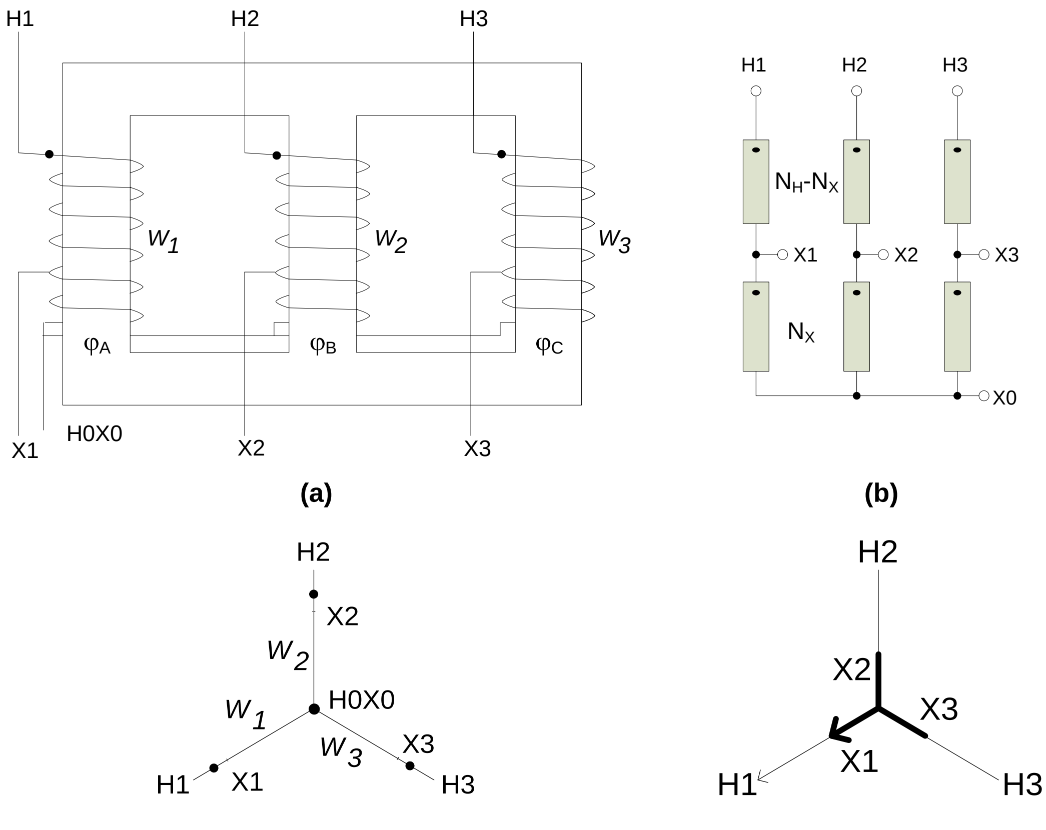

Figure 2-22- Two-Winding autotransformer: a) Schematic transformer diagram, b) Winding connection diagram, c) Vector diagram, d) Phase displacement vector diagram

2.8.1 Two-Winding Autotransformer: Positive and Negative Sequence Generic Model

To construct the circuit model of a two-winding autotransformer, the winding on each phase or leg can be considered as a separate winding. As described in Section 1.10, the equivalent circuit of an autotransformer is generally similar to the equivalent circuit of a regular two-winding transformer. Therefore, the generic model of a three-phase two-winding autotransformer for positive and negative sequence is similar to that of a single-phase transformer, as shown in Figure 2-1, except that, due to having a common winding between the primary and secondary, the equivalent series impedance parameters, theoretically, are as follows:

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$$R_{eq} = R_1 + \left(\frac{N_H}{N_X} - 1\right)^2 R_2$$
$$X_{eq} = X_1 + \left(\frac{N_H}{N_X} - 1\right)^2 X_2$$
$$Z_H = R_1 + jX_1$$
$$Z_X = \left(\frac{N_H - N_X}{N_H}\right)^2 (R_2 + jX_2)$$
$$Z'_X = \left(\frac{N_H - N_X}{N_X}\right)^2 (R_2 + jX_2)$$

This generic model is applicable for all types of autoconnected transformers as well as for single-phase autotransformers, three-phase shell types, 4- and 5-legged core types, and for three banks of single-phase transformers.

2.8.2 Two-Winding Autotransformer: Procedure to Determine Generic Model Parameters

The procedure to determine the equivalent circuit parameters from test results is the same as that for the two-winding Y-Y connected transformers described in Section 2.4.2, except that for the zero-sequence model the connection type of autotransformer is same as the zero-sequence model of a grounded Y-Y transformer. The next section describes how the zero-sequence equivalent circuit of a two-winding autotransformer is modelled.

2.8.3 Two-Winding Autotransformer: Zero-Sequence Equivalent Circuit

The zero-sequence equivalent circuit of a bank of three single-phase autotransformers connected as three-phase and shell-type three-phase autotransformers in order that the neutral point is solidly grounded is same as the positive sequence equivalent circuit. If the neutral point is not grounded, the zero-sequence equivalent circuit is an open circuit. If the neutral point is grounded through an impedance Z_G , as shown in Figure 2-23, this impedance carries the sum of the ground current in all three windings. The voltage drop on this impedance will be $3Z_G(I_X - I_H)$. If this grounding impedance is transferred to the high-voltage side it appears as an impedance $3Z_G\, a_T{}^2$ in zero-sequence excitation. Autotransformers are usually grounded without grounding impedance.

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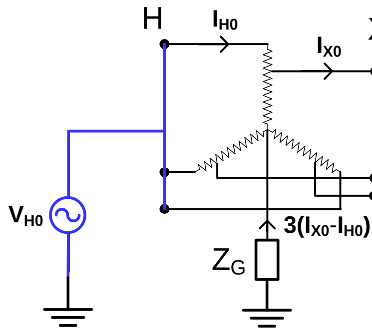
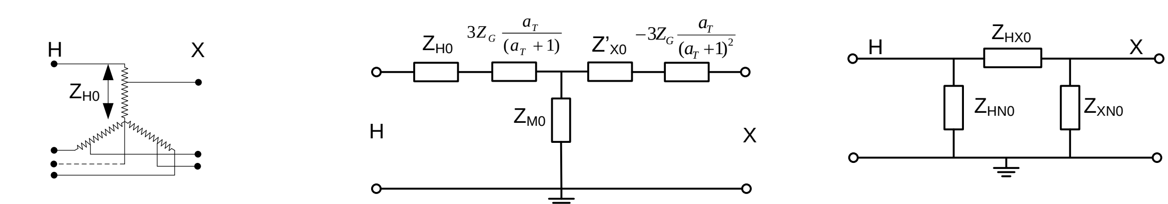


Figure 2-23- Zero-sequence excitation of an autotransformer

The zero-sequence equivalent circuit of a three-legged core-type autotransformer, as shown in Figure 2-24, is similar to the zero-sequence equivalent circuit of a grounded Y-y connected transformer, except for the neutral point grounding impedance effect on the parameters. As described above, if the neutral point is grounded through a grounding impedance, this impedance appears as an impedance $3Z_G \frac{a_T}{a_T+1}$ in the high-voltage side and as a negative impedance $3Z_G \frac{a_T}{(a_T+1)^2}$ in the low- voltage side. When the neutral is ungrounded, $Z_G = \infty$ and the impedances of the equivalent star also become infinite because there are apparently no paths for zero sequence currents between the windings although a physical circuit exists and an ampere-turn balance can be obtained. The zero-sequence model of an autotransformer is also similar to its positive sequence model. The explanations and equation described above and in Section 2.4.2 are valid for the zero-sequence model as well. The zero-sequence impedance tests to determine the zero-sequence parameters from the test measurements described in Section 1.15.3 c) are similar to those of a Y-y-connected transformer.



a) Connection type **b) T-Model** **c) π-Model**

Figure 2-24- Zero-sequence equivalent circuits of Y-Y transformers

2.8.4 Example 5: A Practical Two-Winding Autotransformer (Y-Y connected)

Figure 2-25 shows the nameplate information of a 250/138 kV GRDY, 100/134.4/160 MVA two-winding autotransformer. The neutral point is solidly grounded. The schematic diagram and vector diagram of this type of transformer is shown in Figure 2-22. Nominal voltage of the primary is 250 kV and nominal voltage of the secondary is 138 kV. It has a 19 steps on-load tap changer in the midpoint terminal. Figure 1-28-a shows the schematic diagram of this type of tap changer. As described in Section 1.12, this type of tap changer is used when the voltage on the secondary is to be kept constant while the voltage on the high-voltage side can vary. Accordingly, the flux in

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the core is constant. The transformer test report is shown in Figure 2-26. It shows the load losses test has been conducted for three tap positions including nominal tap ratio and ±7.5% nominal voltages. To determine the transformer generic model parameters, only the nominal tap ratio test results are used.

The required information to determine the generic model parameters listed in Table 1-1 is extracted from the test report. These data are shown in Table 2-13. The calculated parameters for the generic model are shown in Table 2-14.

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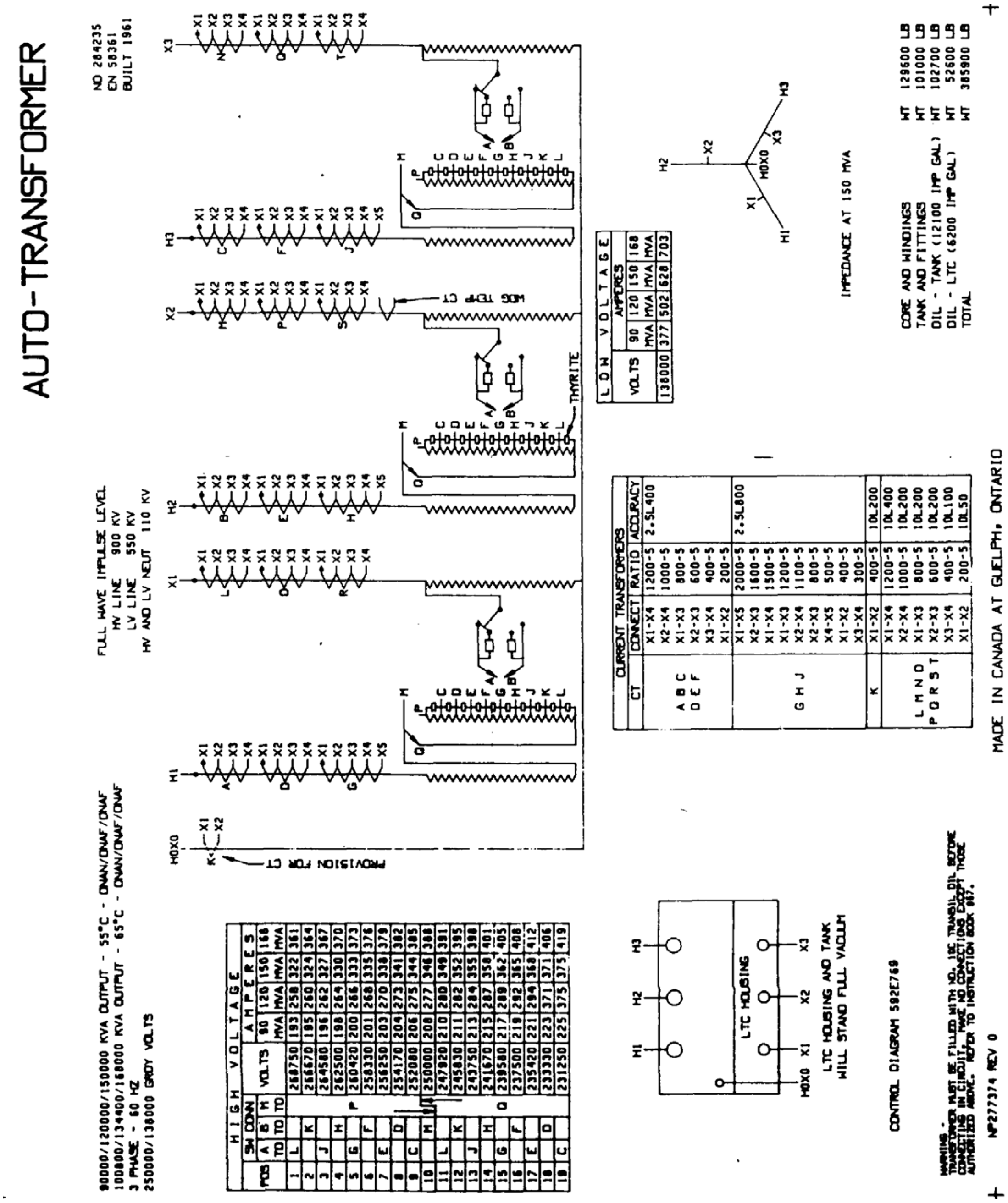

Figure 2-25- Example 5: Autotransformer nameplate

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RECORD OF TRANSFORMER TESTS

SUPERCEDED By TEST REPORT 79-11-06

Rating 90/120/150 MVA-OUTPUT-55-ONS/ONP/ONPP-3-60-250/138 KV GrdY

Customer Calgary Power Ltd.

Notice 58361 S.O. 721127 Reg. No. 9261-1412

Serial Numbers		284235			Guarantees
NO-LOAD LOSSES	Volts	138000			
Connection	Amps.	1.11			
250 KV-(138 KV)	K.W.	81.33			97 KW
		Pos. 1	Pos. 10	Pos. 19	
	Temp. °C.	75	75	75	
LOAD LOSSES	Volts	12320 = 8.90	11680 = 8.47	11400 = 8.26	Pos. 10 8.8%
Connection	Amps.	628	628	628	
250 KV-(138 KV)	K.W. 150 MVA	339.50	302.40	351.10	
Total Loss 150 MVA		420.83	383.73	432.43	Pos. 10 450 KW
RESISTANCE	H.V. Conn. Series	.5075	.4245	.5075	
between terminals	L.V. Conn. Common	.4120	.4120	.4120	
at 25° C75°C	Tertiary				
EFFICIENCY	5/4 Load	99.70			99.55
Based On	4/4 Load	99.75			99.70
150 MVA	3/4 Load	99.80			99.76
Pos. 10	2/4 Load	99.79			99.75
	1/4 Load	99.73			99.68
LOAD	100% P.F.				
REGULATION at	% P.F.				
HEAT RUN		ONS	ONPP		
% Load		100	100		
Gals. Water per Minute					
Hours Run		7½ hrs.	10 hrs.		
TEMPERATURE	Idler Oil	23.4	23.9		
°C	Water In				
	Water Out				
OIL RISE BY THERMOMETER		49.0	50.2		
RISE BY R.M.	H.V. Coils	45.5	48.7		55
	L.V. Coils	43.9	46.6		55
	Tertiary				

Zero Sequence Impendance Z_1 = 317 Ohms Z_2 = 103 Ohms Z_3 = 6.22 Ohms
at 150 MVA - 240 KV base

INSULATION TEST

	H.V. to L.V., Tertiary and Core 34000	Volts	1	Minutes
Impulse Tests in	L.V. to Tertiary and Core	Volts		Minutes
Separate Report	Tertiary to Core	Volts		Minutes
	Induced Voltage HV - 395 KV	Times Normal	7200 cyc.	Minutes
	" " LV - 230 KV		7200 cyc.	

Reported 5th Mar 62 Certified Correct

Approved By

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Figure 2-26- Example 5: Autotransformer test results

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Table 2-13- Information Required for Modelling the Transformer in Example 5

Item	Transformer Parameter	Symbol	Values
General			
1	Transformer ONAN Ratings	MVA_{ONAN}	90 MVA
2	Winding Voltages (primary, secondary, …)	V_H, V_X,… V_P, V_S, … V_1, V_2, …	250 kV / 138 kV
3	Connection type	-	Autotransformer
4	Tap range	t_1, t_2, …	± 7.5%
5	Number of tap steps	-	18
6	Winding with an adjustable tap	-	Primary (high) side
7	Phase angle of windings	θ_1, θ_2, …	0°
No Load Loss Test Results			
8	No-load loss test MVA	$MVA_{NL\ Test}$	-
9	No-load loss	P_{NL}	81.33 kW
10	Excitation current	I_{exc}	1.11 A
11	Tap setting for no-load loss test	t_{NL}	Nominal , tap 10
Load Loss Test Results			
12	Load loss test MVA	$MVA_{SC\ Test}$, …	150 MVA
13	Load loss	P_{SC}, P_{LL_HX}, …	302.40 kW
14	Impedance	I_Z, or Z_{HX}, …	8.47 %
15	Reactance	I_X, or X_{HX}, …	Not reported
16	Tap setting for load loss test	t_{SC}	Nominal
Zero-Sequence Test Results			
17	Zero-sequence open circuit test results	Z_1, Z_2	317Ω, 103Ω
18	Zero-sequence short circuit test results	Z_3	6.22Ω
19	Zero-sequence T-model parameters	Z_{H0}, Z'_{X0} Z_{M0} for the T-model	-
20	Grounding configuration	Windings neutral point grounding method	Solidly grounded
21	Grounding Impedance	Z_{GH}, Z_{GX}, …	0, 0
22	Zero-sequence impedance test MVA and kV		150 MVA and 240 kV

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Table 2-14- Example 5: Generic Model Parameters of the Transformer

Type	Parameters in Per Unit	Parameters in SI Units
Windings' leakage impedance	$z = \%I_Z/100 = 0.08479$ pu	$Z_{H-X} = \frac{V_{SC}}{I_{SC}} = 35.292\Omega$
Load losses equivalent resistance	$r = \frac{P_{SC}}{MVA_{SCTest} \times 1000} = 0.002016$ pu	$R_{H-X} = \frac{P_{SC}}{I_{SC}^2} = \frac{P_{SC}}{3I_{H\,rated}^2} = 0.840\ \Omega$
Windings' leakage reactance	$x = \%I_Z/100 = 0.08468$ pu	$X_{H-X} = \sqrt{Z_{H-X}^2 - R_{H-X}^2} = 35.282\ \Omega$
Magnetizing branch admittance	$y = \%I_{exc.}/100 = 0.00295$ pu	$Y_X = \frac{I_{OC}}{V_{OC}} = \frac{\%I_{exc}/100}{Z_{X\,base}} = 1E-5\ \mho$ or $Y_H = \frac{\%I_{exc}/100}{Z_{H\,base}} = 4.248E-6\ \mho$
No Load losses equivalent conductance	$g = \frac{P_{NL}}{MVA_{NLTest} \times 1000} = 0.0009037$ pu	$G_X = \frac{P_{OC}}{V_{OC}^2} = \frac{P_{NL}}{V_{X\,rated}^2} = 4.2706E-6\ \mho$ or $G_H = \frac{P_{NL}}{V_{H\,rated}^2} = 1.3013E-6\ \mho$
Magnetizing branch susceptance	$b = -\sqrt{y^2 - g^2} = -0.00281$ pu	$B_X = -\sqrt{Y_X^2 - G_X^2} = -1.327E-5\ \mho$ or $B_H = -\sqrt{Y_H^2 - G_H^2} = -4.0438E-6\ \mho$
Zero-sequence parameters	$Z_{H0} = 0.7608$ pu $Z'_{X0} = 0.2472$ pu $Z_{M0} = 0.0149$ pu $Z_{HN0} = 0.8217$ pu $Z'_{XN0} = 13.606$ pu $Z_{HX0} = 0.2670$ pu	$Z_G = 0$ $Z_{H0} = 317\Omega$ $Z'_{X0} = 103\Omega$ $Z_{M0} = 6.22\Omega$ $Z_{HN0} = 342.36\Omega$ $Z'_{XN0} = 5669\Omega$ $Z_{HX0} = 111.24\Omega$

2.9 Two-Winding Voltage Regulator Transformers

Distribution systems are designed so voltage magnitudes remain within the specified range required by ANSI C84. This can be accomplished through the use of a suitably-controlled voltage regulator. Regulating power transformers called load-tap-changing transformers and single-phase or three-phase step-voltage regulators are typical transformer-type equipment used to improve the voltage profile of a system. The voltage regulators are used in substations or (sometimes) in transmission line circuits to regulate the voltages of feeder circuits. They are also used along transmission lines where voltage sag is a problem. Step-voltage regulators with on-load tap changing are used to maintain the voltage within a required range.

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The design of a step-voltage regulator consists of an autotransformer with a line-end load tap-changing mechanism in which the common winding makes up a shunt circuit connected from line to neutral (and supplies the excitation), and the tapping winding makes up the series winding and provides the voltage for compensation. The primary and secondary have the same voltage ratings. According to IEEE C57.15, step regulators can be connected in a Type “A” or Type “B” connection, as shown in Figure 2-27 and Figure 2-28.

A Type-A step-voltage regulator has the primary circuit connected directly to the shunt winding of the regulator. The series winding is connected to the shunt winding and through the taps to the regulated circuit, as shown in Figure 2-27. In this type of regulator the core excitation varies because the shunt winding is connected across the primary circuit.

A Type-B step-voltage regulator has the primary circuit connected, via taps, to the series winding of the regulator. The series winding is connected directly to the regulated circuit, as in Figure 2-28. In this type of regulator the core excitation is constant because the shunt winding is connected across the regulated circuit.

The voltage change is obtained by changing the taps of the series winding of the autotransformer and, as a result, varying the transformer ratio V_{Source}/V_{Load}. The position of the tap is determined by a control circuit called the line drop compensator. Standard step regulators contain a reversing switch enabling a ±10% regulator range, usually in 32 steps of approximately 0.625% each. The raise position in which the voltage regulator boosts the voltage is called the boost position, and the lower position in which the voltage regulator bucks the voltage is called the bucks position. The polarity of a voltage regulator is intrinsic to its design. The relative polarity of the shunt winding and the series windings of a step-voltage regulator in the boost and buck modes will be different in Type-A and Type-B voltage regulators. The voltage regulation of a step voltage regulator is given by :

$$V_{Load} = \begin{cases} \dfrac{V_{Source}}{1 \pm N\Delta V} & Type - A \\ V_{Source}(1 \pm N\Delta V) & Type - B \end{cases}$$

in which N is the tap position and ΔV is the voltage per tap in per unit of the nominal voltage of the windings. Also, positive N is for the raised position and negative N is for the lowed position. For a 32 steps step voltage regulator $\Delta V = 0.625$. It is called a 32- 5/8% step voltage regulator.

When the windings of three single-phase regulators are connected internally to form a three-phase regulator, the regulator is operated so that the taps on all windings change at the same time and, as a result, only one compensator circuit is required. Three-phase regulators will only be connected in a three-phase wye or closed delta.

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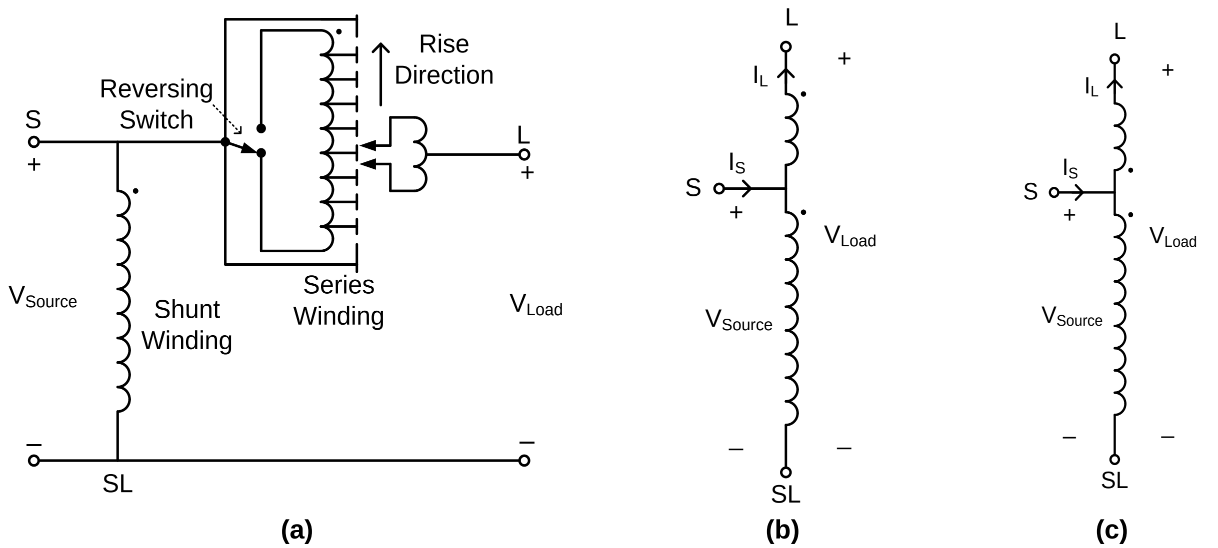

Figure 2-27- a) Schematic diagram of a single-phase Type-A step voltage regulator, b) Boost position, c) Buck position

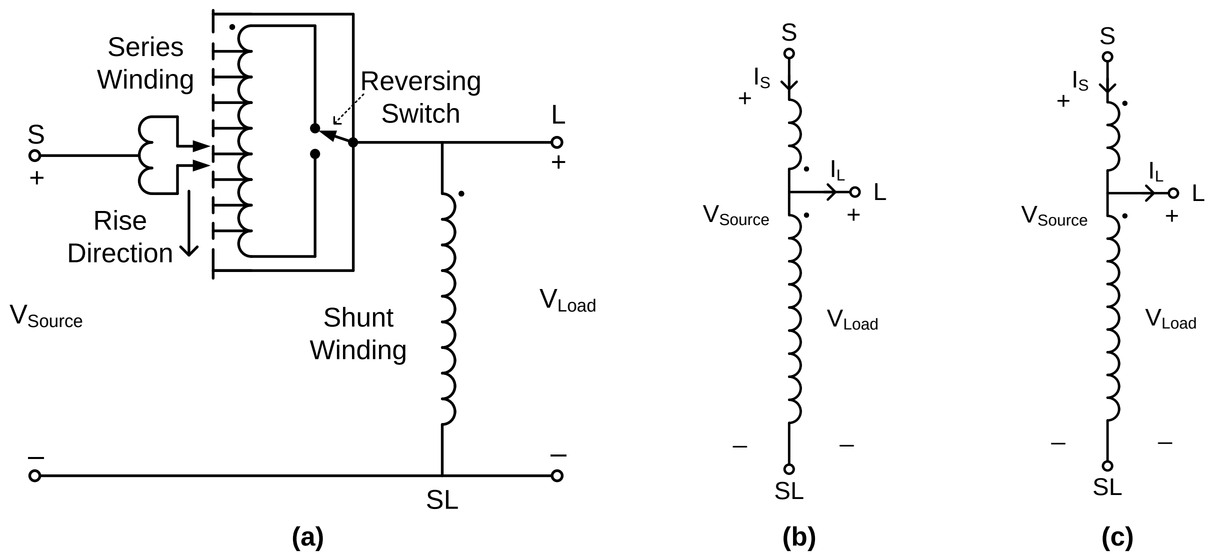

Figure 2-28- a) Schematic diagram of single-phase Type-B step voltage regulator, b) Boost position, c) Buck position

Three-phase regulators will only be connected in a three-phase wye or a closed delta. In this guide, only the three-phase wye-connected step-voltage regulator is considered. Practically, the neutral point in a wye connection is not for grounding; therefore it is not accessible in the transformer terminals.

The impedance of a step-voltage regulator transformer is very low and the short-circuit currents in the transformer terminals are determined mainly by the characteristics of the system at the

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location of the transformer. The inherent impedance of any components directly connected to the voltage regulator by short buses or cables must be arranged so that there will be no practical possibility of a fault between them.

In the Alberta network, the voltage regulator transformers are usually connected after YY transformers to regulate the voltage of the load feeder, and both neutral points of the transformer have been grounded. The voltage regulator transformer's neutral point is grounded as well.

The load losses of a voltage regulator are losses dissipated at a specified load carried by the voltage regulator. Load losses are measured by applying sufficient voltage across the shunt winding to cause a specified current to flow in the windings while the series winding is short-circuited. The tap position should not be in the normal position because in the normal tap position the primary is immediately connected to the secondary without any windings turn between them.

Load loss is the average load loss in four tap positions including the maximum and adjacent-to-maximum buck positions and the maximum and adjacent-to-maximum boost positions with rated current in the windings. Usually, the test results do not include load loss for all of these four tap positions; the test results usually have only the results for the maximum buck position and the maximum boost position. In this case, the load loss is the average of these two values. Because both reported load losses, (or even four load losses, if reported), are measured at the rated current, the series impedance parameters of the equivalent circuit are the average value of the parameters at the reported positions.

As mentioned in Section 1.15.1, and according to IEEE C57.15, the no-load losses in step-voltage regulator transformers is the average of the no-load losses in the neutral and the next adjacent boost position with rated voltage applied to the shunt, or, for voltage regulators that do not include a series transformer, applied to the series winding.

2.9.1 Two-Winding Voltage Regulator Transformer: Positive and Negative Sequence Generic Model

The positive and negative sequence equivalent circuit of a voltage regulator transformer is similar to that of the two-winding transformer shown in Figure 2-29. But, the series impedance is more dependent on the position of the tap-changer in a voltage regulator transformer than it is in a regular transformer. The more accurate equivalent circuit will be the one using the impedance table, as discussed in the Transformer Impedance Table in Appendix-F. However, the approximate series impedance, which is similar to that of regulator transformers, can be used in most studies with a high level of accuracy. As mentioned above, the series impedance parameters of the equivalent circuit are the average value of the parameters at the reported positions.

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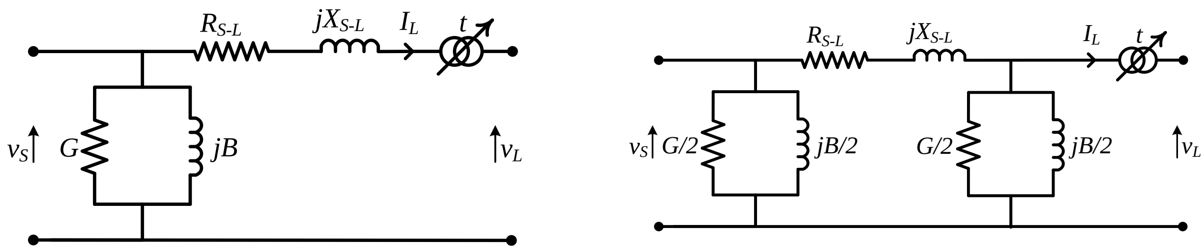

Figure 2-29 - Voltage regulator transformer generic: a) Simplified model, b) π -model

2.9.2 Two-Winding Voltage Regulator Transformer: Zero-Sequence Equivalent Circuit

The connection type of voltage regulator transformers is practically a grounded Y- Y connection. However, the internal connection of a voltage regulator transformer is more complicated than that of a regular Y-Y connected transformer. Therefore, the zero-sequence equivalent circuit of a voltage regulator transformer depends on whether or not the neutral points are connected to ground. In voltage regulator transformers, the main neutral point is called S_0L_0, and through it the zero-sequence current of the source side and the load side flow to the ground. This main neutral point is usually connected to the ground. As shown in Table 1-2 and Table 2-2, line 4, the zero-sequence equivalent circuit of a voltage regulator is similar to that of a solidly-grounded Y-Y connected transformer (YN-yn).

2.9.3 Example 6: A Practical Two-Winding Voltage Regulator Transformer

Figure 2-30 shows the nameplate information of a 4.16/2.4 kV, 15/20/25 MVA two-winding voltage regulator transformer. This VR transformer is a two-core two-winding yy-connected transformer in one tank. It is also called a Series Booster Transformer [10]. Figure-B1-b in Appendix B shows the schematic circuit diagram of one phase of the transformer and its tap-changer connection. The neutral points of both secondary windings are connected to the tank and grounded through the tank. The equivalent schematic diagram of the transformer is similar to Figure 2-27. The neutral point of the Y-connected primary winding of the first core, S_0L_0, is accessible to be grounded based on the design plan. The test results, the schematic diagram of this VR transformer, the winding schematic diagram, and the vector diagram are shown in Figure 2-31, Figure 2-32, and Figure 2-33. The voltage ratio of the load terminal to the source terminal can be shown as follows:

$$V_L = \left(1 \pm \frac{N_{22}}{N_{21}} \times \frac{N_{12}}{N_{11}}\right) V_S$$

In this transformer:

$$max\left(\frac{N_{22}}{N_{21}} \times \frac{N_{12}}{N_{11}}\right) = \pm\%10$$

Similar to the autotransformers, the cores are not designed to the full power rating of the transformer because the full power of the transformer is not converted through the magnetic

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cores. However, the secondary windings set of the second core (the windings between the S terminals and the L terminals) are designed to withstand the full load current.

As can be seen, the nominal voltage of this voltage regulator transformer is 4.16 kV. The transformer can regulate from 3.744 kV to 4.576 kV on the source terminals to 4.16 kV at the load terminal. It has one (1) two-status switch and nine (9) tap positions. The two-status switch changes the direction of regulation from positive regulation to negative regulation and vice versa. Although it is not stated in the nameplate, the tap-changer is a graded tap-changer because it is located close to a neutral point grounded through the transformer tank.

The main core of this two-core transformer is always excited by a voltage in the range of ±10% of nominal voltage. The excitation of the second core depends on the amount of voltage adjust the voltage transformer makes. In other words, it depends on the tap position of the tap changer. Therefore, the core loss in the main core is approximately constant (within 81% to 122% of the rated voltage no load loss). But in the second core, the core loss depends on the tap position. It should be noted that when the transformer operates in buck conditions the input voltage is higher than the nominal voltage, (which should be considered in the transformer design). Therefore, it is assumed that the transformer always operates in the linear area.

The second core meets different voltages depending on the tap position. In the normal tap position, the output voltage is equal to the input voltage, and the voltage on the second core is zero because there is no boost or buck voltage on the second core windings.

As mentioned in the last two paragraphs of Section 2.9, the load loss is assumed to be the average value of losses in positions 1 and 17 as provided in the test report. The no load loss of a voltage regulator transformer is the no load loss of the neutral tap position and the next adjacent boost position with rated voltage applied to either the shunt or the series winding for voltage regulators that do not include a series transformer. In this example, the no load loss for the next adjacent boost position has not been reported. Because it is normally expected that a system operates at rated voltage, using the neutral tap position to model the magnetizing branch can be a realistic assumption. The information required to model this transformer is given in Table 2-15.

The test report states that the load losses test for tap position 1 was carried out at the rated nominal current. This is a requirement for a full load losses test, but it is not identified for tap position 17 while parameters have been provided for this position. Since the generic model is the linear model of transformer, it is assumed that the no load losses test current at position 17 is the nominal current as well. In consequence, the series impedance parameters are an average value of the parameters at position 1 and position 17.

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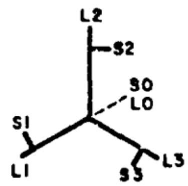
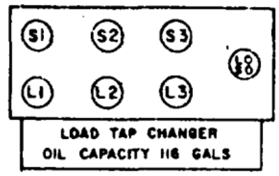


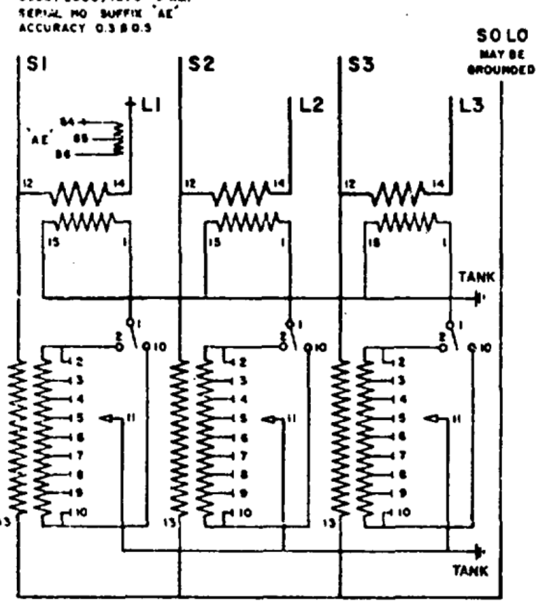


DURATHERM INSULATION
FOR 65 C RISE

IMPULSE LEVEL (BIL)
75 KV

TANK DESIGNED
FOR ±5 PSI

CURRENT TRANSFORMER
3000/2000/1000 : 5 AMP
SERIAL NO SUFFIX 'AE'
ACCURACY 0.3 B 0.5



CONTROL CIRCUIT DWG. NO. 76720-D

CONNECTIONS						
DIAL POS'N	R JOINS	H JOINS	VOLTS	AMP ONAN	AMP ONAF	AMP ONAF
17		11 - 10	4576	1893	2518	3154
16		11 - 9	4524	1914	2523	3190
15		11 - 8	4472	1937	2552	3228
14		11 - 7	4420	1959	2612	3266
13		11 - 6	4368	1983	2644	3304
12	1 - 2	11 - 5	4316	2007	2675	3344
11		11 - 4	4264	2031	2708	3385
10		11 - 3	4212	2056	2741	3427
9E		11 - 2				
9D		11 - 2				
9C		11 - 1				
9		11 - 1	4160	2082	2776	3470
9B		11 - 10				
9A		11 - 10				
8		11 - 9	4108			
7		11 - 8	4056			
6	1 - 10	11 - 7	4004			
5		11 - 6	3952			
4		11 - 5	3900	2082	2776	3470
3		11 - 4	3848			
2		11 - 3	3796			
1		11 - 2	3744			

REGULATED 90 % TO 110 %

OIL FILLED VOLTAGE REGULATOR

15000 KVA CIRCUIT CAPACITY AT 55 C RISE ONAN
20000 KVA CIRCUIT CAPACITY AT 55 C RISE ONAF
25000 KVA CIRCUIT CAPACITY AT 55 C RISE ONAF
VOLTAGE 4160Y/2400 3 PHASE 60 HZ
MAX LOAD 2082/2776/3470 AMP ONAN/ONAF/ONAF
% IZ AT 75 C ONAN MAX TAP POSITION
MIN TAP POSITION

NET WEIGHTS
CORE & COILS 10800 LB
TANK & FITTINGS 9900 LB
OIL 1240 GALS 10600 LB
TOTAL WEIGHT 31300 LB
SERIAL NO

BUILT IN CANADA TO CSA C88-1968

Figure 2-30 - Example 6: Voltage regulator transformer nameplate

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MOLONEY ELECTRIC CORPORATION CD-18366 CERTIFIED TEST REPOR

CUSTOMER				Purchase Order No.	
SALES ORDER #		UNIT #	COIL #		TYPE ONAN/ONAF/ONAF
	H.V. ± 10% REGLT. 4160Y/2400	L.V. –	PHASE 3	HZ 60	TEMPERATURE 55 °C

Serial No.							GUARANTEE
NO LOAD LOSSES		TAP POS'N 17	TAP POS'N 9		TAP POS'N 1		
VOLTS 4576	AMPS	0.87	0.47	4160 V	1.16	3744 V	
	% Iex	0.437	0.212		0.524		
	WATTS	4375	2310		4694		6200
5034	AMPS	1.89	1.38	4576 V	2.42	4118 V	
	% Iex	0.95	0.624		1.094		
	WATTS	6253	3498		6330		
	AMPS						
	% Iex						
	WATTS						

LOAD LOSSES	15 MVA		20 MVA		25 MVA		GUARANTEE
CONNECTION OR TAP	Pos.'n 1 *	17	Pos.'n 1*	17	Pos.'n 1*	Pos.'n 17	
IMPEDANCE %	1.566	1.419	2.089	1.9016	2.627	2.386	
REACTANCE %	1.553	1.410	2.072	1.890	2.605	2.372	
WATTS 75 °C	27051	23342	48044	42361	75094	64884	
TOTAL LOSSES	31745	27717	52738	46736	79788	69259	31000

RESISTANCES	AVERAGE BETWEEN TERMINALS					
TF C	23.5	23.5				
OHMS EXT.WDG.	0.04959	0.04959	– –	–	–	–
OHMS HV & REGL. WINDING	0.03139	0.03139	– –	–	–	–
SERIES	0.0004547	0.0004547	–	–	–	–

EFFICIENCY %	POS'N 1	POS'N 17	POS'N 1	POS'N 17	POS'N 1	POS'N 17
5/4 LOAD	99.72	99.78	99.65	99.72	99.57	99.66
4/4 "	99.77	99.81	99.71	99.77	99.65	99.72
3/4 "	99.80	99.84	99.77	99.81	99.72	99.78
2/4 "	99.83	99.86	99.81	99.85	99.79	99.84
1/4 "	99.81	99.84	99.83	99.86	99.83	99.87

REGULATION %						
100% P.F.	–	–	–	–	–	–
% P.F.						
80% P.F.	–	–	–	–	–	–

POS.'N 1 * = TESTED AT RATED NOMINAL CURRENT.

TYPE TESTS

SERIAL#	TEMPERATURE RISE H.V.	L.V.	OIL	
3876/1	51.7	45.5	43.6	@ 15 MVA
3876/1	50.2	50.2	36.2	@ 25 MVA

DIELECTRIC TESTS:

APPLIED; H.V.	19
APPLIED, L.V.	19
INDUCED, FOR 7200 HZ	200
IMPULSE	–

ALL UNITS RECEIVE TESTS FOR RATIO AND POLARI TESTS ARE MADE IN ACCORD WITH RELEVANT CANADI STANDARDS.

ENTERED BY DATE 12 June, 79 APPROVED BY

Figure 2-31 - Example 6: Voltage regulator transformer test results

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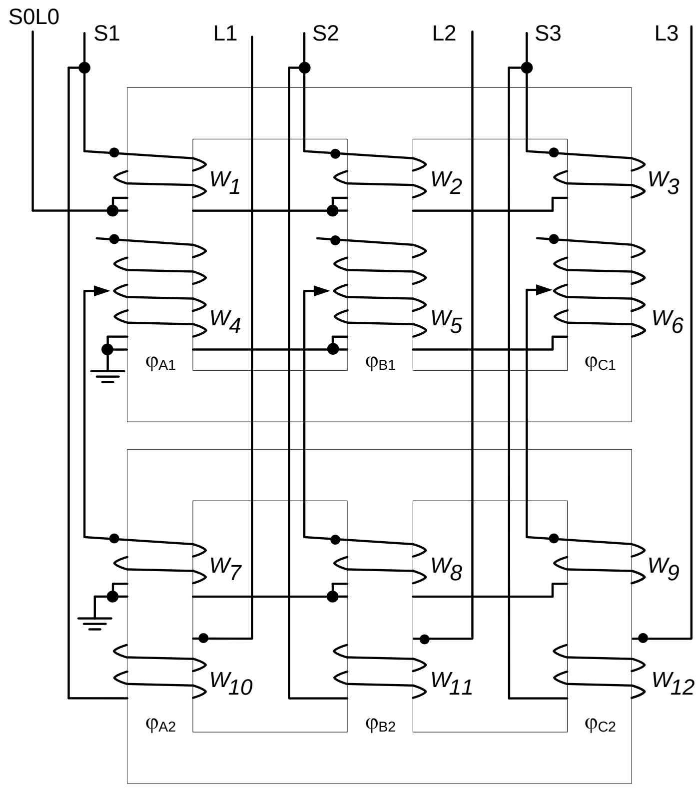
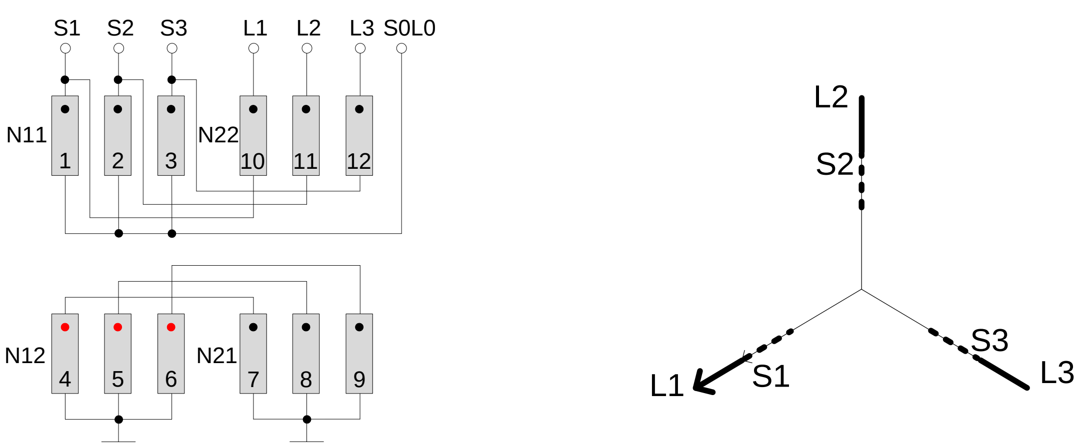


Figure 2-32 - Example 6: Schematic diagram of the voltage regulator transformer



(a) **(b)**

Figure 2-33 – Example 6: Voltage regulator transformer: a) Windings connection diagram, b) Vector diagram

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Table 2-15 - Information Required for Modelling the Voltage Transformer in Example 6

Item	Transformer Parameter	Symbol	Values
General			
1	Transformer ONAN ratings	MVA_{ONAN}	15 MVA
2	Winding voltages (Source, Load , …) in this transformer	V_S, V_L V_H, V_X,…	4.160 kV
3	Connection type	-	Voltage regulator transformer
4	Tap range	t_1, t_2, …	± 10%
5	Number of tap steps	-	17
6	Winding with an adjustable tap	-	Secondary of first core
7	Phase angle of windings	θ_1, θ_2, …	0°
No Load Loss Test Results			
8	No-load loss test MVA	$MVA_{NL\ Test}$	15
9	No-load loss	P_{NL}	2.31 kW
10	Excitation current	I_{exc}	0.212%
11	Tap setting for no-load loss test	t_{NL}	Nominal
Load Loss Test Results			
12	Load loss test MVA	$MVA_{SC\ Test}$, …	15 MVA
13	Load loss	$P_{SC,}$ $P_{LL\_HX, …}$	27.051 kW, 23.342 kW
14	Impedance	I_Z, or Z_{HX}, …	1.566 %, 1.419 %
15	Reactance	I_X, or X_{HX}, …	1.553 %, 1.410 %
16	Tap setting for load loss test	t_{SC}	Tap 1 , tap 17
Zero-Sequence Test Results			
17	Zero-sequence open circuit test results	Z_1, Z_2	
18	Zero-sequence short circuit test results	Z_3	
19	Zero-sequence T-model parameters	Z_{H0}, Z'_{X0} Z_{M0} for the T-model	-
20	Grounding configuration	Windings neutral point grounding method	Solidly grounded
21	Grounding Impedance	Z_{GH}, Z_{GX}, …	0, 0
22	Zero-sequence impedance test MVA and kV		

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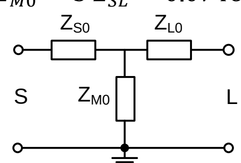
Table 2-16 - Example 6: Generic Model Parameters of the Voltage Regulator Transformer

Type	Parameters in Per Unit	Parameters in SI Units
Average Values	$z = \frac{1.566+1.419}{2} = \%I_Z/100 = 1.4925\%$ $x = \frac{1.553+1.41}{2} = \%I_Z/100 = 1.4815\%$ $P_{SC} = \frac{27.051+23.342}{2} = 25.1965$ kW	
Windings' leakage impedance	$z = \%I_Z/100 = 1.4925$ $z = 0.014925$ *pu*	V_{Rated} =4.16 kV, $S_{base} = 15\ MVA$ $Z_{\ Base} = \frac{V_{Rated}{}^2}{S_{base}} = 1.154\ \Omega$ $Z_{S\ Base} = Z_{L\ Base} = Z_{Base}$ $I_{Rated} = \frac{V_{Rated\_Phase}}{Z_{base}} = 2.082\ kA$ $Z_{S-L} = Z_{Base} * z = 0.01722\ \Omega$
Windings' leakage reactance	$x = 0.014815$ *pu*	$X_{S-L} = Z_{Base} * x = 0.01709\ \Omega$
Load losses equivalent resistance	$r = \frac{P_{SC}}{MVA_{SCTest} \times 1000} = 0.00168$ *pu* *Test:* $r = \sqrt{z^2 - x^2} = 0.001809$ *pu*	$R_{S-L} = \frac{P_{SC}}{I_{SC}{}^2} = \frac{P_{SC}}{3 I_{S\_Rated}{}^2} = 1.938E-3\ \Omega$ $Test1: R_{S-L} = Z_{Base} * r = 1.938E-3\ \Omega$ $Test2: R_{S-L} = Z_{Base} * 1.809E-3$ $= 2.087E-3\ \Omega$ It is close.
Magnetizing branch admittance	$y = \%I_{exc.}/100 = 0.00212$ *pu*	$Y_S = Y_L = \frac{I_{OC}}{V_{OC}} = \frac{\%I_{exc}/100}{Z_{H\,base}} = 0.00184$ ℧
No Load losses equivalent conductance	$g = \frac{P_{NL}}{MVA_{NL\,Test} \times 1000} = 0.000154$ *pu*	$G_S = G_L = \frac{P_{OC}}{V_{OC}{}^2} = \frac{P_{NL}}{V_{Rated}{}^2} = 0.13348E-3$ ℧
Magnetizing branch susceptance	$b = -\sqrt{y^2 - g^2} = -0.002114$ *pu*	$B_S = B_L = -\sqrt{Y_S{}^2 - G_S{}^2} = -1.835E-3$ ℧
Zero-sequence parameters: According to Table 1-4 , in Section 1.16, the zero-sequence parameters are estimated as : *	$Z_{S0} = 0.9\ Z_{SL} = 0.01343$ *pu* $Z_{L0} = 0.1\ Z_{SL} = 1.492E-3$ *pu* $Z_{M0} = 5\ Z_{SL} = 0.0746$ *pu* 	Z_{S0} =0.0155 Ω Z_{L0} =0.00172 Ω $Z_{M0} = 0.08612\ \Omega$

* Since coefficients 0.9 and 0.1 depend on the tap position and the boost or buck direction, dividing the series equivalent impedance into two equal impedances for each terminal is a good way to estimate the zero-sequence impedance.

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2.10 Zigzag Transformers (Two-Winding Bushing)

The purpose of a zigzag transformer is to provide a return path to the earth fault current in delta-connected systems. As described in Section 1.19.7, it may contain only six windings in three legs connected in zigzag to provide a ground connection, or it may contain nine windings and supply some loads or auxiliary loads. The schematic transformer diagram, vector representation, vector diagram, and phase displacement vector diagram of a zigzag-connected transformer are shown in Figure 2-34. The vector group of two-winding autotransformers is YN-yn. The neutral point is generally grounded in autotransformers.

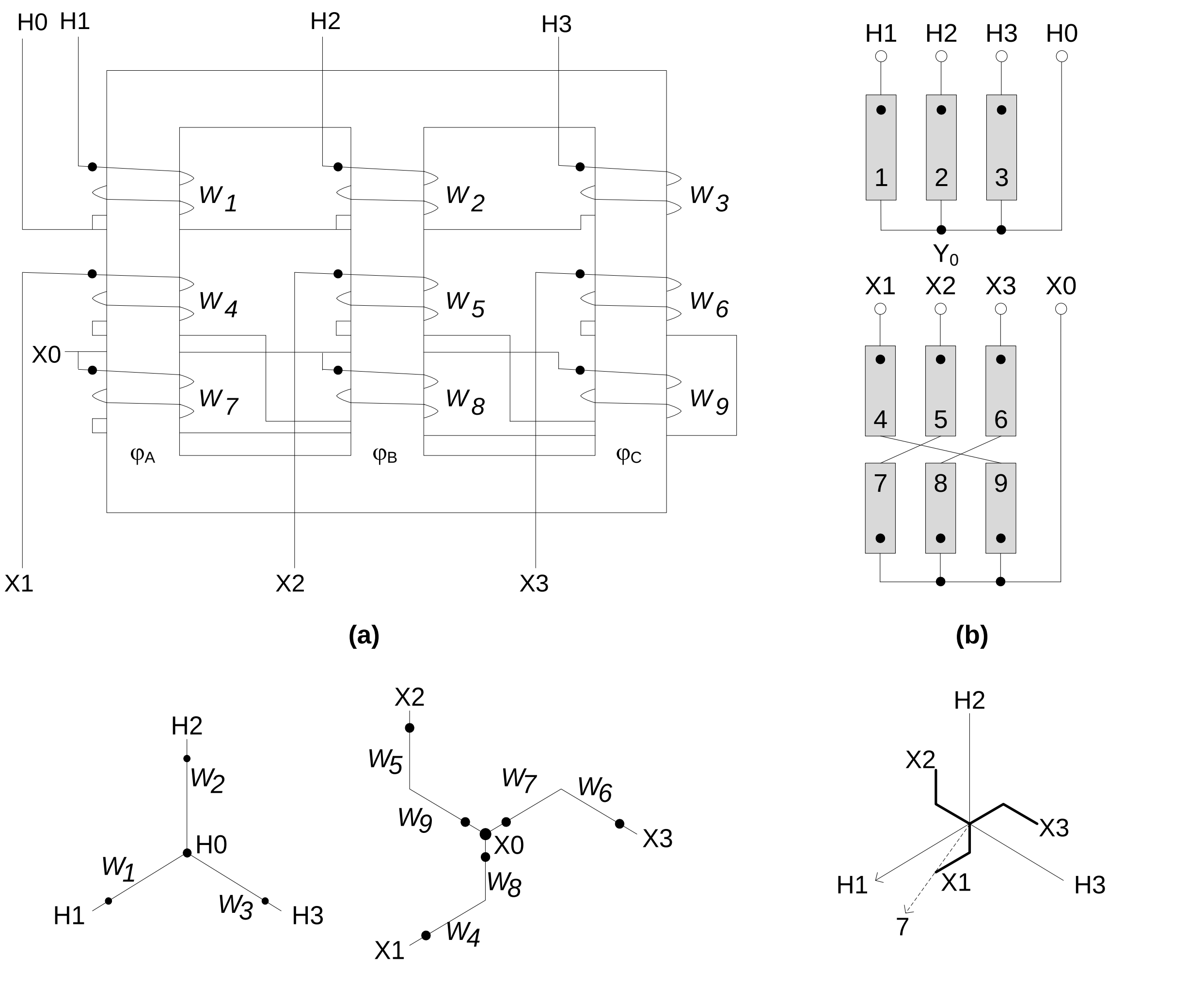

Figure 2-34- The zigzag transformer: a) Schematic transformer diagram, b) Winding connection diagram, c) Vector diagram, d) Phase displacement vector diagram

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3 Determination of Low-Frequency Parameters of Three-Winding Transformers

3.1 Introduction

Three-phase three-winding transformers are widely used in power systems. When the MVA rating of the third winding is considerably lower than that of the primary or secondary winding ratings, the third winding is called a tertiary winding. A tertiary winding may be used when the actual loads or the auxiliary loads in a substation must be supplied at a voltage level that is different than that of the primary voltage level or the secondary voltage level. The tertiary winding may be connected to reactive power compensating devices such as condensers, shunt reactors, or capacitor banks for the injection of reactive power into a system to maintain the voltage within the specified limit. In the above mentioned applications, the tertiary winding is loaded. In some cases, an unloaded delta-connected tertiary winding called the stabilizing winding may be required. The stabilizing winding plays the following roles in the system [7]:

- Under an asymmetrical load condition, when the zero-sequence impedance is smaller , a delta-connected tertiary winding provides a pass to the current to flow in such a way that the ampere-turn between the three windings is balanced.
- A Y-Y-connected transformer is rarely used in a power system except in high-voltage transmission systems for reasons of cost saving and safety. A Y connection is susceptible to third harmonics and voltage transients when not grounded. A delta-connected tertiary winding can provide a closed-circuit pass for the third harmonic magnetizing current and would cause the core flux and induced voltage to be sinusoidal. This could prevent interference in telephone lines caused by third harmonic currents and voltages.

Sometimes in power transformers a third winding forms a double-secondary winding. Such transformers are often used to supply high-density loads in cities. The third winding provides economic benefits because there is not as much high-voltage switchgear required. If the two secondary-winding terminals are not connected to the same bus, the third winding provides the additional benefit of limiting low-voltage system short-circuit currents. Double-secondary transformers can be used for the connection of two generators to a power network. Transformers with three windings are used for the interconnection of three transmission lines at three different voltage levels. In this guide, all these transformers are recognized as three-winding transformers. The modelling procedure for three-winding transformers is used to model these types of transformers.

In multi-winding transformers, the windings may have different MVA ratings. In two-winding transformers, the primary and secondary have the same MVA rating. However, the tertiary winding of a three-winding transformer may have a different MVA rating. In multi-winding transformers, the rated power of each winding should be given on the nameplate. The impedance of each winding may be normalized based on the rating of its winding or it could be referred to a common base. In multi-winding transformers, the loading combinations should be indicated unless the rated power of one of the windings is the sum of the rated powers of the other windings.

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3.2 Single-Phase Three-Winding Transformers

Figure 3-1 shows a schematic diagram of a three-winding transformer wound around a core. In three-phase transformers, the three windings of each phase are wound around the same leg.

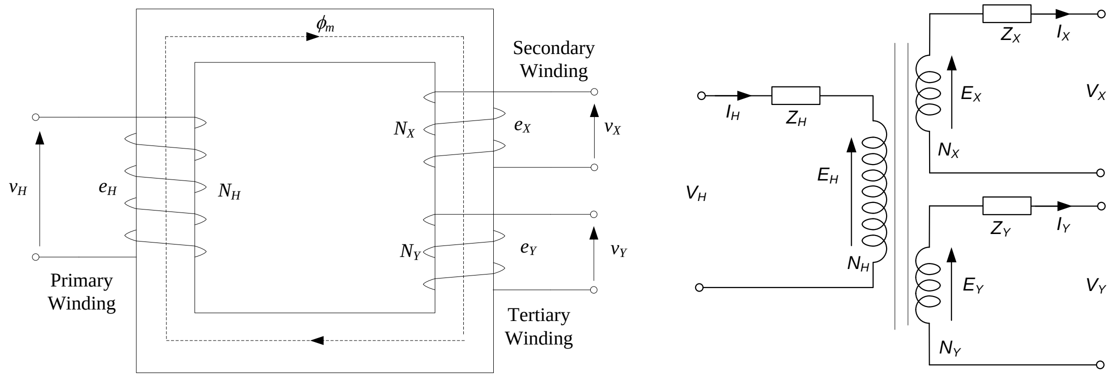

Figure 3-1- Schematic diagram of a transformer with three windings

The ideal conditions for a three-winding transformer (which are similar to those of a two-winding ideal transformer) are:

$$\frac{E_1}{N_1} = \frac{E_2}{N_2} = \frac{E_3}{N_3}$$

$$E_1 I_1 = E_2 I_2 + E_3 I_3$$

This equation means that the net power into a three-winding ideal transformer is zero.

3.2.1 Single-Phase Three-Winding Transformer Generic Model

A single-phase three-winding transformer can be modelled as shown in Figure 3-2. The model includes the equivalent leakage impedance of three windings and, in a manner similar to that employed for two-winding transformers, the magnetizing current and core losses are modelled as a magnetizing branch. This model is a traditional model and is of limited application. It is reasonably accurate when the transformer core is not saturated. When the magnetizing inductance is saturated the connection location of the magnetizing branch is important. Arbitrary location of the magnetizing branch in multi-winding transformers is one of the drawbacks of this traditional model. Another equivalent circuit model [5] that is very accurate when the model is used to describe the behavior of the magnetic core is proposed in the literature, but because power system study software mostly uses the traditional model it is not described here.

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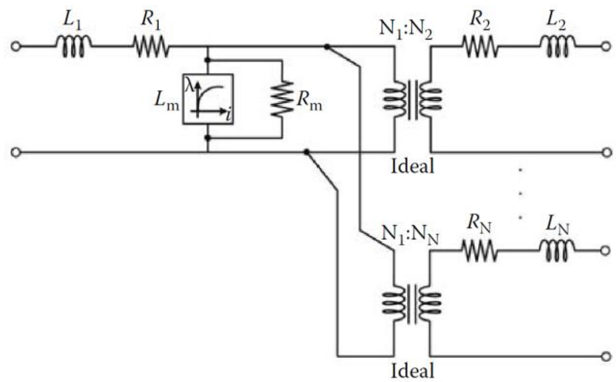

Figure 3-2- Star equivalent circuit representation of a multi-winding transformer (generic model)

To determine the parameters of a three-winding transformer, typically one no-load test and three load-losses tests are conducted. The measurements in the load-losses tests are performed on the three different two-winding combinations and the results are recalculated, allocating impedances and losses to individual windings. Total losses for specified loading cases involving all these windings are then determined accordingly.

Some three-winding transformers have one primary and two secondary windings. The secondary windings have the same rated power, rated voltage, and equal impedance to the primary. These transformers are usually referred to as double-secondary transformers. In these transformers, the symmetrical loading might be tested by an extra test with both secondary windings short-circuited simultaneously.

Manufacturers do not usually provide three-load-losses test results in the test results summary sheet, particularly for double-secondary transformers or transformers with tertiary windings. In more than 98% of three-winding transformers there is only one load losses test result in the test results sheet. This test should be conducted on the full rating of the unit from the high-voltage winding to both low-voltage windings. Both low-voltage windings are short-circuited, a test voltage is applied to the high-voltage side, and the active power and applied voltage are measured while the rating current flows in the high-voltage winding. It is important to realize when the fully loaded high-voltage winding divides its MVA capacity between the low-voltage windings.

In some transformers the rated power of the high-voltage winding is the sum of the rated powers of all low-voltage windings. In these transformers, when the rated current flows in the high-voltage winding the other two windings carry the rating current as well. In some transformers, the full load rating of the high-voltage side is less than the sum of the two low-voltage ratings. In these transformers, when the high-voltage winding is fully loaded the other two windings never carry the full load current. Therefore, the current at the high-voltage winding should be held at the rated value during the load losses test. This monitoring procedure is a bit different than the monitoring procedure for three separate load-losses tests. For conducting three load-losses tests in three-winding transformers between pairs of windings, the current in the winding that has the lowest MVA rating is monitored. The test is conducted while the lowest MVA rating winding carries the rating current.

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3.2.2 Leakage Impedances in Three-Winding Transformers

To measure the two-winding leakage impedances between winding 1 and winding 2, the secondary winding terminals are short-circuited and the tertiary winding terminals are left open circuit. The two-winding leakage impedances between winding 1 and winding 3 and between winding 2 and winding 3 are measured in a similar manner. The leakage impedances measured in this way are referred to as Z_{H-X} , Z_{H-Y} , and Z_{X-Y} . These notations correspond to the notation Z_{HX} used previously for two-winding transformers. The three load losses tests give:

$$Z_{H-X} = \frac{V_H}{I_H}\bigg|_{\substack{V_X=0 \\ I_Y=0}}$$

$$Z_{H-Y} = \frac{V_H}{I_H}\bigg|_{\substack{V_Y=0 \\ I_X=0}}$$

$$Z_{X-Y} = \frac{V_X}{I_X}\bigg|_{\substack{V_Y=0 \\ I_H=0}}$$

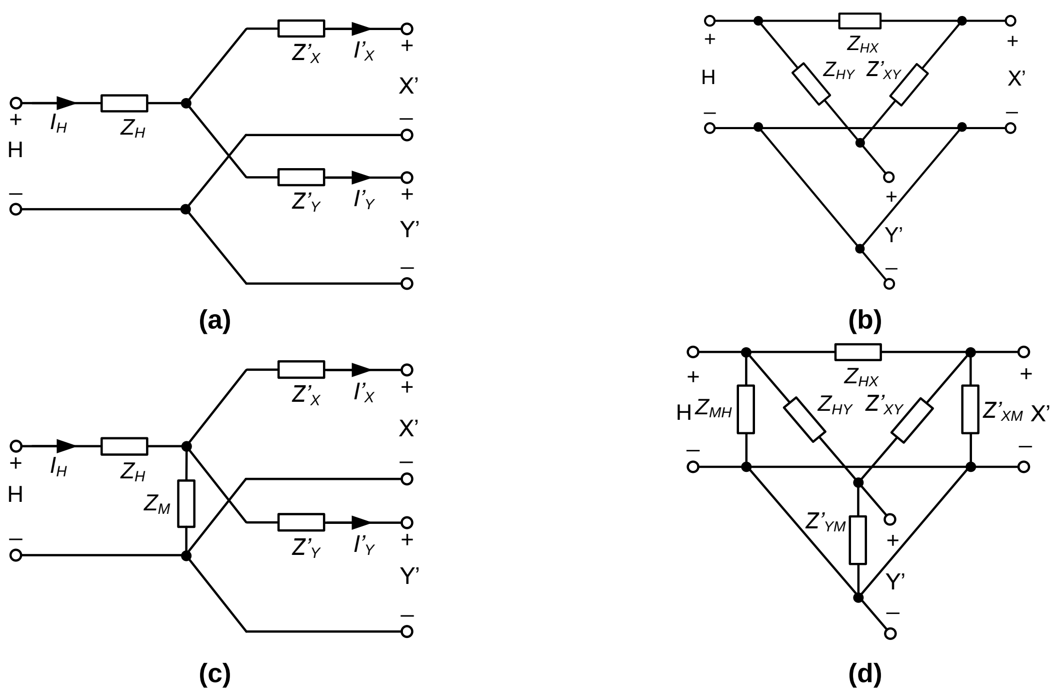

Figure 3-3- The equivalent circuit of a three-winding transformer: a) T-model without magnetizing branch, b) π-model without magnetizing branch, c) T-model with magnetizing branch, d) π -model with magnetizing branch

It should be noted that all these impedances have a resistance and a reactance, and that Z_{H-X} and Z_{H-Y} are measured from the terminal of winding 1, and Z_{X-Y} is measured from the terminal of winding 2.

$$Z_{H-X} = Z_H + Z'_X = Z_H + \left(\frac{N_H}{N_X}\right)^2 Z_X$$
$$Z_{H-Y} = Z_H + Z'_Y = Z_H + \left(\frac{N_H}{N_Y}\right)^2 Z_Y$$
$$Z_{X-Y} = Z_X + Z''_Y = Z_X + \left(\frac{N_X}{N_Y}\right)^2 Z_Y$$

in which Z'_X and Z'_Y are the transferred leakage impedances of the secondary and tertiary windings to the primary side, respectively. Z''_Y is the tertiary leakage impedance transferred to the secondary side. Solving these equations for the leakage impedances gives:

$$Z_H = \frac{1}{2}\left(Z_{H-X} + Z_{H-Y} - \left(\frac{N_H}{N_X}\right)^2 Z_{X-Y}\right)$$
$$Z_X = \frac{1}{2}\left(\frac{N_X}{N_H}\right)^2 \left(Z_{H-X} + \left(\frac{N_H}{N_X}\right)^2 Z_{X-Y} - Z_{H-Y}\right)$$
$$Z_Y = \frac{1}{2}\left(\frac{N_Y}{N_H}\right)^2 \left(Z_{H-Y} + \left(\frac{N_H}{N_X}\right)^2 Z_{X-Y} - Z_{H-X}\right)$$

These equations in per-unit form become:

$$z_{H-X} = z_H + z_X$$
$$z_{H-Y} = z_H + z_Y$$
$$z_{X-Y} = z_X + z_Y$$

Solving these per-unit equations gives:

$$z_H = \frac{z_{H-X} + z_{H-Y} - z_{X-Y}}{2}$$
$$z_X = \frac{z_{HX} - z_{H-Y} + z_{X-Y}}{2}$$
$$z_Y = \frac{-z_{H-X} + z_{H-Y} + z_{X-Y}}{2}$$

As mentioned in the previous section, manufacturers sometimes do not provide complete three-load losses test results between pairs of windings in the summery test report, particularly for double-secondary transformers. They usually report one short-circuit test result under the unit full load condition. Figure 3-4 shows the test diagram and equivalent circuit of the transformer leakage impedances for this test. The reported one-load losses test gives:

$$Z_H + Z'_X || Z'_Y = Z_{H-X\&Y} = Z_{H-X||Y} = \left.\frac{V_H}{I_H}\right|_{\substack{V_X=0 \\ V_Y=0}}$$

Theoretically, this calculated equivalent impedance seen from the high-voltage terminal does not give a direct way to separate Z_H , Z'_X , and Z'_Y , but it does give an extermination of the X/R ratio for positive-sequence leakage impedances. In some three-winding transformers the rated power of the high-voltage winding is the sum of the rated powers of all low-voltage windings. In these transformers, when rated current flows in the high-voltage winding the other two windings also

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carry the rated current. In some transformers, the full load rating of the high-voltage side is less than the sum of the two low-voltage ratings. In these transformers, the sum of the rated power in two low voltage windings must never exceed the power rating of the high-voltage side.

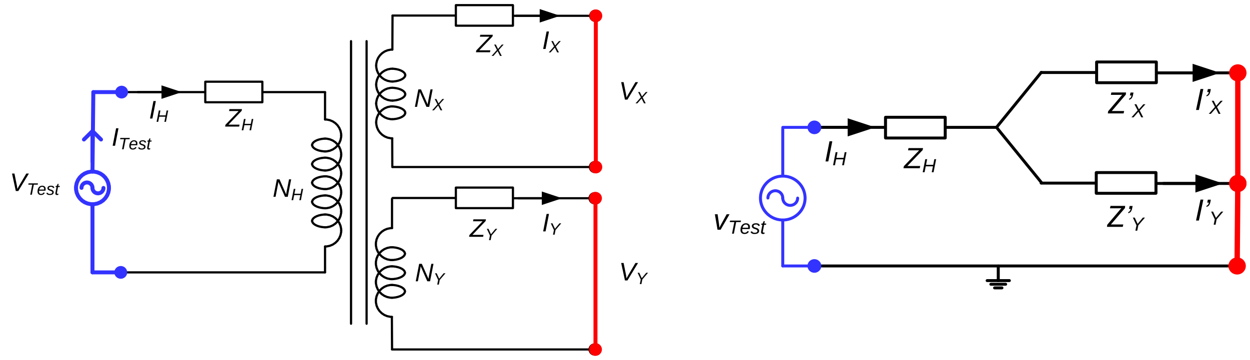

Figure 3-4- Diagram for only one load-losses test in three-winding transformers: a) Test diagram, b) Equivalent circuit of leakage impedances

3.2.3 Magnetizing Branch Impedance in Three-Winding Transformers

The magnetizing branch impedance in multi-winding transformers is calculated through one no-load losses test. It is the same as the two-winding transformer no-load test, and the same formulas are applicable.

3.2.4 Single-Phase Three-Winding Transformer Modelling Procedure

Table 3-1 summarizes how the equations described above can be used to calculate three-winding transformer parameters. To model a single-phase three-winding transformer, the following steps should be followed:

Step 1: The transformer data listed in Table 1-1 should be extracted from the available data, or assumptions should be made based on Table 1-3 and Table 1-4. As mentioned above, windings in multi-winding transformers may have different VA ratings. The measurements may be normalized based on the rating of the transformer's own winding on the test report; in such a case, they must be referred to a common base.

Step 2: The equivalent circuit parameters should be calculated using the formulas given in Table 3-1.

For three-phase three-winding transformers another step should be followed to obtain the zero-sequence parameters.

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Table 3-1- Formulas to Calculate Generic Model Parameters of a Three-Winding Transformer from a Test Report

Test	Parameters	Parameters in Per Unit	Parameters in SI Units
Load Losses Tests (Three short-circuit tests)	Two-Winding leakage impedances	$z_{H-X} = \frac{\%I_{Z\,H-X}}{100}\Big\rvert_{\substack{X:\,SC\\Y:\,OC}}$ $z_{H-Y} = \frac{\%I_{Z\,H-Y}}{100}\Big\rvert_{\substack{X:\,OC\\Y:\,SC}}$ $z_{X-Y} = \frac{\%I_{Z\,X-Y}}{100}\Big\rvert_{\substack{H:\,OC\\Y:\,SC}}$	$Z_{H-X} = \frac{V_H}{I_H}\Big\rvert_{\substack{X:\,SC\\Y:OC}} = \frac{\%I_{Z\,HX}}{100}\Big\rvert_{\substack{X:\,SC\\Y:OC}} \times Z_{H\,base} = \frac{\%I_{Z\,HX}}{100}\Big\rvert_{\substack{X:\,SC\\Y:OC}} \times \frac{{V_{H\,rated\,[kV]}}^2}{MVA_{Test\,[MVA]}}\,\Omega$ $Z_{H-Y} = \frac{V_H}{I_H}\Big\rvert_{\substack{X:\,OC\\Y:\,SC}} = \frac{\%I_{Z\,H-Y}}{100}\Big\rvert_{\substack{X:\,OC\\Y:\,SC}} \times Z_{H\,base} = \frac{\%I_{Z\,H-Y}}{100}\Big\rvert_{\substack{X:\,OC\\Y:\,SC}} \times \frac{{V_{H\,rated\,[kV]}}^2}{MVA_{Test\,[MVA]}}\,\Omega$ $Z_{X-Y} = \frac{V_X}{I_X}\Big\rvert_{\substack{H:\,OC\\Y:\,SC}} = \frac{\%I_{Z\,X-Y}}{100}\Big\rvert_{\substack{H:\,OC\\Y:\,SC}} \times Z_{X\,base} = \frac{\%I_{Z\,X-Y}}{100}\Big\rvert_{\substack{H:\,OC\\Y:\,SC}} \times \frac{{V_{X\,rated\,[kV]}}^2}{MVA_{Test\,[MVA]}}\,\Omega$
	Two-Winding equivalent resistances	$r_{H-X} = \frac{P_{LL\,HX\,[kW]}}{MVA_{LL\,Test\,[MVA]}\times 1000}\Big\rvert_{\substack{X:\,SC\\Y:\,OC}}$ $r_{H-Y} = \frac{P_{LL\,HT\,[kW]}}{MVA_{LL\,Test\,[MVA]}\times 1000}\Big\rvert_{\substack{X:\,OC\\Y:\,SC}}$ $r_{X-Y} = \frac{P_{LL\,XT[kW]}}{MVA_{LL\,Test[MVA]}\times 1000}\Big\rvert_{\substack{H:\,OC\\Y:\,SC}}$	$R_{H-X} = \frac{P_{LL\,HX\,[kW]}\times {V_{H\,rated\,[kV]}}^2}{{MVA_{LL\,Test\,[MVA]}}^2\times 1000}\Big\rvert_{\substack{X:\,SC\\Y:\,OC}}\,\Omega$ $R_{H-Y} = \frac{P_{LL\,HT\,[kW]}\times {V_{H\,rated\,[kV]}}^2}{{MVA_{LL\,Test\,[MVA]}}^2\times 1000}\Big\rvert_{\substack{X:\,OC\\Y:\,SC}}\,\Omega$ $R_{X-Y} = \frac{P_{LL\,XT\,[kW]}\times {V_{X\,rated\,[kV]}}^2}{{MVA_{LL\,Test\,[MVA]}}^2\times 1000}\Big\rvert_{\substack{H:\,OC\\Y:\,SC}}\,\Omega$
	Two-Winding leakage reactances	$x_{H-X} = \sqrt{{z_{H-X}}^2 - {r_{H-X}}^2}$ $x_{H-Y} = \sqrt{{z_{H-Y}}^2 - {r_{H-Y}}^2}$ $x_{X-Y} = \sqrt{{z_{X-Y}}^2 - {r_{X-Y}}^2}$	$X_{H-X} = \sqrt{{Z_{H-X}}^2 - {R_{H-X}}^2}\,\Omega$ $X_{H-Y} = \sqrt{{Z_{H-Y}}^2 - {R_{H-Y}}^2}\,\Omega$ $X_{X-Y} = \sqrt{{Z_{X-Y}}^2 - {R_{X-Y}}^2}\,\Omega$
	Calculated equivalent windings' resistance and leakage reactance (T-model parameters)	$r_H = \frac{r_{H-X}+r_{H-Y}-r_{X-Y}}{2}$ $r_X = \frac{r_{H-X}-r_{H-Y}+r_{X-Y}}{2}$ $r_Y = \frac{-r_{H-X}+r_{H-Y}+r_{X-Y}}{2}$ $x_H = \frac{x_{H-X}+x_{H-Y}-x_{X-Y}}{2}$ $x_X = \frac{x_{H-X}-x_{H-Y}+x_{X-Y}}{2}$ $x_Y = \frac{-x_{H-X}+x_{H-Y}+x_{X-Y}}{2}$	$R_H = \frac{1}{2}\left(R_{H-X} + R_{H-Y} - \left(\frac{N_H}{N_X}\right)^2 R_{X-Y}\right)\Omega$ $R_X = \frac{1}{2}\left(\frac{N_X}{N_H}\right)^2\left(R_{H-X} - R_{H-Y} + \left(\frac{N_H}{N_X}\right)^2 R_{X-Y}\right)\Omega$ $R_Y = \frac{1}{2}\left(\frac{N_Y}{N_H}\right)^2\left(-R_{H-X} + R_{H-Y} + \left(\frac{N_H}{N_X}\right)^2 R_{X-Y}\right)\Omega$ $X_H = \frac{1}{2}\left(X_{H-X} + X_{H-Y} - \left(\frac{N_H}{N_X}\right)^2 X_{X-Y}\right)\Omega$ $X_X = \frac{1}{2}\left(\frac{N_X}{N_H}\right)^2\left(X_{H-X} - X_{H-Y} + \left(\frac{N_H}{N_X}\right)^2 X_{X-Y}\right)\Omega$ $X_Y = \frac{1}{2}\left(\frac{N_Y}{N_H}\right)^2\left(-X_{H-X} + X_{H-Y} + \left(\frac{N_H}{N_X}\right)^2 X_{X-Y}\right)\Omega$

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Test	Parameters	Parameters in Per Unit	Parameters in SI Units
No Load Test (One open circuit test)	Magnetizing branch admittance	$y = \lvert g + jb \rvert = \%I_{exc.}/100$ pu	$Y = \frac{I_{OC}}{V_{OC(phase)}}$ $\mho$ $Y_X = \frac{I_{OC}}{V_{OC}} = \frac{\%I_{exc}/100}{Z_{X\,base}}$ $\mho$ or $Y_H = \frac{\%I_{exc}/100}{Z_{H\,base}}$ $\mho$ $Y_Y = \frac{\%I_{exc}/100}{Z_{Y\,base}}$ $\mho$ $Z_{X,Y\&H\ base}$ are at no load MVA base
	No Load losses equivalent conductance	$g = \frac{P_{NL[kW]}}{MVA_{NLTest[MVA]} \times 1000}$ pu	$G = \begin{cases} \frac{P_{OC}}{V_{OC(phase)}^{2}} & \text{For single-phase} \\ \frac{P_{OC}}{V_{OC(line)}^{2}} & \text{For three-phase} \end{cases}$ $\mho$ $G_Y = \frac{P_{NL[kW]}}{V_{Y\,rated[kV]}^{2} \times 1000}$ $\mho$ or $G_X = \frac{P_{NL[kW]}}{V_{X\,rated[kV]}^{2} \times 1000}$ $\mho$ or $G_H = \frac{P_{NL[kW]}}{V_{H\,rated[kV]}^{2} \times 1000}$ $\mho$
	Magnetizing branch susceptance	$b = -\sqrt{y^2 - g^2}$ pu	$B_Y = -\sqrt{Y_Y^{\,2} - G_Y^{\,2}}$ $\mho$ or $B_X = -\sqrt{Y_X^{\,2} - G_X^{\,2}}$ $\mho$ or $B_H = -\sqrt{Y_H^{\,2} - G_H^{\,2}}$ $\mho$

3.3 Three-Winding Three-Phase Transformers

The structure of a three-winding three-phase transformer is similar to that of a two-winding three-phase transformer, but it has one additional winding at each winding set. The modelling procedure is the same as that for a single-phase three-winding transformer (described previously). The equations in Table 3-1 are used to calculate the positive sequence parameters of all types of three-winding transformers.

The zero-sequence equivalent circuit of a three-winding transformer depends on the connection type of the windings set and on whether the neutral point in the Y-connected winding is grounded or not, which is discussed in Section 1.15.3. The zero-sequence equivalent circuits of different types of three-winding transformers are listed in Table 1-2. The zero-sequence current does not

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flow through the transformer windings unless it has at least one grounded Y connection. Depending on the connection types of the three-winding transformers, the zero-sequence equivalent circuit parameters can be calculated from the zero-sequence test measurements.

3.4 Three-Winding Transformers with Wye Primary, Wye Secondary, and Wye Tertiary

The schematic transformer diagram, vector representation, vector diagram, and phase displacement vector diagram of a three-winding Y-y-y-connected transformer are shown in Figure 3-7. The vector group of this connection is Y0y0y6. In practical applications, the low-voltage side of a Y-y-y-connected transformer should be grounded through a resistance to limit the earth fault current.

3.4.1 Three-Winding Y-y-y Transformer: Positive and Negative Sequence Generic Model

The generic model of a three-phase three-winding Y-y-y transformer for positive and negative sequence is similar to that of a single-phase three-winding transformer, shown in Figure 3-3.

3.4.2 Three-Winding Y-y-y Transformer: Procedure to Determine Generic Model Parameters

The procedure to model a three-phase three-winding Y-y-y transformer in positive or negative sequence is same as the single-phase transformer modelling procedure described in Section 3.2.4, except that the zero-sequence should be determined. The next section describes how the zero-sequence equivalent circuit of a three-winding Y-y-y transformer is modelled.

3.4.3 Three-Winding Y-y-y Transformer: Zero-Sequence Equivalent Circuit

The zero-sequence equivalent circuit of a Y-y-y-connected transformer depends on whether the neutral points are connected to ground or not. Therefore, there are six different types of zero-sequence equivalent circuits for this connection; however, some of them are not practical. In practice, the neutral points are grounded in all three-winding sets of a Y-y-y-connected transformer. The total zero-sequence impedance in this connection consists of a series connection that is the sum of all three zero-sequences, as shown in Figure 3-5. Under ground-fault conditions, the zero-sequence impedances of the high-voltage winding are greatly influenced by its return path to the source of supply, and it cannot be relied on that its value is zero. This is an issue for protection setups.

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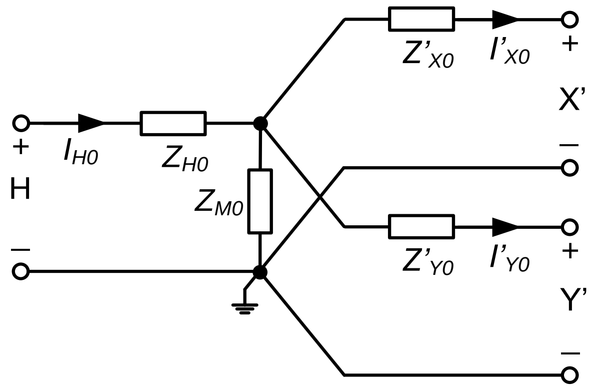

Figure 3-5- The zero-sequence equivalent circuit of a three-winding YNynyn transformer

3.4.4 Example 6: A Practical Three-Winding Y-y-y Transformer

Figure 3-6 shows the nameplate information of a 245/26/26 kV, 50/66.7/83.3 MVA three-winding Y-y-y-connected transformer. The schematic diagram and vector diagram of this type of transformer is shown in Figure 3-7. Nominal voltage of the high-voltage winding is 245 kV, and for both low-voltage windings it is 26 kV. The primary winding rating has not been specified separately. It is assumed that it is equal to the transformer MVA rating. The low-voltage windings are equal and have the same MVA rating given, 41.7 MVA. Since the transformer MVA rating is not greater than the sum of the MVA ratings of the two other windings, the secondary and tertiary windings are not to supply 41.7 MVA full load at the same time. The total load that can be supplied through two windings should be less than 50 MVA, which is the primary MVA rating. It has a 24-step on-load tap changer in the neutral-point end of the high-voltage side. The neutral point of the high-voltage windings is solid grounded and in both low-voltage windings the neutral point is grounded through 1 ohm reactance. Since the neutral points of all windings are somehow grounded, the zero-sequence current can flow through all windings. Therefore, the zero-sequence equivalent circuit can be shown as in Figure 3-5. The test results for this transformer and another similar transformers have been reported as in Figure 3-8-a and Figure 3-8-b. These test results show that only one load-losses test has been conducted for the nominal tap position at 117.8 A. It means the load-losses test has been conducted at 50 MVA, while both low-voltage windings are short-circuited. To determine the transformer generic model parameters only the nominal tap ratio test results are used. The nominal tap position is position 10.

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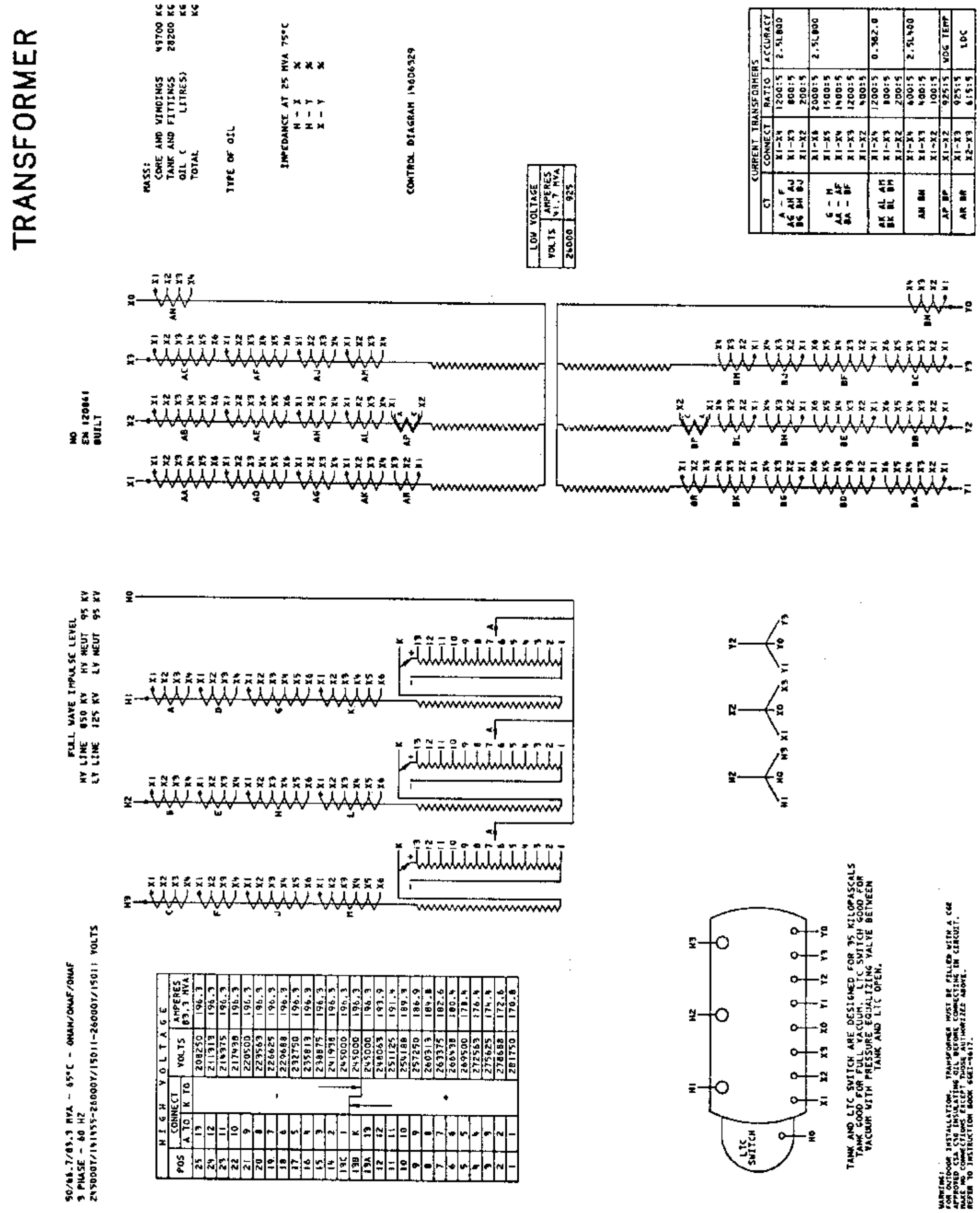

Figure 3-6 - Example 6: Transformer nameplate

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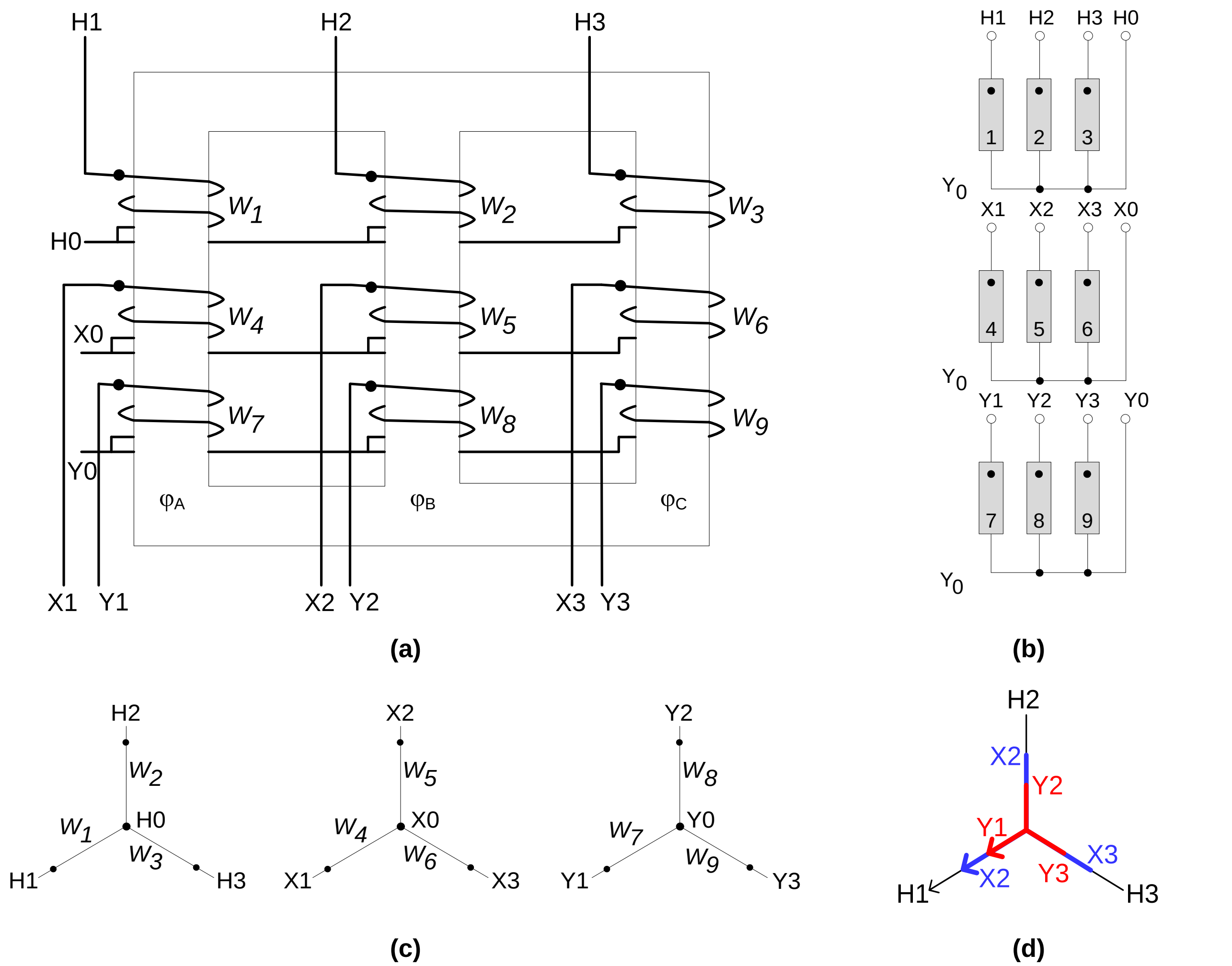

Figure 3-7- Three-winding Yy0y0 transformer with wye primary, wye secondary, and wye tertiary: a) Schematic transformer diagram, b) Winding connection diagram, c) Vector diagram, d) Phase displacement vector diagram

The information required to determine the generic model parameters listed in Table 1-1 is extracted from the test report. These data are shown in Table 3-2. The calculated parameters for the generic model are shown in Table 3-3, and the zero-sequence equivalent circuit is shown in Figure 3-5. In the test report, only two measurements have been provided for the zero-sequence: $Z_{H-X\,0}$ and $Z_{H-Y\,0}$. The magnetizing branch impedance has been assumed to be infinity. With only these two data, Z_{H0} , Z'_{X0} , and Z'_{Y0} cannot be determined separately. Therefore, as shown in Figure 3-9, Z_{H0} is assumed to be zero. This circuit is approximately correct when coupling between the high-voltage winding and the low-voltage windings is considered.

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RECORD OF TRANSFORMER TESTS

RATING 50/66.7/83.3MVA-65°C-ONAN/AF/AF-3-60-245/141.455-26/15.011-26/15.011 kV

ENG. NOTICE 120861 REQ.NO. CUST.ORDER NO.

NOTE: Unless otherwise expressed, all values are based on 50 MVA

		Example6		
SERIAL NUMBER		289516	289517	GUARANTEE
O LOAD LOSS AT 100% VOLTS	AMPS	1.42	1.33	47.5
ONNECTION	KW	47.656	46.32	
O LOAD LOSS AT 110% VOLTS	AMPS	7.31	6.98	
ONNECTION	KW	72.8	70.757	
OAD LOSS 75°C AT 117.8 AMPS	VOLTS	25382	25380	
TION LTC 13	KW	116.852	117.444	134.0
JTAL LOSS 75°C	KW	164.508	163.764	
ESISTANCE 75°C	HV LTC 13	2.912	2.938	
ETWEEN TERMINALS	LV (X)	.04433	.04473	
HMS	LV (Y)	.0443	.04453	
JXILIARY LOSSES 18 FANS		25.49 KW	25.44 KW	
RO PHASE IMPEDANCE 25 MVA		H - X	7.81%	8.0%
MVA		H - Y	7.81%	8.0%

Figure 3-8-a- Example 6: Transformer test results, Page 1

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RECORD OF TRANSFORMER TESTS

SERIAL NUMBER		289516	289517	GUARANTEE
	H-X LTC 13	9.7%	9.65	9.5
POSITIVE	H-Y LTC 13	9.67%	9.7	9.5
	X-Y	18.05%	18.02	18.2
IMPEDANCE	X-Y 3RD HARMONIC	54.06%		
25 MVA	X-Y 5TH HARMONIC	90.74%		

ːAT RUN ON SERIAL NO. 289516 CONNECTION LTC 25

		WINDING RISE BY RESISTANCE					
MVA	TIME	HV	LV(X)	LV(Y)	GUARANTEE	TOP OIL RISE	AMBIENT TEMP.
]	24 HRS	44.9	47.8	37.5	65°	46.5	31.0
	24 HRS	42.1	48.2	35.6	65°	41.4	30.1

	5 0 MVA			8 3.3 MVA		
ÆRAGE OIL TEMP	6 7.5 °C			5 6 .5°C		
JND. TEMP	HVX	LVX	LVY	HV	LVX	LVY
JP OVER AVE	8.8	8.8	8.8	12.8	12.8	12.8
IT SPOT OVER TOP	0	1.0	1.0	0	3.1	3.1

SULATION TESTS

PLIED HV TO BOTH LV'S AND GROUND 34 kV FOR 1 MIN

TENTIAL LV TO HV, LV(Y) AND GROUND 34 kV FOR 1 MIN.

STS LV(Y) TO HV, LV(X) AND GROUND 34 kV FOR 1 MIN.

DUCED | 479 kV FOR 7200 CYCLES 423 kV FOR 1 HOUR RIV LESS THAN 100 uv

PULSE TESTS: HV 850 LIL

LV 125 LIL

CERTIFIED CORRECT ____________ DATE 82-10-07

Figure 3-8-b- Example 6: Transformer test results, Page 2

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Table 3-2- Information Required for Modelling the Transformer in Example 6

Item	Transformer Parameter	Symbol	Values
General			
1	Transformer ONAN Ratings	MVA_{ONAN}	50 MVA
2	Winding Voltages (primary, secondary, …)	V_H, V_X, V_Y, … V_P, V_S, … V_1, V_2, …	245 kV/26 kV/26 kV
3	Connection type	-	Transformer
4	Tap range	t_1, t_2, …	± 30%
5	Number of tap steps	-	24
6	Winding with an adjustable tap	-	Primary (high) side
7	Phase angle of windings	θ_1, θ_2, θ_3…	0°, 0°
No Load Loss Test Results			
8	No-load loss test MVA	$MVA_{NL\ Test}$	-
9	No-load loss	P_{NL}	47.656 kW
10	Excitation current	I_{exc}	1.42 A
11	Tap setting for no-load loss test	t_{NL}	Nominal
Load Loss Test Results			
12	Load loss test MVA	$MVA_{SC\ Test}$, …	@ 117.8A (H-X&Y @ 50MVA)
13	Load loss	P_{SC}, P_{LL_HX}, …	116.852 kW
14	Impedance (Voltage)	I_Z, or Z_{HX}, …	25382V
15	Reactance	I_X, or X_{HX}, …	Not reported
16	Tap setting for load loss test	t_{SC}	Nominal (13)
17	Positive-sequence impedance between Pair Windings	H-X, H-Y, X-Y @MVA	9.7%, 9.67%, 18.05% @ 25MVA
Zero-Sequence Test Results			
18	Zero-sequence open circuit test results	Z_1, Z_2	-
19	Zero-sequence short circuit test results	Z_3	-
20	Zero-sequence T-model parameters	Z_{H0}, Z'_{X0} Z_{M0} for the T-model	-
21	Zero-sequence impedances between Pair Windings	$Z_{H\text{-}X\ 0}$, $Z_{H\text{-}Y\ 0}$, for the T-model	7.81%, 7.81% @ 25MVA
22	Grounding configuration	Windings neutral point grounding method	Primary Solidly grounded
23	Grounding Impedance	Z_{GX}, Z_{GY}, …	1Ω reactance

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Table 3-3- Example 6: Generic Model Parameters of the Transformer

Type	Parameters in Per Unit	Parameters in SI Unit
Windings' leakage impedance	$z_H = \frac{z_{H-X}+z_{H-Y}-z_{X-Y}}{2} = 0.0132$ pu $z_X = \frac{z_{H-X}-z_{H-Y}+z_{X-Y}}{2} = 0.1808$ pu $z_Y = \frac{-z_{H-X}+z_{H-Y}+z_{X-Y}}{2} = 0.1802$ pu	$Z_b = \frac{V_{rated}{}^2}{S_b}$ $Z_H = z_H \times Z_{H-base} = 15.8467\Omega$ $Z'_X = z_X \times Z_{H-base} = 217.05\Omega$ $Z'_Y = z_Y \times Z_{H-base} = 216.33\Omega$
Load losses test equivalent impedance	$z_{H-X\&Y} = \frac{Z_{H-X\&Y}}{Z_{H\,base}} = \frac{\frac{V_{SC}}{\sqrt{3}\times I_{SC}}}{\frac{V_{H\,rated}{}^2}{MVA_{rated}}}$ $z_{H-X\&Y} = 10.36\%$ $r_{H-X\&Y} = 0.002337$pu $x_{H-X\&Y} = \sqrt{z_{H-X\&Y}{}^2 - r_{H-X\&Y}{}^2}$ $x_{H-X\&Y} = 0.103574$pu	$Z_{H-X\&Y} = \frac{V_{SC\_Phase}}{I_{SC\_Phase}} = \frac{25382}{\sqrt{3}\times 117.8} = 124.4\Omega$ $R_{H-X\&Y} = \frac{P_{SC}}{3\times I_{SC_{Phase}}{}^2}$ $R_{H-X\&Y} = \frac{116.852\times 1000}{3\times 117.8^2} = 2.807\Omega$ $X_{H-X\&Y} = \sqrt{Z_{H-X\&Y}{}^2 - R_{H-X\&Y}{}^2} = 124.37\Omega$
Verification	$z_{H-X\|\|Y} = z_H + z_X\|\|z_X = 0.10345$ pu $z_{H-X\&Y} \cong z_{H-X\|\|Y}$	$Z_{H-X\|\|Y} = Z_H + Z'_X\|\|Z'_Y = 124.2\ \Omega$ $Z_{H-X\&Y} \cong Z_{H-X\|\|Y}$
Magnetizing branch admittance	$y = \%I_{exc.}/100 = 0.01205$ pu	$Y_H = \frac{I_{OC}}{V_{OC}} = 1.0039E-5$ $\mho$ or
No-load losses equivalent conductance	$g = \frac{P_{NL}}{MVA_{NLTest}\times 1000} = 9.53E-4$ pu	$G_H = \frac{P_{OC}}{V_{OC}{}^2} = \frac{P_{NL}}{V_{H\,rated}{}^2} = 7.94E-7$ $\mho$
Magnetizing branch susceptance	$b = -\sqrt{y^2 - g^2} = -0.012$ pu	$B_H = -\sqrt{Y_H{}^2 - G_H{}^2} = -1E-5$ $\mho$
Zero-sequence parameters	$z_{HX0} = 0.0781 * 50/25 = 0.152$ pu $z_{HY0} = 0.0781 * 50/25 = 0.152$ pu $z_{H0} = 0\ pu$ $z'_{X0} = 0.152$ pu $z'_{X0} = 0.152$ pu $z_{M0} = \infty$ $z_{HN0} = \infty$ $z'_{XN0} = \infty$ $z'_{YN0} = \infty$	$Z_{GH} = 0$ $Z_{GX} = 1\ \Omega$ $Z'_{GX} = 88.791\ \Omega$ $Z_{GY} = 1\ \Omega$ $Z'_{GY} = 88.791\ \Omega$ $Z_{H0} = 0\Omega$ $Z'_{X0} = 182.4\ \Omega$ $Z'_{Y0} = 182.4\ \Omega$ $Z_{M0} = \infty$ $Z_{HN0} = \infty$ $Z'_{XN0} = \infty$

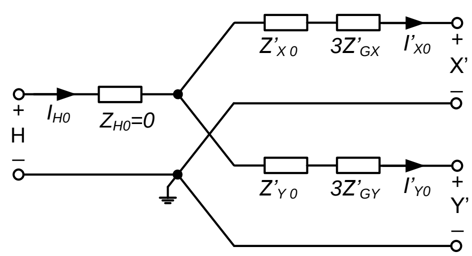

Figure 3-9 - The zero-sequence equivalent circuit of Example 6

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3.5 Three-Winding Transformers with Wye Primary, Wye Secondary, and Delta Tertiary

A Y connection is susceptible to third harmonics and voltage transients when not grounded. To incorporate the advantage of a Y winding and the advantages of delta winding, a third winding, a delta tertiary winding, is built into the two-winding star-star transformer. This Y-y-delta transformer not only traps ground fault currents and offers high impedance to third harmonics, it allows for connecting the following:

- A capacitor bank – for voltage or power factor correction
- Reactors – for limiting ground fault currents (resonant grounding)
- Resistors – for limiting ground fault currents
- A station service transformer – ac power for equipment inside the substation
- A distribution system – to power a town or an industrial customer

In addition to the abovementioned applications, Y-y-delta-connected transformers are also used as converter station transformers. They provide two identical three-phase systems with 30° phase displacement. The transformer supplies a 12-pulse (two 6-pulse) full-bridge line-triggered converter.

The schematic transformer diagram, vector representation, vector diagram, and phase displacement vector diagram of a Y-y-delta-connected transformer is shown in Figure 3-10.

3.5.1 Three-Winding Y-y-delta Transformer: Positive and Negative Sequence Generic Model

The generic model of a three-phase three-winding Y-y-delta transformer for positive and negative sequence is similar to that of a single-phase three-winding transformer, as shown in Figure 3-3.

3.5.2 Three-Winding Y-y-delta Transformer: Procedure to Determine Generic Model Parameters

The procedure to model a three-phase three-winding Y-y-delta transformer in positive or negative sequence is same as the single-phase transformer procedure described in Section 3.2.4, except that the zero-sequence should be determined. The next section describes how the zero-sequence equivalent circuit of a three-winding Y-y-delta transformer is modelled.

3.5.3 Three-Winding Y-y-delta Transformer: Zero-Sequence Equivalent Circuit

The zero-sequence equivalent circuit of a Y-y-d-connected transformer depends on whether the neutral points are connected to ground or not. Therefore, there are four different types of zero-sequence equivalent circuits, as shown in Table 3-4; however, some of them may not be used in practice. In practice, the neutral point of the low-voltage side is not grounded if the transformer connects an SVC to the network. Both neutral points may be grounded if the tertiary (third) winding is a buried winding that does not supply the load. Under ground-fault conditions, the zero-sequence current flows in the delta winding. To limit this current, sometimes the delta tertiary winding is closed through a resistance.

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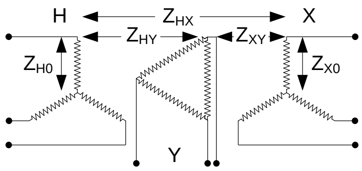
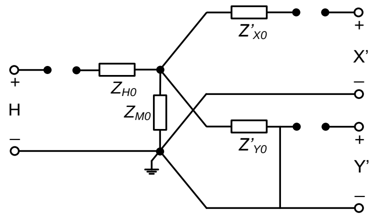
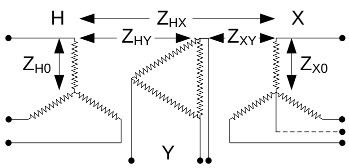
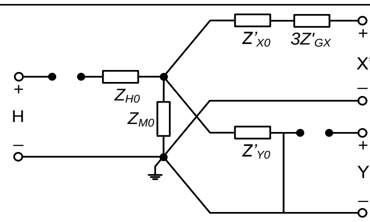
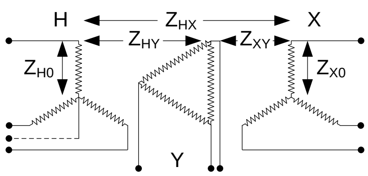
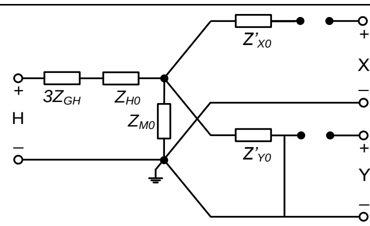
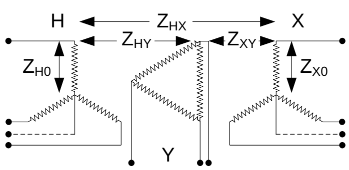
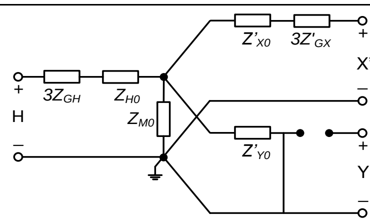
Table 3-4- Zero-Sequence Equivalent Circuits of Wye-wye-delta-Connected Three-Winding Transformers

	Connection Type	T-Model	Symbol
1			Y-y-d
2			Y-yn-d
3			YN-y-d
4			YN-yn-d

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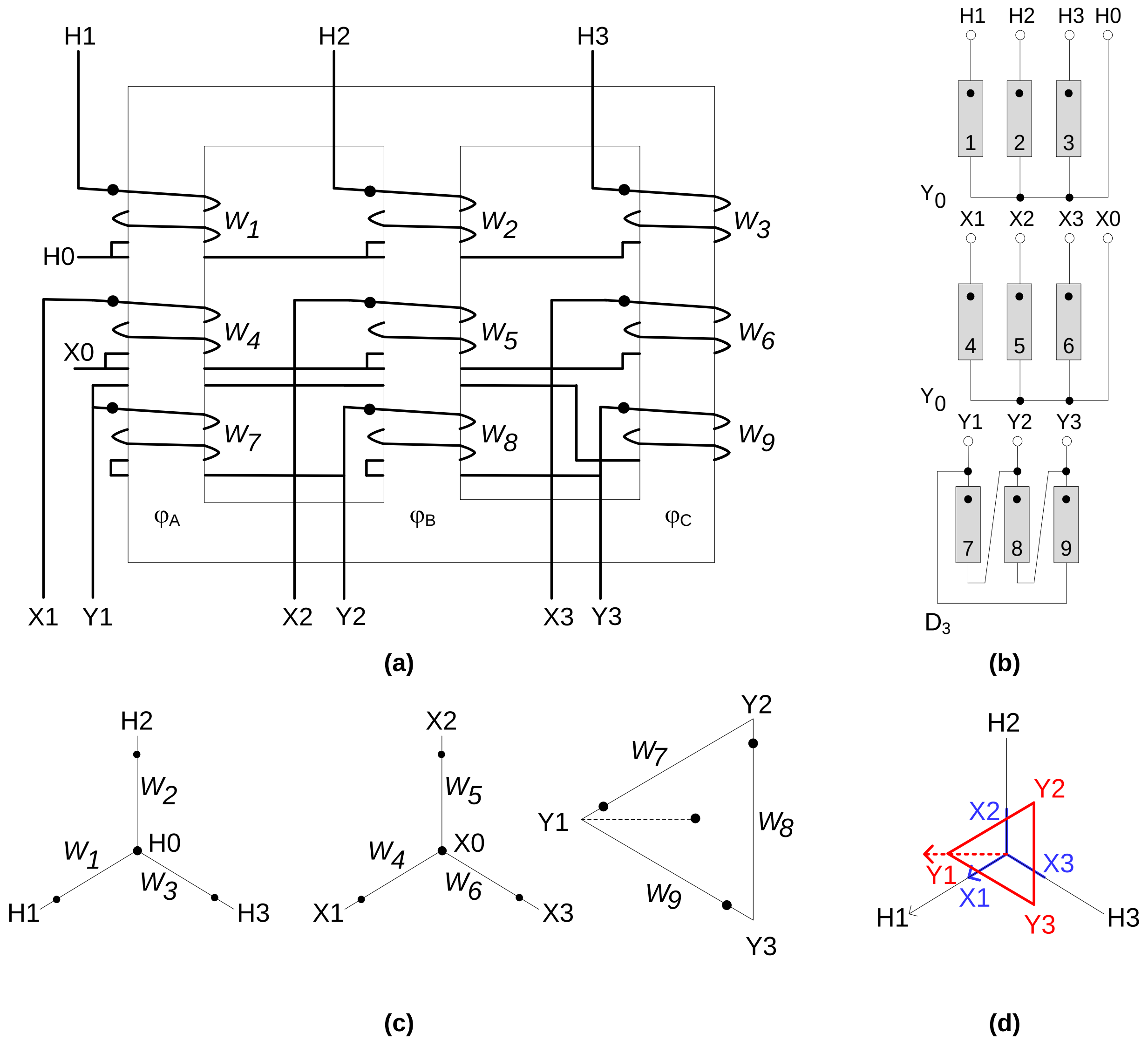

Figure 3-10- Three-Winding Yy0d6 transformer with wye primary wye secondary and delta tertiary: a) Schematic transformer diagram, b) Winding connection diagram, c) Vector diagram, d) Phase displacement vector diagram

3.5.4 Example 7: A Practical Three-Winding Y-Y-Delta Connected Transformer

Figure 3-11 shows the nameplate information of a 250/20/20 kV, 150/200/250 MVA three-winding Yyd-connected SVC transformer. The neutral points of the high-voltage windings are solidly grounded. The schematic diagram and vector diagram of this type transformer are shown in Figure 3-10. Nominal voltage of the primary is 250 kV and both low-voltage windings are 20 kV. The high-voltage winding MVA rating is the sum of two low-voltage MVA ratings in all cooling classes. This transformer has not been equipped with a tap changer because the reactive power at the low-voltage side is not controlled by the voltage amplitude. A part of the transformer test

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report that contains information required for calculating the transformer parameters extracted from the detailed test report is shown in Figure 3-12-a to Figure 3-12-g. To determine the transformer generic model parameters, only the nominal tap ratio test results are used.

The modelling procedure proposed in Section 3.2.4 would be applied to obtain the T-model equivalent circuit, but the measured load-losses of the windings have not been corrected in the test report. The required information for modelling the transformer is listed in Table 3-5. However, as shown in Figure 3-12-e, this model has been given in the test report for 125 MVA and 60 Hz base. These results are listed in Table 3-6.To obtain the T-model equivalent circuit parameters at the high-voltage winding's ONAN MVA base, the parameters at 125 MVA are multiplied to the MVAs ratio (150/125=1.2) as follows:

$$z_{H@\ ONAN\ MVA} = z_{H@\ 125} \times \frac{150}{125} = 7.17\%$$

$$z'_{X@\ ONAN\ MVA} = z'_{X@\ 125} \times \frac{150}{125} = 4.482\%$$

$$z'_{Y@\ ONAN\ MVA} = z'_{Y@\ 125} \times \frac{150}{125} = 4.278\%$$

The magnetizing branch, which is assumed to have been modelled at the high-voltage winding, is calculated from the no-load test.

$$I_{exc}\% = 0.024\% \text{ @ 250 MVA}$$

$$y = \frac{I_{exc}\%}{100} \div \frac{150}{250} = 4E-4$$

$$Y_H = \frac{y}{Z_{H\ base}} = 4E-4 \times \frac{240^2}{150} = 1.042E-6\ \mho$$

$$g_{@\ ONAN\ MVA} = \frac{P_{NL}}{MVA_{NLTest} \times 1000} \div \frac{MVA_{NLTest}}{MVA_{\ ONAN}} = 3.173\text{E}-4\ \text{pu}$$

$$b_{@ONAN\ MVA} = -\sqrt{y^2 - g^2} = -2.4356E-4\Omega$$

$$B_H = -\sqrt{{Y_H}^2 - {G_H}^2} = -6.34E-7\Omega$$

The zero-sequence equivalent circuit of this transformer has been given in the test report at 125 MVA, as shown in Figure 3-12-f. In a manner similar to that used for the positive-sequence equivalent circuit parameters, the zero-sequence impedance is converted to ONAN MVA base as well. Because the low-voltage wye-connected winding is not grounded, the zero-sequence equivalent circuit of this transformer is an impedance from the high-voltage terminal and open circuit from the low-voltage terminals.

$$z_{H0@\ ONAN\ MVA} = z_{H0@\ 125} \times \frac{150}{125} = 0.0984pu = 37.78\ \Omega = 2.81 + \text{j}37.6\ \Omega$$

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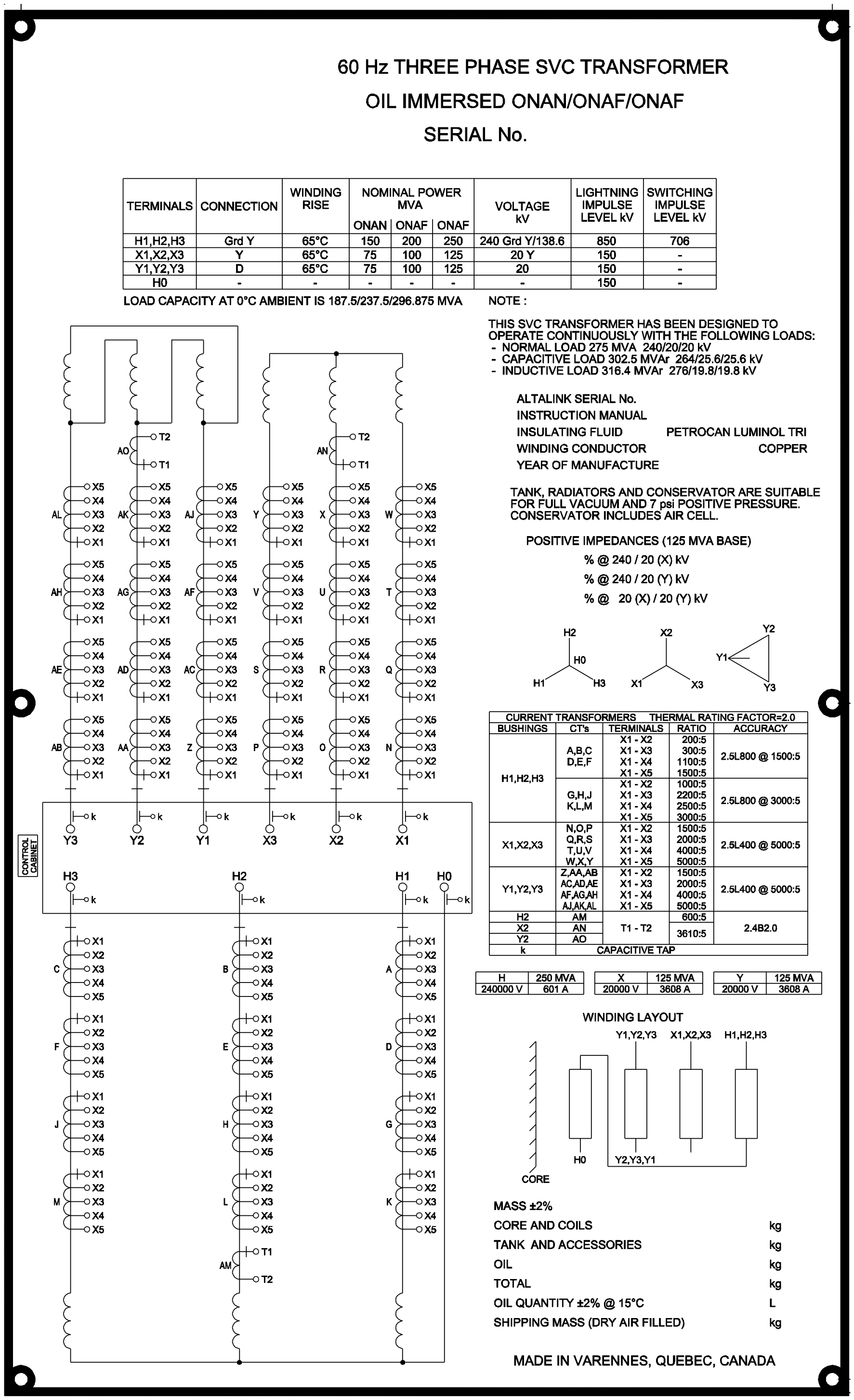

Figure 3-11- Example 7: Transformer nameplate

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TEST REPORT ON THE UNIT SERIAL

2011-10-21

4.0 NO LOAD LOSSES & MAGNETIZING CURRENT

MEASUREMENTS BEFORE DIELECTRICS							
APPLIED VOLTAGE			RMS CURRENT		NO LOAD LOSSES		
% OF RATED VOLTAGE	RMS (KV)	MEAN (KV)	MEASURED (% OF RATED I)	GUARANTEED (% OF RATED I)	MEASURED (KW)	CORRECTED (KW)	GUARANTEED (KW)
80	16.0	16.0	0.020	-	30.5	30.5	-
90	18.0	18.0	0.022	-	38.6	38.6	-
100	20.0	20.0	0.024	-	47.9	47.9	-
105	21.0	21.0	0.024	-	53.1	53.1	-
110	22.0	22.0	0.025	-	58.6	58.6	-
135	26.9	27.0	0.059	-	102.1	102.5	-

I% is based on 250 MVA

MEASUREMENTS AFTER DIELECTRICS							
APPLIED VOLTAGE			RMS CURRENT		NO LOAD LOSSES		
% OF RATED VOLTAGE	RMS (KV)	MEAN (KV)	MEASURED (% OF RATED I)	GUARANTEED(% OF RATED I)	MEASURED (KW)	CORRECTED (KW)	GUARANTEED (KW)
80	16.0	16.0	0.020	-	30.4	30.5	-
90	18.0	18.0	0.022	-	38.6	38.6	-
100	19.9	20.0	0.024	0.030	47.5	47.6	67.0
105	21.0	21.1	0.025	-	53.1	53.2	-
110	22.0	22.1	0.025	-	58.7	58.9	-
135	26.5	26.9	0.048	-	92.9	94.3	-

I% is based on 250 MVA

Figure 3-12-a- Example 7: Transformer test results, Page 1

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TEST REPORT ON THE UNIT SERIAL

2011- 10-21

5.0 LOAD LOSSES, IMPEDANCE

LOAD LOSSES CORRECTED AT 85°C, 250 MVA H / X +Y								
WINDINGS				MEAN	MEAN WINDING	LOAD LOSSES		
KV	TC POS	KV	KV	CURRENT (A)	TEMPERATURE °C	MEASURED (KW)	CORRECTED (KW)	GUARANTEED (KW)
240	-	20	20	601.9	21.1	855.8	1007.4	1190

LOAD LOSSES CORRECTED AT 85°C, 125 MVA H / X								
WINDINGS				MEAN	MEAN WINDING	LOAD LOSSES		
KV	TC POS	KV	TC POS	CURRENT (A)	TEMPERATURE °C	MEASURED (KW)	CORRECTED (KW)	GUARANTEED (KW)
240	-	20	-	300.9	20.7	319.5	-	-

LOAD LOSSES CORRECTED AT 85°C, 125 MVA H / Y								
WINDINGS				MEAN	MEAN WINDING	LOAD LOSSES		
KV	TC POS	KV	TC POS	CURRENT (A)	TEMPERATURE °C	MEASURED (KW)	CORRECTED (KW)	GUARANTEED (KW)
240	-	21.4	-	301.4	20.7	337.4	-	-

LOAD LOSSES CORRECTED AT 85°C, 125 MVA X / Y								
WINDINGS				MEAN	MEAN WINDING	LOAD LOSSES		
KV	TC POS	KV	TC POS	CURRENT (A)	TEMPERATURE °C	MEASURED (KW)	CORRECTED (KW)	GUARANTEED (KW)
20	-	20	-	499.4	20.7	8.8	-	-

Figure 3-12-b- Example 7: Transformer test results, Page 2

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IMPEDANCE H / X +Y						
WINDINGS				MEASURED	IMPEDANCE (BASE 250 MVA)	
KV	TC POS	KV	KV	VOLTAGE (KV)	MEASURED (%)	GUARANTEED (%)
240	-	20	20	37.7	15.7	-

IMPEDANCE H / X +Y								
WINDINGS				FREQUENCY	MEASURED	MEASURED	IMPEDANCE (BASE 250 MVA)	
KV	TC POS	KV	KV	(Hz)	CURRENT (A)	VOLTAGE (KV)	MEASURED (%)	GUARANTEED (%)
240	-	20	20	180	1.11	0.21	46.93	-
240	-	20	20	300	0.67	0.21	78.21	-
240	-	20	20	420	0.48	0.21	109.55	-
240	-	20	20	540	0.37	0.21	141.01	-
240	-	20	20	660	0.30	0.21	172.58	-
240	-	20	20	780	0.26	0.21	204.47	-

IMPEDANCE H / X						
WINDINGS				MEASURED	IMPEDANCE (BASE 125 MVA)	
KV	TC POS	KV	TC POS	VOLTAGE (KV)	MEASURED (%)	GUARANTEED (%)
240	-	20	-	23.3	9.7	9.5

IMPEDANCE H / X									
WINDINGS				FREQUENCY	MEASURED	MEASURED	IMPEDANCE (BASE 125 MVA)		
KV	TC POS	KV	TC POS	(Hz)	CURRENT (A)	VOLTAGE (KV)	MEASURED (%)	R (Ω)	X (Ω)
240	-	20	-	60	2.69	0.21	9.71	2.02	44.68
240	-	20	-	180	0.90	0.21	29.09	3.02	134.00
240	-	20	-	300	0.54	0.21	48.49	4.75	223.37
240	-	20	-	420	0.38	0.21	67.96	7.24	313.08
240	-	20	-	540	0.30	0.21	87.53	10.47	403.20
240	-	20	-	660	0.24	0.21	107.27	14.50	494.10
240	-	20	-	780	0.20	0.21	127.20	19.33	585.80

Figure 3-12-c- Example 7: Transformer test results, Page 3

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IMPEDANCE H / Y						
WINDINGS				MEASURED VOLTAGE (KV)	IMPEDANCE (BASE 125 MVA)	
KV	TC POS	KV	TC POS		MEASURED (%)	GUARANTEED (%)
240	-	20	-	22.9	9.5	9.5

IMPEDANCE H / Y									
WINDINGS				FREQUENCY (Hz)	MEASURED CURRENT (A)	MEASURED VOLTAGE (KV)	IMPEDANCE (BASE 125 MVA)		
KV	TC POS	KV	TC POS				MEASURED (%)	R (Ω)	X (Ω)
240	-	20	-	60	2.74	0.21	9.52	2.09	43.83
240	-	20	-	180	0.92	0.21	28.51	3.19	131.34
240	-	20	-	300	0.55	0.21	47.49	4.97	218.79
240	-	20	-	420	0.39	0.21	66.53	7.48	306.50
240	-	20	-	540	0.30	0.21	85.66	10.75	394.57
240	-	20	-	660	0.25	0.21	104.88	14.73	483.07
240	-	20	-	780	0.21	0.21	124.27	19.53	572.31

IMPEDANCE X / Y						
WINDINGS				MEASURED VOLTAGE (KV)	IMPEDANCE (BASE 125 MVA)	
KV	TC POS	KV	TC POS		MEASURED (%)	GUARANTEED (%)
20	-	20	-	0.2	7.3	6.8

IMPEDANCE X / Y									
WINDINGS				FREQUENCY (Hz)	MEASURED CURRENT (A)	MEASURED VOLTAGE (KV)	IMPEDANCE (BASE 125 MVA)		
KV	TC POS	KV	TC POS				MEASURED (%)	R (Ω)	X (Ω)
20	-	20	-	60	20.32	0.01	7.43	0.02	0.24
20	-	20	-	180	13.85	0.01	22.19	0.03	0.71
20	-	20	-	300	8.34	0.01	36.92	0.04	1.18
20	-	20	-	420	5.97	0.01	51.62	0.06	1.65
20	-	20	-	540	4.64	0.01	66.31	0.09	2.12
20	-	20	-	660	3.80	0.01	80.98	0.12	2.59
20	-	20	-	780	3.22	0.01	95.64	0.15	3.06

Figure 3-12-d- Example 7: Transformer test results, Page 4

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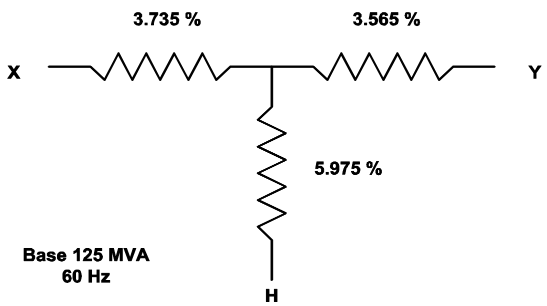

The equivalent "T" network impedances at 300Hz are Zh=29.85%, Zx=18.55%, Zy=17.55%. The calculated equivalent impedance for the 5th harmonic is Zeq=38.87% (Minimum 37.4% as specified in ABB Facts 1JNR100017-542)

Figure 3-12-e- Example 7: Transformer test results, Page 5

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6.0 ZERO SEQUENCE IMPEDANCE

ZERO SEQUENCE IMPEDANCE							
VOLTAGE APPLIED	TERMINAL SHORT CIRCUITED	VOLTAGE (KV)	CURRENT (A)	Z (%) (BASE 125 MVA)	R (Ω))	X (Ω)	POSITION DETC
H1, H2, H3	X1, X2, X3,Y2, H0, GND	6.29	500.50	8.18	2.81	37.6	-
H1, H2, H3	Y2, H0, GND	6.27	499.70	8.17	2.81	37.5	-

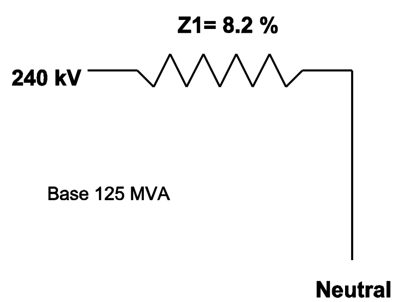

Figure 3-12-f- Example 7: Transformer test results, Page 6

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7.0 X TO R RATIO & VOLTAGE REGULATION

X TO R RATIO			
CONNECTION	**X % (250 MVA)**	**R% (85°C)**	**X/R**
H / (X+Y)	15.695	0.403	38.949

VOLTAGE REGULATION CALCULATED H/(X+Y)			
	POWER FACTOR LAGGING (%)		
MVA	**100**	**90**	**80**
250	1.622	8.108	10.428
200	1.105	6.350	8.421
150	0.683	4.658	6.101

Figure 3-12-g- Example 7: Transformer test results, Page 7

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Table 3-5-Information Required for Modelling the Transformer in Example 7

Item	Transformer Parameter	Symbol	Values			
General						
			H		X	Y
1	Transformer ONAN Ratings	MVA_{ONAN}	150		75	75
2	Winding Voltages (primary, secondary, …)	V_H, V_X,…(kV) V_P, V_S,…(kV) V_1, V_2, …(kV)	240 Grd Y		20	20
3	Connection type	-	Wye		Wye	Delta
4	Tap range	t_1, t_2, …	-		-	-
5	Number of tap steps	-	-		-	-
6	Winding with an adjustable tap	-	-		-	-
7	Phase angle of windings	θ_1, θ_2, …	0°		0°	30°
No Load Loss Test Results (between Pair of Windings)						
8	No-load loss test MVA	$MVA_{NL\ Test}$	250 MVA			
9	No-load loss	P_{NL}	47.6 kW			
10	Excitation current	I_{exc}	0.024 %			
11	Tap setting for NL Loss test	t_{NL}	-			
Load Loss Test Results						
	Between Pair of Windings		H-X	H-Y	X-Y	H-X&Y @ Full-Load
12	Load loss test MVA	$MVA_{SC\ Test}$,	125	125	125	250
13	Load Losses	P_{LL} (kW)	319.5*	337.4*	8.8*	1007.4
14	Mean Test Current	A	300.9	301.4	499.4	601.9
15	Test Voltage	kV	23.3	22.9	0.2	37.7
16	Impedance	I_Z%	9.7%	9.5%	7.3%	15.7%
17	Reactance	I_X%	-	-	-	-
18	Resistance	I_R%	-	-	-	-
Zero-Sequence Test Results						
			Short Circuit		Open Circuit	
19	Test MVA	$MVA_{SC\ Test}$,	125		125	
20	Test Voltage (From H Side)	kV	6.29		6.27	
21	Impedance	I_Z%	8.18%		8.17%	
22	Reactance	Ω	37.6		37.5	
	Resistance	Ω	2.81		2.81	

* These values are not corrected value at 85°C; therefore they cannot be used for modelling calculations

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Table 3-6 - Example 7: Generic Model Parameters of the Transformer

Type	Parameters in Per Unit	Parameters in SI Units[1]
Windings' leakage impedance	$z_H = 5.975\%$ @ 125 MVA $z_X = 3.735\%$ @ 125 MVA $z_Y = 3.565\%$ @ 125 MVA $z_{H@\,ONAN\,MVA} = z_{H@\,125} \times \frac{150}{125}$ $z_{H@\,ONAN\,MVA} = 7.17\%$ $z'_{X@\,ONAN\,MVA} = 4.482\%$ $z'_{Y@\,ONAN\,MVA} = 4.278\%$	$Z_{b\,H} = \frac{V_{H\,rated}^{2}}{S_b} = \frac{240^2}{150} = 384\ \Omega$ $Z_H = z_H \times Z_{H-base} = 27.533\Omega$ $Z'_X = z_X \times Z_{H-base} = 17.21\Omega$ $Z'_Y = z_Y \times Z_{H-base} = 16.43\Omega$ Verification: $Z_{H-X\|\|Y} = Z_H + Z'_X\|\|Z'_Y = 35.938\ \Omega$ From full load-losses test: $Z_{H-X\|\|Y} = 36.162\ \Omega$
Magnetizing branch admittance	$y = \frac{I_{exe}\%}{100} \times \frac{250}{150} = 0.04\%$@ ONAN MVA $y = 4E-4$ pu	$Y_H = \frac{y}{Z_{H-base}} = 1.042E-6\ ℧$ or $Z_{b\,X} = \frac{V_{X\,rated}^{2}}{S_b} = \frac{20^2}{150} = 2.667\ \Omega$ $Y_X = \frac{y}{Z_{X-base}} = 1.5E-4\ ℧$ or
No-Load losses equivalent conductance	$g = \frac{P_{NL}}{MVA_{NLTest} \times 1000} \times \frac{250}{150}$ @ONAN MVA $g = 3.173E-4pu$ @ ONAN MVA	$G_H = \frac{P_{OC}}{V_{OC}^{2}} = \frac{P_{NL}}{V_{H\,rated}^{2}} = 8.263E-7\ ℧$ $G_X = \frac{P_{NL}}{V_{X\,rated}^{2}} = 1.19E-4\ ℧$
Magnetizing branch susceptance	$b = -\sqrt{y^2 - g^2} = 2.4356E-4\ pu$	$B_H = -\sqrt{Y_H^{\,2} - G_H^{\,2}} = -6.34E-7\ ℧$
Zero-Sequence parameters	$z_0 = z_{H0} + z_{M0} = 8.2\%@125MVA$ $z_{0@\,ONAN} = z_{H0@\,125} \times \frac{150}{125}$ $z_{0@\,ONAN} = 0.082 \times \frac{150}{125} = 0.0984$ pu	$Z_{H0} = z_{0@\,ONAN} \times Z_{b\,H}$ $Z_{H0} = 0.0984 \times 384 = 37.78\ \Omega$ $Z_{H0} = 2.81 + j37.6\ \Omega$

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3.6 Three-Winding Transformers with Delta Primary, Wye Secondary, and Wye Tertiary

In practical applications, the low-voltage side windings should be grounded through a resistance or reactance to limit the earth fault currents. This connection type is usually used in double-secondary transformers, which means that both low-voltage windings are identical. As can be seen in the nameplate information of Example 8 in Section 3.6.4, they have the same ratings.

3.6.1 Three-Winding D-y-y Transformer: Positive and Negative Sequence Generic Model

The generic model of a three-phase three-winding D-y-y transformer for positive and negative sequence is similar to that of a single-phase three-winding transformer, as shown in Figure 3-3. The three leakage impedances are obtained from three load-losses test measurements through the equation given in Table 3-1.

3.6.2 Three-Winding D-y-y Transformer: Procedure to Determine Generic Model Parameters

The procedure to model a three-phase three-winding D-y-y transformer in positive or negative sequence is the same as the single-phase transformer procedure described in Section 3.2.4, except that the zero-sequence should be determined. The next section describes how the zero-sequence equivalent circuit of a three-winding D-y-y transformer is modelled.

In practice, the three positive-sequence leakage impedances obtained from three load-losses tests between the pair of windings are reported directly in the test reports.

3.6.3 Three-Winding D-y-y Transformer: Zero-Sequence Equivalent Circuit

The zero-sequence equivalent circuit of a D-y-y-connected transformer depends on whether the neutral points have been grounded or not. It is assumed that the both low-voltage neutral points have been grounded; therefore, the zero-sequence equivalent circuit is as shown in Figure 3-13.

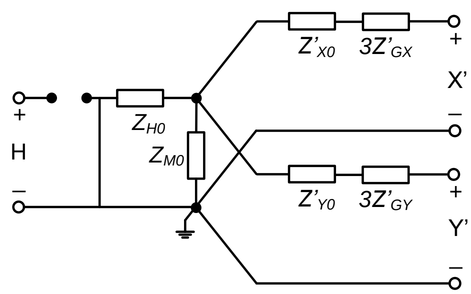

Figure 3-13- Zero-sequence equivalent circuit of a grounded D-y-y-connected transformer

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3.6.4 Example 8: A Practical Three-Winding D-y-y Transformer

Figure 3-14 shows the nameplate information of a 18.5/2.4/2.4 kV, 18/24 MVA three-winding Dy1y1 connected transformer. The test reports for this transformer are shown in Figure 3-15. The required information to model the transformer is extracted from the test report and listed in Table 3-7. Table 3-8 shows the calculation of the T-model equivalent circuit impedances. Both neutral points have been solidly grounded (the practical ground impedances are not available; therefore impedance = 0).

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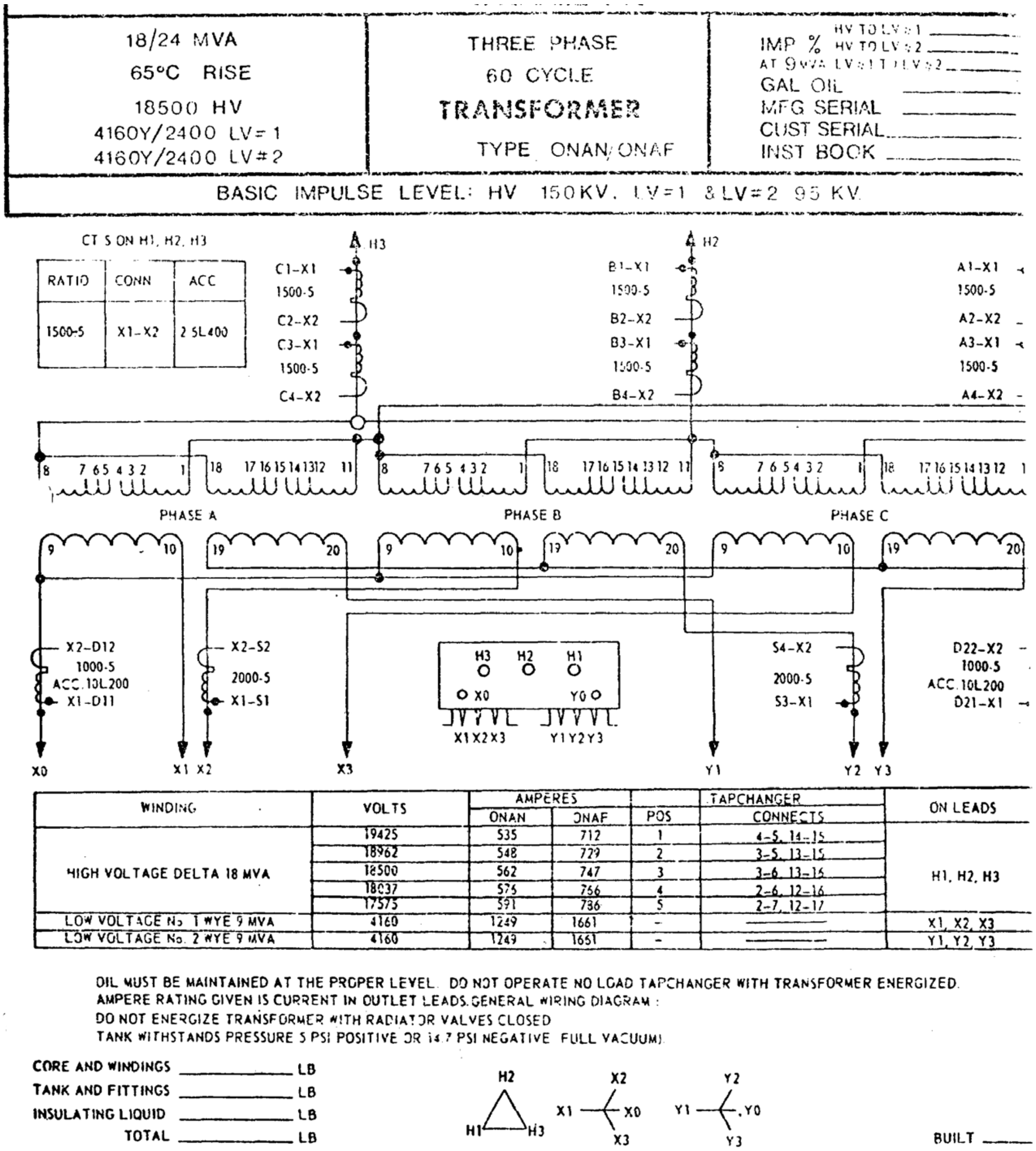

WINDING	VOLTS	AMPERES ONAN	AMPERES ONAF	POS	TAPCHANGER CONNECTS	ON LEADS
HIGH VOLTAGE DELTA 18 MVA	19425	535	712	1	4-5, 14-15	H1, H2, H3
	18962	548	729	2	3-5, 13-15	
	18500	562	747	3	3-6, 13-16	
	18037	575	766	4	2-6, 12-16	
	17575	591	786	5	2-7, 12-17	
LOW VOLTAGE No. 1 WYE 9 MVA	4160	1249	1661	-		X1, X2, X3
LOW VOLTAGE No. 2 WYE 9 MVA	4160	1249	1661	-		Y1, Y2, Y3

OIL MUST BE MAINTAINED AT THE PROPER LEVEL. DO NOT OPERATE NO LOAD TAPCHANGER WITH TRANSFORMER ENERGIZED.
AMPERE RATING GIVEN IS CURRENT IN OUTLET LEADS. GENERAL WIRING DIAGRAM:
DO NOT ENERGIZE TRANSFORMER WITH RADIATOR VALVES CLOSED
TANK WITHSTANDS PRESSURE 5 PSI POSITIVE OR 14.7 PSI NEGATIVE (FULL VACUUM)

CORE AND WINDINGS ______ LB
TANK AND FITTINGS ______ LB
INSULATING LIQUID ______ LB
TOTAL ______ LB

BUILT ____

Figure 3-14- Example 8: Transformer nameplate information

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Purchaser
Test APRIL 1973 Purchaser's Order No. G.O. S.O. No. 3-S-7248
ONAN/ONAF Phase 3 Cy. 60 Insulating Fluid OIL L.Spec. Polarity SUBT

Winding H.V.	Winding L.V. #1	Winding L.V. #2
Kva 18000/24000	Kva 9000/12000	Kva 9000/12000
Voltage 18500 DELTA	Voltage 4160 WYE	Voltage 4160 WYE

RESISTANCES, EXCITING CURRENT, LOSSES AND IMPEDANCE – Based on normal rating, unless otherwise stated. Losses and regulation are based on wattmeter measurements. For three-phase transformers the resistances are the sum of the three phases in series. Pos. #1

SERIAL NO.	RESISTANCE IN OHMS AT 75°C WINDINGS			% EXCITE CURRENT AT 100% RATED VOLTAGE	NO LOAD LOSS WATTS AT 100% RATED VOLTAGE	18.5 Kv TO 4.16 * Kv 18000 Kva		18.5 Kv TO 4.16* Kv 24000 Kva		TO	
	H.V.	LV#1	LV #2			LOAD LOSS WATTS 75°C	% IMP 75°C	LOAD LOSS WATTS 75°C	% IMP 75°C	LOAD LOSS WATTS 75°C	% IMP 75°C
A-3-S-7248	0.359	0.0108	0.01087	0.69	16500	80000	6.7	143800	8.9	*LV#1 & LV#2	
						Total Loss	% Imp 75°C	Total Loss	% Imp 75°C	Total Loss	% Imp 75°C
AVERAGE					16500	96500	6.7	160200	8.9		
GUARANTEE					18000	108000	6.5	178000			

REGULATION AT 75°C		100% PF	% PF	80% PF	% PF
	AVERAGE				
	GUARANTEE				

TEMPERATURE RISES – Average rise in degrees C., corrected to instant of shutdown, of transformer.
Serial No. A-3-S-7248 with windings connected and loaded as follows:
HV Winding 17.575 Kv 591 Amp.: LV #1 Winding 4.16 Kv 1249 Amp.
LV#2 Winding 4.16 Kv 1249 Amp. until constant temperature rise was reached.

	RISE OF WINDINGS BY RESISTANCE				TOP FLUID RISE	AMBIENT TEMP.		WATER		
	H.V.	L.V.#1	L.V.#2	GUARANTEE		INGOING WATER	IDLER OR ROOM	RISE	GALLONS PER MIN.	POUNDS PRESSUR
ONAN	51	59.0	47.8	65	49.3					
ONAF	54.9	60.3	55.8	65	45.6					

INSULATION TESTS	WINDING	VOLT RATING	TEST VOLTAGE APPLIED IN Kv	DURATION OF TEST IN SECONDS
APPLIED POTENTIAL TESTS (Voltage applied between each winding and all other windings connected to core and ground.)	H.V.	18500	50	60
	L.V.#1	4160	26	60
	L.V.#2	4160	26	60

INDUCED POTENTIAL TEST: Two times rated voltage ~~across full winding~~; Kv from Kv
Line terminal to ~~ground~~ line; at 180 cycles per second for 7200 cycles

REMARKS
NAMEPLATE #206P454
% IMPEDANCE BETWEEN H.V.-L.V.#1 = 6.45
H.V.-L.V.#2 = 6.50
L.V. #1 - L.V. #2 = 12.78
} based on 9 MVA

We hereby certify that this is a true report based on factory tests made in accordance with the latest Transformer Test Code C57.2 of the American Standards Association and that each transformer withstood the above insulation tests.

Signed Date May 22, 1973 Approved

Page ___ of ___ Pages

Figure 3-15- Example 8: Transformer test results

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Table 3-7- Information Required for Modelling the Transformer of Example 8

Item	Transformer Parameter	Symbol	Values
General			
1	Transformer ONAN Ratings	MVA_{ONAN}	18 MVA
2	Winding Voltages (primary, secondary, …)	V_H, V_X, V_Y, … V_P, V_S, … V_1, V_2, …	18.5kV/2.4kV/2.4kV
3	Connection type	-	Dyy
4	Tap range	t_1, t_2, …	± 30%
5	Number of tap steps	-	5 (OCTC)
6	Winding with an adjustable tap	-	Primary (high) side
7	Phase angle of windings	θ_1, θ_2, θ_3…	30°,30°
No Load Loss Test Results			
8	No-load loss test MVA	$MVA_{NL\ Test}$	-
9	No-load loss	P_{NL}	16.5 kW
10	Excitation current	$\%I_{exc}$	0.69 A
11	Tap setting for no-load loss test	t_{NL}	Nominal
Load Loss Test Results			
12	Load loss test MVA	$MVA_{SC\ Test}$, …	(H-X+Y @ 18MVA)
13	Load loss	$P_{SC,}$ $P_{LL\_HX, \ldots}$	80 kW
14	Impedance (Voltage)	I_Z, or Z_{HX}, …	6.7%
15	Reactance	I_X, or X_{HX}, …	Not reported
16	Tap setting for load loss test	t_{SC}	Nominal (13)
17	Positive-sequence impedance between Pair Windings	H-X, H-Y, X-Y @MVA	6.45%, 6.50%, 12.78% @ 9MVA
Zero-Sequence Test Results			
18	Zero-sequence open circuit test results	Z_1, Z_2	-
19	Zero-sequence short circuit test results	Z_3	-
20	Zero-sequence T-model parameters	Z_{H0}, Z'_{X0} Z_{M0} for the T-model	-
21	Zero-sequence impedances between Pair Windings	$Z_{H\text{-}X\ 0}$, $Z_{H\text{-}Y\ 0}$, for the T-model	-
22	Grounding configuration	Windings neutral point grounding method	Solidly grounded
23	Grounding Impedance	Z_{GX}, Z_{GY}, …	0 Ω reactance

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Table 3-8- Example 8: Generic Model Parameters of the Transformer

Type	Parameters in Per Unit	Parameters in SI Units[1]
Windings' leakage impedance	$z_H = \frac{z_{H-X}+z_{H-Y}-z_{X-Y}}{2} = 0.0017$ $z_X = \frac{z_{H-X}-z_{H-Y}+z_{X-Y}}{2} = 0.1273$ $z_Y = \frac{-z_{H-X}+z_{H-Y}+z_{X-Y}}{2} = 0.1283$ @ 18MVA	$Z_b = \frac{{V_{rated}}^2}{S_b} = \frac{18.5^2}{18}$=19.014 Ω $Z_H = z_H \times Z_{Z_{H-base}} = 0.0323\Omega$ $Z'_X = z_X \times Z_{H-base} = 2.42\Omega$ $Z'_Y = z_Y \times Z_{Z_{H-base}} = 2.44\Omega$ Verification: $Z_{H-X\|\|Y} = Z_H + Z'_X \|\| Z'_Y = 1.2473\ \Omega$ From full load-losses test: $Z_{H-X\|\|Y} = 1.274\ \Omega$
Magnetizing branch admittance	$y = \%I_{exc.}/100 = 0.0069$ *pu*	$Y_H = \frac{I_{OC}}{V_{OC}} = 3.63E-4$ ℧ or
No-Load losses equivalent conductance	$g = \frac{P_{NL}}{MVA_{NL\,Test} \times 1000} = 0.00092$ *pu*	$G_H = \frac{P_{OC}}{{V_{OC}}^2} = \frac{P_{NL}}{{V_{H\,rated}}^2} = 4.821E-5$ ℧
Magnetizing branch susceptance	$b = -\sqrt{y^2 - g^2} = -0.0068$ *pu*	$B_H = -\sqrt{{Y_H}^2 - {G_H}^2} = -3.6E-4$ ℧
Zero-Sequence parameters (Based on assumptions)	$z_{H0} = 0.85 \times z_H$ $z'_{X0} = 0.90 \times z'_X$ $z'_{Y0} = 0.90 \times z'_Y$ $z_{M0} = \infty$	

3.7 Three-Winding Transformers with Delta Primary, Wye Secondary, and Delta Tertiary

The tertiary winding in this type of connection is not provided to supply a considerable amount of load; it might be used for a local small load such as substation lighting. In practice, if the VA rating of the delta-connected tertiary winding is significantly less than the VA rating of the other windings it cannot be considered as a single winding in modelling. Even in practice, it is not recognized as a three-winding transformer by practical engineers. However, the zero-sequence current can flow through this winding. Therefore, the tertiary winding should withstand the zero-sequence fault current if one of the other windings is a grounded Y connection. For example, Figure 3-16 shows the nameplate information of a D-y-d-connected transformer. It is a 5.76 MVA 20 kV/900 V distribution transformer. This transformer does not have a test results report, but the impedances have been provided on the transformer nameplate. These parameters can be used to obtain the positive-sequence equivalent circuit. The zero-sequence equivalent circuit of this transformer depends on whether the neutral point of the secondary winding is grounded or not. If it has been grounded, the zero-sequence equivalent circuit is only one impedance from the secondary terminal and is an open circuit from the other terminals (See line 24 in Table 1-2). Since the zero-sequence test results are not available, the transformer can be considered as a two-winding transformer with Delta-wye connected (See Section 2.7)

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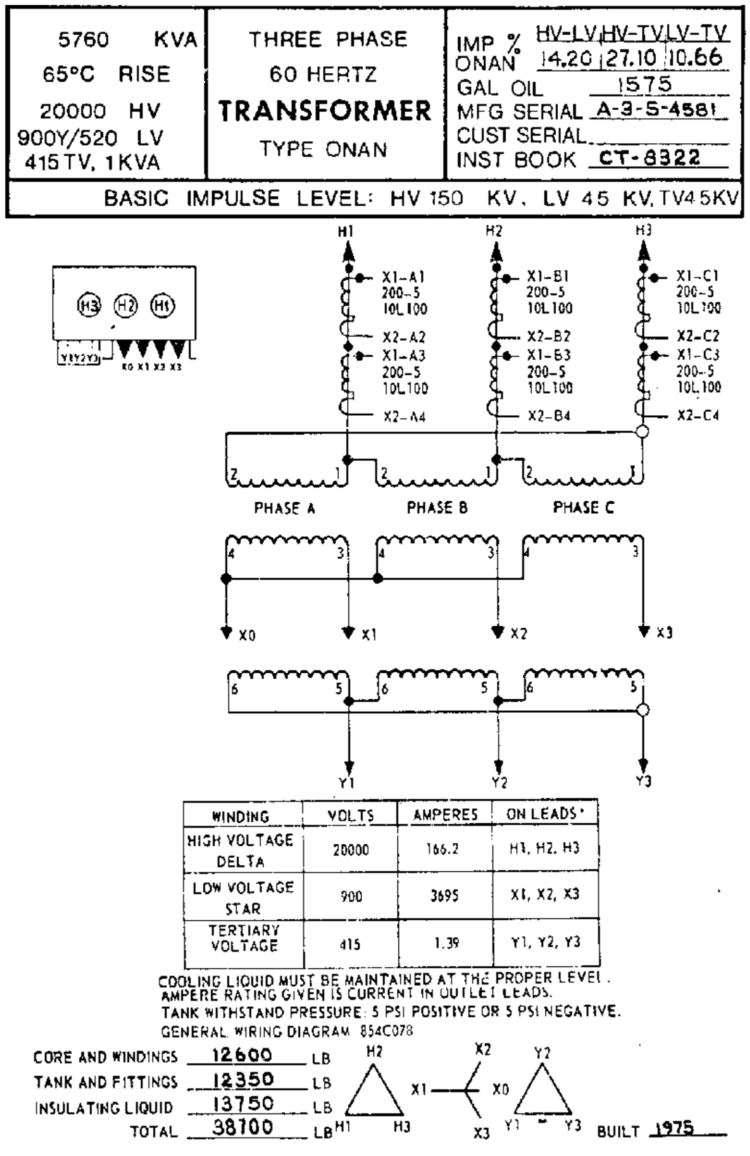


Figure 3-16- Transformer nameplate, no test results for this transformer

3.8 Three-Winding Autotransformers: Autotransformers with Tertiary Winding (Wye-wye with Delta Tertiary)

Power autotransformers usually have a delta-connected tertiary winding to reduce third-harmonic voltage to permit the transformation of unbalanced three-phase loads. Figure 3-17 shows the schematic transformer diagram, vector representation, vector diagram, and phase displacement vector diagram of an autotransformer with a delta-connected tertiary winding.

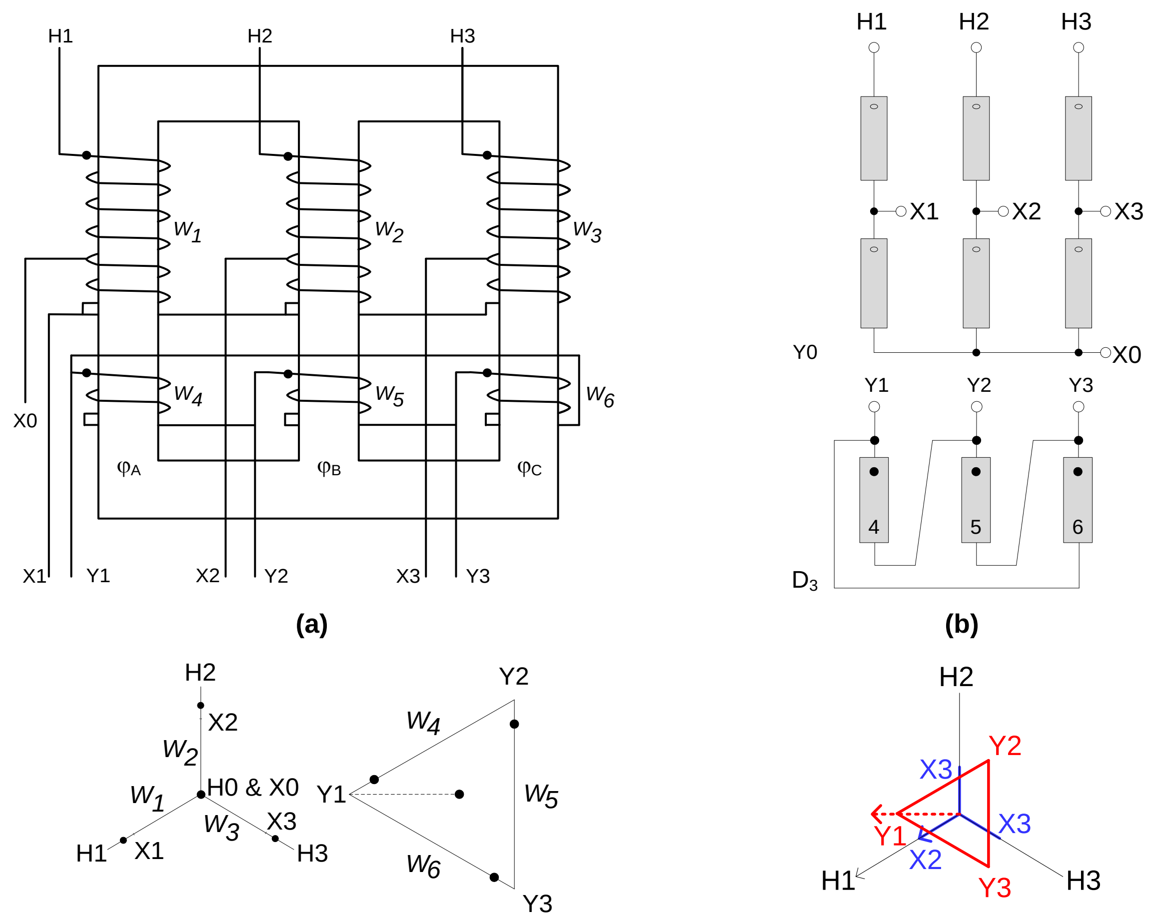


Figure 3-17- Autotransformer with delta tertiary: a) Schematic transformer diagram, b) Winding connection diagram, c) Vector diagram, d) Phase displacement vector diagram

The tertiary winding sometimes supplies the station auxiliary loads or power factor improvement equipment. If loading of the tertiary winding is not required, the winding terminals should not be brought out. However, one "corner" of the delta may be brought out so that it may be grounded if this will supply a current path to ground during ground faults. Another alternative is to bring the two-winding "ends" out and make the corner of the delta outside the tank. This arrangement allows the resistance of the delta to be measured during maintenance [10].

3.8.1 Autotransformer with Delta-Connected Tertiary Winding: Positive and Negative Sequence Generic Model

The generic model of an autotransformer with a delta-connected tertiary winding for positive and negative sequence is similar to that of a single-phase three-winding transformer, as shown in Figure 3-3.

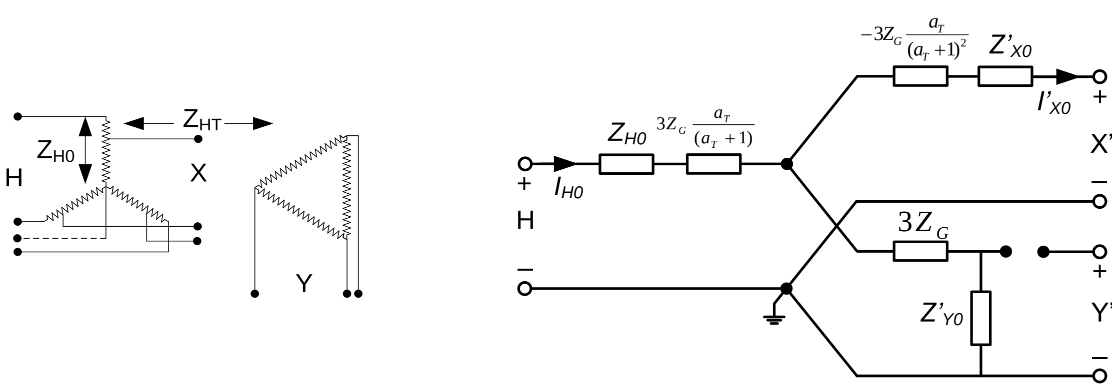
3.8.2 Autotransformer with Delta-Connected Tertiary Winding: Procedure to Determine Generic Model Parameters

The procedure to model an autotransformer with a delta-connected tertiary winding in positive or negative sequence is same as the single-phase transformer procedure described in Section 3.2.4, except that the zero-sequence should be determined. The next section describes how the zero-sequence equivalent circuit of an autotransformer with delta-connected tertiary winding is modelled.

3.8.3 Autotransformer with Delta-Connected Tertiary Winding: Zero-Sequence Equivalent Circuit

The zero-sequence equivalent circuit of an autotransformer is described in Section 2.8.3. The neutral point of autotransformers is usually grounded without grounding impedance.

The zero-sequence equivalent circuit of a three-winding autotransformer, as shown in Figure 3-18, is similar to the zero-sequence equivalent circuit of a grounded Y-y-d-connected three-winding transformer, except for the neutral point grounding impedance effect on the parameters. As described in Section 2.8.3, if the neutral point is grounded through a grounding impedance, this impedance appears as an impedance $3Z_G \frac{a_T}{a_T+1}$ in the high-voltage side of an auto-connection and as a negative impedance $3Z_G \frac{a_T}{(a_T+1)^2}$ in the low- voltage side of auto-connection. The grounding impedance also appears as an impedance $3Z_G$ in the series with tertiary winding zero-sequence impedance. When the neutral is ungrounded, $Z_G = \infty$ and the impedances of the equivalent star also become infinite because there are apparently no paths for zero sequence currents between the windings although a physical circuit exists and an ampere-turn balance can be obtained. The zero-sequence model of a three-winding autotransformer is also similar to its positive sequence model. The explanations and equation of the positive-sequence model are valid for the zero-sequence model as well.



a) Connection type **b) T-Model**

Figure 3-18- Zero-Sequence equivalent circuits of an autotransformer with delta-connected tertiary

3.8.4 Example 9: A Practical Three-Winding Autotransformer, (Yy Connected Autotransformer with Delta Tertiary Winding)

Figure 3-19 shows the nameplate information of a 132/72 GRD/4.16 kV, 18.750/25 MVA three-winding autotransformer with delta-connected tertiary winding. The neutral point of autotransformer is solidly grounded. The schematic diagram and vector diagram of this type transformer are shown in Figure 3-17. Nominal voltage of the primary is 132 kV. It has two 5-steps on-load tap changer in the midpoint terminal. Figure 3-20 shows the transformer test report. The tertiary winding cannot be loaded simultaneously with auto-connected low-voltage windings. Therefore, the full-load losses test has been conducted between autotransformer terminals in nominal voltages while the tertiary windings terminals are open circuit. The information required to determine the generic model parameters extracted from the test report are shown in Table 3-9 . The calculated parameters for the generic model are shown in Table 3-10.

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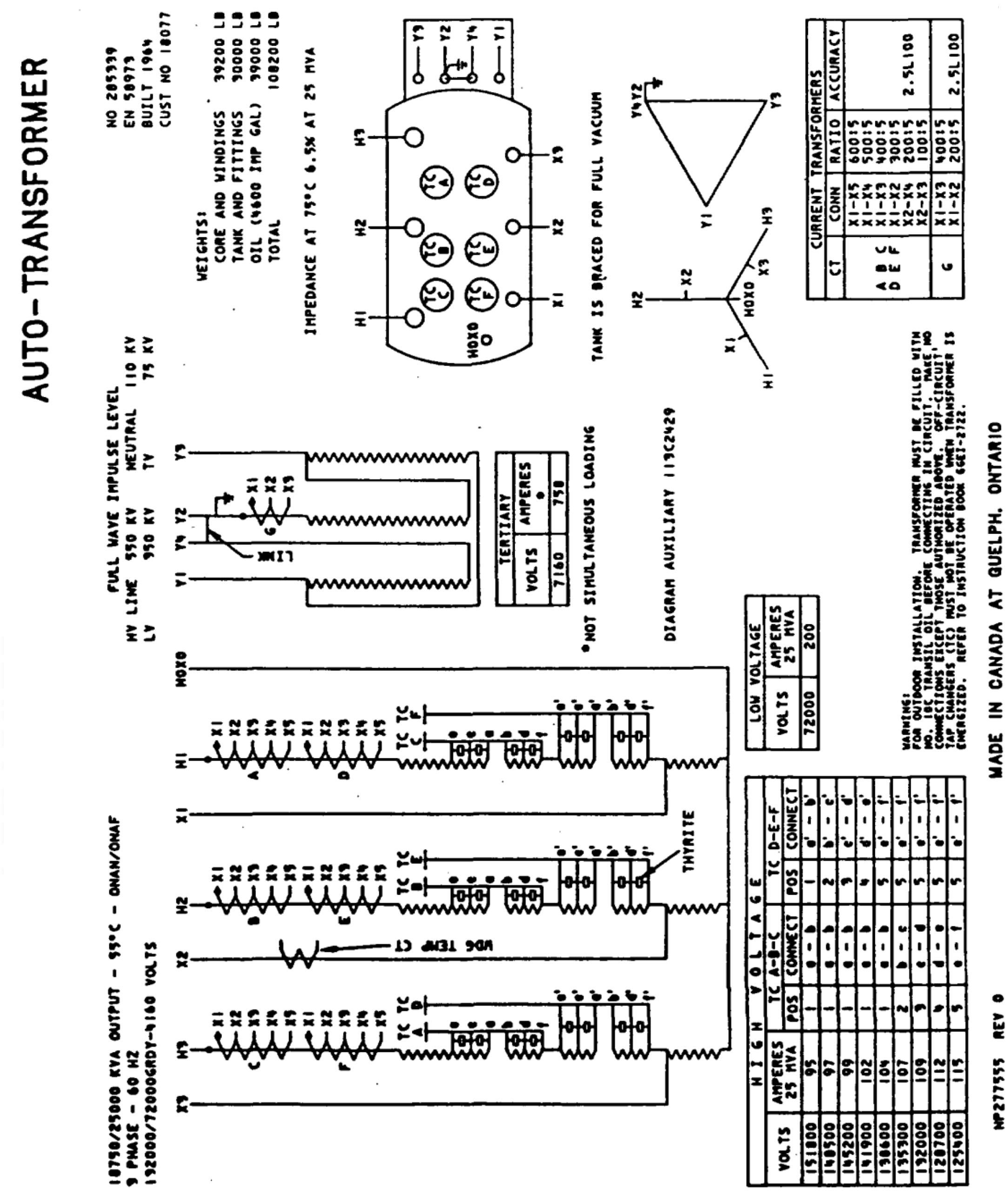

Figure 3-19- Example 9: Three-Winding autotransformer nameplate information

RECORD OF TRANSFORMER TESTS

Rating 18750 KVA OUTPUT-55C-ONS-3-60-132/72 KV GRD.Y-4160

Customer

r. Notice — S.O. — Reg. No.

Serial Numbers					Guarantees
NO-LOAD LOSSES	Volts	4160			
Connection	Amps.	10.1			
13200-(4160)	K.W.	21.55			
	Temp. °C.	75			
LOAD LOSSES	Volts	3532 = 4.91%	MAX. IMPEDANCE		6% MAX.
Connection	Amps.	150	AT 151.8 KV -5.21%		
132000-(72000)	K.W.	48.46			
	TOTAL LOSS AT 75C	70.01			
RESISTANCE	H.V. Conn. 132 KV	2.615			
between terminals	L.V. Conn.	2.125			
at 75° C	Tertiary				
EFFICIENCY	5/4 Load IMPEDANCE	H.V. TO T.V.	11.9 % AT 18750	KVA	
Based On	4/4 Load				
	3/4 Load IMPEDANCE	L.V. TO T.V.	5.4 % AT 18750	KVA	
	2/4 Load				
	1/4 Load				
FULL LOAD	100% P.F.		ZERO	SEQUENCE IMPEDANCE	
REGULATION at	% P.F.				
				X-T 5.21%	
HEAT RUN		ONS		X-H//T 2.20%	
% Load		100		H-T 10.00%	
Gals. Water per Minute				H-X//T 4.25%	
Hours Run		50			
TEMPERATURE	Idler Oil	25.1			
°C	Water In				
	Water Out				
OIL RISE BY THERMOMETER		39.9			
RISE BY R.M.	H.V. Coils	41.1			55°C
	L.V. Coils	42.7			55°C
	Tertiary				

INSULATION TEST

H.V. to L.V., Tertiary and Core	34000	Volts	1	Minutes
L.V. to Tertiary and Core		Volts		Minutes
Tertiary to Core	19000	Volts	1	Minutes
Induced Voltage 230 KV AT H.V. TERM.	Times Normal	7200 CYC.		Minutes

Date Reported 18 JUNE 64 — Certified Correct

Approved By

CM 240

Figure 3-20- Example 9: Three-Winding autotransformer test results

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Table 3-9- Information Required for Modelling the Transformer of Example 9

Item	Transformer Parameter	Symbol	Values
General			
1	Transformer ONAN Ratings	MVA_{ONAN}	18.75 MVA
2	Winding Voltages (primary, secondary, …)	V_H, V_X,… V_P, V_S, … V_1, V_2, …	132 kV/72 kV/4.16 kV
3	Connection type	-	Auto+delta
4	Tap range	t_1, t_2, …	± 50%
5	Number of tap steps	-	10
6	Winding with an adjustable tap	-	Auto Midpoint
7	Phase angle of windings	θ_1, θ_2, …	0°, 30°
No Load Losses Test Results			
8	No-load losses test MVA	$MVA_{NL\ Test}$	18.75 MVA
9	No-load losses	P_{NL}	21.55 kW
10	Excitation current	I_{exc}	10.1A From Tertiary
11	Tap setting for no-load loss test	t_{NL}	Nominal
Load Losses Test Results			
12	Load loss test MVA (H to X)	$MVA_{SC\ Test}$, …	18.75 MVA
13	Load loss	P_{SC}, P_{LL_HX}, …	48.46 kW
14	Impedance or Applied Voltage	I_Z, or Z_{HX}, … V_{Test} (Phase)	(Max 5.21% @151.8kV) 3532 (=4.91 %)
15	Reactance	I_X, or X_{HX}, …	Not reported
16	Tap setting for load loss test	t_{SC}	Nominal
17	Positive-sequence impedance between Pair Windings	H-X, H-Y, X-Y @MVA	4.91%, 11.9%, 5.4% @ 18.75MVA
Zero-Sequence Test Results			
18	Zero-sequence open circuit test results	Z_1, Z_2	-
19	Zero-sequence short circuit test results	X-Y, X-H||Y H-Y, H-X||Y	5.21%, 5.20% 10.00%, 4.25% (assumed @ 18.75MVA)
20	Zero-sequence T-model parameters	Z_{H0}, Z'_{X0} Z_{M0} for the T-model	-
21	Grounding configuration	Solidly Grounded	0 Ohm
22	Grounding Impedance	Z_{GH}, Z_{GX}, …	-

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Table 3-10- Example 9: Generic Model Parameters of the Transformer

Type	Parameters in Per Unit	Parameters in SI Units[1]
Load losses test equivalent impedance	$z_{H-X} = \frac{Z_{H-X}}{Z_{H\,base}} = \frac{\frac{V_{SC}}{\sqrt{3}\times I_{SC}}}{\frac{V_{H\,rated}^2}{MVA_{rated}}}$ $z_{H-X} = 4.91\%$ $r_{H-X} = 0.002584\text{pu}$ $x_{H-X} = \sqrt{z_{H-X}^2 - r_{H-X}^2}$ $x_{H-X} = 0.049\text{pu}$	$Z_{H-X} = \frac{V_{SC\_Phase}}{I_{SC\_Phase}} = \frac{3532}{82.012} = 43.067\Omega$ Verification: $z_{H-X} = \frac{43.067}{929.28} = 4.63\%$ (In the report it is 4.91%) then $Z_{H-X} = 45.63\Omega$ $R_{H-X} = \frac{P_{SC}}{3\times I_{SC_{Phase}}^2}$ $R_{H-X} = \frac{48.46\times 1000}{3\times 82.012^2} = 2.402\Omega$ $X_{H-X} = \sqrt{Z_{H-X}^2 - R_{H-X}^2} = 45.56\Omega$
Windings' leakage impedance	$z_H = \frac{z_{H-X}+z_{H-Y}-z_{X-Y}}{2} = 0.05705$ $z'_X = \frac{z_{H-X}-z_{H-Y}+z_{X-Y}}{2} = -0.00795$ $z'_Y = \frac{-z_{H-X}+z_{H-Y}+z_{X-Y}}{2} = 0.06195$	$Z_{H-base} = \frac{V_{rated\,H}^2}{S_b} = \frac{132^2}{18.75} = 929.28\Omega$ $Z_H = z_H \times Z_{Z_{H-base}} = 53.015\Omega$ $Z'_X = z_X \times Z_{H-base} = -7.39\Omega$ $Z'_Y = z_Y \times Z_{Z_{H-base}} = 57.57\Omega$
Magnetizing branch admittance	$Z_{H-base} = \frac{V_H^2}{MVA_{ONAN}} = 929.28\ \Omega$ $y = Y_H \times Z_{H-base} = 0.00672\ pu$ $y = \%I_{exc.}/100 = 0.672\ \%$	$Y_Y = \frac{I_{OC}}{V_{OC\,Ph}} = 0.00728\ \mho$ $Y_H = 7.2305E-6\ \mho$
No-load losses equivalent conductance	$g = \frac{P_{NL}}{MVA_{NL\,Test}\times 1000} = 0.001149pu$	$G_Y = \frac{P}{V_{OC}^2} = 0.001245\ \mho$ $G_H = \frac{g}{Z_H} = 1.2364E-6\mho$
Magnetizing branch susceptance	$b = -\sqrt{y^2 - g^2} = -0.00662\ pu$	$B_H = -\sqrt{Y_H^2 - G_H^2} = -7.124E-6\ \mho$
Zero-sequence parameters	$z'_{X-Y0} = z'_{X0} + z'_{Y0} = 5.21\%$ $z'_{X-H\|\|Y0} = z'_{X0} + z_{H0}\|\|z'_{Y0} = 2.2\%$ $z_{H-Y0} = z_{H0} + z'_{Y0} = 10\%$ $z_{H0} = 4.51\%$ $z'_{X0} = -0.273\%$ $z'_{Y0} = 5.486\%$ Verification : $z_{H-X\|\|Y0} = 4.25\%$ $z_{H-X\|\|Y0} = z_{H0} + z'_{X0}\|\|z'_{Y0} = 4.223\% \approx 4.25\%$ @ primary	$Z_{H0} = 41.91\Omega$ $Z'_{X0} = -2.54\ \Omega$ $Z'_{Y0} = 50.98\ \Omega$

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4 Determination of the Low-Frequency Parameters of Four-Winding Transformers

Multi-Winding transformers with more than two windings coupled to the same core are used in power and distribution systems for a variety of purposes. In some cases, such as interconnecting three or more circuits with different voltages or isolating two or more secondary circuits, a multi-winding transformer may be less costly and more efficient than a number of two-winding transformers. The use of multi-winding transformers is discussed in Sections 1.11 and 3.1. Four-winding transformers are used only as rectifier transformers or (sometimes) in SVC or Statcom systems.

A four-winding transformer coupled to the same core is a special type of multi-winding transformer. It is not commonly used because of the interdependence of the voltage regulation of each winding to the loading on the other windings. Sometimes a four-winding transformer is preferred to two single transformers. The quaternary (fourth) winding usually plays the role of a tertiary delta-connected winding when it is connected as delta. It might also supply some auxiliary loads in the substation.

Figure 4-1 shows the schematic diagram of a four-winding transformer wound around a core. In three-phase transformers, four windings of each phase are wound around the same leg. In multi-winding transformers it is not common to label a winding as primary, secondary, etc., but such labeling helps distinguish between the windings. The MVA rating of a high-voltage winding is usually higher than the MVA rating of other windings; thus it is conventionally called the primary. The secondary and tertiary (third) windings are usually at the same MVA rating, which may be half the MVA rating of the primary winding. Therefore, in practice, the primary and secondary windings may be known, respectively, as the first secondary and the second secondary. In this guide, they are considered as the secondary and tertiary (third) windings because separate circuits should be assigned for each winding in modelling.

For a four-winding transformer the ideal conditions are:

$$\frac{E_H}{N_H} = \frac{E_X}{N_X} = \frac{E_Y}{N_Y} = \frac{E_Z}{N_Z}$$
$$E_H I_H = E_X I_X + E_Y I_Y + E_Z I_Z$$

The pervious equation means that the net power into a four-winding ideal transformer is zero.

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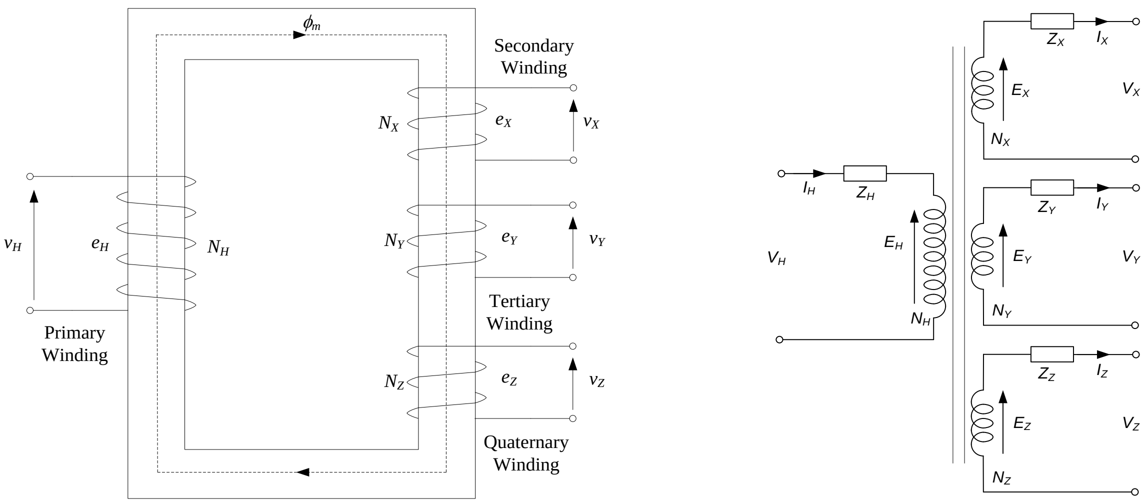

(a) **(b)**

Figure 4-1- Schematic diagrams of a single-phase transformer with four windings: a) Windings diagram, b) Electrical diagram

4.1 The Equivalent Circuit for a Four-Winding Transformer

The equivalent circuit for a four-winding transformer is more complicated than that of a three-winding transformer, and involves a complex circuit of six different impedances. In recent years, various modelling approaches have been proposed to characterize transformer winding behaviour and its dependence on frequency and geometry effects. In this guide, only one model is described, the π-model equivalent circuit.

4.1.1 The Positive-Sequence Equivalent Circuit for a Four-Winding Transformer

An N-winding transformer can be modelled in low frequency operations (non-transient model) as an N-loop linear element circuit electromagnetically coupled to all other loops. Due to the low-frequency modelling the winding capacitances are neglected. The T-model equivalent circuit of a multi-winding transformer with N windings is shown in Figure 3-2. When there are more than three windings (circuits), transformers cannot, in general, be represented by a pure star- or mesh-equivalent circuit. The equivalent circuit should have $\mathrm{N(N-1)/2}$ independent impedance links. Therefore, the T-model equivalent circuit is not considered for four-winding transformers. The π-model equivalent circuit of a four-winding transformer is shown in Figure 4-2-a and Figure 4-2-b with and without magnetizing, respectively. The approximate equivalent circuit can be obtained if the magnetizing branch is neglected. This model, known as the extended cantilever model (ECM), is shown in Figure 4-2-b [15]. The equivalent circuit presented in Figure 4-2-a is an over-determined model used only in special cases.

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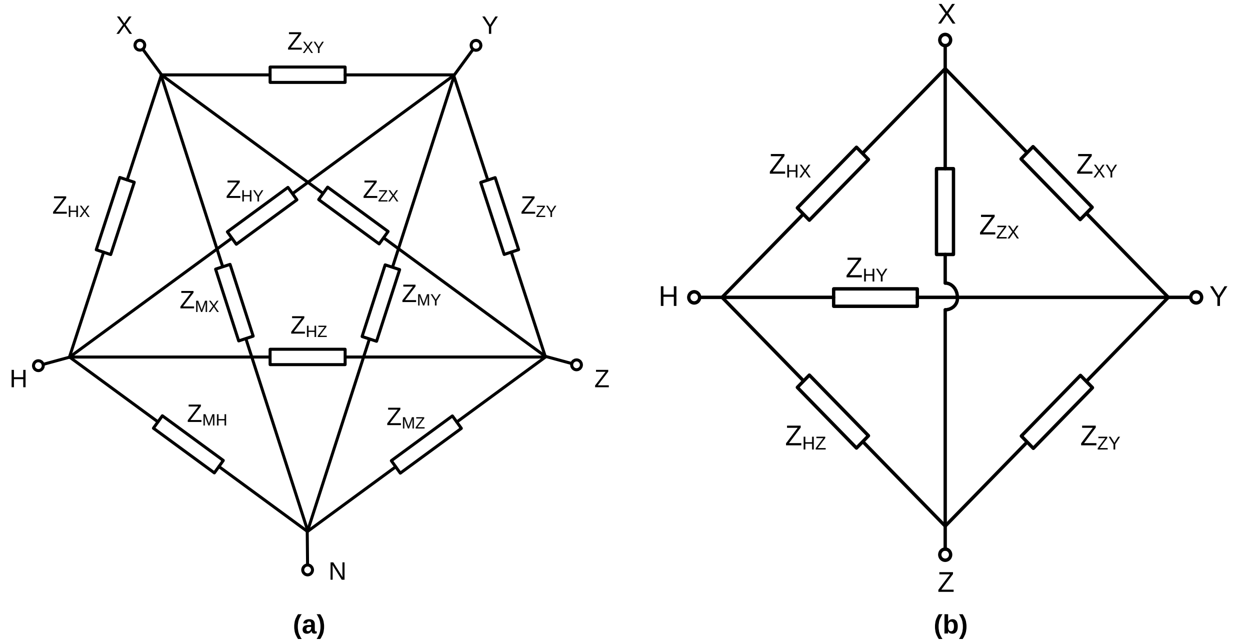

Figure 4-2- The π-model equivalent circuit of one phase of a four-winding transformer: a) With magnetizing branch, b) Without magnetizing branch (Extended cantilever model)

As mentioned in Section 3, the equivalent circuit parameters of multi-winding transformers can be extracted from short-circuit test measurements between different pairs of windings. In practice, the measured impedances between all pairs of windings are reported based on the lowest MVA rating of the two windings because the short-circuit test is conducted at the full-load MVA rating of the winding. The full-load losses test of a transformer should be conducted and the results should be reported on the summary test report. If the MVA rating of the primary is the sum of the secondary and tertiary MVA ratings and if it is equal to the ONAN MVA rating of transformer, in the secondary and tertiary windings the terminals are short-circuited while the primary winding is excited to flow the rating current in all three windings. In this case another short-circuit test should be conducted based on the quaternary winding MVA rating. Table 4-1 lists eight load losses tests including six tests between a pair of windings and two full-load losses tests: one from the primary winding and another from the auxiliary winding.

However, the effect of the magnetizing current is not taken into account in order to simplify the model, but it can be considered on only one of the winding's terminals. It is usually considered on the high-voltage (primary) winding and the associated no-load losses test is conducted from the high-voltage side according to the test standards.

The extended cantilever model shown in Figure 4-2-b is a more mathematical model. However, this model has six independent impedances, and it seems to be a simple and reasonable model, but calculating impedances from test measurements is not easy. Some impedances may also appear negative, which is the main disadvantage of this model. The negative impedance cannot be explained practically. Therefore, another equivalent circuit has been suggested for four-winding transformers, one that has the advantage of being free from negative elements. This

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equivalent circuit has eight elements, of which only six elements are significantly different. This model is shown in Figure 4-3.

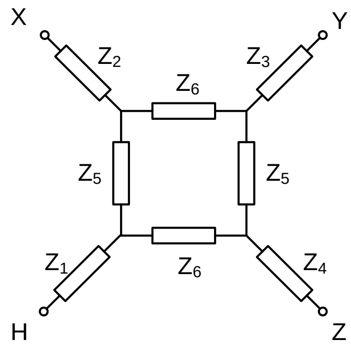

Figure 4-3- Equivalent circuit for four-winding transformers

Table 4-1- List of Load Losses Tests for a Four-Winding Transformer with Equivalent Impedance (According to Equivalent Circuit Shown in Figure 4-3)

	Type of Load Losses Test	@ MVA Winding	Measured Impedance	Equivalent Impedance According to Figure 4-3	Windings Status			
					H	X	Y	Z
1	Between pair of winding	X	Z_{H-X}	$Z_1 + Z_2 + Z_5 \| \| (Z_5 + 2Z_6)$	T	S	O	O
2		Y	Z_{H-Y}	$Z_1 + Z_3 + (Z_5 + Z_6) \| \| (Z_5 + Z_6)$	T	O	S	O
3		Z	Z_{H-Z}	$Z_1 + Z_4 + Z_6 \| \| (2Z_5 + Z_6)$	T	O	O	S
4		Y	Z_{X-Y}	$Z_2 + Z_3 + Z_6 \| \| (2Z_5 + Z_6)$	O	T	S	O
5		Z	Z_{Z-X}*	$Z_2 + Z_4 + (Z_5 + Z_6) \| \| (Z_5 + Z_6)$	O	S	O	T
6		Z	Z_{Z-Y}*	$Z_3 + Z_4 + Z_5 \| \| (Z_5 + 2Z_6)$	O	O	S	T
7	Full-Load from H to X and Y	H	$Z_{H-X\&Y}$	Z_7 (defined below)	T	S	S	O
8	Full-Load from Z to X and Y	Z	$Z_{Z-X\&Y}$*	Z_8 (defined below)	O	S	S	T

T: Excited for the test
S: Short-circuited
O: Open circuit
* These should be converted to the high-voltage side

$$Z_7 = Z_1 + \frac{Z_2 \times Z_3}{Z_2 + Z_3 + Z_6} + \left(Z_5 + \frac{Z_2 \times Z_6}{Z_2 + Z_3 + Z_6}\right) || \left(Z_5 + Z_6 + \frac{Z_3 \times Z_6}{Z_2 + Z_3 + Z_6}\right)$$
$$Z_8 = Z_4 + \frac{Z_2 \times Z_3}{Z_2 + Z_3 + Z_6} + \left(Z_5 + Z_6 + \frac{Z_2 \times Z_6}{Z_2 + Z_3 + Z_6}\right) || \left(Z_5 + \frac{Z_3 \times Z_6}{Z_2 + Z_3 + Z_6}\right)$$

Table 4-1 shows six load-losses tests conducted between six pairs of windings and two full-load-losses tests, one conducted from the high-voltage winding at the transformer MVA rating and one from the auxiliary winding at the auxiliary winding MVA rating. The six independent impedances shown in Figure 4-3 can be obtained by solving the following six linear equations:

$$Z_1 + Z_2 + \frac{Z_5}{2} + \frac{Z_5 \times Z_6}{2(Z_5 + Z_6)} = Z_{H-X}$$

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$$Z_1 + Z_3 + \frac{Z_5}{2} + \frac{Z_6}{2} = Z_{H-Y}$$
$$Z_1 + Z_4 + \frac{Z_6}{2} + \frac{Z_5 \times Z_6}{2(Z_5 + Z_6)} = Z_{H-Z}$$
$$Z_2 + Z_3 + \frac{Z_6}{2} + \frac{Z_5 \times Z_6}{2(Z_5 + Z_6)} = Z'_{X-Y}$$
$$Z_2 + Z_4 + \frac{Z_5}{2} + \frac{Z_6}{2} = Z'_{Z-X}$$
$$Z_3 + Z_4 + \frac{Z_5}{2} + \frac{Z_5 \times Z_6}{2(Z_5 + Z_6)} = Z'_{Z-Y}$$

in which $\mathrm{Z'}_{\mathrm{X-Y}}$, $\mathrm{Z'}_{\mathrm{Z-X}}$, and $\mathrm{Z'}_{\mathrm{Z-Y}}$ are converted impedances to the high-voltage side. Thus, the equivalent circuit impedances are given by:

$$Z_1 = \frac{1}{2}(Z_{H-X} + Z_{H-z} - Z'_{Z-X} + Z_{Com})$$
$$Z_2 = \frac{1}{2}(Z_{H-X} - Z_{H-Y} + Z'_{X-Y} + Z_{Com})$$
$$Z_3 = \frac{1}{2}(Z'_{X-Y} - Z'_{Z-X} + Z'_{Z-Y} + Z_{Com})$$
$$Z_4 = \frac{1}{2}(-Z_{H-Y} + Z_{H-Z} + Z'_{Z-Y} + Z_{Com})$$
$$Z_5 = \frac{1}{2}(Z_{H-Y} - Z_{H-Z} - Z'_{X-Y} + Z'_{Z-X} - Z_{Com})$$
$$Z_6 = \frac{1}{2}(-Z_{H-X} + Z_{H-Y} + Z'_{Z-X} - Z'_{Z-Y} - Z_{Com})$$

in which :

$$Z_{Com} = \sqrt{(-Z_{H-X} + Z_{H-Y} + Z'_{Z-X} - Z'_{Z-Y})(Z_{H-Y} - Z_{H-Z} - Z'_{X-Y} + Z'_{Z-X})}$$

Another solution might be found, which is given by:

$$Z_1 = \frac{1}{2}(Z_{H-X} + Z_{H-z} - Z'_{Z-X} - Z_{Com})$$
$$Z_2 = \frac{1}{2}(Z_{H-X} - Z_{H-Y} + Z'_{X-Y} - Z_{Com})$$
$$Z_3 = \frac{1}{2}(Z'_{X-Y} - Z'_{Z-X} + Z'_{Z-Y} - Z_{Com})$$
$$Z_4 = \frac{1}{2}(-Z_{H-Y} + Z_{H-Z} + Z'_{Z-Y} - Z_{Com})$$
$$Z_5 = \frac{1}{2}(Z_{H-Y} - Z_{H-Z} - Z'_{X-Y} + Z'_{Z-X} + Z_{Com})$$
$$Z_6 = \frac{1}{2}(-Z_{H-X} + Z_{H-Y} + Z'_{Z-X} - Z'_{Z-Y} + Z_{Com})$$

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4.1.2 The Zero-Sequence Equivalent Circuit for a Four-Winding Transformer

The zero-sequence equivalent circuit of a four-winding transformer depends on the connection type of the windings and the neutral points grounding of the wye-connections. In general, the basic concepts are similar those listed in Table 1-2 for other transformers. Due to the large number of connection types, the zero-sequence equivalent circuits of all possible connection types of four-winding transformers are not presented in this section; however, the zero-sequence equivalent circuits will be presented for a practical example.

4.2 Example 10, Practical Four-Winding Transformers with Delta Primary, Delta Secondary, Wye Tertiary, and Wye Quaternary

Figure 4-4 shows the nameplate information of a 138/4.7/4.7/13.8 kV, 15 MVA four-winding D-d-y-y-connected transformer. It should be noted that this transformer is a rectifier transformer and that it is a special case. The nominal ratings of the high-voltage winding are 15 MVA/138 kV. The nominal ratings of the delta secondary and the wye tertiary windings are 7.5 MVA/4.7 kV and supply a rectifier load, and the 13.8 kV “quaternary” supplies the local ac services. These circuits would need to be modelled separately. The two-page test results are shown in Figure 5-5-a and Figure 5-5-b. The required information for modelling extracted from the test report is listed in Table 4-2. The positive-sequence equivalent circuit shown in Figure 4-3 is calculated from the given formulas. The six independent impedances are given below at 15 MVA/138 kV. The auxiliary-winding neutral point is connected to ground. Therefore, the zero-sequence current can only flow in the auxiliary windings set and the other windings sets are open circuit for zero-sequence current, as shown in Figure 4-6.

$$z_1 = 0.01081 + j0.078911$$
$$z_2 = 0.01554 + j0.167781$$
$$z_3 = 0.01543 + j0.168946$$
$$z_4 = 0.0118 - j0.0018537$$
$$z_5 = -0.023019 - j0.120363$$
$$z_6 = -0.018699 + j0.00289$$

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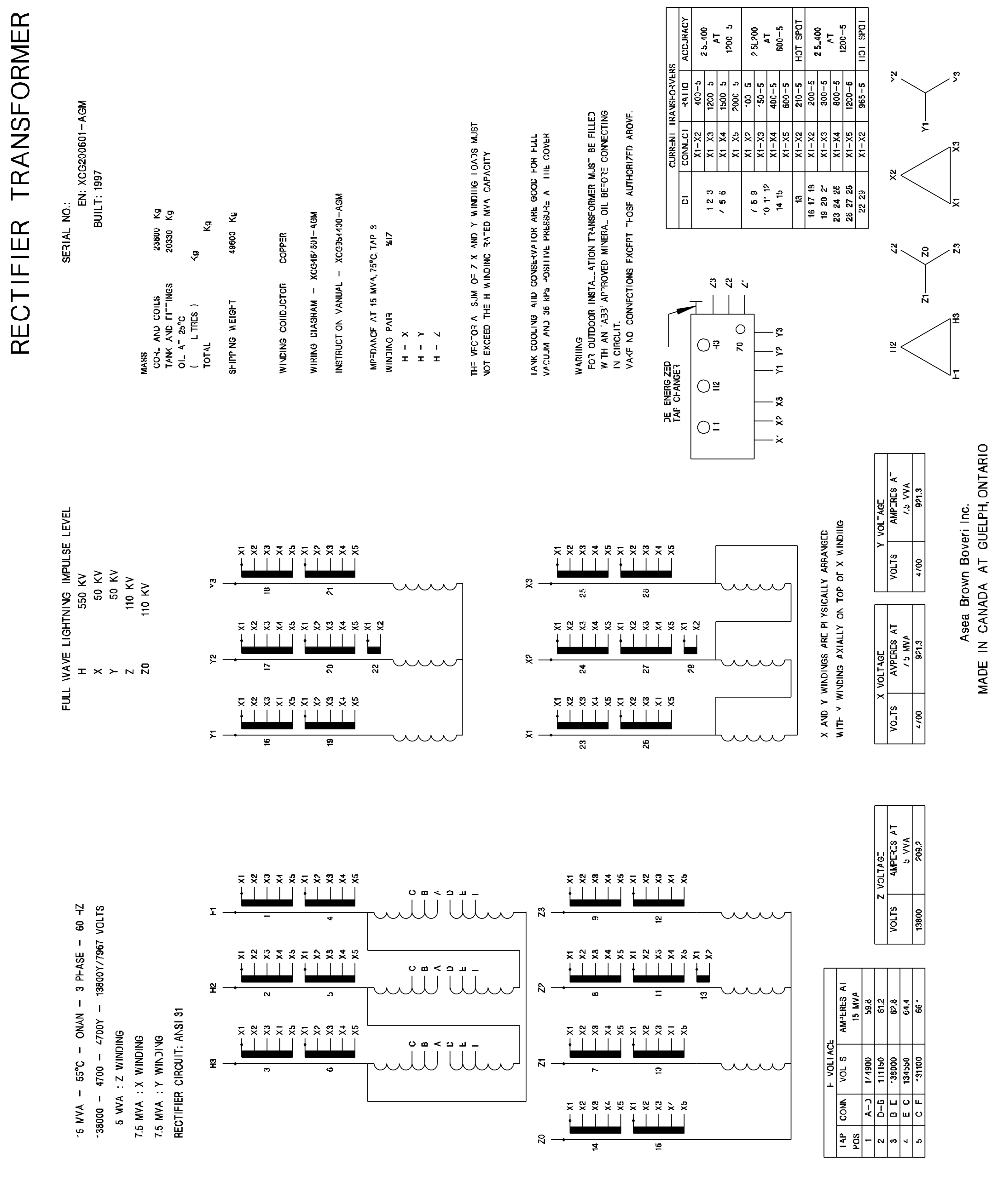

Figure 4-4- Example 10: Transformer nameplate

CUSTOMER :
RATING : 15 MVA VOLTAGE 138 KV-4.7KV-4.7KV-13.8KV
REQ No: CUSTOMER No..
EN No : SERIAL No....

NO LOAD LOSS AND % EXCITING CURRENT @ 15 MVA

KV APPLIED		Before Ins. Tests					Final Test	
% ER	KV	Loss/KW	Guar.	% Iex	Guar.		Loss/KW	% Iex
80	11.04	11.672		0.102			11.527	0.104
90	12.42	15.211		0.122			15.021	0.121
100	13.80	19.917	22.500	0.204	--		20.333	0.184
105	14.49	23.975		0.323			24.457	0.329
110	15.18	28.256		0.908	--		30.228	0.860

Load Loss

R.A.	MVA	Loss @ Meas. Temp				Loss @ Rated Temp.		
		Wdg.	Meas	Temp.		Calc.	Temp.	Guar.
3	15	H-X&Y	40.15	24.3		45.58	75	48.00
5	15	H-X&Y	41.16	24.3		46.78	75	N/A
1	15	H-X&Y	39.21	24.3		44.47	75	N/A

Figure 4-5-a- Example 10: Transformer test results, Page 1

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CUSTOMER :			
RATING :	15 MVA	VOLTAGE 138 KV-4.7KV-4.7KV-13.8KV	
REQ No:		CUSTOMER No..	
EN No :		SERIAL No....	

% IMPEDANCE

Wdg.	R.A.	MVA	Meas	%IX	%IR	%Iz	Temp.
H-X&Y	3	15	10.37	10.367	0.268	10.371	75.0
H - X	3	7.5	9.33	9.326	0.277	9.330	75.0
H - Y	3	7.5	9.46	9.456	0.269	9.460	75.0
x - Y	3	7.5	16.92	16.909	0.616	16.922	75.0
H - Z	3	5	2.62	2.617	0.132	2.621	75.0
Z-X&Y	3	5	0.74	0.730	0.121	0.744	75.0
Z - X	3	5	3.58	3.573	0.216	3.581	75.0
Z - Y	3	5	3.57	3.564	0.214	3.571	75.0

HEAT RUN :

	MVA	Avg Oil	Top Oil	** Wdg Rise @ Max.Amps			
		Rise *	Rise *	HV	LV(X)	LV(Y)	LV(Z)
ONAN	15	31.4	37.7	34.6	41.9	51.0	33.4
ONAF	N/A						

* TOTAL LOSSES INJECTED INCLUDING EFFECTS OF HARMONICS = 92.9 KW.

** INCLUDING EFFECTS OF HARMONICS

NOISE LEVEL : NOT REQUIRED

Figure 4-5-b- Example 10: Transformer test results, Page 2

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Table 4-2- Information Required for Modelling the Four-Winding Transformer of Example 10

Item	Transformer Parameter	Symbol	Values					
General								
			H		X	Y		Z
1	Transformer ONAN Ratings	MVA_{ONAN}	15		7.5	7.5		5
2	Winding Voltages (primary, secondary, …)	V_H, V_X,…(kV) V_P, V_S,…(kV) V_1, V_2, …(kV)	138		4.7	4.7		13.8
3	Connection type	-	Delta		Delta	Wye		Wye
4	Tap range	t_1, t_2, …	-		-	-		-
5	Number of tap steps	-	-		-	-		-
6	Winding with an adjustable tap	-	-		-	-		-
7	Phase angle of windings	θ_1, θ_2, …	0°		0°	30°		30°
No Load Loss Test Results (between Pair of Windings)								
8	No-load loss test MVA	$MVA_{NL\ Test}$	15 MVA					
9	No-load loss	P_{NL}	19.917 kW					
10	Excitation current	I_{exc}	0.204 %					
11	Tap setting for no-load loss test	t_{NL}	Nominal					
Load Loss Test Results								
	Between Pair of Windings		H-X	H-Y	H-Z	X-Y	Z-X	Z-Y
12	Load loss test MVA	$MVA_{SC\ Test}$,	7.5	7.5	5	7.5	5	5
13	Impedance	I_Z%	9.33	9.46	2.621	16.922	3.581	3.571
14	Reactance	I_X%	9.326	9.456	2.617	16.909	3.573	3.564
15	Resistance	I_R%	0.277	0.269	0.132	0.616	0.216	0.214
	At Full-Load		H-X&Y			Z-X&Y		
16	Load loss test MVA	$MVA_{SC\ Test}$,	15			5		
17	Impedance	I_Z%	10.371			0.744		
18	Reactance	I_X%	10.367			0.730		
19	Resistance	I_R%	0.268			0.121		
20	Tap setting for no-load loss test	t_{NL}	Nominal					
Zero-Sequence Test Results								
The zero-sequence information has not been provided in the test report.								

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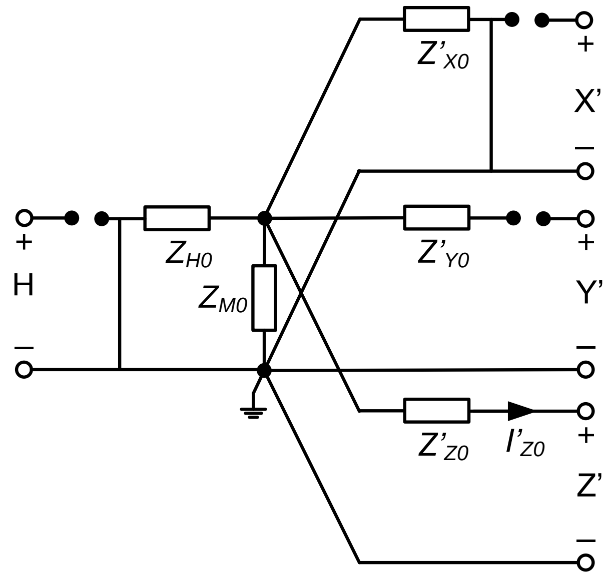

Figure 4-6- The zero-sequence equivalent circuit of Example 10

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5 Phase-Shifting Transformers

5.1 Introduction

Phase-Shifting transformers (PSTs) can be used to control the active power flow in a complex power transmission network efficiently. They are used to improve the transient stability of power systems. They can adjust the input voltages and currents by an angle using a tap changer, and operate by adding a $\pm 90°$ component of voltage to the input voltage. There are other methods for introducing the effect of a quadrature voltage, such as an HVDC link; however, unless response time is very important such a link would be more costly than phase-shifting transformers.

For three-phase phase-shifting transformers, the quadrature voltage can be derived by interconnecting sections of windings from other phases. This can be accomplished in a number of ways, giving rise to a large number of configurations. In this guide, only a few common configurations will be considered. Phase-Shifting capability can be combined with voltage-magnitude control in the same transformer, which results in a more complex unit involving two sets of tap changers. This will not be discussed in this modelling guide.

The use of phase-shifting transformers can be illustrated by considering a transmission line carrying a normal load current in an interconnected network. A PST can control the power flow along the transmission line between the end buses of two lines. As an example, the option of using a PST in an interconnected network was finalized after comparing it with other options such as the use of an HVDC link or the use of series capacitors. As shown in Figure 5-1, a normal load current determined by the line's impedance flows along the line without PST operation, which means:

$$\Delta V = V_L - V_L = 0$$
$$I_X = 0$$

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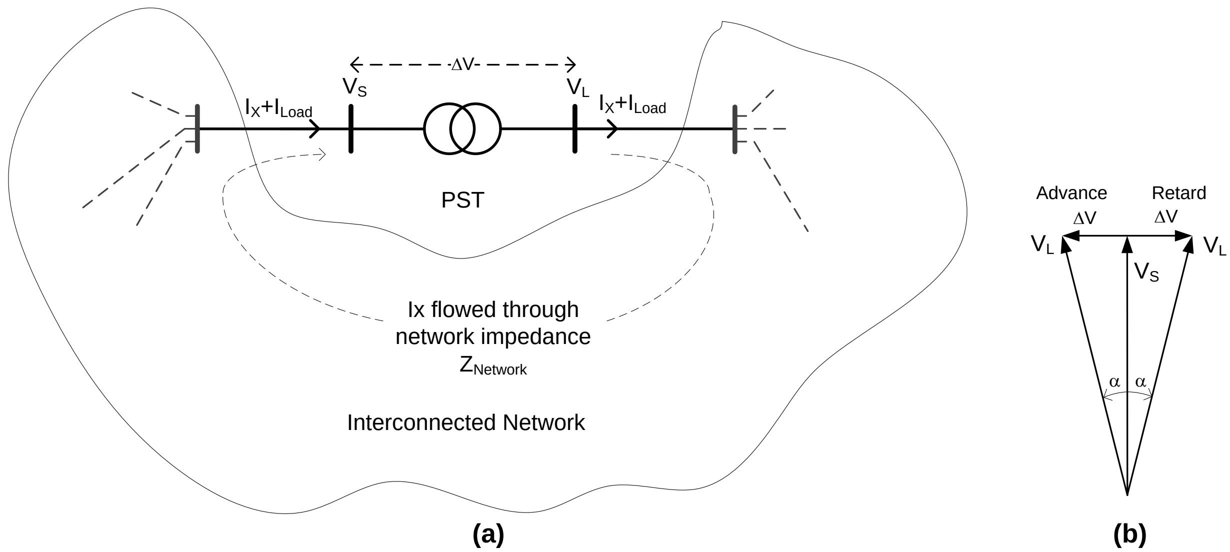

Figure 5-1- An interconnected network equipped with a phase-shifting transformer: a) Network, b) Advance and retard modes vector diagram

The PST provides a controlled phase shift (advance or retard) through a proper tap changer between the primary (source) and secondary (load) terminals, as shown in Figure 5-1-b. In the phase-advance mode, the voltage vector at the output of the PST is made to lead the input voltage vector by adding a leading quadrature voltage to the source voltage. In the phase-retard mode, a lagging quadrature voltage is added to the source voltage so that the voltage vector at the output of the PST lags the input voltage. In both cases, a circulating current superimposed on the load current will flow around the system. This circulating current is caused by non-zero ΔV provided by the PST. Thus:

$$I_X = \frac{\Delta V}{Z_{Network}}$$

Since the network impedance is largely inductive, the voltage ΔV will need to be approximately in quadrature with the circulating current. Due to the quadrature voltage, phase shifting transformers are also called quadrature booster transformers.

5.2 Phase-Shifting Transformers Typical Configurations

Phase-shifting transformers can be constructed with many different winding configurations, depending on the rated voltage, the power output, and the amount of phase shift required. The amount of phase shift required directly affects the rating and size of the PST. Presently, in practice, there are two types of PST designs: single-core and two-core. The single-core design is used for small phase shifts and for lower MVA and voltage ratings. The two-core design is normally used for bulk power transfer with phase-shifting transformers with large ratings. It consists of two transformers, one associated with the line terminals and the other associated with the tap changer.

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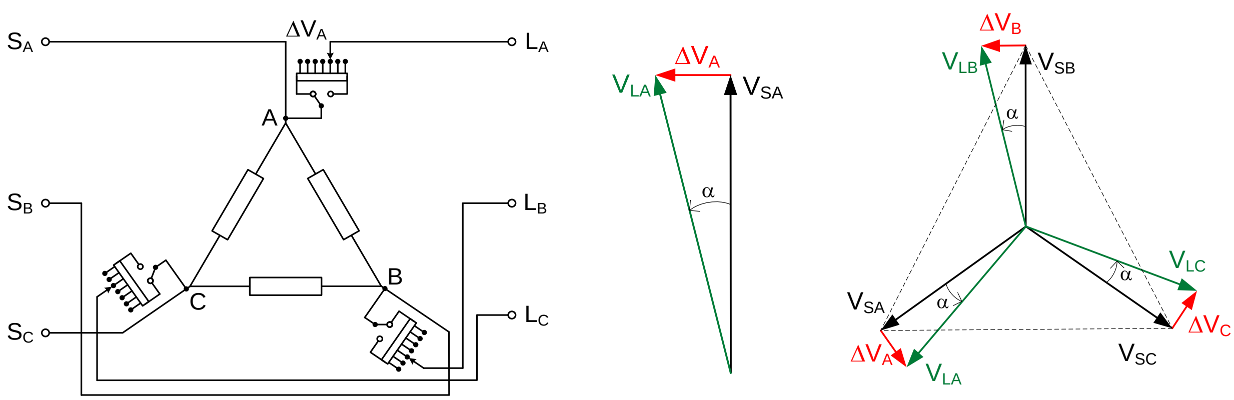
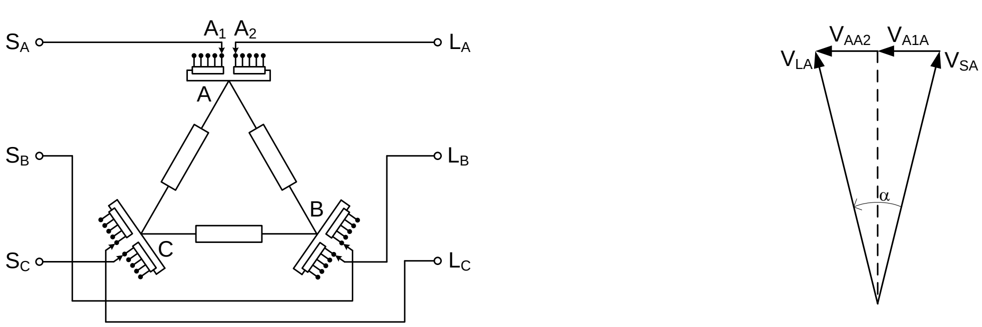
The single-core design PST can be constructed with a delta-connected exciting winding and one tap winding and one OLTC with a reversing switch, as shown in Figure 5-2. In this configuration, which is called an asymmetrical delta connection, the regulating windings are wound on the same core limb as the exciting winding. The phase shift between the source (S) and load (L) terminals is achieved by connecting the regulating winding, as shown in Figure 5-2. Its voltage is in phase with that of the exciting winding between the other two phase terminals. The voltage magnitudes of the S and L terminals are equal under the no-load condition. The vector diagrams show the phase shift advancement obtained for the load terminal voltage with respect to the source terminal voltage. Normally, this phase shift can be varied during operation in definite steps by the OLTC tap changer. The phase retard can be achieved, as can phase advance, if the reversing switch is changed.



(a) (b) (c)

Figure 5-2- Asymmetrical delta configuration PST: a) Schematic diagram, b) Single-phase vector diagram, c) Three-phase vector diagram

The delta-connected configuration can also be constructed with two tap windings and an OLTC at each phase without a reversing switch, as shown in Figure 5-3. Under the no load condition, the voltage magnitudes at the source and at the load terminals are equal. This configuration is known as a standard delta connection. The main problem with the single-core design is that the tap changer is operating at line voltage, and is therefore expensive.



(a) (b)

Figure 5-3- Symmetrical delta configuration PST: a) Schematic diagram, b) Single-phase vector diagram

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The single-core PST configuration shown in Figure 5-4 has an OLTC with linear regulation and without a reversing switch; this type is known as delta-hexagonal PST. In this configuration, the regulating winding is wound on the same core limb as the main exciting winding. The regulating winding of Phase A is located between Phases B and C, and produces a phase shift (retard), as shown in the figure.

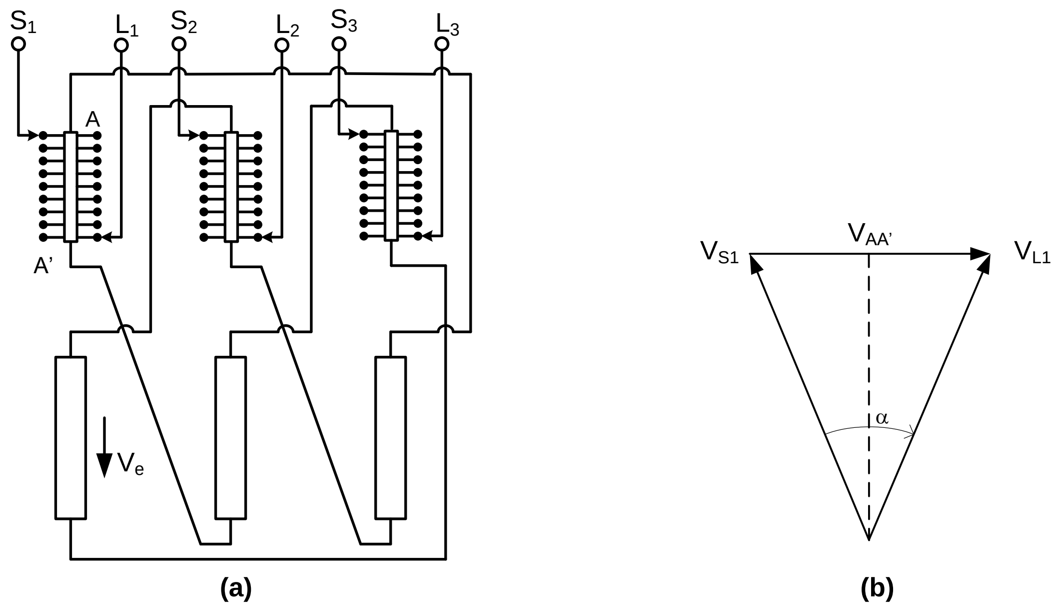

Figure 5-4- Delta-Hexagonal configuration PST: a) Schematic diagram, b) Single-phase vector diagram

The two configurations of the single-core design PST discussed above are cases of line end regulation. The tap changer and regulating (tap) winding are directly exposed to system disturbances (overvoltages and short-circuit currents); therefore, the cost of the OLTC increases. Additional impedances may have to be connected to the load-side terminals to protect the tap changer from short-circuit currents because no transformer impedance is present at a phase angle of zero. In the case of an OLTC with a reversing switch, during the switch operation the tap winding is momentarily disconnected from the main winding. Its potential is determined by the potentials of adjacent windings and the capacitances (between windings and between windings and ground). This causes a high recovery voltage across the tap changer contacts.

The two-core design is normally used for large PST ratings and a larger range of phase-angle shifts. As shown in Figure 5-5, the two-core PST basically consists of the series unit and the exciting unit with the same MVA ratings in separate tanks for larger ratings and higher voltages or in the same tank for smaller ratings and lower voltages. The winding of the series unit between the source and load terminals at each phase is split into two halves. The main winding of the exciting unit is connected to the connection point of these two split windings. The advantage of this arrangement is that the tap winding in the exciting unit and the winding aa' in the series unit can be designed independently while windings 'AA' and 'BB' form a part of the HV network. The voltage level of the tap winding and the 'aa' winding can be chosen to reduce tap changer cost.

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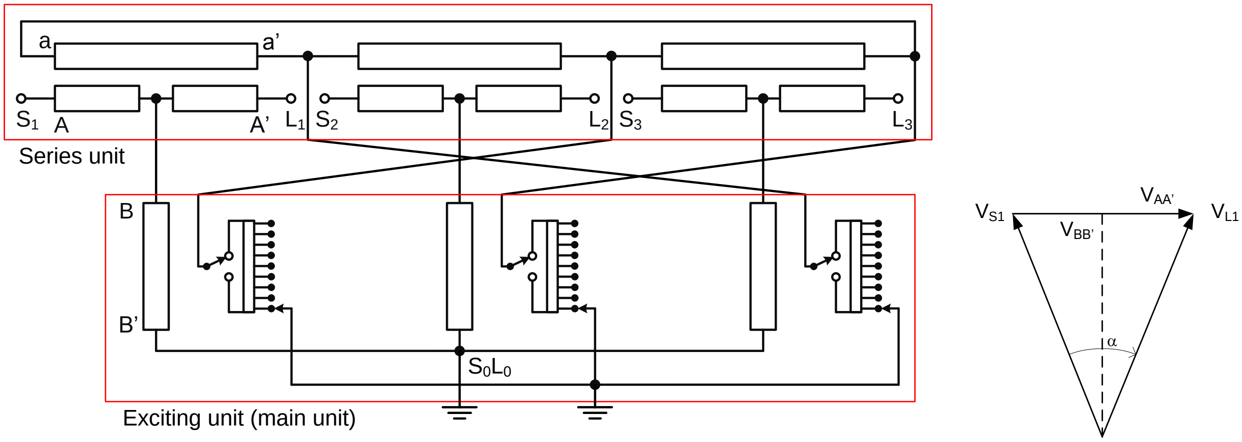

(a) **(b)**

Figure 5-5- Two-core configuration of a PST: a) Schematic diagram, b) Single-phase vector diagram

5.3 Phase-Shifting Transformer Equivalent Circuit

The derivation of the equivalent circuit for a PST is more complex than the derivation of the equivalent circuit for a regular transformer. However, the basic principles discussed in the first sections are valid for PST modelling.

Some assumptions can be made to simplify the PST model:

- The exciting current can be neglected , as it is very low in transformers that used modern designs.
- The individual phases can be modelled in terms of their leakage impedances.
- The phase angle steps may not be equal at different tap positions; however, for power flow and transient stability studies equal step size is usually assumed.
- The appropriate interconnection is chosen to produce a positive phase shift at a positive tap setting.
- Negative-sequence circuits have the opposite phase shift in relation to positive-sequence circuits because interchanging two phases in three-phase systems is equivalent to inputing a negative-sequence set of voltages. Therefore, by interchanging two phases a negative phase shift at a positive tap setting is produced.
- Because of the differences in per-unit bases for the input and winding quantities, per-unit quantities are not as convenient in this analysis. Most of the calculation described here is carried out in terms of impedances in ohms. However, the per-unit equivalent impedance based on the windings MVA rating, which is assumed to be constant, will be expressed.
- Since the output quantities are rotated counterclockwise on a vector diagram relative to the input quantities in a positive phase shift, output voltages and currents lead the input voltages and currents.

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- The zero-sequence circuits have zero phase shifts. The zero-sequence quantities are also all in phase with each other.

5.3.1 Standard Delta Phase-Shifting Transformer

The connection diagram in Figure 5-6 shows that the tapped windings are on the same core as the corresponding parallel windings on the delta. The taps are symmetrically placed with respect to the point of contact at the delta vertex. This means that $E_{a'} = E_{a''}$, and so on, for other phases. It also ensures there is no change in the current or no-load voltage magnitude from the input to the output. Each phase consists of one parallel (and opposite) winding and two tap windings with impedances Z_a , $Z_{a'}$, and $Z_{a''}$, respectively.

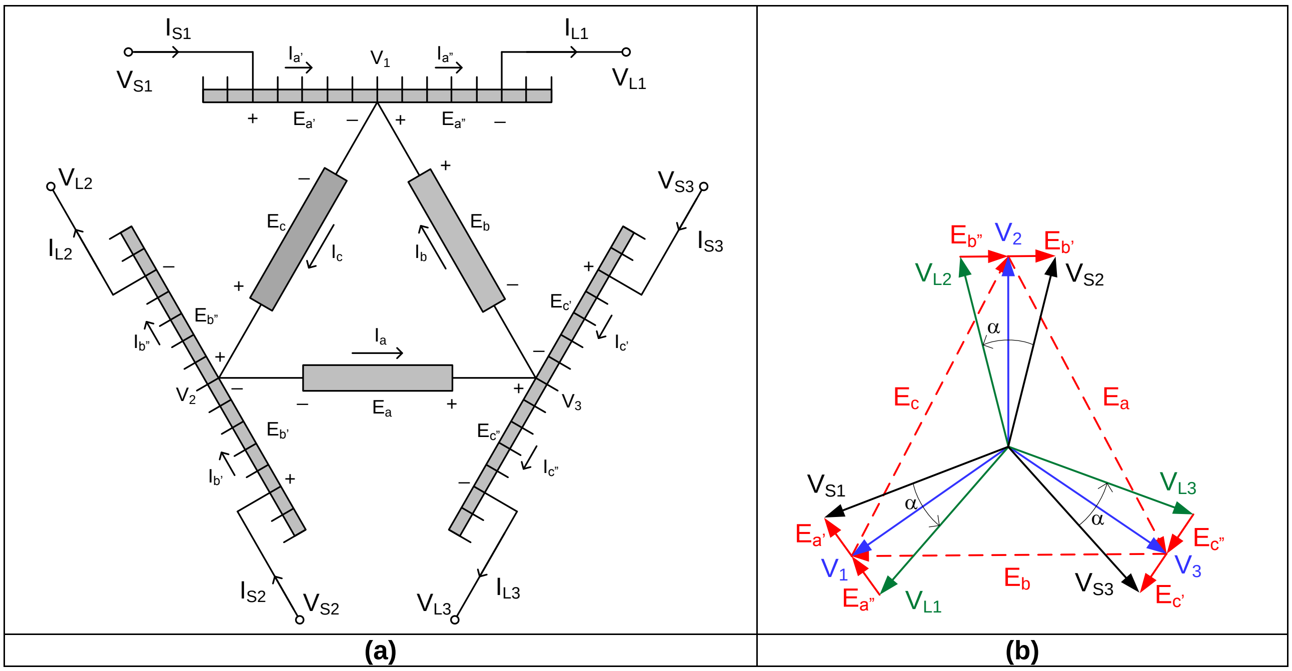

Figure 5-6- Schematic diagram of a standard delta phase-shifting transformer: a) Circuit diagram, b) Vector diagram

5.3.2 Positive-Sequence Equivalent Circuit of Standard Delta Phase-Shifting Transformer

As shown in Figure 5-6-b, the voltages V_1 , V_2 , and V_3 designate the phasor voltage at the delta connection vertices. Depending on the tap position, the amount of phase shift is given as:

$$\theta = 2\tan^{-1}\frac{\sqrt{3}}{n}$$

in which n is the turns ratio and is defined as the ratio of the turns in one of the delta windings to the turns in one of the tap windings.

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$$n = \frac{N_a}{N_{a'}} = \frac{E_a}{E_{a'}}$$

Both tap windings should have the same number of turns. It can also be shown that:

$$I_{L1} = e^{j\theta} I_{S1}$$
$$V_{L1} = (V_{S1} - Z_{eq}.I_{S1})e^{j\theta}$$

in which Z_{eq} is given as:

$$Z_{eq} = Z_{a'} + Z_{a"} + \frac{4Z_a}{n^2 + 3}$$

In terms of a two-winding transformer, Z_{eq} is given as:

$$Z_{eq} = Z_{a'a"} + \left(\frac{2}{n^2 + 3}\right)(Z_{aa'} + Z_{aa"} - n^2 Z_{a'a"})$$

Note that the Z_{eq} depends on the turns ratio, and with $N_{a'} = 0$, $n = \infty$, $Z_{a'a"} = 0$ so:

$$Z_{eq} = 0$$

In this case, the input is directly connected to the output and bypasses the coils.

Z_{eq} can also be expressed in per-unit terms. Because the input MVA and the voltage base are different than the input MVA and the voltage base of the windings, it must be specified which base MVA and voltage base are used. If the terminal bases are taken they are the terminal power per phase and phase voltage base. Therefore, the rated input current base and impedance base can be given as:

$$I_{base\ in} = P_{base\ in}/V_{base\ in}$$
$$Z_{base\ in} = \frac{{V_{base\ in}}^2}{P_{base\ in}}$$

in which $P_{base\ in}$ is the rated input power base (MVA rating), and $V_{base\ in}$ is the rated input voltage base. Because the transformation ratio is 1:1 in terms of magnitude, the output base values are the same as the input base values. It is assumed that the input MVA rating is the common power base for the input and for all windings. Therefore, the two windings impedance base is related to the input impedance base and also the voltage base and the winding voltage base as follows:

$$\frac{Z_{base\ a\ wdg}}{Z_{base\ in}} = \frac{|E_a|^2}{|V_{S1}|^2} = \frac{3n^2}{n^2 + 3}$$
$$\frac{Z_{base\ a'\ wdg}}{Z_{base\ in}} = \frac{|E_{a'}|^2}{|V_{S1}|^2} = \frac{3}{n^2 + 3}$$

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in which $Z_{base\ a\ wdg}$ and $Z_{base\ a\prime\ wdg}$ are the impedance bases of the delta winding and the tap windings, respectively. Therefore Z_{eq} in per-unit terms is given as:

$$z_{eq} = \frac{3z_{a'a"}}{n^2+3} + \frac{6n^2(z_{aa'} + z_{aa"} - z_{a'a"})}{(n^2+3)^2}$$

According to the previous equations, the positive sequence equivalent circuit of a standard delta-connected phase-shifting transformer is as shown in Figure 5-7.

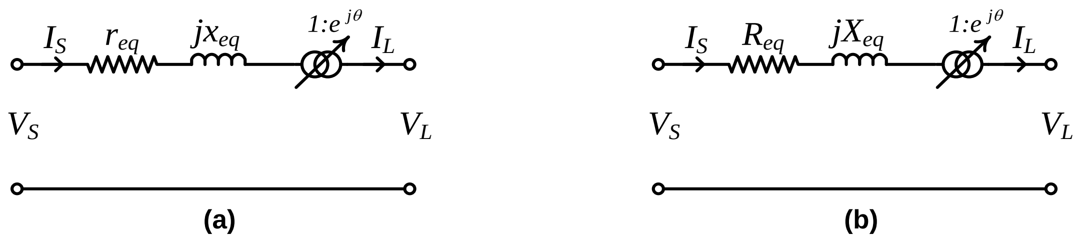

Figure 5-7- The positive-sequence equivalent circuit of a phase-shifting transformer: a) In pu, b) In real values

5.3.3 Negative-Sequence Equivalent Circuit of Standard Delta Phase-Shifting Transformer

The negative-sequence equivalent circuit of a standard delta phase-shifting transformer is obtained by changing θ to $-\theta$ with Z_{eq} unchanged from the positive-sequence equivalent circuit.

5.3.4 Zero-Sequence Equivalent Circuit of Standard Delta Phase-Shifting Transformer

The zero-sequence equivalent circuit of a standard delta phase-shifting transformer can be derived from Figure 5-6 with all voltage and current vectors taken to be zero-sequence. The phase shift between the zero-sequence input and output currents is always zero. The zero-sequence equivalent circuit of this type of PST is only a series impedance, as shown in Figure 5-8.

Figure 5-8- The zero-sequence equivalent circuit of a phase-shifting transformer: a) In pu, b) In real values

Under zero-sequence conditions, the zero-sequence impedance can be given by:

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$$Z_{eq0} = Z_{a'0} + Z_{a"0} + \frac{4Z_{a0}}{n^2}$$

And in terms of two-winding impedances, Z_{eq0} can be given by:

$$Z_{eq0} = Z_{a'a"0} + \frac{2(Z_{aa'0} + Z_{aa"0} - n^2 Z_{a'a"0})}{n^2}$$

The equivalent per-unit zero-sequence impedance is given by :

$$z_{eq0} = \frac{3}{n^2 + 3}[2(z_{aa'0} + z_{aa"0}) - z_{a'a"0}]$$

5.3.5 Two-Core Phase-Shifting Transformer

The connection diagram of a two-core phase-shifting transformer is shown in Figure 5-9. The input and output coils are part of a series unit and are attached to the exciter unit at their midpoint. The series unit uses a three-winding model; whereas, the exciter unit uses a two-winding model.

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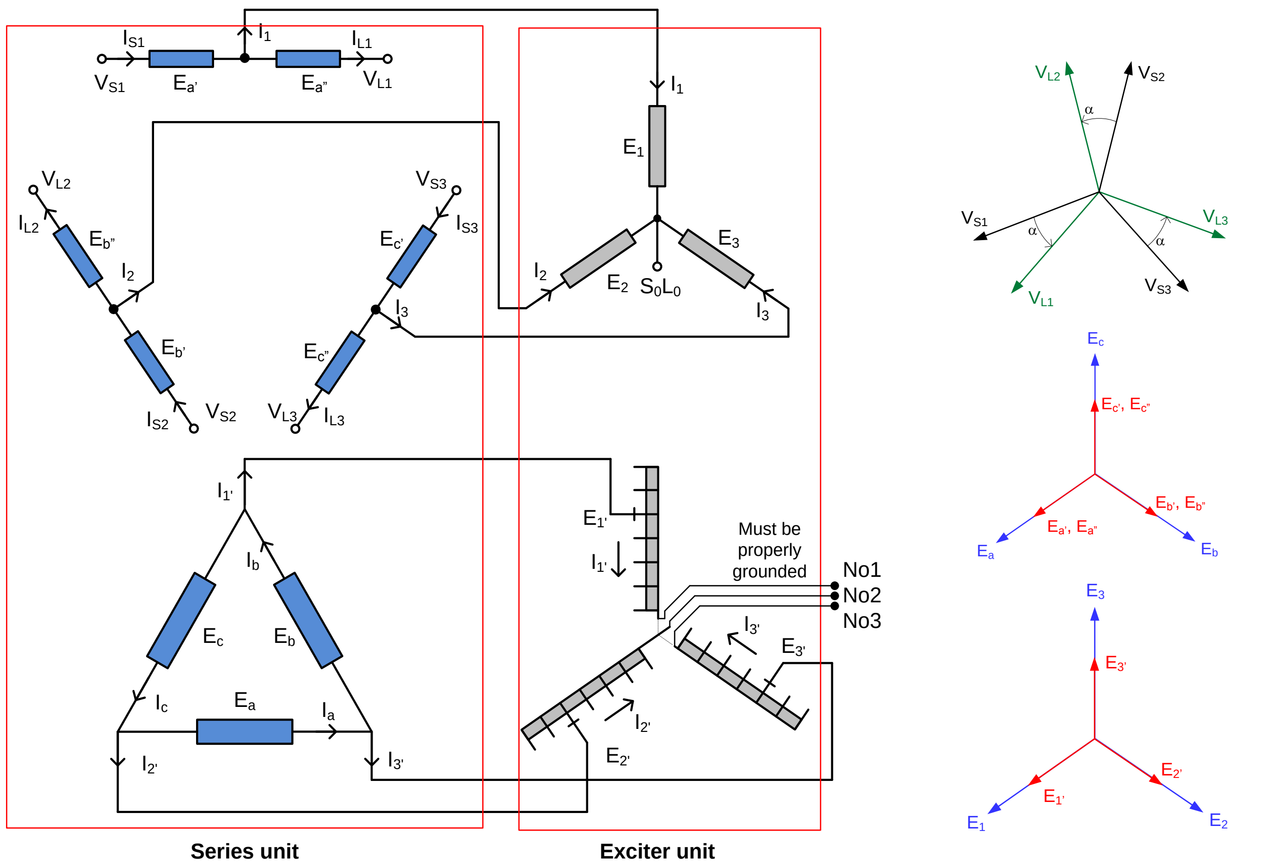

(a) (b)

Figure 5-9- Schematic diagram of a two-core phase-shifting transformer: a) Circuit diagram, b) Vector diagrams

5.3.6 Positive-Sequence Equivalent Circuit of a Two-Core Phase-Shifting Transformer

Depending on the tap position, the amount of phase shift is given as:

$$\theta = 2\tan^{-1}\left(\frac{\sqrt{3}}{n_e n_s}\right)$$

in which n_s, the turns ratio of the series unit, is defined as the ratio of delta winding turns to the turns in the first or the second half of the input-output winding. Also, n_s, the turns ratio of the exciter unit, is defined as the ratio of the turns in the wye-connected winding connected to the midpoint of the input–output winding to the turns in the tapped winding. The exciter unit turns ratio will depend on the tap position.

$$n_s = \frac{N_1}{N_{1'}} = \frac{E_1}{E_{1'}}$$

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$$n_e = \frac{N_a}{N_{a\prime}} = \frac{E_a}{E_{a\prime}}$$

The equation between the input and output of a phase-shifting transformer is as follows:

$$I_{L1} = e^{j\theta} I_{S1}$$
$$V_{L1} = \left(V_{S1} - Z_{eq}.I_{S1}\right)e^{j\theta}$$

in which Z_{eq} for a two-core phase shifting transformer is given as:

$$Z_{eq} = Z_{a\prime} + Z_{a"} + \left(\frac{12}{(n_e n_s)^2 + 3}\right)\left(Z_{11\prime} + \frac{{n_e}^2}{3} Z_a\right)$$

In terms of two-winding transformer Z_{eq} is given as:

$$Z_{eq} = Z_{a\prime a"} + \left(\frac{12}{(n_e n_s)^2 + 3}\right)\left(Z_{11\prime} + \frac{{n_e}^2}{6}\left(Z_{aa\prime} + Z_{aa"} - {n_s}^2 Z_{a\prime a"}\right)\right)$$

The positive-sequence equivalent circuit of a two-core phase-shifting transformer is similar to that of a standard delta phase-shifting transformer, as shown in Figure 5-7. Similarly, the Z_{eq} depends on the exciting transformer turns ratio, n_e, and with $N_{a\prime} = 0$, $n_e = \infty$, so:

$$Z_{eq} = Z_{a' a"} + \frac{4Z_a}{{n_s}^2}$$

In per-unit terms, the power base is assumed constant for all windings and input. The impedance base definitions for all windings except the tap changer winding are as follows:

$$\frac{Z_{base\ a\ wdg}}{Z_{base\ in}} = \frac{|E_a|^2}{|V_{S1}|^2} = \frac{3{n_s}^2}{(n_e n_s)^2 + 3}$$
$$\frac{Z_{base\ a\prime\ wdg}}{Z_{base\ in}} = \frac{|E_{a\prime}|^2}{|V_{S1}|^2} = \frac{3}{(n_e n_s)^2 + 3}$$
$$\frac{Z_{base\ 1\ wdg}}{Z_{base\ in}} = \frac{|E_1|^2}{|V_{S1}|^2} = \frac{(n_e n_s)^2}{(n_e n_s)^2 + 3}$$

In which, $Z_{base\ a\ wdg}$, $Z_{base\ a\prime\ wdg}$, and $Z_{base\ 1\ wdg}$ are the impedance bases of the delta windings, the input-output windings, and the exciter windings, respectively. Therefore, Z_{eq} in per-unit terms is given as:

$$z_{eq} = \left(\frac{3}{(n_e n_s)^2 + 3}\right)\left\{z_{a\prime a"} + \left(\frac{4(n_e n_s)^2}{(n_e n_s)^2 + 3}\right)\left[z_{11\prime} + \frac{1}{2}\left(z_{aa\prime} + z_{aa"} - z_{a\prime a"}\right)\right]\right\}$$

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The negative-sequence circuit has the same equivalent impedance, but it has a phase-angle shift in the opposite direction to that of the positive-sequence circuit.

The equivalent-series impedance of the PST shown in Figure 5-7 is a function of the PST tap position. Consequently, it varies with the phase-shifting angle. Therefore, the accurate modelling of a PST requires a table that shows equivalent impedance at each tap position an impedance table. This table is not the impedance correction table, but it is similar. The PST is a special type of power transformer, and a complete test report for it is usually provided by the manufacturer. Therefore, the equivalent series impedance for all tap positions can be found in the test report. Even if the load losses test results are not reported completely for all tap positions, they are usually reported for some tap positions, and the series impedance can be calculated for those tap positions. For rest of the positions, the series impedance can be calculated from interpolation or from simple curve-fitting methods that can be found in basic numerical engineering programs. If defining an individual impedance for each tap position in the PST model is not possible, the equivalent impedance at the nominal tap position, which is often position 17 ($\theta = 0°$), can be assumed for all operating conditions of the transformer.

5.3.7 Negative-Sequence Equivalent Circuit of a Two-Core Phase-Shifting Transformer

The negative-sequence equivalent circuit of a two-core phase-shifting transformer is obtained by changing θ to $-\theta$ with Z_{eq} unchanged from the positive-sequence equivalent circuit.

5.3.8 Zero-Sequence Equivalent Circuit of Standard Delta Phase-Shifting Transformer

A phase-shifting transformer cannot provide phase shift under zero-sequence excitation. Therefore, the phase shift between the zero-sequence input and the output currents is always zero. The zero-sequence equivalent circuit of a two-core phase-shifting transformer can be derived from Figure 5-9 with all voltage and current vectors taken to be zero-sequence. As shown in Figure 5-8, the zero-sequence equivalent circuit of a PST is only a series impedance.

5.4 Example 11: Practical Phase Shifting Transformer

Figure 5-10 shows the nameplate information of a 260000/GRDY/150111 V, 360/480/600 MVA two-core phase-shifting transformer. It has a 32 steps on-load tap changer that can provide ±25.1º phase shift between input and output. The required information for modelling extracted from a test report of more than two hundred pages is shown in Figure 5-11-a to Figure 5-11-i. As mentioned above, a PST transformer is modelled as series impedance and as an ideal transformer with a complex and unity turns ratio. Similar to regular power transformers, a constant magnetizing branch can also be considered in a PST equivalent circuit based on no-load test measurements.

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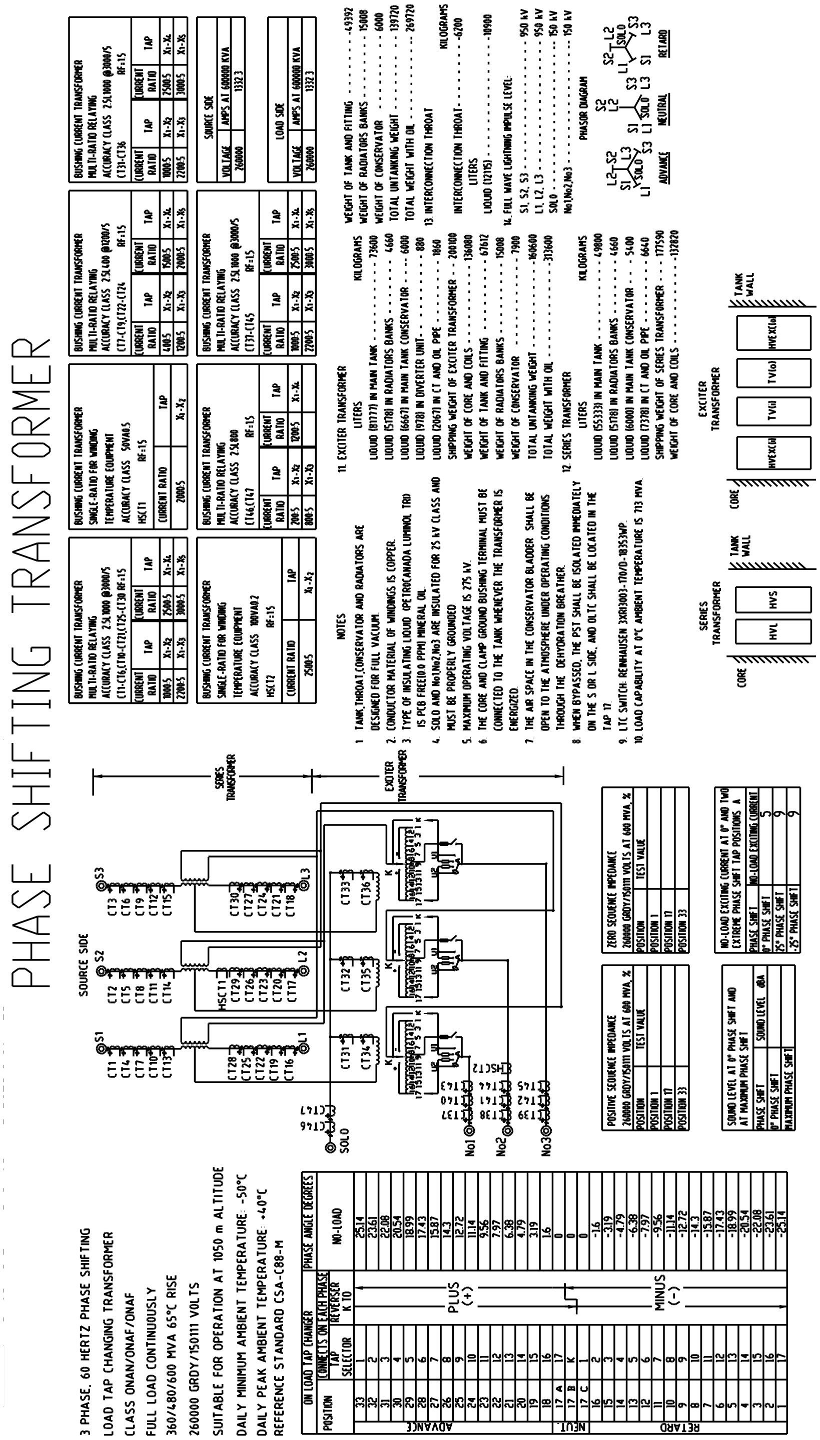

Figure 5-10- Example 11: The phase-shifting transformer nameplate

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Test result table:

No.	Test item	Guaranteed value	Measuring value	Uncertainty	Result
1	Measurement of phase-angle and voltage ratio (Routine test)	Measured value should be provided	/	/	Provided
2	Measurement of turns ratio (Routine test)	Measured value should be provided	/	/	Provided
3	Measurement of winding resistance (Routine test)	Measured value should be provided	/	/	Provided
4	Measurement of insulation resistance (Routine test)	Measured value should be provided	/	/	Provided
5	Measurement of capacitance and power factor of windings (Routine test)	Measured value should be provided	/	/	Provided
6	Measurement of capacitance and power factor of bushings (Otherl test)	Measured value should be provided	/	/	Provided
7	Measurement of zero-sequence impedance (Other test)	Measured value should be provided		/	Provided
8	Measurement of short-circuit impedance and load loss (Routine test)	H.V.-L.V. Short-circuit impedance(%): Tap1 ≤15 Tap17≤10 Tap33≤15 Load loss(kW): Tap1 <1250 Tap33<1250	13.63 8.85 13.64 1200 1203	/	OK

Figure 5-11-a- Example 11: Transformer test results

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Test result table:

No.	Test item	Guaranteed value	Measuring value	Uncertainty	Result
9	Measurement of no-load loss and current (Routine test)	No-load loss (kW): Tap1 <275 Tap33<275	239.1 238.0	/	OK
10	Temperature rise test (Design test)	Temperature-rise (K) Top oil: ⩽65 Average winding: ⩽65	Series T Exciter T 46.2 47.3 H 49.9 48.7 L 51.7 54.8	/	OK
11	Applied voltage test (Routine test)	S0L0 terminal: 50 kV 60s N01-N02-N03 terminal: 50 kV 60s	50 kV 60s 50 kV 60s	/	OK
12	Lightning impulse test (Routine test)	S and L line terminal FW/CW 950/1050 kV S0L0 neuter terminal FW/--- 150/--- kV No1 No2 No3 neuter terminal FW/--- 150/--- kV	The waves are showed on Appendix A	/	OK
13	Switching impulse test (Routine test)	S and L line terminal 790 kV	The waves are showed on Appendix B	/	OK
14	Induced voltage tests and partial discharge measurement (Routine test)	Test frequency ⩾50Hz $1.7\times Um/\sqrt{3}$ Duration: 72s	100 Hz 270 kV 72s	/	OK
		$1.5\times Um/\sqrt{3}$ Duration: 60min Partial discharge (pC): ⩽500	Partial discharge (pC): Tap1 S.W. 10~15; L.W. 10~15; Tap33 S.W. 7~220; L.W. 9~65;	/	OK
15	Measurement of acoustic sound level (Other test)	Sound level dB (A) at 0.3m: ⩽72 at 2.0m: ⩽75	69 68	/	OK

Figure 5-11-b- Example 11: Transformer test results

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Test Report

1 . Rated value

Serial No.		Numbers of phases	3
Code of product		Rated frequency	60 Hz
Type of product			
Type of cooling	ONAN /ONAF/ ONAF		
Service conditions	Outdoor		

Rated value	S Terminals	L Terminals
Rated capacity (MVA)	600	600
Rated voltage (V)	260000	260000
Rated current (A)	1332.3	1332.3

Performance parameter (Temp.85℃)		Guarantee value
No-load loss	at maximum phase-angle	＜275 kW
Load loss (based on 600MVA)	at maximum phase-angle	＜1250 kW
Short-circuit impedance (based on 600MVA)	at maximum phase-angle	⩽15%
	at 0° phase-angle	⩽10%
Insulation level	S and L terminals SI/LI/AC 790/950/270 kV SoLo neutral terminal LI/AC 150/50kV N neutral terminal LI/AC 150/50kV	

Figure 5-11-c- Example 11: Transformer test results

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2.3 Measurement of winding resistance

Test date:

Winding		Measured value Ω (30.7℃)			Calibrated value Ω (85℃)		
		Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3
Series Trans.	H.V.	S1L1	S2L2	S3L3	S1L1	S2L2	S3L3
	/	0.04543	0.04540	0.04545	0.05473	0.05470	0.05476
	L.V.	GF	EH	GH	GF	EH	GH
	/	0.02537	0.02527	0.02524	0.03056	0.03044	0.03041

Winding		Measured value Ω (30.7℃)			Calibrated value Ω (85℃)		
		Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3
Exciter Trans.	H.V.	M1-SoLo	M2-SoLo	M3-SoLo	M1-SoLo	M2-SoLo	M3-SoLo
	/	0.2433	0.2441	0.2439	0.2931	0.2941	0.2938
	L.V.	H-No1	G-No2	E-No3	H-No1	G-No2	E-No3
	1	0.011426	0.011384	0.011382	0.01377	0.01371	0.01371
	2	0.010814	0.010760	0.010751	0.01303	0.01296	0.01295
	3	0.010083	0.010035	0.010032	0.01215	0.01209	0.01209
	4	0.009464	0.009414	0.009406	0.01140	0.01134	0.01133
	5	0.008736	0.008690	0.008689	0.01052	0.01047	0.01047
	6	0.008116	0.008071	0.008066	0.009778	0.009724	0.009718
	7	0.007394	0.007344	0.007343	0.008908	0.008848	0.008846
	8	0.006777	0.006724	0.006724	0.008165	0.008101	0.008101
	9	0.006055	0.006004	0.006004	0.007295	0.007233	0.007233
	10	0.005438	0.005379	0.005390	0.006551	0.006480	0.006494
	11	0.004718	0.004664	0.004668	0.005684	0.005619	0.005624
	12	0.004104	0.004045	0.004050	0.004944	0.004873	0.004879
	13	0.003385	0.003328	0.003334	0.004078	0.004009	0.004017
	14	0.002769	0.002712	0.002710	0.003336	0.003267	0.003265
	15	0.002051	0.001991	0.001998	0.002471	0.002399	0.002407
	16	0.001441	0.001377	0.001371	0.001736	0.001659	0.001652
	17	0.0005040	0.0004760	0.0005211	0.000607	0.000573	0.000628
	18	0.001387	0.001326	0.001312	0.001671	0.001598	0.001581

Figure 5-11-d- Example 11: Transformer test results

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Winding		Measured value Ω (30.7℃)			Calibrated value Ω (85℃)		
		Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3
Exciter Trans.	19	0.002099	0.002040	0.002024	0.002529	0.002458	0.002438
	20	0.002729	0.002669	0.002648	0.003288	0.003215	0.003190
	21	0.003434	0.003380	0.003361	0.004137	0.004072	0.004049
	22	0.004063	0.004007	0.003987	0.004895	0.004827	0.004803
	23	0.004768	0.004713	0.004697	0.005744	0.005678	0.005659
	24	0.005397	0.005342	0.005326	0.006502	0.006436	0.006417
	25	0.006101	0.006049	0.006033	0.007350	0.007288	0.007268
	26	0.006731	0.006674	0.006671	0.008109	0.008041	0.008037
	27	0.007437	0.007384	0.007379	0.008960	0.008896	0.008890
	28	0.008068	0.008015	0.008010	0.009720	0.009656	0.009650
	29	0.008775	0.008722	0.008723	0.01057	0.01051	0.01051
	30	0.009407	0.009356	0.009354	0.01133	0.01127	0.01127
	31	0.010114	0.010060	0.010071	0.01218	0.01212	0.01213
	32	0.010749	0.010695	0.010703	0.01295	0.01288	0.01289
	33	0.011453	0.011404	0.011412	0.01380	0.01374	0.01375
Test instrument: JYR40D transformer winding resistance meter				No.:		No. of certificate:	
				Accuracy: 0.2%			

Winding		Measured value Ω (27.4℃)			Calibrated value Ω (85℃)		
		Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3
Series Trans. And Exciter Trans.	L.V.	No1-No2	No2-No3	No3-No1	No1-No2	No2-No3	No3-No1
	1	0.03910	0.03907	0.03915	0.04770	0.04766	0.04776
	2	0.03785	0.03783	0.03790	0.04617	0.04615	0.04624
	3	0.03644	0.03641	0.03649	0.04445	0.04442	0.04452
	4	0.03521	0.03518	0.03525	0.04295	0.04292	0.04300
	5	0.03380	0.03376	0.03383	0.04123	0.04118	0.04127
	6	0.03256	0.03253	0.03260	0.03972	0.03968	0.03977
	7	0.03115	0.03111	0.03118	0.03800	0.03795	0.03804
	8	0.02991	0.02987	0.02995	0.03649	0.03644	0.03654
	9	0.02851	0.02846	0.02854	0.03478	0.03472	0.03482

Figure 5-11-e- Example 11: Transformer test results

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Winding		Measured value Ω (27.4℃)			Calibrated value Ω (85℃)		
		Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3
Series Trans. And Exciter Trans.	10	0.02726	0.02723	0.02730	0.03326	0.03322	0.03330
	11	0.02585	0.02582	0.02589	0.03154	0.03150	0.03158
	12	0.02462	0.02459	0.02466	0.03003	0.03000	0.03008
	13	0.02322	0.02318	0.02325	0.02833	0.02828	0.02836
	14	0.02200	0.02195	0.02202	0.02684	0.02678	0.02686
	15	0.02060	0.02054	0.02062	0.02513	0.02506	0.02516
	16	0.01935	0.01932	0.01939	0.02361	0.02357	0.02365
	17	0.01755	0.01758	0.01763	0.02141	0.02145	0.02151
	18	0.01926	0.01920	0.01930	0.02350	0.02342	0.02354
	19	0.02067	0.02063	0.02070	0.02522	0.02517	0.02525
	20	0.02191	0.02186	0.02193	0.02673	0.02667	0.02675
	21	0.02332	0.02327	0.02332	0.02845	0.02839	0.02845
	22	0.02455	0.02450	0.02457	0.02995	0.02989	0.02997
	23	0.02595	0.02590	0.02596	0.03166	0.03160	0.03167
	24	0.02719	0.02714	0.02721	0.03317	0.03311	0.03319
	25	0.02860	0.02854	0.02862	0.03489	0.03482	0.03491
	26	0.02982	0.02979	0.02985	0.03638	0.03634	0.03642
	27	0.03123	0.03120	0.03126	0.03810	0.03806	0.03814
	28	0.03246	0.03243	0.03250	0.03960	0.03956	0.03965
	29	0.03388	0.03383	0.03391	0.04133	0.04127	0.04137
	30	0.03511	0.03507	0.03515	0.04283	0.04278	0.04288
	31	0.03652	0.03648	0.03657	0.04455	0.04450	0.04461
	32	0.03777	0.03772	0.03781	0.04608	0.04602	0.04613
	33	0.03917	0.03913	0.03923	0.04778	0.04774	0.04786
Test instrument: JYR40D transformer winding resistance meter				No.:		No. of certificate:	
				Accuracy: 0.2%			

Figure 5-11-f- Example 11: Transformer test results

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2.6 Measurement of capacitance and power factor of bushings

Test date: Air Temp. 31℃

Type No.	Series No.	Phase	Capacitance (pF)	PF(%)
345F028A	09F0348-03	S1	483.7	0.37
	09F0348-02	S2	484.6	0.36
	09F0348-05	S3	482.1	0.39
	09F0348-04	L1	485.9	0.38
	09F0348-01	L2	485.2	0.39
	09F0348-06	L3	484.4	0.37
035F043A	09F0349-04	S0L0	891.1	0.18
035F043A	09F0349-01	No1	888.8	0.19
	09F0349-03	No2	884.6	0.21
	09F0349-02	No3	888.4	0.20
Test instrument: JYC-II dissipation factor measuring system	No.	No. of certificate:		
	Accuracy: capacitance: ± (1% reading+2pF) tan δ : ± (1% reading+0.04%)			

2.7 Measurement of zero-sequence impedance

Test date: 2010.07.26 Oil Temp.31.0℃

Tap	Voltage U_T (V)	Current I_T (A)	Power P_T(W)	Zero-sequence impedance per phase Based on 600MVA	
				R+jX(Ω)	Z_K(%)
01	1168	347.6	9468	0.24+j10.1	8.95
17	1144	340.4	8748	0.23+j10.1	8.95
33	1149	341.7	9444	0.24+j10.1	8.95

Test circuit :Applied voltage between S1-S2-S3 and L1-L2-L3

Calculating equation:

$$Z_k = \frac{3 \times U_T \div I_T}{U_R \div \sqrt{3} \div I_R} \times 100(\%) \qquad R = \frac{3 \times P_T}{I_T^2} \qquad X = \frac{3 \times U_T}{I_T}$$

Remark: U_R=260000V
I_R=1332A

Test instrument: D6100 wide band power analyzer	No.:	No. of certificate
	Accuracy: ± 0.5%	

Figure 5-11-g- Example 11: Transformer test results

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2.8 Measurement of short-circuit impedance and load loss

Test date: 2010.07.26 f = 60 Hz

Winding S to L		Rated voltage (kV)	Measured Current (A)	Short circuit impedance		Load loss		
				(85℃) Calibrated value (%)	(85℃) Guarantee value (%)	(31.0℃) Measured value (kW)	(85℃) Calibrated value (kW)	(85℃) Guarantee value (kW)
Based on 600 MVA								
Tap	1	260 / 260	1335	13.63	≤15	1064	1200	<1250
Tap	5	260 / 260	1350	11.66	/	895.5	1004	/
Tap	9	260 / 260	1339	10.18	/	751.2	837.7	/
Tap	13	260 / 260	1339	9.21	/	640.2	709.7	/
Tap	17	260 / 260	1344	8.85	≤10	561.5	615.2	/
Tap	21	260 / 260	1340	9.20	/	640.9	710.5	/
Tap	25	260 / 260	1353	10.16	/	752.8	839.3	/
Tap	29	260 / 260	1328	11.64	/	894.5	1003	/
Tap	33	260 / 260	1337	13.64	≤15	1068	1203	<1250
Test instrument: D6100 wide band power analyzer				No.:		No. of certificate:		
				Accuracy: ± 0.5%				

Figure 5-11-h- Example 11: Transformer test results

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2.9 Measurement of no-load loss and current

Test date: 2010.07.29 f = 60 Hz

Tap	Applied voltage (kV)	Average-voltage (kV)	rms voltage (kV)	No-load Current Based on 600MVA (Amps)	(%)	No-load loss (kW) Calibrated value	Guarantee value
After the dielectric test							
1	1.00Ur	60.60	60.66	2.540	0.044	239.1	<275
	1.10Ur	66.68	67.23	3.833	0.067	335.7	/
5	1.00Ur	46.00	45.83	2.930	0.039	187.1	/
	1.10Ur	50.53	50.16	3.865	0.051	243.4	/
9	1.00Ur	30.89	30.80	4.070	0.036	156.5	/
	1.10Ur	33.97	33.94	5.963	0.053	216.2	/
13	1.00Ur	15.53	15.48	7.845	0.035	136.8	/
	1.10Ur	17.05	17.02	11.45	0.051	191.9	/
17	1.00Ur	3.879	3.851	36.61	0.041	125.1	/
	1.10Ur	4.263	4.200	46.61	0.052	161.4	/
21	1.00Ur	15.47	15.42	8.507	0.038	135.3	/
	1.10Ur	17.06	17.03	12.10	0.054	192.1	/
25	1.00Ur	30.85	30.76	4.310	0.038	155.7	/
	1.10Ur	33.92	33.86	5.920	0.053	213.4	/
29	1.00Ur	45.97	45.82	3.030	0.040	186.2	/
	1.10Ur	50.59	50.34	3.925	0.052	245.5	/
33	1.00Ur	60.52	60.58	2.560	0.045	238.0	<275
	1.10Ur	66.66	67.01	3.599	0.063	333.4	/

110% rated voltage at rated frequency is applied to the test terminals of low-voltage winding, successfully hold for 4 hours, with LTC at 33.

Test instrument: D6100 wide band power analyzer	No.	No. of certificate:
	Accuracy: ± 0.5%	

Figure 5-11-i- Example 11: Transformer test results, Page 9

The PST positive-sequence equivalent circuit shown in Figure 5-7 is calculated from the following formulas. In Figure 5-11-h , Section 2.8, load losses test results for 9 tap positions have been provided. According to these measurements, the transformer equivalent series impedance for each tap position is calculated as shown in Table 5-1. For the other positions for which test results have not been provided, the approximate impedances and reactances can be calculated from interpolation. For this, two four-order polynomial equations have been obtained from curve-fitting methods for "Z" and "X" shown in Figure 5-12 and Figure 5-13 as follows:

$$Z = -8.0399E - 6 \times Tap^4 + 0.00055605 \times Tap^3 + 0.0085749 \times Tap^2 - 0.61773 \times Tap + 15.962$$

$$X = -8.0327E - 6 \times Tap^4 + 0.00055556 \times Tap^3 + 0.008582 \times Tap^2 - 0.61769 \times Tap + 15.96$$

$$R = \sqrt{Z^2 - X^2}$$

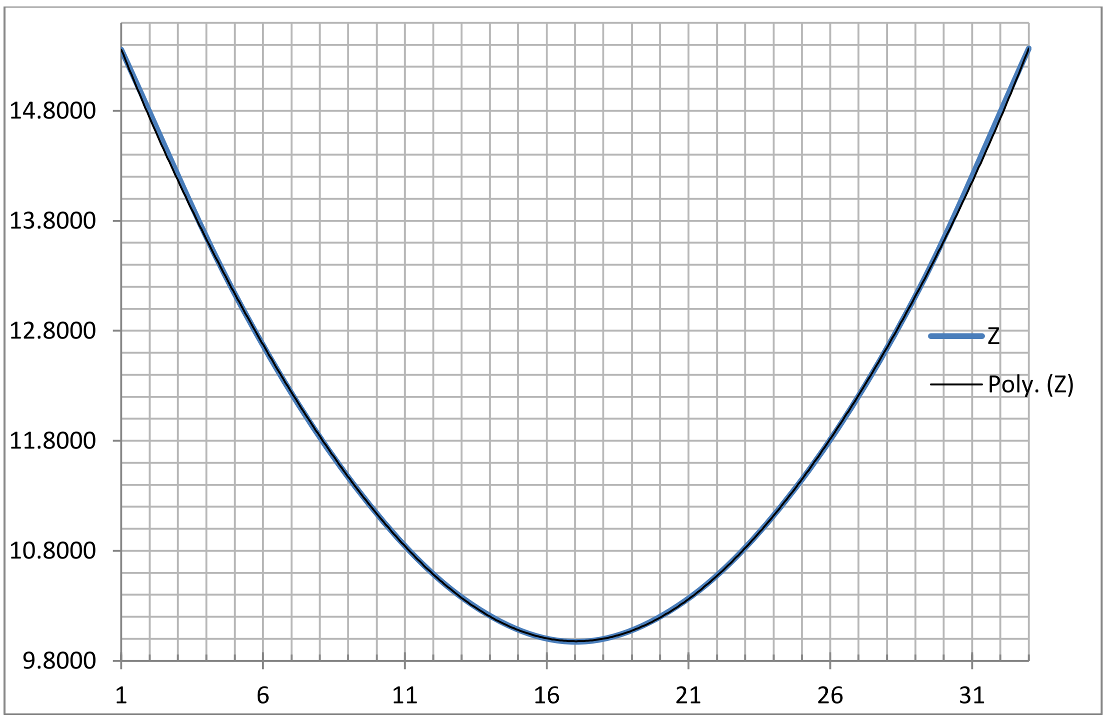

Figure 5-12- The PST series impedance versus tap position

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Table 5-1- The PST series impedance parameters calculated from test results for the given tap positions

Tap	Iz%[1] @600 MVA	P_{LL}[1] (kW)	I_{Test}[1]	r[2]	z[3]	x[4]	r[5]	z[6]	x[7]	R[8]	Z[9]	X[10]
				Pu @600 MVA (Test)			Pu @360 MVA			Ω		
1	13.63	1200	1335	0.00200	0.13630	0.13629	0.001200	0.08178	0.08177	0.2253	15.356	15.355
5	11.66	1004	1350	0.00167	0.11660	0.11659	0.001004	0.06996	0.06995	0.1885	13.137	13.136
9	10.18	837.7	1339	0.00140	0.10180	0.10179	0.000838	0.06108	0.06107	0.1573	11.470	11.468
13	9.21	709.7	1339	0.00118	0.09210	0.09209	0.000710	0.05526	0.05526	0.1333	10.377	10.376
17	8.85	615.2	1344	0.00103	0.08850	0.08849	0.000615	0.05310	0.05310	0.1155	9.971	9.9703
21	9.20	710.5	1340	0.00118	0.09200	0.09199	0.000711	0.05520	0.05520	0.1334	10.365	10.364
25	10.16	839.3	1353	0.00140	0.10160	0.10159	0.000839	0.06096	0.06095	0.1576	11.447	11.446
29	11.64	1003	1328	0.00167	0.11640	0.11639	0.001003	0.06984	0.06983	0.1883	13.114	13.113
33	13.64	1203	1337	0.00201	0.13640	0.13639	0.001203	0.08184	0.08183	0.2259	15.368	15.366

1: Given in the test report,

2: Assuming that $I_{Test} \cong I_{H\,rated}$ then $r_{pu\,@600MVA} = \frac{P_{SC\,(kW)}}{MVA_{SC\,Test} \times 1000}$

3: $z_{pu\,@600MVA} = \frac{I_Z\%}{100}$

4: $x_{pu\,@600MVA} = \sqrt{{z_{pu\,@600MVA}}^2 - {r_{pu\,@600MVA}}^2}$

5: $r_{pu\,@360MVA} = r_{pu\,@600MVA} \times \frac{360}{600}$

6: $z_{pu\,@360MVA} = z_{pu\,@600MVA} \times \frac{360}{600}$

7: $x_{pu\,@360MVA} = x_{pu\,@600MVA} \times \frac{360}{600}$

8: $R = Z_{base\,@600MVA} \times r_{pu\,@600MVA}$ or $R = \frac{P_{SC\,(kW)}}{3 \times {I_{Test}}^2} \cong \frac{P_{SC\,(kW)}}{3 \times {I_{H\,rated}}^2}$ in which

$Z_{base\,@600MVA} = \frac{MVA_{Test}}{{V_{H\,(kV)}}^2} = \frac{600}{260^2} = 112.667$

9: $Z = Z_{base\,@600MVA} \times z_{pu\,@600MVA}$

10: X= $Z_{base\,@600MVA} \times x_{pu\,@600MVA}$ or $X = \sqrt{Z^2 - R^2}$

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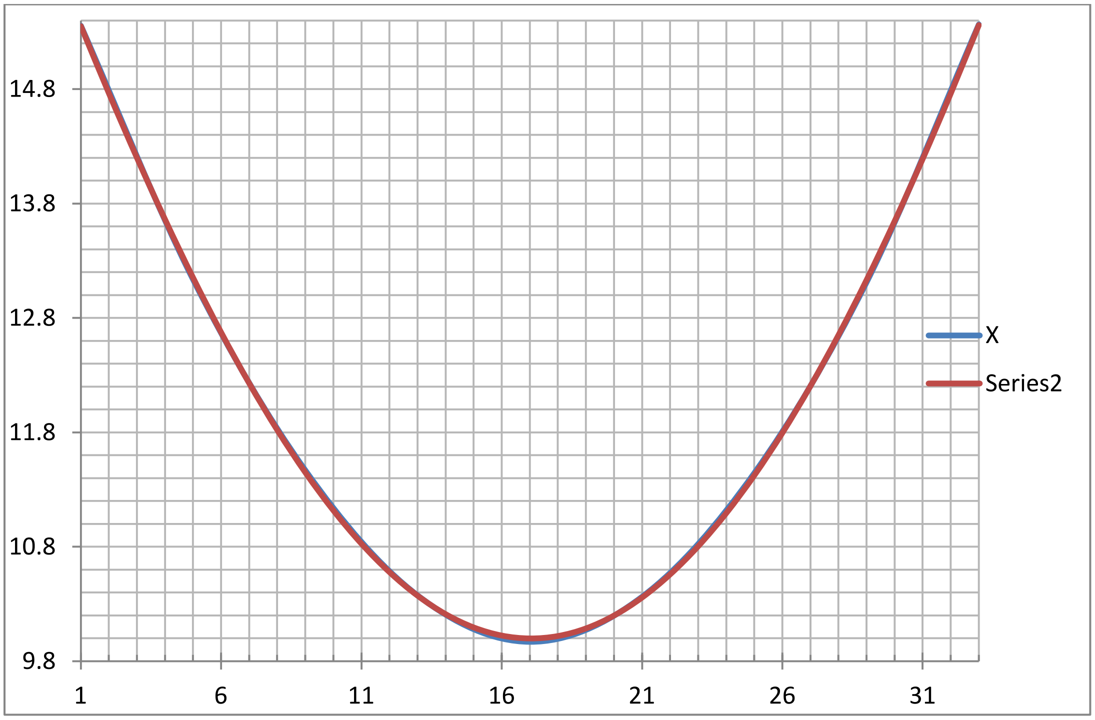

Figure 5-13- The PST series reactance versus tap position

The parameters obtained from these equations for all tap positions are given in Table 5-2, the phase- shifting transformer impedance table.

The end points of the auxiliary windings, which usually are brought out from the transformer as shown in Figure 5-10, are connected to ground. Therefore, the zero-sequence current can only flow in the auxiliary windings set. The other windings sets are open circuit for zero-sequence current, as shown in Figure 5-8.

As mentioned in Section 5.3.8, a phase-shifting transformer cannot provide phase shift under zero-sequence excitation. Therefore, the phase shift between the zero-sequence input and the output currents is always zero. As shown in Figure 5-8, the zero-sequence equivalent circuit of a PST is only a series impedance. This impedance has been calculated in Figure 5-11-g , Section 2.7 of the test report. It is 0.24+j10.1Ω.

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Table 5-2- The Impedance Table Calculated through Interpolation for all Tap Positions

Tap	R [Ω]	X [Ω]	Z [Ω]
1	0.24490	15.35144	15.35339
2	0.23658	14.76326	14.76516
3	0.22789	14.19852	14.20035
4	0.21903	13.66005	13.66181
5	0.21016	13.15052	13.15220
6	0.20144	12.67240	12.67400
7	0.19299	12.22796	12.22948
8	0.18495	11.81927	11.82072
9	0.17743	11.44823	11.44961
10	0.17054	11.11653	11.11784
11	0.16436	10.82568	10.82692
12	0.15900	10.57697	10.57816
13	0.15452	10.37153	10.37268
14	0.15099	10.21028	10.21140
15	0.14846	10.09396	10.09505
16	0.14698	10.02309	10.02417
17	0.14656	9.99804	9.99911
18	0.14721	10.01893	10.02001
19	0.14893	10.08575	10.08685
20	0.15169	10.19825	10.19938
21	0.15544	10.35601	10.35717
22	0.16015	10.55840	10.55962
23	0.16574	10.80463	10.80590
24	0.17213	11.09368	11.09501
25	0.17926	11.42435	11.42576
26	0.18701	11.79526	11.79675
27	0.19529	12.20483	12.20639
28	0.20400	12.65127	12.65292
29	0.21299	13.13263	13.13436
30	0.22215	13.64673	13.64854
31	0.23132	14.19123	14.19312
32	0.24034	14.76358	14.76554
33	0.24904	15.36104	15.36306

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6 TASMo Model of Transformers

6.1 Introduction

TASMo is a data model that represents the physical elements of the electric power transmission system. Data in TASMo allows a power system analyst to mathematically model the electrical characteristics of transmission lines, transformers, machines, and devices. This information can be used for power system studies such as load flow studies, stability studies, and short-circuit calculations. It also can be used to compile statistics about the Alberta Interconnected Electric System (AIES). More information about TASMo can be found at the AESO website.

The information in TASMo can help companies plan projects, identify opportunities, assess opportunities, and/or compete for infrastructure projects. Connection to the Alberta power transmission network requires a connection process that involves formal stages and a gated approach. The AESO monitors this process to ensure that all customers are given open and fair access. One of the required documents is the Project Data Update Package (PDUP). The purpose of the PDUP and the Supplementary Data Forms is standardization of the presentation of project data submissions to the Alberta Electric System Operator (AESO), which improves the project models posted on the AESO website for use in project studies. The PDUP forms are subject to change in the future.

Currently, three PDUP forms have to be filled out to identify the transformers:

- The Facility and Elements form (Figure 6-1), which identifies the elements being added or modified
- The Transformer Windings form (Figure 6-2), which identifies the windings and bushing of the transformer
- The Transformer Impedance form (Figure 6-3), which identifies the transformer impedances

The data for the fields in these three forms come from a number of sources, including the transformer nameplate and transformer test reports, as discussed in the previous sections. In some cases, due to lack of available information the required data can be estimated according to Table 1-3 in Section 1.16. See Table 6-1 and Table 6-2 for information regarding how to fill out the Transformer Windings form and the Transformer Impedances form.

The parameters of the generic model have been defined with V_{base} and S_{base} equal to the transformer voltage base and power base. Since the fields in the Transformer Windings form are also based on the transformer voltage and power base, no conversion from the generic model is required. The positive-sequence and zero-sequence fields of the Transformer Impedance form are based on the system voltage and 100 MVA; therefore, the generic model parameters need to be converted. To convert values from the generic model to system voltage and 100 MVA, use the following equations:

$$Z_{TASMo} = Z_{generic} \frac{V_{generic}^2}{S_{generic}} \frac{S_{TASMo}}{V_{TASMo}^2}$$

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$$Y_{TASMo} = Y_{generic} \frac{S_{generic}}{V_{generic}^2} \frac{V_{TASMo}^2}{S_{TASMo}}$$

Where $V_{generic}$ and $S_{generic}$ are the transformer voltage base and power base, V_{TASMo}, S_{TASMo} are the system voltage and 100 MVA, $Z_{generic}$ and $Y_{generic}$ are the generic model impedance and admittance values, and Z_{TASMo} and Y_{TASMo} are the impedance and admittance values used in the Transformer Impedance form.

Table 6-1- Transformer Winding Form Fields

Field Number	Field Name	Source
1	Element Code	This unique code for the transformer generally contains the substation code/name followed by the transformer identifier.
2	Number of Windings	The number of windings in the transformer.
3	Number of Bushings	The number of bushings on the transformer.
4	Winding	The code used to cross-reference with the bushings and ratings. It can be one of the following: – P (Primary winding) – S (Secondary winding) – T (Tertiary-Voltage bushing)
5	D/Y	Indicates whether the winding is connected in a Delta or Wye configuration.
6	GND	Indicates if the winding is grounded (‘Yes’) or ungrounded (‘No’).
7, 8	Grounding R (Ohm), Grounding X (Ohm)	The external resistance or NGR that the transformer is grounded with (expressed in ohms).
9	Rating Condition	The condition for which the specified rating is valid; i.e., ONAN, ONAF, ONAF2, etc.
10	Rating (MVA)	The rating expressed in MVA.
11	Installed? (Y/N)	Indicates whether the rating is available (‘Y’) or provisional (‘N’).
12	Bushing	The termination identifier. It can be one of the following: – H (Associated with the primary winding or high-voltage bus of the transformer) – X (Associated with the secondary winding or low-voltage bus of the transformer) – Y (Associated with the tertiary winding [energized or buried]) – M (Associated with the midpoint bus in the case of a three-winding transformer) – S (Associated with the source side winding or the network bus of the voltage regulator transformer) – L (Associated with the load side winding or the load bus of the voltage regulator transformer)
13	Bus	The number of the bus that the bushing connects to.
14	Bushing kV	The rated voltage of the bushing. It can be different from the nominal voltage of the bus it is connected to.

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Field Number	Field Name	Source
15, 16	Max Tap (pu), Min Tap (pu)	The per unit operable ranges of the transformer at the voltage level the bushing is rated for.
17	N Taps	The number of tap changers on the transformer.
18	Actual Tap	The per unit nominal operating voltage of the transformer. For bushings without a tap changer the value will be 1.
19	Tap Changing Strategy	This will be one of the following values: OFF, OLTC-M, OLTC-S, OLTC-A, FIXED. – OFF indicates off-load tap changing. – OLTC-M indicates on-load tap changing (manual-local). – OLTC-S indicates on-load tap changing (supervisory). – OLTC-A indicates on-load tap changing (automatic). – Fixed indicates fixed taps.
20	Regulated Bus	The remote bus intended to be controlled by the tap changer (empty if not applicable).
21	Control Bushing	The bushing intended to be controlled by the tap changer (empty if not applicable).
22, 23	VMAX, VMIN	For a voltage-controlling tap-changer: the maximum and minimum allowable operable voltage at the controlled bus.. For phase-shifting tap changer: specify the control band as the power flow into the bushing. These values should be based on the system voltage and 100 MVA.

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Table 6-2- Transformer Impedances Form Fields

Field Number	Field Name	Source
1	XFMR	This is the same as the element code in the Transformer Winding form.
2, 3	From Bus, To Bus	The termination bushings. – H represents the transformer primary high side. – X represents the transformer secondary low side. – Y represents the transformer tertiary. – M represents the fictitious midpoint bus in the modelling of a 3-winding transformer
4	Circuit ID	A two-character circuit identifier for the transformer.
5	MVA Base	The MVA Base associated with the core and copper losses recorded in fields 12 through 16.
6, 7	Positive-Sequence and Zero-Sequence R, X	The positive-sequence and zero-sequence real and reactive impedances for every series branch in the equivalent circuit expressed in per unit on a 100 MVA base and at system nominal voltage.
8, 9, 10, 11	Positive-Sequence and Zero-Sequence GFROM, BFROM, GTO, BTO	The positive-sequence and zero-sequence real and reactive shunt admittances to ground for every shunt branch in the equivalent circuit expressed in per unit on a 100 MVA base and at system nominal voltage.
12	Short Circuit	Short-circuit impedances expressed in % impedance in a load loss short-circuit test.
13	Copper Loss	Short-circuit copper losses expressed in kW in a short-circuit test.
14	Open Circuit	Open-circuit excitation current expressed in % excitation current in an excitation no-load open-circuit test.
15	Core Loss	Open-circuit core losses expressed in kW in an excitation no-load open-circuit test.
16	Short Circuit	Short-circuit impedances expressed in % impedance in a zero-sequence impedance test.

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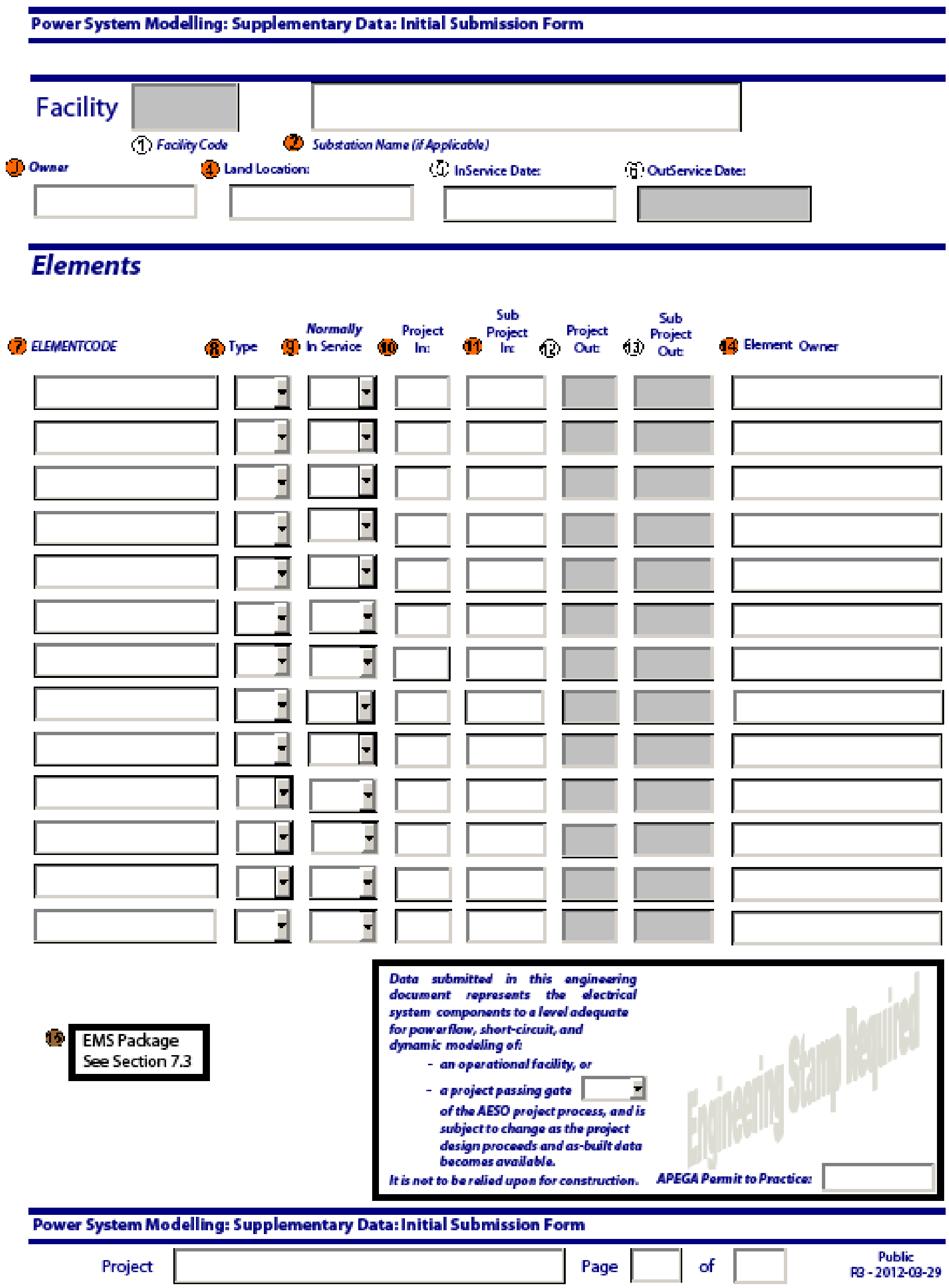

Power System Modelling: Supplementary Data: Initial Submission Form

Facility

① Facility Code ② Substation Name (if Applicable)

③ Owner ④ Land Location: ⑤ InService Date: ⑥ OutService Date:

Elements

⑦ ELEMENTCODE ⑧ Type ⑨ Normally In Service ⑩ Project In: ⑪ Sub Project In: ⑫ Project Out: ⑬ Sub Project Out: ⑭ Element Owner

⑮ EMS Package See Section 7.3

Data submitted in this engineering document represents the electrical system components to a level adequate for powerflow, short-circuit, and dynamic modeling of:

- an operational facility, or
- a project passing gate of the AESO project process, and is subject to change as the project design proceeds and as-built data becomes available.

It is not to be relied upon for construction.

Engineering Stamp Required

APEGA Permit to Practice:

Power System Modelling: Supplementary Data: Initial Submission Form

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Figure 6-1- Facility and Elements form

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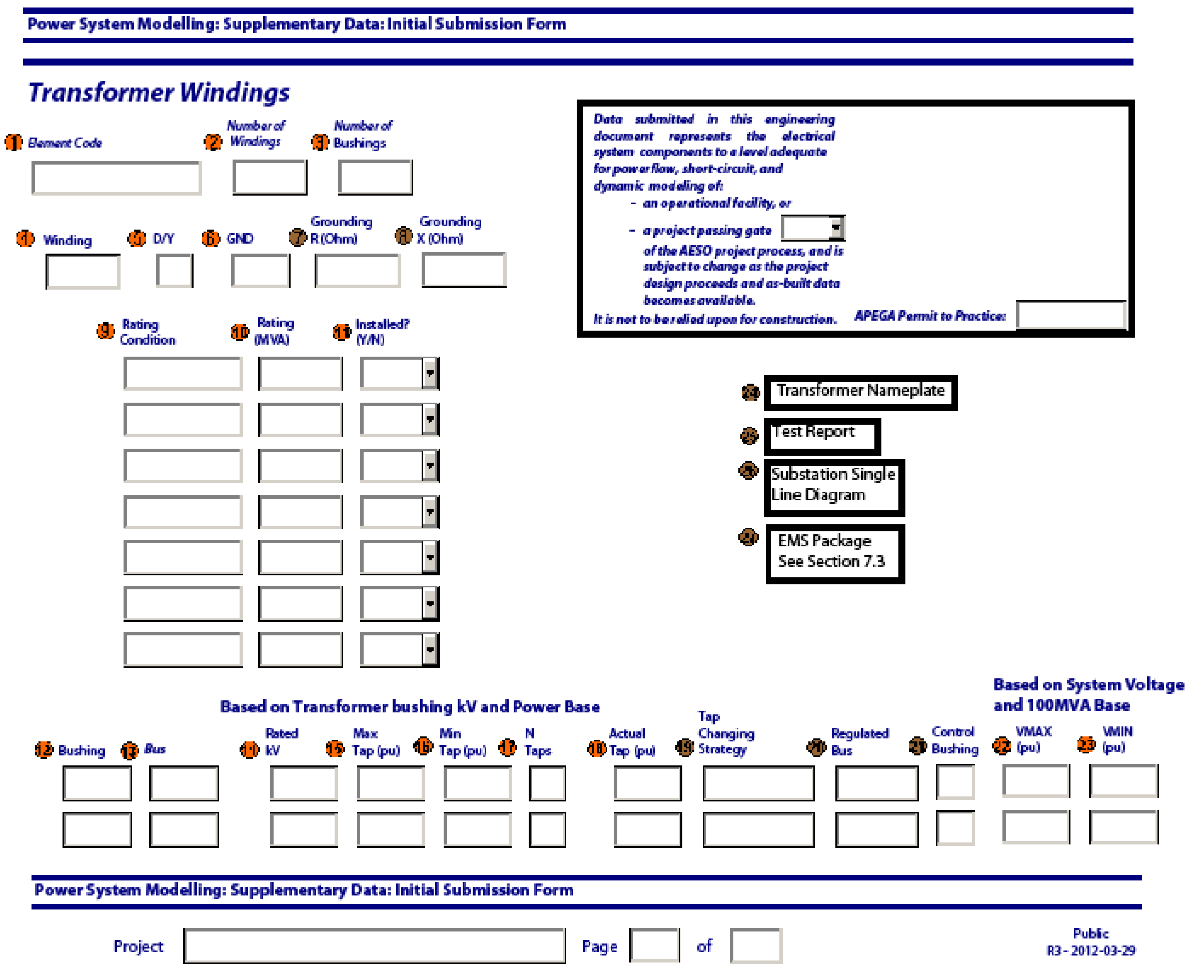

Power System Modelling: Supplementary Data: Initial Submission Form

Transformer Windings

1 Element Code | 2 Number of Windings | 3 Number of Bushings

4 Winding | 5 D/Y | 6 GND | 7 Grounding R (Ohm) | 8 Grounding X (Ohm)

9 Rating Condition | 10 Rating (MVA) | 11 Installed? (Y/N)

Data submitted in this engineering document represents the electrical system components to a level adequate for power flow, short-circuit, and dynamic modeling of:
- an operational facility, or
- a project passing gate [ ] of the AESO project process, and is subject to change as the project design proceeds and as-built data becomes available.
It is not to be relied upon for construction. **APEGA Permit to Practice:**

24 Transformer Nameplate
25 Test Report
26 Substation Single Line Diagram
27 EMS Package See Section 7.3

Based on Transformer bushing kV and Power Base

Based on System Voltage and 100MVA Base

12 Bushing | 13 Bus | 14 Rated kV | 15 Max Tap (pu) | 16 Min Tap (pu) | 17 N Taps | 18 Actual Tap (pu) | 19 Tap Changing Strategy | 20 Regulated Bus | 21 Control Bushing | 22 VMAX (pu) | 23 VMIN (pu)

Power System Modelling: Supplementary Data: Initial Submission Form

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Figure 6-2- Transformer Windings form

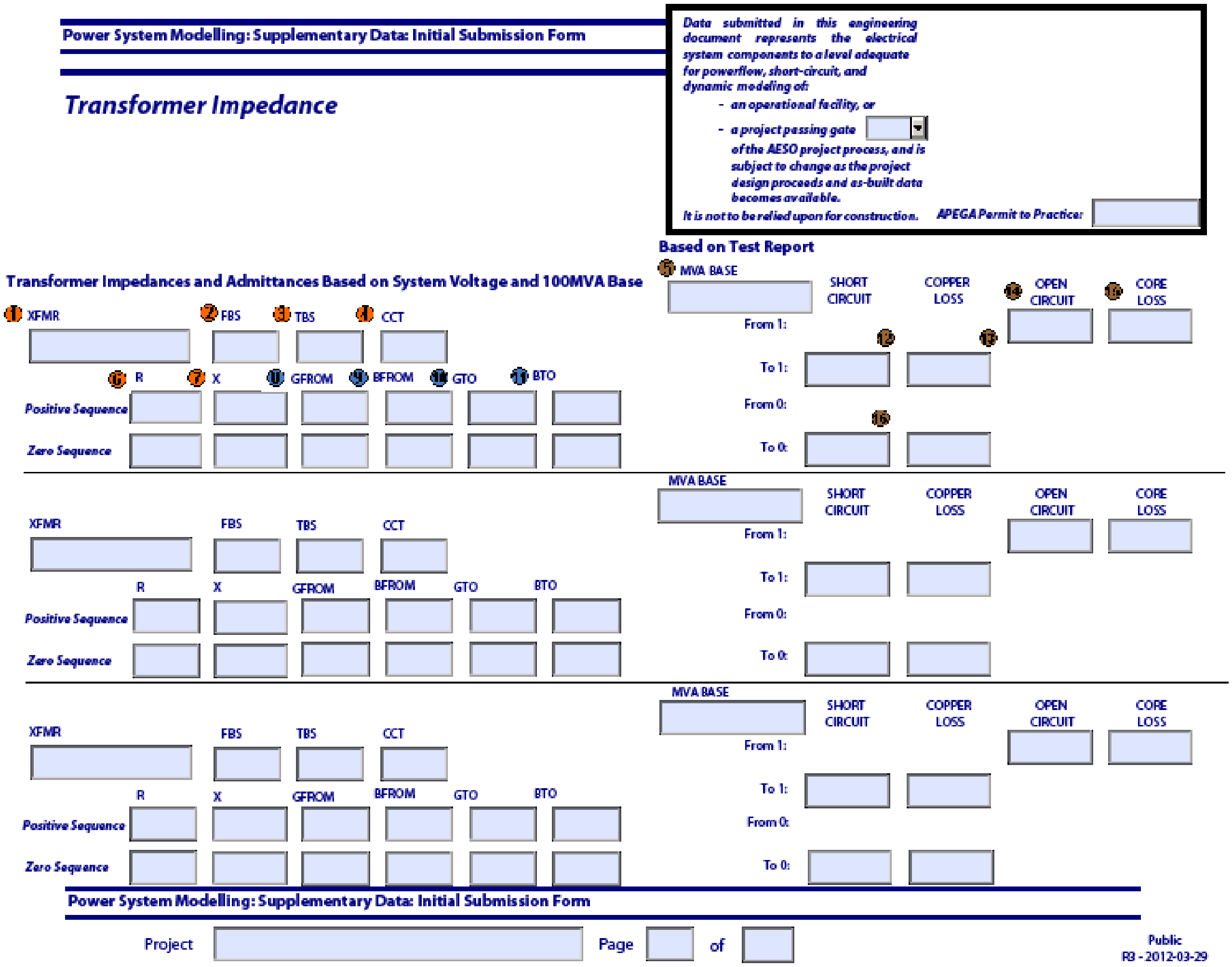

Figure 6-3- Transformer Impedance form

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6.2 Two-Winding Transformers

6.2.1 Two-Winding Transformer with Wye Primary and Wye Secondary

This transformer type requires that two Transformer Windings forms and the first section of the Transformer Impedance form be filled out. The forms should be filled out as seen in Table 6-3, Table 6-4, and Table 6-5. The example values come from the example transformer found in Section 2.4.4. System bus voltages of 138 kV and 25 kV have been assumed for the primary and secondary windings, respectively.

Table 6-3- Y-Y Transformer Windings Form 1

Field Number	Field Name	Generic Model Source	Form Value
2	Number of Windings	Transformer Type	2
3	Number of Bushings	Transformer Type	2
4	Winding	Primary Winding Data	P
5	D/Y	Transformer Type	Y
6	GND	Grounding Configuration	Y
7	Grounding R (Ohm)	Grounding Impedance	0
8	Grounding X (Ohm)	Grounding Impedance	0
9	Rating Condition	Transformer ONAN Ratings	ONAN
			ONAF
			ONAF2
10	Rating (MVA)	Transformer ONAN Ratings	15
			20
			25
11	Installed?	Always Y	Y
			Y
			Y
12	Bushing	Transformer Type Primary Winding	H
14	Bushing kV	Winding Voltages	138
15	Max Tap (pu)	Tap Range	1.1
16	Min Tap	Tap Range	0.9
17	N Taps	Number of Tap Steps	17

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Table 6-4- Y-Y Transformer Windings Form 2

Field Number	Field Name	Generic Model Source	Form Value
2	Number of Windings	Transformer Type	2
3	Number of Bushings	Transformer Type	2
4	Winding	Secondary Winding Data	S
5	D/Y	Transformer Type	Y
6	GND	Grounding Configuration	Y
7	Grounding R (Ohm)	Grounding Impedance	0
8	Grounding X (Ohm)	Grounding Impedance	0
9	Rating Condition	Transformer ONAN Ratings	ONAN
			ONAF
			ONAF2
10	Rating (MVA)	Transformer ONAN Ratings	15
			20
			25
11	Installed?	Always Y	Y
			Y
			Y
12	Bushing	Transformer Type Secondary Winding	X
14	Bushing kV	Winding Voltages	26.5
15	Max Tap (pu)	Tap Range	1
16	Min Tap	Tap Range	1
17	N Taps	Number of Tap Steps	1

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Table 6-5- Y-Y Transformer Impedance Form

Field Number	Field Name	Generic Model Source	Generic Model Value	Form Value
3	From Bus	Primary Bushing	-	H
4	To Bus	Secondary Bushing	-	X
5	MVA Base	No Load Loss/Load Loss Test MVA	15	15
6	Positive Sequence R	Load Losses Equivalent Resistance	0.00278	0.01852
	Zero Sequence R	Z_{HX0}	0.07942	0.52949
7	Positive Sequence X	Windings' Leakage Reactance	0.07675	0.51167
	Zero Sequence X	Z_{HX0}	0	0
8	Positive Sequence GFROM	No Load Losses Equivalent Conductance	0.00077	0.00012
	Zero Sequence GFROM	$\frac{1}{Z'_{XN0}}$	0.21931	0.03290
9	Positive Sequence BFROM	Magnetizing Branch Susceptance	-0.00090	-0.00014
	Zero Sequence BFROM	$\frac{1}{Z'_{XN0}}$	0	0
10	Positive Sequence GTO	Not Used	-	0
	Zero Sequence GTO	$\frac{1}{Z_{HN0}}$	1.92440	0.28869
11	Positive Sequence BTO	Not Used	-	0
	Zero Sequence BTO	$\frac{1}{Z_{HN0}}$	0	0
12	Short Circuit	Load Loss Test Impedance	7.68	7.68
13	Copper Loss	Load Loss	41.66	41.66
14	Open Circuit	Excitation Current	0.119	0.119
15	Core Loss	No-Load Loss	11.61	11.61

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6.2.2 Two-Winding Transformer with Wye Primary and Delta Secondary

This transformer type requires that two Transformer Windings forms and the first section of the Transformer Impedance form be filled out. The forms should be filled out as seen in Table 6-6, Table 6-7 and Table 6-8. The example values come from the example transformer found in Section 2.5.4. System bus voltages of 69 kV and 13.8 kV have been assumed for the primary and secondary windings, respectively.

Table 6-6- Y-D Transformer Windings Form 1

Field Number	Field Name	Generic Model Source	Form Value
2	Number of Windings	Transformer Type	2
3	Number of Bushings	Transformer Type	2
4	Winding	Primary Winding Data	P
5	D/Y	Transformer Type	Y
6	GND	Grounding Configuration	Y
7	Grounding R (Ohm)	Grounding Impedance	0
8	Grounding X (Ohm)	Grounding Impedance	0.50
9	Rating Condition	Transformer ONAN Ratings	ONAN
			ONAF
			ONAF2
10	Rating (MVA)	Transformer ONAN Ratings	50
			66
			83
11	Installed?	Always Y	Y
			Y
			Y
12	Bushing	Transformer Type Primary Winding	H
14	Bushing kV	Winding Voltages	72
15	Max Tap (pu)	Tap Range	1.1
16	Min Tap	Tap Range	0.9
17	N Taps	Number of Tap Steps	17

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Table 6-7- Y-D Transformer Windings Form 2

Field Number	Field Name	Generic Model Source	Form Value
2	Number of Windings	Transformer Type	2
3	Number of Bushings	Transformer Type	2
4	Winding	Secondary Winding Data	S
5	D/Y	Transformer Type	D
6	GND	Grounding Configuration	N
7	Grounding R (Ohm)	Grounding Impedance	0
8	Grounding X (Ohm)	Grounding Impedance	0
9	Rating Condition	Transformer ONAN Ratings	ONAN
			ONAF
			ONAF2
10	Rating (MVA)	Transformer ONAN Ratings	50
			66
			83
11	Installed?	Always Y	Y
			Y
			Y
12	Bushing	Transformer Type Secondary Winding	X
14	Bushing kV	Winding Voltages	13.8
15	Max Tap (pu)	Tap Range	1
16	Min Tap	Tap Range	1
17	N Taps	Number of Tap Steps	1

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Table 6-8- Y-D Transformer Impedance Form

Field Number	Field Name	Generic Model Source	Generic Model Value	Form Value
3	From Bus	Primary Bushing	-	H
4	To Bus	Secondary Bushing	-	X
5	MVA Base	No Load Loss/Load Loss Test MVA	50	50
6	Positive Sequence R	Load Losses Equivalent Resistance	0.00192	0.00418
	Zero Sequence R	Z_{HX0}	0	0
7	Positive Sequence X	Windings' Leakage Reactance	0.11638	0.25345
	Zero Sequence X	Z_{HX0}	0.11247	0.24493
8	Positive Sequence GFROM	No Load Losses Equivalent Conductance	0.000689	0.00032
	Zero Sequence GFROM	Not Used	-	0
9	Positive Sequence BFROM	Magnetizing Branch Susceptance	-0.00058	-0.00027
	Zero Sequence BFROM	Not Used	-	0
10	Positive Sequence GTO	Not Used	-	0
	Zero Sequence GTO	$\frac{1}{Z_{HN0}}$	0	0
11	Positive Sequence BTO	Not Used	-	0
	Zero Sequence BTO	$\frac{1}{Z_{HN0}}$	-207.34	-95.220
12	Short Circuit	Load Loss Test Impedance	11.64	11.64
13	Copper Loss	Load Loss	96.014	96.014
14	Open Circuit	Excitation Current	0.09	0.09
15	Core Loss	No-Load Loss	34.467	34.467

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6.2.3 Two-Winding Transformer with Delta Primary Delta Secondary

This transformer type requires that two Transformer Windings forms and the first section of the Transformer Impedance form be filled out. The forms should be filled out as seen in Table 6-9, Table 6-10, and Table 6-11. The example values come from the example transformer found in Section 2.6.4. System bus voltages of 69 kV and 2.4 kV have been assumed for the primary and secondary windings, respectively.

Table 6-9- D-D Transformer Windings Form 1

Field Number	Field Name	Generic Model Source	Form Value
2	Number of Windings	Transformer Type	2
3	Number of Bushings	Transformer Type	2
4	Winding	Primary Winding Data	P
5	D/Y	Transformer Type	D
6	GND	Grounding Configuration	N
7	Grounding R (Ohm)	Grounding Impedance	0
8	Grounding X (Ohm)	Grounding Impedance	0
9	Rating Condition	Transformer ONAN Ratings	ONAN
10	Rating (MVA)	Transformer ONAN Ratings	7.5
11	Installed?	Always Y	Y
12	Bushing	Transformer Type Primary Winding	H
14	Bushing kV	Winding Voltages	66
15	Max Tap (pu)	Tap Range	1.05
16	Min Tap	Tap Range	0.95
17	N Taps	Number of Tap Steps	5

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Table 6-10- D-D Transformer Windings Form 2

Field Number	Field Name	Generic Model Source	Form Value
2	Number of Windings	Transformer Type	2
3	Number of Bushings	Transformer Type	2
4	Winding	Secondary Winding Data	S
5	D/Y	Transformer Type	D
6	GND	Grounding Configuration	N
7	Grounding R (Ohm)	Grounding Impedance	0
8	Grounding X (Ohm)	Grounding Impedance	0
9	Rating Condition	Transformer ONAN Ratings	ONAN
10	Rating (MVA)	Transformer ONAN Ratings	7.5
11	Installed?	Always Y	Y
12	Bushing	Transformer Type Secondary Winding	X
14	Bushing kV	Winding Voltages	2.4
15	Max Tap (pu)	Tap Range	1
16	Min Tap	Tap Range	1
17	N Taps	Number of Tap Steps	1

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Table 6-11- D-D Transformer Impedance Form

Field Number	Field Name	Generic Model Source	Generic Model Value	Form Value
3	From Bus	Primary Bushing	-	H
4	To Bus	Secondary Bushing	-	X
5	MVA Base	No Load Loss/Load Loss Test MVA	7.5	7.5
6	Positive Sequence R	Load Losses Equivalent Resistance	0.00548	0.06687
	Zero Sequence R	Not Used	-	0
7	Positive Sequence X	Windings' Leakage Reactance	0.06920	0.84418
	Zero Sequence X	Not Used	-	0
8	Positive Sequence GFROM	No Load Losses Equivalent Conductance	0.00165	0.00014
	Zero Sequence GFROM	Not Used	-	0
9	Positive Sequence BFROM	Magnetizing Branch Susceptance	-0.00986	-0.00081
	Zero Sequence BFROM	Not Used	-	0
10	Positive Sequence GTO	Not Used	-	0
	Zero Sequence GTO	Not Used	-	0
11	Positive Sequence BTO	Not Used	-	0
	Zero Sequence BTO	Not Used	-	0
12	Short Circuit	Load Loss Test Impedance	6.93	6.93
13	Copper Loss	Load Loss	41.11	41.11
14	Open Circuit	Excitation Current	1	1
15	Core Loss	No-Load Loss	12.35	12.35

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6.2.4 Two-Winding Transformer with Delta Primary Wye Secondary

This transformer type requires that two Transformer Windings forms and the first section of the Transformer Impedance form be filled out. The forms should be filled out as seen in Table 6-12, Table 6-13, and Table 6-14. The example values come from the example transformer found in Section 2.7.4. System bus voltages of 138 kV and 13.8 kV have been assumed for the primary and secondary windings, respectively.

Table 6-12 – D-Y Transformer Windings Form 1

Field Number	Field Name	Generic Model Source	Form Value
2	Number of Windings	Transformer Type	2
3	Number of Bushings	Transformer Type	2
4	Winding	Primary Winding Data	P
5	D/Y	Transformer Type	D
6	GND	Grounding Configuration	N
7	Grounding R (Ohm)	Grounding Impedance	0
8	Grounding X (Ohm)	Grounding Impedance	0
9	Rating Condition	Transformer ONAN Ratings	ONAN
			ONAF
			ONAF2
10	Rating (MVA)	Transformer ONAN Ratings	20
			26.6
			33.3
11	Installed?	Always Y	Y
			Y
			Y
12	Bushing	Transformer Type Primary Winding	H
14	Bushing kV	Winding Voltages	138
15	Max Tap (pu)	Tap Range	1.1
16	Min Tap	Tap Range	0.9
17	N Taps	Number of Tap Steps	17

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Table 6-13- D-Y Transformer Windings Form 2

Field Number	Field Name	Generic Model Source	Form Value
2	Number of Windings	Transformer Type	2
3	Number of Bushings	Transformer Type	2
4	Winding	Secondary Winding Data	S
5	D/Y	Transformer Type	Y
6	GND	Grounding Configuration	Y
7	Grounding R (Ohm)	Grounding Impedance	40.0
8	Grounding X (Ohm)	Grounding Impedance	0
9	Rating Condition	Transformer ONAN Ratings	ONAN
			ONAF
			ONAF2
10	Rating (MVA)	Transformer ONAN Ratings	20
			26
			33.3
11	Installed?	Always Y	Y
			Y
			Y
12	Bushing	Transformer Type Secondary Winding	X
14	Bushing kV	Winding Voltages	13.8
15	Max Tap (pu)	Tap Range	1
16	Min Tap	Tap Range	1
17	N Taps	Number of Tap Steps	1

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Table 6-14- D-Y Transformer Impedance Form

Field Number	Field Name	Generic Model Source	Generic Model Value	Form Value
3	From Bus	Primary Bushing	-	H
4	To Bus	Secondary Bushing	-	X
5	MVA Base	No Load Loss/Load Loss Test MVA	20	20
6	Positive Sequence R	Load Losses Equivalent Resistance	0.00278	0.01388
	Zero Sequence R	Z_{HX0}	0.08640	0.43200
7	Positive Sequence X	Windings' Leakage Reactance	0.06855	0.34273
	Zero Sequence X	Z_{HX0}	0	0
8	Positive Sequence GFROM	No Load Losses Equivalent Conductance	0.00115	0.00023
	Zero Sequence GFROM	$\frac{1}{Z'_{XN0}}$	0.23805	0.04761
9	Positive Sequence BFROM	Magnetizing Branch Susceptance	-0.00352	-0.00070
	Zero Sequence BFROM	$\frac{1}{Z'_{XN0}}$	0	0
10	Positive Sequence GTO	Not Used	-	0
	Zero Sequence GTO	Not Used	-	0
11	Positive Sequence BTO	Not Used	-	0
	Zero Sequence BTO	Not Used	-	0
12	Short Circuit	Load Loss Test Impedance	6.8602	6.8602
13	Copper Loss	Load Loss	55.505	55.505
14	Open Circuit	Excitation Current	0.3705	0.3705
15	Core Loss	No-Load Loss	22.991	22.991

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6.2.5 Two-Winding Autotransformer (Wye-Wye)

This transformer type requires that one Transformer Windings form and the first section of the Transformer Impedance form be filled out. The forms should be filled out as seen in Table 6-15 and Table 6-16. The example values come from the example transformer found in Section 2.8.4. System bus voltages of 250 kV and 138 kV have been assumed for the primary and secondary buses, respectively.

Table 6-15- Y-Y Autotransformer Transformer Windings Form

Field Number	Field Name	Generic Model Source	Form Value
2	Number of Windings	Transformer Type	2
3	Number of Bushings	Transformer Type	2
4	Winding	Primary Winding Data	P
5	D/Y	Transformer Type	Y
6	GND	Grounding Configuration	Y
7	Grounding R (Ohm)	Grounding Impedance	0
8	Grounding X (Ohm)	Grounding Impedance	0
9	Rating Condition	Transformer ONAN Ratings	ONAN
			ONAF
			ONAF2
10	Rating (MVA)	Transformer ONAN Ratings	90
			120
			150
11	Installed?	Always Y	Y
			Y
			Y
12	Bushing	Transformer Type Primary Winding	H
			X
14	Bushing kV	Winding Voltages	250
			138
15	Max Tap (pu)	Tap Range	1.075
			1
16	Min Tap	Tap Range	0.925
			1
17	N Taps	Number of Tap Steps	18
			1

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Table 6-16- Y-Y Autotransformer Transformer Impedance Form

Field Number	Field Name	Generic Model Source	Generic Model Value	Form Value
3	From Bus	Primary Bushing	-	H
4	To Bus	Secondary Bushing	-	X
5	MVA Base	No Load Loss/Load Loss Test MVA	150	150
6	Positive Sequence R	Load Losses Equivalent Resistance	0.00121	0.00146
	Zero Sequence R	Z_{HX0}	8.16387	9.84263
7	Positive Sequence X	Windings' Leakage Reactance	0.05081	0.06125
	Zero Sequence X	Z_{HX0}	0	0
8	Positive Sequence GFROM	No Load Losses Equivalent Conductance	0.00090	0.00075
	Zero Sequence GFROM	$\frac{1}{Z'_{XN0}}$	6.24270	5.17795
9	Positive Sequence BFROM	Magnetizing Branch Susceptance	-0.002806	-0.00233
	Zero Sequence BFROM	$\frac{1}{Z'_{XN0}}$	0	0
10	Positive Sequence GTO	Not Used	-	0
	Zero Sequence GTO	$\frac{1}{Z_{HN0}}$	2.02839	1.68242
11	Positive Sequence BTO	Not Used	-	0
	Zero Sequence BTO	$\frac{1}{Z_{HN0}}$	0	0
12	Short Circuit	Load Loss Test Impedance	8.47	8.47
13	Copper Loss	Load Loss	302.4	302.4
14	Open Circuit	Excitation Current	0.177	0.177
15	Core Loss	No-Load Loss	81.33	81.33

6.2.6 Two-Winding Voltage Regulator Transformer

This transformer type requires that two Transformer Windings forms and the first section of the Transformer Impedance form be filled out. The forms should be filled out as shown in Table 6-17, Table 6-18, and Table 6-19. The example values come from the example transformer in Section 2.4.4. System bus voltages of 3.744 kV and 4.16 kV have been assumed for the primary and secondary windings, respectively.

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Table 6-17- Votlage Regulator Transformer Windings Form 1

Field Number	Field Name	Generic Model Source	Form Value
2	Number of Windings	Transformer Type	2
3	Number of Bushings	Transformer Type	2
4	Winding	Primary Winding Data	P
5	D/Y	Transformer Type	Y
6	GND	Grounding Configuration	Y
7	Grounding R (Ohm)	Grounding Impedance	0
8	Grounding X (Ohm)	Grounding Impedance	0
9	Rating Condition	Transformer ONAN Ratings	ONAN
			ONAF
			ONAF2
10	Rating (MVA)	Transformer ONAN Ratings	15
			20
			25
11	Installed?	Always Y	Y
			Y
			Y
12	Bushing	Transformer Type Primary Winding	S
14	Bushing kV	Winding Voltages	4.16
15	Max Tap (pu)	Tap Range	1.25
16	Min Tap	Tap Range	0.75
17	N Taps	Number of Tap Steps	17

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Table 6-18- Voltage Regulator Transformer Windings Form 2

Field Number	Field Name	Generic Model Source	Form Value
2	Number of Windings	Transformer Type	2
3	Number of Bushings	Transformer Type	2
4	Winding	Secondary Winding Data	S
5	D/Y	Transformer Type	Y
6	GND	Grounding Configuration	Y
7	Grounding R (Ohm)	Grounding Impedance	0
8	Grounding X (Ohm)	Grounding Impedance	0
9	Rating Condition	Transformer ONAN Ratings	ONAN
			ONAF
			ONAF2
10	Rating (MVA)	Transformer ONAN Ratings	15
			20
			25
11	Installed?	Always Y	Y
			Y
			Y
12	Bushing	Transformer Type Secondary Winding	L
14	Bushing kV	Winding Voltages	4.16
15	Max Tap (pu)	Tap Range	1
16	Min Tap	Tap Range	1
17	N Taps	Number of Tap Steps	1

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Table 6-19- Voltage Regulator Transformer Impedance Form

Field Number	Field Name	Generic Model Source	Generic Model Value	Form Value
3	From Bus	Primary Bushing	-	S
4	To Bus	Secondary Bushing	-	L
5	MVA Base	No Load Loss/Load Loss Test MVA	15	15
6	Positive Sequence R	Load Losses Equivalent Resistance	0.00168	0.01383
	Zero Sequence R	Z_{SL0}	0.00171	0.01407
7	Positive Sequence X	Windings' Leakage Reactance	0.01482	0.12193
	Zero Sequence X	Z_{SL0}	0.01508	0.12413
8	Positive Sequence GFROM	No Load Losses Equivalent Conductance	0.00015	0.00019
	Zero Sequence GFROM	$\frac{1}{Z'_{LN0}}$	1.33605	0.16233
9	Positive Sequence BFROM	Magnetizing Branch Susceptance	-0.00211	-0.00026
	Zero Sequence BFROM	$\frac{1}{Z'_{LN0}}$	-11.7835	-1.4317
10	Positive Sequence GTO	Not Used	-	0
	Zero Sequence GTO	$\frac{1}{Z_{SN0}}$	0.14853	0.01804
11	Positive Sequence BTO	Not Used	-	0
	Zero Sequence BTO	$\frac{1}{Z_{SN0}}$	-1.3092	-0.15908
12	Short Circuit	Load Loss Test Impedance	7.68	1.4925
13	Copper Loss	Load Loss	41.66	25.197
14	Open Circuit	Excitation Current	0.119	0.212
15	Core Loss	No-Load Loss	11.61	2.31

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6.3 Three-Winding Transformers

6.3.1 Three-Winding Transformer with Wye Primary, Wye Secondary, and Wye Tertiary

This transformer type requires that three Transformer Winding forms and all three sections of the Transformer Impedance form be filled out. See Table 6-20, Table 6-21, Table 6-22, and Table 6-23. The example values come from the example transformer found in Section 3.4.4. System bus voltages of 240 kV, 25 kV, and 25 kV have been assumed for the primary, secondary, and tertiary windings, respectively.

Table 6-20- Y-Y-Y Transformer Windings Form 1

Field Number	Field Name	Generic Model Source	Form Value
2	Number of Windings	Transformer Type	3
3	Number of Bushings	Transformer Type	4
4	Winding	Primary Winding	P
5	D/Y	Transformer Type	Y
6	GND	Grounding Configuration	Y
7	Grounding R (Ohm)	Grounding Impedance	0
8	Grounding X (Ohm)	Grounding Impedance	0
9	Rating Condition	Transformer ONAN Ratings	ONAN
			ONAF
			ONAF2
10	Rating (MVA)	Transformer ONAN Ratings	50
			66.7
			83.3
11	Installed?	Always Y	Y
			Y
			Y
12	Bushing	Primary Bushing Imaginary Middle Bushing	H
			M
14	Bushing kV	Winding Voltages	245
			245
15	Max Tap (pu)	Tap Range	1.3
			1
16	Min Tap (pu)	Tap Range	0.7
			1
17	N Taps	Number of Tap Steps	24
			1

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Table 6-21- Y-Y-Y Transformer Windings Form 2

Field Number	Field Name	Generic Model Source	Form Value
2	Number of Windings	Transformer Type	3
3	Number of Bushings	Transformer Type	4
4	Winding	Secondary Winding	S
5	D/Y	Transformer Type	Y
6	GND	Grounding Configuration	Y
7	Grounding R (Ohm)	Grounding Impedance	0
8	Grounding X (Ohm)	Grounding Impedance	1
9	Rating Condition	Transformer ONAN Ratings	ONAN
			ONAF
			ONAF2
10	Rating (MVA)	Transformer ONAN Ratings	25
			33.4
			41.7
11	Installed?	Always Y	Y
			Y
			Y
12	Bushing	Secondary Bushing	X
14	Bushing kV	Winding Voltages	26
15	Max Tap (pu)	Tap Range	1
16	Min Tap (pu)	Tap Range	1
17	N Taps	Number of Tap Steps	1

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Table 6-22- Y-Y-Y Transformer Windings Form 3

Field Number	Field Name	Generic Model Source	Form Value
2	Number of Windings	Transformer Type	3
3	Number of Bushings	Transformer Type	4
4	Winding	Tertiary Winding	T
5	D/Y	Transformer Type	Y
6	GND	Grounding Configuration	Y
7	Grounding R (Ohm)	Grounding Impedance	0
8	Grounding X (Ohm)	Grounding Impedance	1
9	Rating Condition	Transformer ONAN Ratings	ONAN
			ONAF
			ONAF2
10	Rating (MVA)	Transformer ONAN Ratings	25
			33.4
			41.7
11	Installed?	Always Y	Y
			Y
			Y
12	Bushing	Tertiary Bushing	Y
14	Bushing kV	Winding Voltages	26
15	Max Tap (pu)	Tap Range	1
16	Min Tap (pu)	Tap Range	1
17	N Taps	Number of Tap Steps	1

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Table 6-23- Y-Y-Y Transformer Impedance Form

Field Number	Field Name	Generic Model Source	Generic Model Value	Form Value
3	From Bus	Primary Bushing	-	H
4	To Bus	Imaginary Middle Bushing	-	M
5	MVA Base	No Load Loss/Load Loss Test MVA	50	50
6	Positive Sequence R	Two-Winding Equivalent Resistances	0	0
	Zero Sequence R	R_{H0}	0	0
7	Positive Sequence X	Two-Winding Leakage Reactances	0.01320	0.02751
	Zero Sequence X	X_{H0}	0	0
8	Positive Sequence GFROM	No Load Losses Equivalent Conductance	0.00095	0.00046
	Zero Sequence GFROM	Not Used	-	0
9	Positive Sequence BFROM	Magnetizing Branch Susceptance	-0.01201	-0.00576
	Zero Sequence BFROM	Not Used	-	0
10	Positive Sequence GTO	Not Used	-	0
	Zero Sequence GTO	Not Used	-	0
11	Positive Sequence BTO	Not Used	-	0
	Zero Sequence BTO	Not Used	-	0
12	Short Circuit	Load Loss Test Impedance	10.36	10.36
13	Copper Loss	Load Loss	116.852	116.852
14	Open Circuit	Excitation Current	1.205	1.205
15	Core Loss	No-Load loss	47.656	47.656
Second Winding	From Bus	Secondary Bushing	-	X
	To Bus	Imaginary Middle Bushing	-	M
	MVA Base	No Load Loss/Load Loss Test MVA	50	50
	Positive Sequence R	Two-Winding Equivalent Resistances	0	0
	Zero Sequence R	R_{X0}	0.15620	0.32555
	Positive Sequence X	Two-Winding Leakage Reactances	0.18080	0.37682
	Zero Sequence X	X_{X0}	0	0
	Positive Sequence GFROM	Not Used	-	0
	Zero Sequence GFROM	Not Used	-	0
	Positive Sequence BFROM	Not Used	-	0
	Zero Sequence BFROM	Not Used	-	0
	Positive Sequence GTO	Not Used	-	0
	Zero Sequence GTO	Not Used	-	0
	Positive Sequence BTO	Not Used	-	0
	Zero Sequence BTO	Not Used	-	0
	Short Circuit	Load Loss Test Impedance	10.36	10.36

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Field Number	Field Name	Generic Model Source	Generic Model Value	Form Value
	Copper Loss	Load Loss	116.852	116.852
	Open Circuit	Excitation Current	0.01205	0.01205
	Core Loss	No-Load Loss	47.656	47.656
From Bus To Bus	From Bus	Tertiary Bushing	-	Y
	To Bus	Imaginary Middle Bushing	-	M
	MVA Base	No Load Loss/Load Loss Test MVA	50	50
	Positive Sequence R	Two-Winding Equivalent Resistances	0	0
	Zero Sequence R	R_{Y0}	0.15620	0.32555
	Positive Sequence X	Two-Winding Leakage Reactances	0.18020	0.37557
	Zero Sequence X	X_{Y0}	0	0
	Positive Sequence GFROM	Not Used	-	0
	Zero Sequence GFROM	Not Used	-	0
	Positive Sequence BFROM	Not Used	-	0
	Zero Sequence BFROM	Not Used	-	0
	Positive Sequence GTO	Not Used	-	0
	Zero Sequence GTO	Not Used	-	0
	Positive Sequence BTO	Not Used	-	0
	Zero Sequence BTO	Not Used	-	0
	Short Circuit	Load Loss Test Impedance	10.36	10.36
	Copper Loss	Load Loss	116.852	116.852
	Open Circuit	Excitation Current	0.01205	0.01205
	Core Loss	No-load Loss	47.656	47.656

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6.3.2 Three-Winding Transformer with Wye Primary, Wye Secondary, and Delta Tertiary

This transformer type requires that three Transformer Winding forms and all three sections of the Transformer Impedance form be filled out. See Table 6-24, Table 6-25, Table 6-26, and Table 6-27. The example values come from the example transformer found in Section 3.5.4. System bus voltages of 240 kV, 20 kV, and 20 kV have been assumed for the primary, secondary, and tertiary windings, respectively.

Table 6-24- Y-Y-D Transformer Windings Form 1

Field Number	Field Name	Generic Model Source	Form Value
2	Number of Windings	Transformer Type	3
3	Number of Bushings	Transformer Type	4
4	Winding	Primary Winding	P
5	D/Y	Transformer Type	Y
6	GND	Grounding Configuration	Y
7	Grounding R (Ohm)	Grounding Impedance	0
8	Grounding X (Ohm)	Grounding Impedance	0
9	Rating Condition	Transformer ONAN Ratings	ONAN
			ONAF
			ONAF2
10	Rating (MVA)	Transformer ONAN Ratings	150
			200
			250
11	Installed?	Always Y	Y
			Y
			Y
12	Bushing	Primary Bushing/Imaginary Middle Bushing	H
			M
14	Bushing kV	Winding Voltages	240
			240
15	Max Tap (pu)	Tap Range	1
			1
16	Min Tap (pu)	Tap Range	1
			1
17	N Taps	Number of Tap Steps	1
			1

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Table 6-25- Y-Y-D Transformer Windings Form 2

Field Number	Field Name	Generic Model Source	Example Value
2	Number of Windings	Transformer Type	3
3	Number of Bushings	Transformer Type	4
4	Winding	Secondary Winding	S
5	D/Y	Transformer Type	Y
6	GND	Grounding Configuration	Y
7	Grounding R (Ohm)	Grounding Impedance	0
8	Grounding X (Ohm)	Grounding Impedance	0
9	Rating Condition	Transformer ONAN Ratings	ONAN
			ONAF
			ONAF2
10	Rating (MVA)	Transformer ONAN Ratings	75
			100
			125
11	Installed?	Always Y	Y
			Y
			Y
12	Bushing	Secondary Bushing	X
14	Bushing kV	Winding Voltages	20
15	Max Tap (pu)	Tap Range	1
16	Min Tap (pu)	Tap Range	1
17	N Taps	Number of Tap Steps	1

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Table 6-26- Y-Y-D Transformer Windings Form 3

Field Number	Field Name	Generic Model Source	Example Value
2	Number of Windings	Transformer Type	3
3	Number of Bushings	Transformer Type	4
4	Winding	Tertiary Winding	T
5	D/Y	Transformer Type	D
6	GND	Grounding Configuration	N
7	Grounding R (Ohm)	Grounding Impedance	0
8	Grounding X (Ohm)	Grounding Impedance	0
9	Rating Condition	Transformer ONAN Ratings	ONAN
			ONAF
			ONAF2
10	Rating (MVA)	Transformer ONAN Ratings	75
			100
			125
11	Installed?	Always Y	Y
			Y
			Y
12	Bushing	Tertiary Bushing	Y
14	Bushing kV	Winding Voltages	20
15	Max Tap (pu)	Tap Range	1
16	Min Tap (pu)	Tap Range	1
17	N Taps	Number of Tap Steps	1

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Table 6-27- Y-Y-D Transformer Impedance Form

Field Number	Field Name	Generic Model Source	Generic Model Value	Form Value
3	From Bus	Primary Bushing	-	H
4	To Bus	Imaginary Middle Bushing	-	M
5	MVA Base	No Load Loss/Load Loss Test MVA	250	250
6	Positive Sequence R	Load Losses Equivalent Resistance	0	0
	Zero Sequence R	R_{H0}	0.09840	0.0656
7	Positive Sequence X	Windings' Leakage Reactance	0.07170	0.0478
	Zero Sequence X	X_{H0}	0	0
8	Positive Sequence GFROM	No Load Losses Equivalent Conductance	0.00032	0.000476
	Zero Sequence GFROM	Not Used	-	0
9	Positive Sequence BFROM	Magnetizing Branch Susceptance	-0.00024	-0.000365
	Zero Sequence BFROM	Not Used	-	0
10	Positive Sequence GTO	Not Used	-	0
	Zero Sequence GTO	Not Used	-	0
11	Positive Sequence BTO	Not Used	-	0
	Zero Sequence BTO	Not Used	-	0
12	Short Circuit	Load Loss Test Impedance	9.7	9.7
13	Copper Loss	Load Loss	319.5	319.5
14	Open Circuit	Excitation Current	0.024	0.024
15	Core Loss	No-Load Loss	47.6	47.6
Second Winding	From Bus	Secondary Bushing	-	X
	To Bus	Imaginary Middle Bushing	-	M
	MVA Base	No Load Loss/Load Loss Test MVA	250	250
	Positive Sequence R	Load Losses Equivalent Resistance	0	0
	Zero Sequence R	R_{X0}	0	0
	Positive Sequence X	Windings' Leakage Reactance	0.11448	0.02988
	Zero Sequence X	X_{X0}	0	0
	Positive Sequence GFROM	Not Used	-	0
	Zero Sequence GFROM	Not Used	-	0
	Positive Sequence BFROM	Not Used	-	0
	Zero Sequence BFROM	Not Used	-	0
	Positive Sequence GTO	Not Used	-	0
	Zero Sequence GTO	Not Used	-	0
	Positive Sequence BTO	Not Used	-	0
	Zero Sequence BTO	Not Used	-	0
	Short Circuit	Load Loss Test Impedance	9.5	9.5
	Copper Loss	Load Loss	337.4	337.4
	Open Circuit	Excitation Current	0.024	0.024

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Field Number	Field Name	Generic Model Source	Generic Model Value	Form Value
	Core Loss	No-Load Loss	47.6	47.6
Third Winding	From Bus	Tertiary Bushing	-	Y
	To Bus	Imaginary Middle Bushing	-	M
	MVA Base	No Load Loss/Load Loss Test MVA	250	250
	Positive Sequence R	Load Losses Equivalent Resistance	0	0
	Zero Sequence R	R_{Y0}	0	0
	Positive Sequence X	Windings' Leakage Reactance	0.04278	0.02852
	Zero Sequence X	X_{Y0}	0	0
	Positive Sequence GFROM	Not Used	-	0
	Zero Sequence GFROM	Not Used	-	0
	Positive Sequence BFROM	Not Used	-	0
	Zero Sequence BFROM	Not Used	-	0
	Positive Sequence GTO	Not Used	-	0
	Zero Sequence GTO	Not Used	-	0
	Positive Sequence BTO	Not Used	-	0
	Zero Sequence BTO	Not Used	-	0
	Short Circuit	Load Loss Test Impedance	7.3	7.3
	Copper Loss	Load Loss	8.8	8.8
	Open Circuit	Excitation Current	0.024	0.024
	Core Loss	No-Load Loss	47.6	47.6

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6.3.3 Three-Winding Transformer with Delta Primary, Wye Secondary, and Wye Tertiary

This transformer type requires that three Transformer Winding forms and all three sections of the Transformer Impedance form be filled out. See Table 6-28, Table 6-29, Table 6-30, and Table 6-31. The example values come from the example transformer found in Section 3.6.4. System bus voltages of 18.5 kV, 2.4 kV, and 2.4 kV have been assumed for the primary, secondary, and tertiary windings, respectively.

Table 6-28- D-Y-Y Transformer Windings Form 1

Field Number	Field Name	Generic Model Source	Form Value
2	Number of Windings	Transformer Type	3
3	Number of Bushings	Transformer Type	4
4	Winding	Primary Winding	P
5	D/Y	Transformer Type	D
6	GND	Grounding Configuration	N
7	Grounding R (Ohm)	Grounding Impedance	0
8	Grounding X (Ohm)	Grounding Impedance	0
9	Rating Condition	Transformer ONAN Ratings	ONAN
			ONAF
10	Rating (MVA)	Transformer ONAN Ratings	18
			24
11	Installed?	Always Y	Y
			Y
12	Bushing	Primary Bushing/Imaginary Middle Bushing	H
			M
14	Bushing kV	Winding Voltages	18.5
			18.5
15	Max Tap (pu)	Tap Range	1.3
			1
16	Min Tap (pu)	Tap Range	0.7
			1
17	N Taps	Number of Tap Steps	5
			1

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Table 6-29- D-Y-Y Transformer Windings Form 2

Field Number	Field Name	Generic Model Source	Form Value
2	Number of Windings	Transformer Type	3
3	Number of Bushings	Transformer Type	4
4	Winding	Secondary Winding	S
5	D/Y	Transformer Type	Y
6	GND	Grounding Configuration	Y
7	Grounding R (Ohm)	Grounding Impedance	0
8	Grounding X (Ohm)	Grounding Impedance	0
9	Rating Condition	Transformer ONAN Ratings	ONAN
			ONAF
10	Rating (MVA)	Transformer ONAN Ratings	9
			12
11	Installed?	Always Y	Y
			Y
12	Bushing	Secondary Bushing	X
14	Bushing kV	Winding Voltages	2.4
15	Max Tap (pu)	Tap Range	1
16	Min Tap (pu)	Tap Range	1
17	N Taps	Number of Tap Steps	1

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Table 6-30- D-Y-Y Transformer Windings Form 3

Field Number	Field Name	Generic Model Source	Example Value
2	Number of Windings	Transformer Type	3
3	Number of Bushings	Transformer Type	4
4	Winding	Tertiary Winding	T
5	D/Y	Transformer Type	Y
6	GND	Grounding Configuration	Y
7	Grounding R (Ohm)	Grounding Impedance	0
8	Grounding X (Ohm)	Grounding Impedance	0
9	Rating Condition	Transformer ONAN Ratings	ONAN
			ONAF
10	Rating (MVA)	Transformer ONAN Ratings	9
			12
11	Installed?	Always Y	Y
			Y
12	Bushing	Tertiary Bushing	Y
14	Bushing kV	Winding Voltages	2.4
15	Max Tap (pu)	Tap Range	1
16	Min Tap (pu)	Tap Range	1
17	N Taps	Number of Tap Steps	1

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Table 6-31- D-Y-Y Transformer Impedance Form

Field Number	Field Name	Generic Model Source	Generic Model Value	Form Value
3	From Bus	Primary Bushing	-	H
4	To Bus	Imaginary Middle Bushing	-	M
5	MVA Base	No Load Loss/Load Loss Test MVA	18	18
6	Positive Sequence R	Load Losses Equivalent Resistance	0	0
	Zero Sequence R	R_{H0}	0	0
7	Positive Sequence X	Windings' Leakage Reactance	0.00170	0.009444
	Zero Sequence X	X_{H0}	0.00145	0.008028
8	Positive Sequence GFROM	No Load Losses Equivalent Conductance	0.00092	0.000165
	Zero Sequence GFROM	Not Used	-	0
9	Positive Sequence BFROM	Magnetizing Branch Susceptance	-0.00684	-0.001231
	Zero Sequence BFROM	Not Used	-	0
10	Positive Sequence GTO	Not Used	-	0
	Zero Sequence GTO	Not Used	-	0
11	Positive Sequence BTO	Not Used	-	0
	Zero Sequence BTO	Not Used	-	0
12	Short Circuit	Load Loss Test Impedance	6.7	6.7
13	Copper Loss	Load Loss	80	80
14	Open Circuit	Excitation Current	0.69	0.69
15	Core Loss	No-Load Loss	16.5	16.5
Second Winding	From Bus	Secondary Bushing	-	X
	To Bus	Imaginary Middle Bushing	-	M
	MVA Base	No Load Loss/Load Loss Test MVA	18	18
	Positive Sequence R	Load Losses Equivalent Resistance	0	0
	Zero Sequence R	R_{X0}	0	0
	Positive Sequence X	Windings' Leakage Reactance	0.12730	0.70722
	Zero Sequence X	X_{X0}	0.11457	0.63650
	Positive Sequence GFROM	Not Used	-	0
	Zero Sequence GFROM	Not Used	-	0
	Positive Sequence BFROM	Not Used	-	0
	Zero Sequence BFROM	Not Used	-	0
	Positive Sequence GTO	Not Used	-	0
	Zero Sequence GTO	Not Used	-	0
	Positive Sequence BTO	Not Used	-	0
	Zero Sequence BTO	Not Used	-	0
	Short Circuit	Load Loss Test Impedance	6.7	6.7
	Copper Loss	Load Loss	80	80
	Open Circuit	Excitation Current	0.69	0.69

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Field Number	Field Name	Generic Model Source	Generic Model Value	Form Value
	Core Loss	No-Load Loss	16.5	16.5
Third Winding	From Bus	Tertiary Bushing	-	Y
	To Bus	Imaginary Middle Bushing	-	M
	MVA Base	No Load Loss/Load Loss Test MVA	18	18
	Positive Sequence R	Load Losses Equivalent Resistance	0	0
	Zero Sequence R	R_{Y0}	0	0
	Positive Sequence X	Windings' Leakage Reactance	0.12830	0.71278
	Zero Sequence X	X_{Y0}	0.11547	0.64150
	Positive Sequence GFROM	Not Used	-	0
	Zero Sequence GFROM	Not Used	-	0
	Positive Sequence BFROM	Not Used	-	0
	Zero Sequence BFROM	Not Used	-	0
	Positive Sequence GTO	Not Used	-	0
	Zero Sequence GTO	Not Used	-	0
	Positive Sequence BTO	Not Used	-	0
	Zero Sequence BTO	Not Used	-	0
	Short Circuit	Load Loss Test Impedance	6.7	6.7
	Copper Loss	Load Loss	80	80
	Open Circuit	Excitation Current	0.69	0.69
	Core Loss	No-Load Loss	16.5	16.5

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6.3.4 *Three-Winding Autotransformer: Autotransformer with Tertiary Winding (Wye-wye with Delta Tertiary)*

This transformer requires that two Transformer Winding forms and all three sections of the Transformer Impedance form be filled out. See Table 6-32, Table 6-33, and Table 6-34. The example values come from the example transformer found in Section 3.8.4. System bus voltages of 132 kV, 69 kV, and 4.16 kV have been assumed for the primary, secondary, and tertiary buses, respectively.

Table 6-32- Y-Y-D Autotransformer Transformer Windings Form 1

Field Number	Field Name	Generic Model Source	Example Value
2	Number of Windings	Transformer Type	2
3	Number of Bushings	Transformer Type	3
4	Winding	Primary Winding	P
5	D/Y	Transformer Type	Y
6	GND	Grounding Configuration	Y
7	Grounding R (Ohm)	Grounding Impedance	0
8	Grounding X (Ohm)	Grounding Impedance	0
9	Rating Condition	Transformer ONAN Ratings	ONAN
10	Rating (MVA)	Transformer ONAN Ratings	18.75
11	Installed?	Always Y	Y
12	Bushing	Primary Bushing Secondary Bushing	H X
14	Bushing kV	Winding Voltages	132 72
15	Max Tap (pu)	Tap Range	1 1.5
16	Min Tap (pu)	Tap Range	1 0.5
17	N Taps	Number of Tap Steps	1 10

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Table 6-33- Y-Y-D Autotransformer Transformer Windings Form 2

Field Number	Field Name	Generic Model Source	Example Value
2	Number of Windings	Transformer Type	2
3	Number of Bushings	Transformer Type	3
4	Winding	Tertiary Winding	T
5	D/Y	Transformer Type	D
6	GND	Grounding Configuration	N
7	Grounding R (Ohm)	Grounding Impedance	0
8	Grounding X (Ohm)	Grounding Impedance	0
9	Rating Condition	Transformer ONAN Ratings	ONAN
10	Rating (MVA)	Transformer ONAN Ratings	5.37
11	Installed?	Always Y	Y
12	Bushing	Tertiary Bushing	Y
14	Bushing kV	Winding Voltages	4.16
15	Max Tap (pu)	Tap Range	1
16	Min Tap (pu)	Tap Range	1
17	N Taps	Number of Tap Steps	1

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Table 6-34- Y-Y-D Autotransformer Transformer Impedance Form

Field Number	Field Name	Generic Model Source	Generic Model Value	Form Value
3	From Bus	Primary Bushing	-	H
4	To Bus	Secondary Bushing	-	X
5	MVA Base	No Load Loss/Load Loss Test MVA	18.75	18.75
6	Positive Sequence R	Load Losses Equivalent Resistance	0.00129	0.00689
	Zero Sequence R	R_{H0}	0.09684	0.51647
7	Positive Sequence X	Windings' Leakage Reactance	0.05702	0.30409
	Zero Sequence X	X_{H0}	0	0
8	Positive Sequence GFROM	No Load Losses Equivalent Conductance	0.00115	0.00216
	Zero Sequence GFROM	Not Used	-	0
9	Positive Sequence BFROM	Magnetizing Branch Susceptance	-0.00371	-0.00695
	Zero Sequence BFROM	Not Used	-	0
10	Positive Sequence GTO	Not Used	-	0
	Zero Sequence GTO	Not Used	-	0
11	Positive Sequence BTO	Not Used	-	0
	Zero Sequence BTO	Not Used	-	0
12	Short Circuit	Load Loss Test Impedance	4.91	4.91
13	Copper Loss	Load Loss	48.46	48.46
14	Open Circuit	Excitation Current	0.388	0.388
15	Core Loss	No-Load Loss	21.55	21.55

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7 References

[1] Electric Machines and Drives, Slemon, Gordon R.,

[2] Power Transformers Principles and Applications, John J. Winders, Jr. PPL Electric Utilities Allentown, Pennsylvania, Marcel Dekker Inc. 2002.

[3] The J & P Transformer Book Twelfth edition A PRACTICAL TECHNOLOGY OF THE POWER TRANSFORMER Martin J. Heathcote, CEng, FIEE, Newnws 1998.

[4] Practical Transformer Handbook Irving M. Gottlieb RE., Newnes 1998.

[5] Power System Transients Parameter Determination, Edited by Juan A. Martinez-Velasco, Taylor & Francis Group, 2010.

[6] Electric power transformer engineering, Edited by James H. Harlow, by CRC Press LLC, 2004.

[7] Transformer Engineering Design and Practice S.V.Kulkarni S.A.Khaparde Indian Institute of Technology, Bombay Mumbai, India, Marcel Dekker Inc. 2004.

[8] Analysis of Faulted Power Systems, Paul M. Anderson, IEEE Press Power Systems, Engineering Series, 1995.

[9] Transformer and Inductor Design Handbook, Third Edition, Revised and Expanded COLONEL WM. T. MCLYMAN Kg Magnetics, Inc. Idyllwild, California, U.S.A. 2004.

[10] Transformer Design Principles With Applications to Core-Form Power Transformers, Second Edition, Robert M. Del Vecchio, ... Taylor & Francis Group, 2010.

[11] Protective Relaying Principles and Applications, Third Edition, J. Lewis Blackburn Thomas J. Domin, Taylor & Francis Group 2006.

[12] Sequence Network Presentation of Transformers in Three Phase System, By Olle I. Elgerd , , Moloney Electric Company, St. Louis, MO, USA, March 1956

[13] On-load tap-changers for power transformers: operation principles, applications and selection, Axel Kramer, MR Publications, 2000

[14] Power Systems Modelling and Fault Analysis: Theory and Practice, By Nasser D. Tleis, Newnes publication, 2008

[15] Short-Circuit Currents, Jurgen Schlabbach, IET Power and Energy Series 51, 2008

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Appendix A. PSS/E V33 Model of Transformers

The modelling of power transformers in the steady-state analysis of electrical networks is important because incorrect data for the positive sequence winding leakage impedance, magnetizing admittance, off-nominal turn ratios, number of tap positions, tap range, or voltage control band of a transformer may lead to incorrect results in the verification of voltage and reactive power control schemes, the assessment of transmission losses, and/or the assessment of system reliability. The main objective of this guide is to help users enter electrical transformer data for the positive sequence model of the electrical network and minimize the inaccuracy of the models.

The transformer equivalent circuit in PSS®E is same as that shown in Figure 1-4 in Section 1. The magnetizing reactance is normally very large in relation to the leakage reactances. It is typically 2000 times larger (in ohms) than the primary leakage reactance. The magnetizing branch can, therefore, be commonly regarded as an open circuit and ignored in power system analyses.

Internally, PSS®E represents a two-winding transformer with the equivalent circuit model shown in Figure A-1

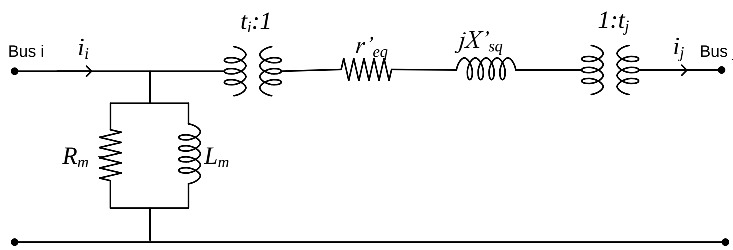

Figure A-1- Two-winding transformer model in PSS®E

This model allows representation of the magnetizing admittance, which is often neglected on the i-side (winding 1) of the transformer. Data entry for this model does not require calculation to obtain the equivalent leakage impedance, magnetizing branch admittance, effective taps, tap step, and tap limits. Data flexibility also allows the user to specify the equivalent leakage impedance in per unit on either system MVA base and winding voltage base (or nominal tap) or on transformer winding MVA base and winding voltage base (or nominal tap), or to specify the windings full-load loss in watts and the leakage impedance magnitude (or impedance voltage) in per unit on a winding MVA base and winding voltage base. The user can choose to enter the tap position by specifying voltages in kV or in per unit on the bus. Figure A-2 shows the standard PSS®E two-winding transformer equivalent circuit in which:

$$\bar{Z}_{eq} = |t_i|^2 r'_{eq} + j|t_i|^2 x'_{eq} = \bar{r}_{eq} + j\bar{x}_{eq}$$
$$t = \frac{t_i}{t_j}$$

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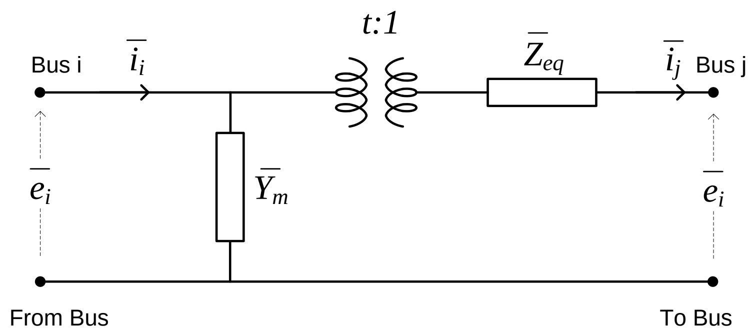

Figure A-2- Standard PSS®E two-winding transformer model equivalent circuit

For zero-sequence calculations, the model used depends on the connection between the windings in the transformer and whether the windings have a path to ground. See Figure 1-2 in Section 1 for a list of different zero-sequence equivalent circuits for two-winding and three-winding transformers. In the PSSE zero sequence data, a connection code identifies the equivalent circuit used by the transformer. See the PSSE manual for details about the different connection codes.

Three-winding transformers are treated as three two-winding transformers connected together at a common "star point" bus. This star point bus is handled internally in PSS®E and is not visible to the user.

The PSS®E software uses two text-based data files for reading in system data..

- A .raw file that defines all of the elements in the system.
- A .seq file that defines the sequence data for the elements.

The .seq file depends on the .raw file for system information and requires that the .raw file be loaded first. Both the .raw file and the .seq file are broken up into different sections that represent the different elements in the system. The .raw file also has a three-line header that identifies system information, and for newer versions, the version of the raw data file.

In the .raw file, a two-winding transformer is represented with the following lines of data (See Table A-7-1 for definitions):

- I,J,K,CKT,CW,CM,MAG1,MAG2,NMETR,'NAME',STAT,O1,F1,O2,F2,O3,F3,O4,F4,VECGRP
- R1-2,X1-2,SBASE1-2
- WINDV1,NOMV1,ANG1,RATA1,RATB1,RATC1,COD1,CONT1,RMA1,RMI1,VMA1,VMI1,NTP1,TAB1,CR1,CX1,CNXA1
- WINDV2,NOMV2

A three-winding transformer is represented with the following lines of data (See Table A-7-1 for definitions):

- I,J,K,CKT,CW,CM,MAG1,MAG2,NMETR,'NAME',STAT,O1,F1,O2,F2,O3,F3,O4,F4, VECGRP
- R1-2,X1-2,SBASE1-2, R2-3,X2-3,SBASE2-3, R3-1,X3-1,SBASE3-1,VMSTAR,ANSTAR
- WINDV1,NOMV1,ANG1,RATA1,RATB1,RATC1,COD1,CONT1,RMA1,RMI1,VMA1,VMI1,NTP1,TAB1,CR1,CX1,CNXA1

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- WINDV2,NOMV2,ANG2,RATA2,RATB2,RATC2,COD2,CONT2,RMA2,RMI2,VMA2,VMI2,NTP2,TAB2,CR2,CX2,CNXA2
- WINDV2,NOMV2,ANG2,RATA2,RATB2,RATC2,COD2,CONT2,RMA2,RMI2,VMA2,VMI2,NTP2,TAB2,CR2,CX2,CNXA2

In the .seq file, a two-winding transformer is represented with the following line of data (See Table A-7-2 for definitions):

- I,J,K,ICKT,CZ0,CZG,CC,RG1,XG1,R01,X01,RG2,XG2,R02,X02,RNUTRL,XNUTRL

A three-winding transformer is represented with the following line of data (See Table A-7-2 for definitions):

- I,J,K,ICKT,CZ0,CZG,CC,RG1,XG1,R01,X01,RG2,XG2,R02,X02,RG3,XG3,R03,X03,RNUTRL,XNUTRL

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Table A-7-1- Raw Data File Field Definitions

Field	Description
I	Bus connected to winding 1.
J	Bus connected to winding 2.
K	Bus connected to winding 3, or 0 for a two-winding transformer
CKT	Circuit identifier
CW	The winding data I/O code which defines the units for WINDV1, WINDV2, and WINDV3: 1 for off-nominal turns ratio in pu of winding bus base voltage 2 for winding voltage in kV 3 for off-nominal turns ratio in pu of nominal winding voltage (NOMV1, NOMV2, NOMV3)
CZ	The impedance data I/O code which defines the units for R1-2, X1-2, R2-3, X2-3, R3-1, and X3-1: 1 for resistance and reactance in pu on system MVA base and winding voltage base 2 for resistance and reactance in pu on a specified MVA base and winding voltage base 3 for transformer load loss in watts and impedance magnitude in pu on a specified MVA base and winding voltage base.
CM	The magnetizing admittance I/O code defines the units for MAG1 and MAG2: 1 for complex admittance in pu on system MVA base and winding 1 bus voltage base 2 for no load loss in watts and exciting current in pu on winding 1 voltage(NOMV1)
MAG1,MAG2	The transformer magnetizing admittance in units as defined by CM
NMETR	The nonmetered end code: 1 for winding 1 bus 2 for winding 2 bus 3 for winding 3 bus (only valid for three-winding transformers)
NAME	Alphanumeric identifier for the transformer
STAT	Transformer status: 0 for out of service 1 for in service 2 for only winding 2 out of service 3 for only winding 3 out of service 4 for only winding 1 out of service Options 2, 3, and 4 are only valid on three-winding transformers.
O1,O2,O3,O4	Owner number for the transformer.
F1,F2,F3,F4	Fractional ownership assigned to each of the owners.
VECGRP	Alphanumeric identifier specifying the vector group based on transformer winding connections and phase angles. This is for information purposes only.
R1-2,X1-2 R2-3,X2-3 R3-1,X3-1	The measured impedances of the transformer between the buses to which the indicated windings are connected in the units specified by CZ.

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Field	Description
SBASE1-2 SBASE2-3 SBASE3-1	The indicated winding's three-phase base MVA of the transformer.
VMSTAR	The voltage magnitude at the hidden star point bus in pu.
ANSTAR	The bus voltage phase angle at the hidden star point bus in degrees.
WINDV1 WINDV2 WINDV3	The indicated winding's off-nominal turns ratio in units indicated by CW.
NOMV1 NOMV2 NOMV3	The indicated winding's nominal voltage base in kV or 0 to indicate that the voltage is assumed to be identical to the base voltage of the connected bus.
ANG1 ANG2 ANG3	The indicated winding's phase shift angle in degrees.
RATA1,RATB1,RATB1 RATA2,RATB2,RATC2 RATA3,RATB3,RATC3	The indicated winding's three three-phase ratings in units determined by the value XFRRAT in the case identifier field, or the present transformer percent loading program option setting in PSS®E. The two valid options for units are: • MVA if XFRRAT ≤ 0 • Current expressed as MVA if XFRRAT > 0
COD1 COD2 COD3	The transformer control mode for automatic adjustments of the indicated winding. 0 for no control (fixed tap and fixed phase shift) 1 for voltage control 2 for reactive power flow control 3 for active power flow control 4 for control of a dc line quantity (only valid for two-winding transformers) 5 for asymmetric active power flow control If the control mode is entered as a positive number, automatic adjustments are enabled; if it is entered as a negative number, automatic adjustments are disabled.
CONT1 CONT2 CONT3	The bus for which voltage is to be controlled by the transformer turns ratio adjustment option when CODX is 1.
RMA1,RMI1 RMA2,RMI2 RMA3,RMI3	When |CODX| is 1, 2, or 3, the upper and lower limits of one of the following: • When |CODX| is 1 or 2 and CW is 1, the off-nominal turns ratio in pu of the indicated winding's bus base voltage • When |CODX| is 1 or 2 and CW is 2, the indicated winding's actual voltage in kV • When |CODX| is 1 or 2 and CW is 3, the off-nominal turns ratio in pu of the indicated winding's voltage • When |CODX| is 3, the phase shift angle in degrees
VMA1,VMI1 VMA2,VMI2 VMA3,VMI3	When |CODX| is 1, 2, or 3, the upper and lower limits of one of the following: • When |CODX| is 1, the voltage at the controlled bus. • When |CODX| is 2, the reactive power flow in the transformer at the indicated winding's bus end in Mvar • When |CODX| is 3, the active power flow into the transformer at the indicated winding's bus end in MW

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Field	Description
NTP1 NTP2 NTP3	The number of tap positions available for the indicated winding.
TAB1 TAB2 TAB3	The number of the transformer impedance correction table that will be applied to the indicated transformer winding.
CR1,CX1 CR2,CX2 CR3,CX3	The load drop compensation impedance for voltage controlling transformers entered in pu on system base. (Used when CODX is 1)
CNXA1 CNXA2 CNXA3	The winding connection angle in degrees. (Used when CODX is 5)

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Table A-7-2- Seq Data File Field Definitions

Field	Description
I	Bus connected to winding 1.
J	Bus connected to winding 2.
K	Bus connected to winding 3 or 0 for a two-winding transformer.
ICKT	Circuit identifier
CZ0	The non-grounding impedance data I/O code defines the units in which impedance values Z01, Z02, and Z03 are specified: 1) for per unit on MVA base and winding X voltage base 2) for per unit on a specified MVA base and winding X voltage base For two-winding transformers, the value CZ0 must be set to 1 when using connection codes 1 through 9. For three-winding transformers, the value CZ0 must be set to 1 when using single digit connection codes 1 through 6, or 3-digit connection codes using digits 1 through 7.
CZG	The grounding impedance data I/O code defines the units in which impedance values ZG1, ZG2, ZG3, and ZNUTRL are specified: 1) for per unit on system MVA base and winding or terminal voltage base 2) for per unit on a specified MVA base and winding or terminal voltage base 3) for ohms For two-winding transformers, the value CZG must be set to 1 when using connection codes 1 through 9. For three-winding transformers, the value CZG must be set to 1 when using single digit connection codes 1 through 6, or 3-digit connection codes using digits 1 through 7.
CC	The winding connection code that indicates the connection and ground paths to be used in modelling the transformer in the zero sequence network. Valid options for two-winding transformers are: 1) series path, no ground path 2) no series path, ground path on winding 1 side 3) no series path, ground path on winding 2 side 4) no series or ground paths 5) series path, ground path on winding 2 side 6) no series path, ground path on winding 1 side, earthing transformer on winding 2 side 7) no series path, earthing transformer on winding 1 side, ground path on winding 2 side 8) series path, ground path on each side 9) series path on each side, ground path at the junction point of the two series paths 20) series path on each side, ground path at the junction point of the two series paths (wye grounded - wye grounded core type transformer) 21) series path, no ground path (wye grounded - wye grounded no core type auto transformer) 22) series path no ground path (wye – wye ungrounded core type auto transformer) Options 11 through 19 are the same as options 1 through 9, but allow for CZ0 and CG0 to be values other than 1. Valid options for three-winding transformers are: 1) series path in all three windings, winding 1 ground path at the star point bus (5-1-1) 2) series path in windings 1 and 2, winding 3 ground path at the star point bus (1-1-3)

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Field	Description
	3) series path in winding 2, ground paths from windings 1 and 3 at the star point bus (3-1-3) 4) no series paths, ground paths from all three windings at the star point bus (3-3-3) 5) series path in windings 1 and 3, ground path at the winding 2 side bus (1-2-1) 6) series path in all three windings, no ground path (1-1-1) 17) series path in windings 1 and 2, winding 3 ground path at the star point bus (wye grounded-wye grounded-delta auto transformer) 18) series path in windings 1 and 2, no ground path in winding 3 (wye-wye-delta ungrounded neutral auto transformer) Options 11 through 16 are the same as 1 through 6, but allow for CZ0 and CG0 to be values other than 1.
RG1,XG1 RG2,XG2 RG3,XG3	The zero sequence grounding impedance on the indicated winding for an impedance grounded transformer in units defined by CZG. The connection code determines how to define this value.
R01,X01 R02,X02 R03,X03	The zero sequence impedance of the indicated winding in units defined by CZ0. The connection code determines how to define this value.
RNUTRL,XNUTRL	The zero sequence common neutral grounding impedance in units defined by CZG. This value is only applicable for CC ≥ 11.

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Table A-7-3- PSSE Seq Data Source

Transformer Type	Field	Generic Model Source
YN-yn	CC	20
	RG1, XG1	RGH, XGH
	R01, X01	RM0, XM0
	RG2, XG2	RGX, XGX
	R02, X02	(RH0+R'X0)/2, (XH0 +X'X0)/2
YN-y	CC	12
	RG1, XG1	RM0, XM0
	R01, X01	ZGH, XGH
	RG2, XG2	Not Used
	R02, X02	Not Used
Y-yn	CC	13
	RG1, XG1	Not Used
	R01, X01	RM0. XM0
	RG2, XG2	RGX, XGX
	R02, X02	Not Used
Y-y	CC	14
	RG1, XG1	Not Used
	R01, X01	Not Used
	RG2, XG2	Not Used
	R02, X02	Not Used
YN-d with earthing transformer	CC	16
	RG1, XG1	RGH, XGH
	R01, X01	R0, X0
	RG2, XG2	Not Used
	R02, X02	Not Used
YN-d without earthing transformer	CC	12
	RG1, XG1	RGH, XGH
	R01, X01	R0, X0
	RG2, XG2	Not Used
	R02, X02	Not Used
Y-d	CC	14
	RG1, XG1	Not Used
	R01, X01	Not Used
	RG2, XG2	Not Used
	R02, X02	Not Used
D-yn with earthing transformer	CC	17
	RG1, XG1	Not Used

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Transformer Type	Field	Generic Model Source
	R01, X01	Not Used
	RG2, XG2	RGX, XGX
	R02, X02	R0, X0
D-yn without earthing transformer	CC	13
	RG1, XG1	Not Used
	R01, X01	Not Used
	RG2, XG2	RGX, XGX
	R02, X02	R0, X0
D-y	CC	14
	RG1, XG1	Not Used
	R01, X01	Not Used
	RG2, XG2	Not Used
	R02, X02	Not Used
D-d	CC	14
	RG1, XG1	Not Used
	R01, X01	Not Used
	RG2, XG2	Not Used
	R02, X02	Not Used
YN auto-transformer	CC	19
	RG1, XG1	Not Used
	R01, X01	RH0+R'X0, XH0+X'X0
	RG2, XG2	RG, XG
	R02, X02	RM0, XM0
Y auto-transformer	CC	22
	RG1, XG1	Not Used
	R01, X01	RM0, XM0
	RG2, XG2	Not Used
	R02, X02	Not Used
YN-yn-yn	CC	16
	RG1, XG1	RGH0, XGH0
	R01, X01	RHX0, XHX0
	RG2, XG2	RGH0, XGH0
	R02, X02	RHY0, XHY0
	RG3, XG3	RGY0, XGY0
	R03, X03	RXY0, XXY0
All other Y-y-y transformers	CC	14
	RG1, XG1	Not Used
	R01, X01	RHX0, XHX0
	RG2, XG2	Not Used

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Transformer Type	Field	Generic Model Source
	R02, X02	RHY0, XHY0
	RG3, XG3	Not Used
	R03, X03	RXY0, XXY0
YN-yn-d	CC	12
	RG1, XG1	RGH0, XGH0
	R01, X01	RHX0, XHX0
	RG2, XG2	RGX0, XGX0
	R02, X02	RHY0, XHY0
	RG3, XG3	Not Used
	R03, X03	RXY0, XXY0
All other Y-y-d transformers	CC	14
	RG1, XG1	Not Used
	R01, X01	RHX0, XHX0
	RG2, XG2	Not Used
	R02, X02	RHY0, XHY0
	RG3, XG3	Not Used
	R03, X03	RXY0, XXY0
All D-y-y transformers	CC	14
	RG1, XG1	Not Used
	R01, X01	RHX0, XHX0
	RG2, XG2	Not Used
	R02, X02	RHY0, XHY0
	RG3, XG3	Not Used
	R03, X03	RXY0, XXY0
YN-d auto-transformer	CC	17
	RG1, XG1	Not Used
	R01, X01	RHX0, XHX0
	RG2, XG2	RGY0, XGY0
	R02, X02	RHY0, XHY0
	RG3, XG3	Not Used
	R03, X03	RXY0, XXY0
Y-d auto-transformers	CC	14
	RG1, XG1	Not Used
	R01, X01	RHX0, XHX0
	RG2, XG2	Not Used
	R02, X02	RHY0, XHY0
	RG3, XG3	Not Used
	R03, X03	RXY0, XXY0

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Two-Winding Transformer Example

See Table A-7-4 and Table A-7-5 for the .raw and .seq values calculated for the Y-Y two-winding transformer example in Section 2.4.4. The tables do not include data such as bus numbers and voltage limits that come from other sources.

Table A-7-4- Y-Y Two-Winding Transformer PSS®E Raw Data

Field	Source	Value
CW	The winding voltages are entered in kV	2
CZ	The Impedance values are converted to system MVA base and winding voltage base	1
CM	The admittance values are converted to system MVA base and winding 1 bus voltage base	1
MAG1	No-load losses equivalent conductance	0.000116
MAG2	Magnetizing branch susceptance	-0.000136
STAT	Assumed to be in service	1
R1-2	Load losses equivalent resistance	0.018516
X1-2	Windings' leakage reactance	0.511665
SBASE1-2	Test MVA base	15
WINDV1	Primary winding voltage	138
NOMV1	Primary winding voltage	138
ANG1	Primary winding phase shift angle	0
RATA1	First Rating (assumes XFRRAT specifies MVA)	15
RATB1	Second Rating (assumes XFRRAT specifies MVA)	20
RATC1	Third Rating (assumes XFRRAT specifies MVA)	25
NTP1	Number of tap steps	17
TAB1	Assumed to be 0	0
WINDV2	Secondary winding voltage	26.5
NOMV2	Secondary winding voltage	25

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Table A-7-5- Y-Y Two-Winding Transformer PSSE Seq Data

Field	Source	Value
CZ0	Chosen for backwards compatibility with older versions of PSS®E	1
CG0	Chosen for backwards compatibility with older versions of PSS®E	1
CC	Chosen based on type of transformer and whether its windings are grounded.	20
RG1	Determined by CC	0
XG1	Determined by CC	0
R01	Determined by CC	0.52133
X01	Determined by CC	0
RG2	Determined by CC	0
XG2	Determined by CC	0
R02	Determined by CC	3.0620
X02	Determined by CC	0
RNEUTRL	Not Used	0
XNEUTRL	Not Used	0

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Three-Winding Transformer Example

See Table A-7-6 and Table A-7-7 for the .raw and .seq values calculated for the Y-Y two-winding transformer example in Section 3.4.4. The tables do not include data such as bus numbers and voltage limits that come from other sources.

Table A-7-6 – Y-Y-Y Three-Winding Transformer PSSE Raw Data

Field	Source	Value
CW	The winding voltages are entered in kV	2
CZ	The Impedance values are converted to system MVA base and winding voltage base	1
CM	The admittance values are converted to system MVA base and winding 1 bus voltage base	1
MAG1	No-load losses equivalent conductance	0.000457
MAG2	Magnetizing branch susceptance	-0.005764
STAT	Assumed to be in service	1
R1-2	Primary winding load losses equivalent resistance	0
X1-2	Primary winding's leakage reactance	0.027511
SBASE1-2	Primary winding test MVA base	25
R2-3	Secondary winding load losses equivalent resistance	0
X2-3	Secondary winding's leakage reactance	0.37682
SBASE2-3	Secondary winding test MVA base	25
R3-1	Tertiary winding load losses equivalent resistance	0
X3-1	Tertiary winding's leakage reactance	0.37557
SBASE3-1	Tertiary winding test MVA base	15
WINDV1	Primary winding voltage	245
NOMV1	Primary winding voltage	245
ANG1	Primary winding phase shift angle	0
RATA1	Primary winding first rating (assumes XFRRAT specifies MVA)	50
RATB1	Primary winding second rating (assumes XFRRAT specifies MVA)	66.7
RATC1	Primary winding third rating (assumes XFRRAT specifies MVA)	83.3
NTP1	Primary winding number of tap steps	24
TAB1	Assumed to be 0	0
WINDV2	Secondary winding voltage	26
NOMV2	Secondary winding voltage	26
ANG2	Secondary winding phase shift angle	0
RATA2	Secondary winding first rating (assumes XFRRAT specifies MVA)	25
RATB2	Secondary winding second rating (assumes XFRRAT specifies MVA)	33.3
RATC2	Secondary winding third rating (assumes XFRRAT specifies MVA)	41.7
NTP2	Secondary winding number of tap steps	1
TAB2	Assumed to be 0	0
WINDV3	Tertiary winding voltage	26

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Field	Source	Value
NOMV3	Tertiary winding voltage	26
ANG3	Tertiary winding phase shift angle	0
RATA3	Tertiary winding first rating (assumes XFRRAT specifies MVA)	25
RATB3	Tertiary winding second rating (assumes XFRRAT specifies MVA)	33.3
RATC3	Tertiary winding third rating (assumes XFRRAT specifies MVA)	41.7
NTP3	Tertiary winding number of tap steps	1
TAB3	Assumed to be 0	0

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Table A-7-7- Y-Y Two-Winding Transformer PSSE Seq Data

Field	Source	Value
CZ0	Chosen for backwards compatibility with older versions of PSS®E	1
CG0	Chosen for backwards compatibility with older versions of PSS®E	1
CC	Chosen based on type of transformer and whether its windings are grounded.	16
RG1	Determined by CC	0
XG1	Determined by CC	0
R01	Determined by CC	0.32555
X01	Determined by CC	0
RG2	Determined by CC	0
XG2	Determined by CC	0.15416
R02	Determined by CC	0.32552
X02	Determined by CC	0
RG3	Determined by CC	0
XG3	Determined by CC	0.15416
R03	Determined by CC	0.65111
X03	Determined by CC	0
RNEUTRL	Not Used	0
XNEUTRL	Not Used	0

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Appendix B. Tap Changer

Technically, there are two generic types of load tap changers on power transformers: in-tank and separate compartment [10].

The in-tank tap changer type (the Jansen type) is seated in the main transformer oil along with the core and coil assembly, and is mounted near the transformer cover. This type of tap-changer is used in the single-phase or three-phase Y-connected neutral end of transformers. For three-phase transformers, three single-phase tap-changers must be used. Usually, this type of tap changer is used for high levels of voltage or currents.

The separate-compartment tap changer type has its own tank, which is assembled separately from the transformer. It is bolted to the side of the tank and connected to the transformer's tapped windings through a connecting board. Some separate-compartment tap changers have two compartments: one for the diverter switch and the other for the selector switch and any changeover switches. They are available in three-phase assemblies, and either Y-connected for application at the neutral end of a three-phase transformer or fully insulated for application at the line end. For Y connections it is economical to put the tap changer in the neutral end of the connection because that location requires lower insulation levels.

Depending on the location of the tapping winding in the transformer, it may operate with a fixed volt per turn or a variable volt per turn. To keep the volt per turn constant, the tap changer should be connected to the regulated side of the transformer. Usually, the low-voltage side of a transformer has a regulated voltage. If a tap changer is placed in that side, for a Y connection it is more economic to place it in the low-potential neutral end because its insulation level can be lower. For a high-current winding the cost of such a tap changer significantly affects the total design of the transformer. Because there are fewer turns in the low-voltage winding and fractional turns cannot be used, it is often impractical to have the tap changer in the low-voltage side. The economical approach to solve the problem of high current is to put the tap changer in the high-voltage side of the transformer; with this arrangement the low-voltage side can still be regulated. This is applicable if the high-voltage side is Y-connected because the tap changer can be placed in the neutral end, and if the transformer is auto-connected the current is reduced. This way, if the low-voltage side is regulated the volt per turn will be variable in the transformer. If a tap changer is placed in the regulated side, the volt per turn will be constant. The variable volt per turn in some cases may be technically or economically the only solution; however, it has the following disadvantages:

1) The core is normally designed for the maximum flux in electromagnetic circuits. The core flux is proportional to the volt per turn in a transformer. The variable volt per turn causes the variable flux in the core. Since the minimum turns require the core to carry the maximum flux, the core must be designed for the minimum turns. Consequently, for variable volt per turn the core would be bigger than its fixed volt per turn counterpart. Therefore, the core would only be used to maximum efficiently at the minimum turn position of the tap changer.

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2) In a variable-flux transformer, the voltage variation per step is not constant, even if the number of turns per step is constant. This is because the volts per turn changes with the step position.
3) A transformer is designed to meet certain guaranteed losses and sound levels at the rated position, which is generally the middle position. If the flux varies in the core, the no-load losses, exciting current, impedance, and sound level of the transformer will also vary. Therefore, it could exceed the guaranteed values significantly in the positions lower than the rated position.
4) The voltage of the third winding in the transformer will vary as the tap changer moves, which might not be desirable.

Another approach that can be taken to put a tap changer in the high-voltage side is using an auxiliary transformer. When regulation is desired in the low-voltage side of a relatively high-current transformer, using an auxiliary transformer may be economical. Figure B-1 shows two connections using an auxiliary transformer to regulate voltage [10].

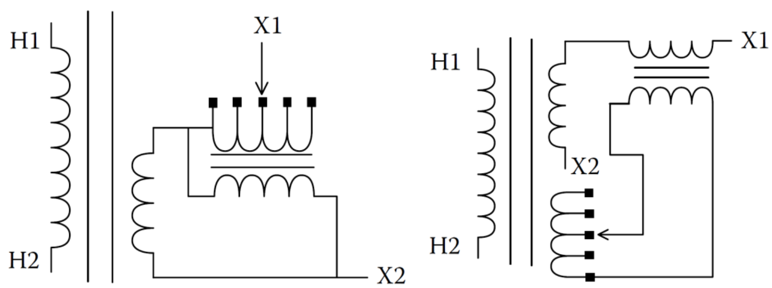

Figure B-1- a) Series voltage regulator, b) Series booster transformer

Practically, a series voltage regulator connection does not help to mitigate the high-current problems of a tap changer, but the main transformer can be optimized independently from the series voltage regulator. In a series booster connection the tap winding is separate from the main transformer windings; therefore, the number of turns per step can be selected so the tap changer caries smaller currents.

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Appendix C. Two-Port Networks Theory

C.1. Overview

Two-Port network theory is used to describe the relationship between a pair of terminals. In this guide, the analysis is restricted to linear networks without any independent source, which is sufficient for transformer modelling.

A schematic diagram of a two-port network is shown in Figure C-1. Each two-port system has exactly two governing equations that show the relationship between the voltage and current at the terminals.

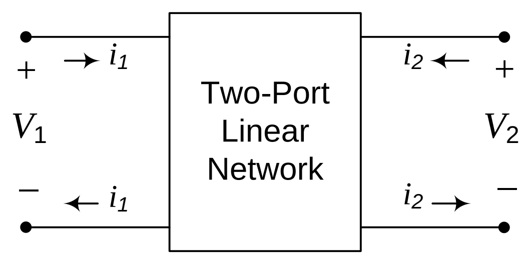

Figure C-1- Voltage and currents in a two-port network

The equations can be written in terms of any pair of network variables, and depending on which variables are being used, the parameters are called impedance, admittance, hybrid, inverse hybrid, transmission, and inverse transmission. In this guide, admittance and impedance parameters are discussed in detail.

C.1. Admittance Parameters of a Two-Port Network

The following equations could be used as the governing equations of the two-port network (the coefficients are admittance parameters):

$$i_1 = y_{11} \cdot V_1 + y_{12} \cdot V_2$$
$$i_2 = y_{21} \cdot V_1 + y_{22} \cdot V_2$$

To calculate the parameters in the above equations, two tests must be carried out on the system, and in each test two network variables should be measured. Figure C-2 shows one of the tests, which consists of short-circuiting Port Two (V2=0), applying voltage V1 at Port One, and measuring the current at both ports (i1 and i2). The Y11 and Y21 parameters are calculated by using the formulas given.

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$$y_{11} = \left.\frac{i_1}{V_1}\right|_{V_2=0}$$

$$y_{21} = \left.\frac{i_2}{V_1}\right|_{V_2=0}$$

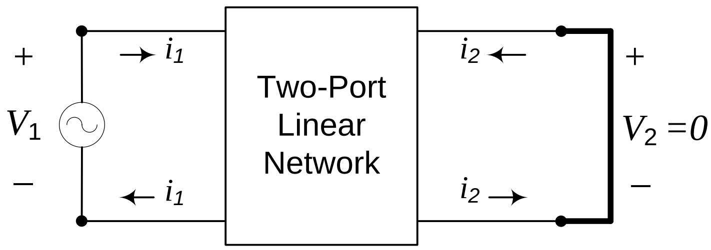

Figure C-2- Test setup for the calculation of admittance parameters (1/2)

The second test consists of short-circuiting Port One (V1=0), applying voltage V2 at Port Two, and measuring the currents at both ports. The Y12 and Y22 parameters are calculated by using the formulas given.

$$y_{12} = \left.\frac{i_1}{V_2}\right|_{V_1=0}$$

$$y_{22} = \left.\frac{i_2}{V_2}\right|_{V_1=0}$$

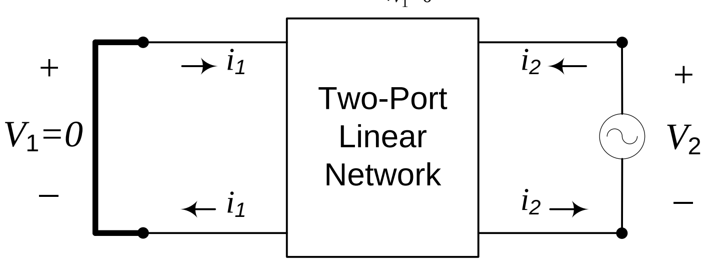

Figure C-3- Test setup for the calculation of admittance parameters (2/2)

The following circuit is called the PI equivalent circuit. It could only be implemented for systems in which Y12=Y21. For passive linear networks such as a two-winding transformer, all three impedances in the PI equivalent will be positive.

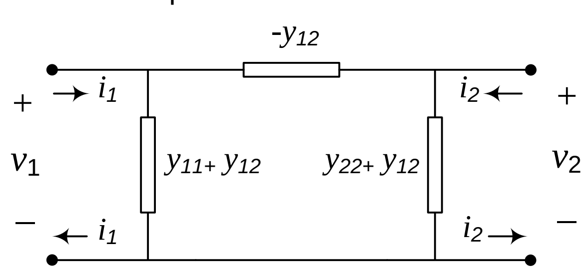

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Figure C-4- PI equivalent circuit for a two-port linear network

C.2. Impedance Parameters of a Two-Port Network

The following equations could be used as the governing equations of the network. The coefficients are impedance parameters.

$$v_1 = z_{11} \cdot i_1 + z_{12} \cdot i_2$$
$$v_2 = z_{21} \cdot i_1 + z_{22} \cdot i_2$$

To calculate the parameters in the above equations, two tests must be carried out on the system, and in each test two network variables should be measured. Figure C-5 shows one of the tests, which consists of leaving Port Two open (I2=0), applying voltage V1 at Port One, and measuring the current at Port One and the voltage at Port Two. By using the formulas given, the Z11 and Z21 parameters are calculated.

$$z_{11} = \left.\frac{v_1}{i_1}\right|_{i_2=0}$$

$$z_{21} = \left.\frac{v_2}{i_1}\right|_{i_2=0}$$

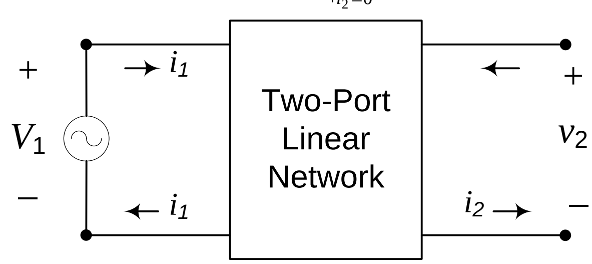

Figure C-5- Test setup for the calculation of impedance parameters (1/2)

The second test consists of leaving Port One open circuit (I1=0), applying voltage V2 at Port Two, and measuring the current at Port Two and the voltage at Port One. Using the following formulas, the Z12 and Z22 parameters are calculated.

$$z_{11} = \left.\frac{v_1}{i_1}\right|_{i_2=0}$$

$$z_{21} = \left.\frac{v_2}{i_1}\right|_{i_2=0}$$

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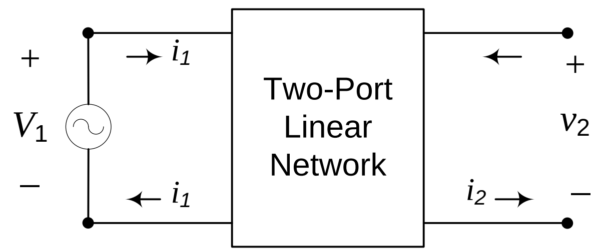

Figure C-6- Test setup for calculation of admittance parameters (2/2)

The following circuit is called the T-equivalent circuit, which could be implemented only for systems in which Z12=Z21. This condition is true for passive linear networks such as a two-winding transformer. All three impedances in the T-equivalent circuit will be positive in such systems.

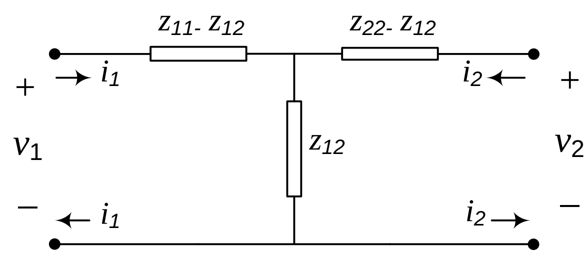

Figure C-7- T-equivalent circuit for a two-port linear network

The T model and the π-model could be easily converted to the other using the standard star-delta conversion.

C.3. Two-Winding Transformer as a Two-Port Network

For simplification, a transformer equivalent circuit transferred to the high-voltage side without an ideal transformer is considered as a two-port network of a transformer. Figure C-8 shows a T-Model of a two-winding transformer.

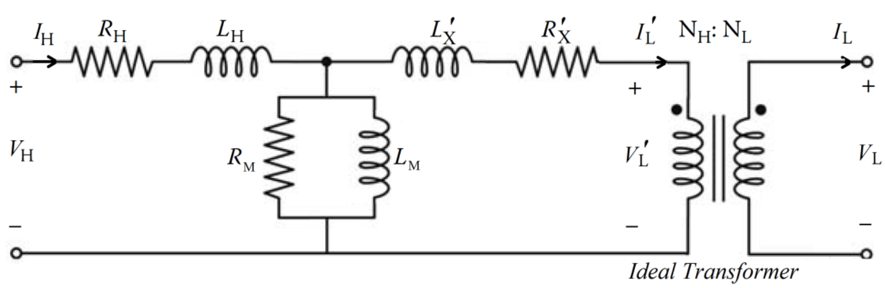

Figure C-8- T-Model of a two-winding transformer

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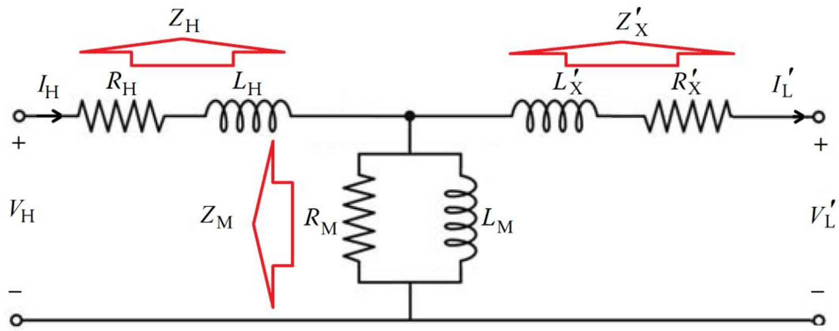

Figure C-9- Transformer equivalent circuit transferred to the high-voltage side as a two-port network

$$V_H = (Z_H + Z_M)\cdot I_H - Z_M \cdot I'_L$$
$$V'_L = Z_M \cdot I_H - (Z'_X + Z_M)\cdot I'_L$$

The transfer impedance matrix, Z, is:

$$Z = \begin{bmatrix} Z_H + Z_M & -Z_M \\ Z_M & -Z'_X - Z_M \end{bmatrix}$$

The transfer admittance matrix, Y, is an inversion of the impedance matrix:

$$Y = \begin{bmatrix} \dfrac{Z_X + Z_M}{Z_H.Z_X + Z_H.Z_M + Z_L.Z_M} & -\dfrac{Z_M}{Z_H.Z_X + Z_H.Z_M + Z_X.Z_M} \\ \dfrac{Z_m}{Z_H.Z_X + Z_H.Z_M + Z_L.Z_M} & -\dfrac{Z_H + Z_M}{Z_H.Z_X + Z_H.Z_M + Z_X.Z_M} \end{bmatrix}$$

Substituting these parameters in Figure C-4 results in C-10. Therefore, C-10-b can be derived as the exact π-model of the transformer if an ideal transformer is taken to account.

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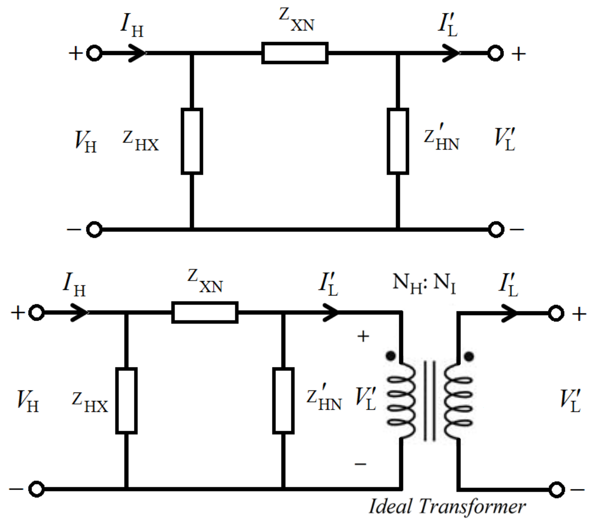

Figure C-10- π-Model of two-winding transformer: Parameter transferred to the high-voltage side, a) Without ideal transformer, b) With ideal transformer

in which:

$$Z_{HN} = Z_M \cdot (1 + \frac{Z_H}{Z'_X} + \frac{Z_H}{Z_M})$$

$$Z'_{XN} = Z_M \cdot (1 + \frac{Z'_X}{Z_H} + \frac{Z'_X}{Z_M})$$

$$Z_{HX} = Z_H + Z'_X + \frac{Z_H Z'_X}{Z_M}$$

In a well-designed transformer, presuming the current densities in both windings are equal, Z_H approximately equals Z'_X. Therefore:

$$Z_{HN} \cong Z_M \cdot (2 + \frac{Z_H}{Z_M})$$

$$Z'_{XN} \cong Z_M \cdot (2 + \frac{Z_H}{Z_M})$$

$$Z_{HX} \cong \frac{1}{2}(Z_H + Z'_X).(2 + \frac{Z_H}{Z_M})$$

In Section 1.4 it is stated that the magnetizing current is 2 - 3% of the full load current. Also, according to the IEEE standard, series reactance is expected to be 7% in a typical power

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transformer. Consequently, the ratio $\frac{Z_H}{Z_M}$ never exceeds 1% ($= \frac{7\%}{2} \times 2\_3\%$); therefore, the previous equation can be simplified again as follows:

$$Z_{HN} \cong 2Z_M$$
$$Z'_{XN} \cong 2Z_M$$
$$Z_{HX} \cong Z_H + Z'_X$$

As a result, when internal information is not known, to separate the magnetizing effect to two branches, the measured magnetizing parameters can be doubled to build the π-model of transformer. The relationship between the parameters of the T-model and the π -model as shown in Figure C-11 is presented as follows:

$$R_{ser} = R_H + R'_X$$
$$L_{ser} = L_H + L'_X$$
$$R_{HN} = R'_{XN} = 2R_M$$
$$L_{HN} = L'_{XN} = 2L_M$$

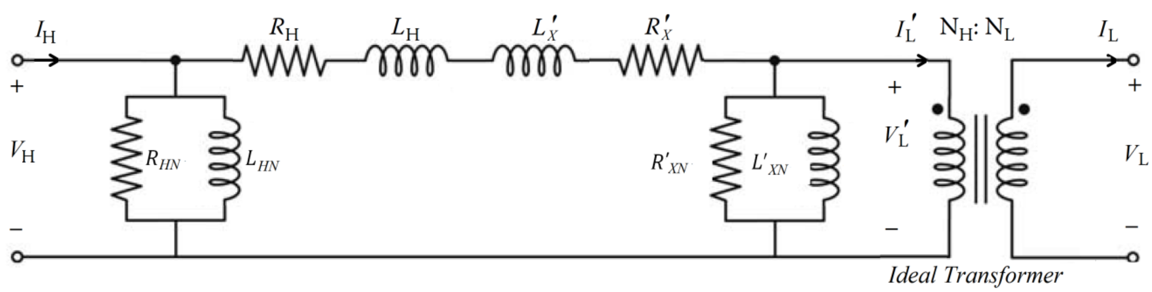

Figure C-11- π - Model of two-winding transformer, (approximate model)

C.4. Verification with a Practical Example: Positive or Negative Sequence π-Model Equivalent Circuit

Transformer parameters calculated from test results while the transformer equivalent circuit has been transferred to the low-voltage side are listed in Table C-1. Since there is no way to know how the load losses parameters can be divided between two-windings, as mentioned, one rough method is to divide it into two equal values.

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Table C-1- Transformer Positive or Negative Sequence Parameters in pu (@ 100 MVA and 25 kV)

	pu
R	0.02386
X	0.55305
G	0.00014
B	0.00022

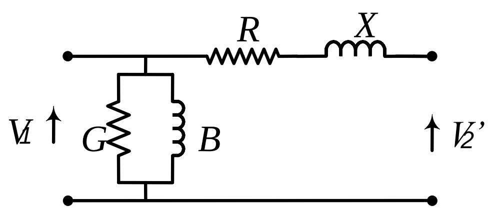

Figure C-12- Transformer model according to the test results

To derive the transformer T-model, as shown in Figure C-9, the series impedance is divided into two equal impedances. Substituting these parameters in the π-model equations gives:

$$Z_{HX} = 0.024 + 055j$$
$$Z_{HN} = Z_{XN} = 4.118 \times 10^3 + 6.471j \times 10^3$$

in which

$$\frac{Z_{HX}}{R + jX} = 1 + 0.000018j \approx 1$$
$$\frac{Z_{HN}}{Z_M} = \frac{Z_{LN}}{Z_M} = 2 + 0.0000361j \approx 2$$

These two equations show that the presented approach to derive the π-model equivalent circuit from T-model has a very small error.

C.4.1. YY Connected Transformer Zero-Sequence Equivalent Circuit

In Section 1.15.3, it is stated that the zero-sequence equivalent circuit of transformers varies depending on the connection type of the transformer and the core structure. In Table 1-2 the zero-sequence equivalent circuits of different connection types of transformer are listed.

The π-model can be derived from the T-model for only a Yy connection grounded at both sides, because for the other types of connections the zero-sequence equivalent circuit is not a two-port network. The procedure to derive the π-model from the T-model is the same as described previously, except the ground impedances should be taken into account in two-port network calculation. The subscript “0” denotes the zero-sequence parameters. Figure C-13 shows the zero-phase sequence model of a Yg-Yg-connected transformer. As shown in Figure C-14, the low-voltage side ground impedance and the low-voltage side winding impedance transferred to the high-voltage side constitutes the T-model zero-sequence equivalent circuit (which is similar to a positive or negative sequence equivalent circuit). This T-model is considered as a two-port network of zero-sequence to derive the zero-sequence π-model.

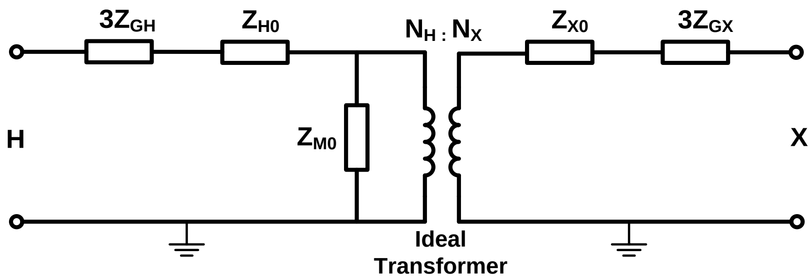

Figure C-13- Zero-sequence model of a Yg-Yg-connected transformer

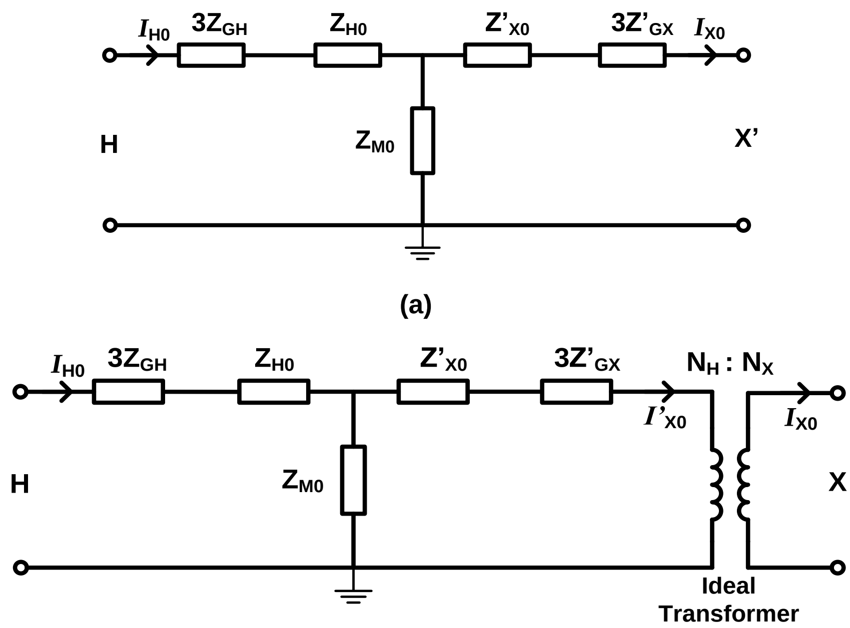

Figure C-14- Zero-sequence T-Model, parameter transferred to the high-voltage side, a) Without ideal transformer, b) With ideal transformer

The two-port network voltage equations for the T-model shown in Figure C 14-a are as follows:

$$V_{H0} = (Z_{H0} + 3Z_{GH} + Z_{M0}) \cdot I_{H0} - Z_{M0} \cdot I'_{X0}$$
$$V'_{X0} = Z_{M0} \cdot I_{H0} - (Z'_{X0} + 3Z_{GX} + Z_{M0}) \cdot I'_{X0}$$

The transfer impedance matrix is:

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$$Z_0 = \begin{bmatrix} Z_{H0} + 3Z_{GH} + Z_{M0} & -Z_{M0} \\ Z_{M0} & -Z'_{X0} - 3Z_{GX} - Z_{M0} \end{bmatrix}$$

The current equations for the π-model are as follows:

$$I_{H0} = (Y_{HN0} + Y_{HX})V_{H0} - Y_{HX}V'_{X0}$$
$$I'_{X0} = Y_{HX}V_{H0} - (Y_{XN0} + Y_{HX})V'_{X0}$$

The transfer admittance matrix, Y, which is an inversion of the impedance matrix, is:

$$Y_0 = \begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{bmatrix} = \begin{bmatrix} Y_{HN0} + Y_{HX} & -Y_{HX} \\ Y_{HX} & -(Y_{XN0} + Y_{HX}) \end{bmatrix}$$

$$y_{11} = \frac{1}{Z_{H0} + 3Z_{GH} + Z_{M0} - \frac{{Z_{M0}}^2}{Z'_{X0} + 3Z_{GX}}}$$

$$y_{12} = -y_{21} = -\frac{1}{Z_{H0} + 3Z_{GH} + Z'_{X0} + 3Z_{GX} + \frac{(Z_{H0} + 3Z_{GH})(Z'_{X0} + 3Z_{GX})}{Z_{M0}}}$$

$$y_{22} = -\frac{1}{Z'_{X0} + 3Z_{GX} + Z_{M0} - \frac{{Z_{M0}}^2}{Z_{H0} + 3Z_{GH} + Z_{M0}}}$$

Substituting these parameters in Figure C-4 results in Figure C-15. Therefore:

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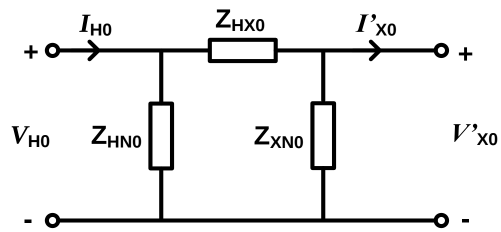
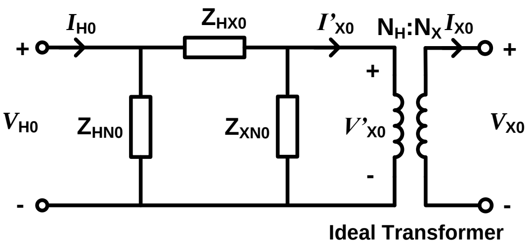


(a)



(b)

Figure C-15- Zero-sequence π-Model, parameter transferred to the high-voltage side, a) Without ideal transformer, b) With ideal transformer

$$Z_{HN0} = Z_{M0}\left(1 + \frac{Z_{H0} + 3Z_{HX}}{Z_{M0}} + \frac{Z_{H0} + 3Z_{GH}}{Z_{X0} + 3Z_{GX}}\right)$$

$$Z_{HX0} = Z_{H0} + 3Z_{GH} + Z_{X0} + 3Z_{GX} + \frac{(Z_{H0} + 3Z_{GH})(Z_{X0} + 3Z_{GX})}{Z_{M0}}$$

$$Z_{XN0} = Z_{M0}\left(1 + \frac{Z_{X0} + 3Z_{GX}}{Z_{M0}} + \frac{Z_{X0} + 3Z_{GX}}{Z_{H0} + 3Z_{GH}}\right)$$

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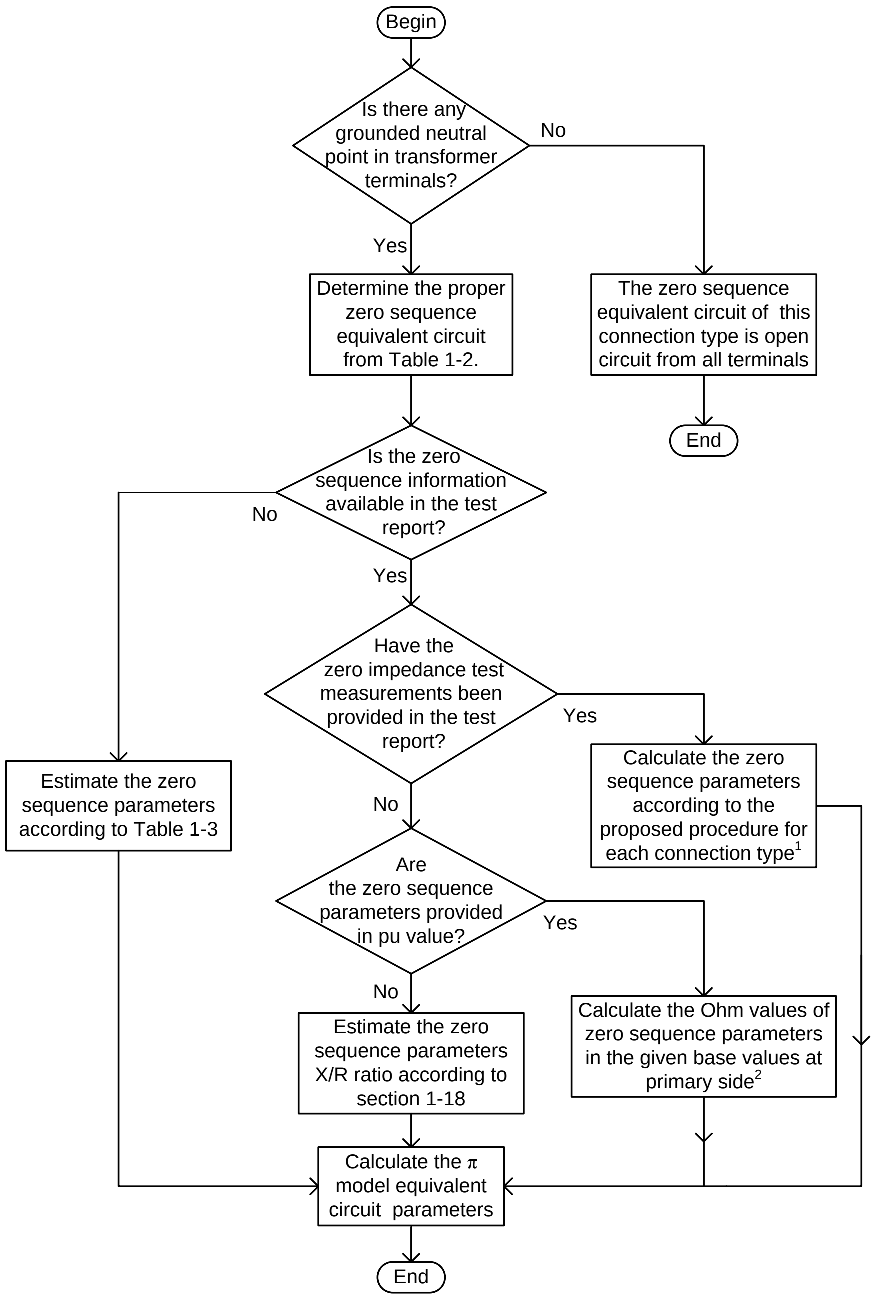
Appendix D. Procedure for Modelling a Transformer in Zero-Sequence



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Appendix E. The Per-Unit System

An interconnected power system typically consists of many different voltage levels. In the Alberta system, nominal bus voltage on the transmission system shall be one of 500 kV, 240 kV, 138 kV, or 69 kV, which may differ somewhat from the actual operating voltage of the transmission system at any location. Table E-1 shows the typical nominal voltages in the Alberta network that have been captured from TASMo. The per-unit system simplifies the analysis of complex power systems by choosing a common set of base parameters in terms of which all systems quantities are defined. The different voltage levels disappear and the overall system reduces to a set of impedances.

Table E-1- Typical nominal voltages in Alberta network (captured from TASMo)

kV	kV	kV	kV
11	20	125	230
11.5	20.5	130	239
12	21	132	240
12.47	22.9	134	245
12.75	23.9	135	246
13	23.9	138	250
13.2	24.49	138.6	251
13.2	24.76	138.8	252
13.5	24.9	139	255
13.73	24.9	140	256
13.8	24.94	142	260
13.8	25	142.4	263
13.86	26	142.5	265
14.2	26.4	142.9	500
14.4	26.5	143.13	525
14.7	27.5	144	
14.9	34.5	145	
15	66	147	
16	69	148.6	
18	69.07	152.4	
19	72		
19.5			

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The primary advantages of the per-unit system are:

1) The per-unit values for transformer impedance, voltage, and current are identical when referred to the primary and secondary. The transformer in a per-unit system is a single impedance. There is no need to reflect impedances from one side of the transformer to the other side.
2) The per-unit values for various components lie within a narrow range regardless of the equipment rating.
3) The per-unit values clearly represent the relative values of the circuit quantities. Many of the scaling constants in equations are eliminated.

The definition of any quantity (voltage, current, power, impedance) in the per-unit system is:

$$\text{Quantity}_{[pu]} = \frac{\text{Quantity}_{[IS\ unit]}}{\text{Base Value of quantity}_{[IS\ unit]}}$$

To characterize a per-unit system, at least two base values should be defined. Once any two of the four base values (V_{base}, I_{base}, S_{base}, and Z_{base}) are defined, the remaining two base values can be determined according their fundamental circuit relationships. Base values are real values, while quantities according to the phasor analysis are complex. Given the four base values, the per-unit quantities are defined as:

$$V_{[pu]} = \frac{V}{V_{base}}$$

$$I_{[pu]} = \frac{I}{I_{base}}$$

$$S_{[pu]} = \frac{S}{S_{base}}$$

$$z_{[pu]} = \frac{Z}{Z_{base}}$$

In practice, the base values of power and voltage are usually selected and the base values of current and impedance are determined as follows:

$$I_{base} = \frac{S_{base}}{V_{base}}$$

$$Z_{base} = \frac{V_{base}}{I_{base}} = \frac{{V_{base}}^2}{S_{base}}$$

In three-phase systems, the abovementioned four equations are the same if line-to-line voltage is taken into account instead of phase voltage except:

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$$I_{base} = \frac{S_{base}}{\sqrt{3}V_{LL\ base}}$$

$$Z_{base} = \frac{V_{ph\ base}}{I_{base}} = \frac{V_{LL\ base}}{\sqrt{3}\ I_{base}} = \frac{{V_{LL\ base}}^2}{S_{base}}$$

In the power systems in which S_{base} is constant for all points of the system, if the ratio of voltage bases on either side of a transformer is chosen to equal the ratio of the transformer voltage ratings, then the transformer per-unit impedance remains unchanged when referred from one side of a transformer to the other. This allows the ideal transformer in the transformer model can be eliminated as shown in Figure 1-8.

Normally, the power system S_{base} and V_{base} are different than the transformers rating values as there are many different types of transformers with different MVA ratings. Also, a transformer may operate in a non-nominal tap setting indicating a voltage level different than the system's nominal voltages level. Therefore, the parameters need to be referred from one per-unit system to another per-unit system. Given the two per-unit systems as a new and an old per-unit system, the per-unit impedance can be referred from the old per-unit system to the new per-unit system as follows:

$$z_{[pu\ New]} = z_{[pu\ Old]} \times \left(\frac{V_{b\ Old}}{V_{b\ New}}\right)^2 \times \frac{S_{b\ New}}{S_{b\ Old}}$$

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Appendix F. Transformer Impedance Table

The parameters of a transformer equivalent circuit depend on the transformer tap position at which the no-load losses and load-losses tests are conducted. That equivalent circuit is more accurate for that tap position. In practice, power transformers are designed to operate optimally at nominal voltage, but since the voltage in a power system varies within an accepted limit, the transformer's voltages ratio needs to be adjusted by LTC or DETC tap changers. The transformer load-losses and no-load losses test results that are used to model the transformer are conducted at the windings' nominal voltages and at the nominal tap position. However, in the test report, load-losses test results might be reported at minimum, at maximum, or at both tap positions as well as at the nominal tap position. These results can be used to calculate the transformer impedance correction table for all tap positions.

The magnetizing branch parameters do not change when the tap position changes. As described in Section 1.15.1, for a no-load losses test the transformer is energized to give 100% peak volts per turn, which results in 100% flux in the core. However, due to technical limitations, normally a low-voltage winding is excited, but generally it does not matter how many turns from which winding are excited in order for 100% peak volts per turn to be applied.

As described in Section 1.13, the series impedance of a transformer changes when the tap position changes. This change is due to the number of tap winding turns that are physically brought in the circuit or brought out of the circuit. If at least two load-losses test results for two different tap positions are available, the impedance change from one tap position to another tap position can be determined. Assuming that the impedance of the tap changer contacts is zero, the calculated impedance change can be extended to other tap positions and the approximate impedance correction table can be determined accordingly.

To present how tap position affects the transform model, a transformer with an LTC tap changer in the high-voltage side is assumed. It is assumed that the voltage at the low-voltage side is constant and the tap is controlled to compensate for voltage variations at the high-voltage side terminal. Figure F-1 shows its T-model equivalent circuit in which subscript “N” denotes the nominal tap position in which the equivalent circuit has been calculated.

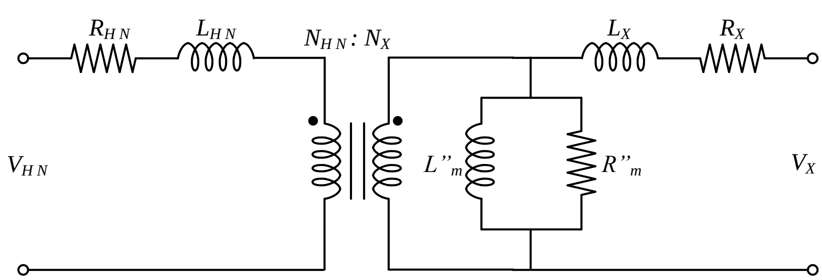

Figure F-1- Transformer T-model equivalent circuit at nominal tap position with the magnetizing branch in the secondary side

As mentioned above, the tap position will not affect the magnetizing branch parameters. Also, it is assumed that the voltage is constant at the secondary side; therefore, considering the

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magnetizing branch in the secondary side clarifies that its parameters will not change with the tap changer. Notwithstanding the magnetizing branch, as shown in Figure F-2, the series impedance of the secondary winding will be constant for different tap positions as well.

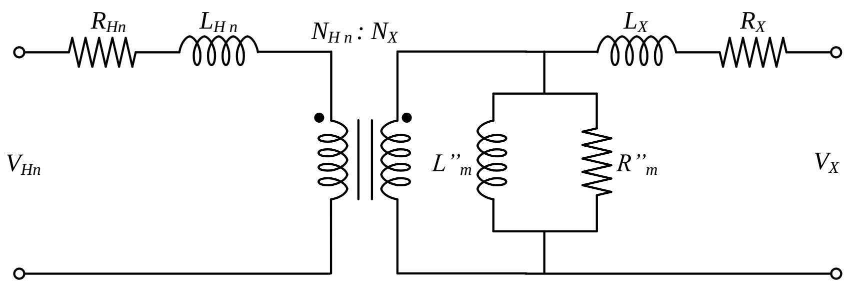

Figure F-2- Transformer T-model equivalent circuit at non-nominal tap position with the magnetizing branch in the secondary side

The effect of the tap position on the resistance and leakage reactance of the high-voltage winding is not similar. As described in Section 1.2.2.d, the winding equivalent resistance includes winding dc resistance, eddy current losses due to the load current, skin effect, and stray losses. The effect on each of these components not only depends on the type of tap changer, it also depends on the inherent type of each component. Therefore, theoretical modelling of this effect is case-dependent. In the linear type of tap changers, if the related tap position voltage is higher than the nominal voltage ($N_{H\,n} > N_{H\,N}$), the dc resistance component is greater than the nominal position dc resistance, but other components are smaller than the nominal components. It should be noted that the other components totally are smaller than the dc resistance component; therefore, dc resistance component change is dominant.

The effect of the tap position on the leakage reactance is different. It varies exponentially with the effective (not total) number of winding turns. However, this effect is linear on the winding ac resistance. In order the winding turns for all tap positions are presented in the transformer nameplate; the effect of the tap position on the leakage reactance can be determined more accurately. But, the number of turns usually is not provided in the transformer nameplate.
As a result, regardless of the type of tap-changer, the transformer equivalent series impedance for all tap positions can be determined through three approaches:

1) *Approach One:* Through test measurements on all tap positions. If a load losses test has been conducted for all tap positions, the series impedance can be calculated from the test measurements for each tap position while the magnetizing branch that is considered at the low voltage side is constant. As shown in Figure F-3, $R_{eq\,n}$, equivalent ac resistance, and $X_{eq\,n}$, windings leakage reactance, are directly determined from load losses test results at tap position n . In practice, a transformer's test report does not include load losses test measurements for all tap positions except in the case of special transformers such as phase-shifting transformers, even if load losses tests have been conducted during the manufacturing process, because the reported test results are a summary test report.

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2) *Approach Two:* Through estimation from at least two load losses test results provided in the test report. The test reports of transformers equipped with tap changers usually include load losses test results at the nominal tap setting and at the minimum and maximum tap positions. The equivalent series impedance and ac resistance of the winding can be calculated for these three tap positions from the provided results. For other tap positions, these parameters can be estimated from curve fitting and interpolation between available data. Since the winding's ac resistance and leakage reactance characteristics versus tap position are similar to a linear characteristic, estimation or curve fitting can usually be accomplished by simple calculation (the MS-Excel curve-fitting feature [Trendline options] is adequate for this purpose). A two-order polynomial curve will give the best estimation. However, it should be noted that for step-voltage regulators and phase-shifting transformers the windings' ac resistance and leakage reactance characteristics versus tap position is not a linear characteristic, and the MS-Excel curve-fitting feature may be not able to estimate an adequate curve or may generate errors; in these cases, other numerical programs are recommended.

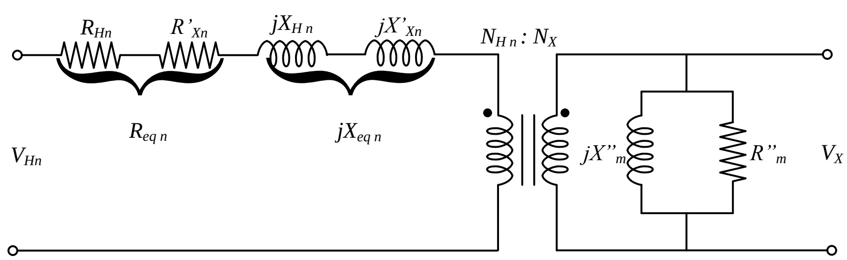

Figure F-3- Transformer equivalent circuit at tap position n

3) *Approach Three:* Through impedance transfer calculation. If the transformer test report includes only one load losses test report conducted on the nominal tap position the only approach is to consider the tap changer operation as an off-nominal turns ratio, as discussed in Section 1.13. This approach is not an accurate approach and may lead to a non-real parameters value, but any additional calculation or non-realistic assumptions may lead to non-realistic results. This method is explained below.

Figure F-4 shows a transformer that operates in a non-nominal tap setting. Its equivalent circuit has been derived from the results of tests that have been conducted at the nominal tap position. The operation in the non-nominal tap setting is shown as an ideal transformer in the high-voltage terminal. This ideal transformer presents the off-nominal turns ratio.

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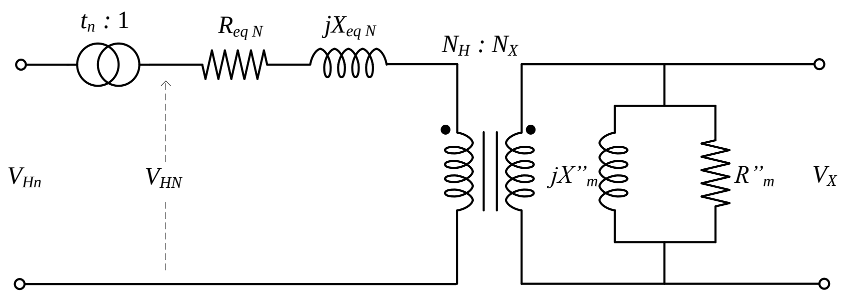

Figure F-4- Transformer equivalent circuit at the nominal tap position while the non-nominal tap setting is shown as an ideal transformer in the terminal (presenting off-nominal turns ratio)

The series impedance can be referred to the terminal side of the off-nominal turns ratio ideal transformer, as shown in Figure F-5. These impedances can be obtained as:

$$R'_{eq\ n} = {t_n}^2 \times R_{eq\ N}$$

$$X'_{eq\ n} = {t_n}^2 \times X_{eq\ N}$$

In which:

$$t_n = \frac{V_{H\ n}}{V_{H\ N}}$$

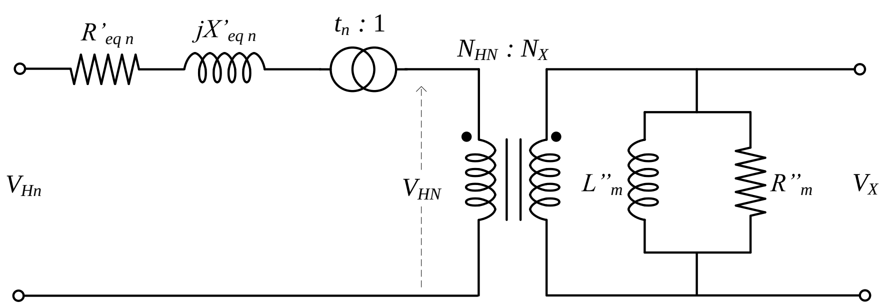

Figure F-5- Transformer equivalent circuit at the non-nominal tap position with transferred windings series impedance to the terminal side of an off-nominal turns ratio ideal transformer

Two ideal transformers can be combined into one transformer with a $t_n \times N_{HN} : N_X$ turns ratio as shown in Figure F-6. In which:

$$t_n \times N_{HN} = N_{Hn}$$

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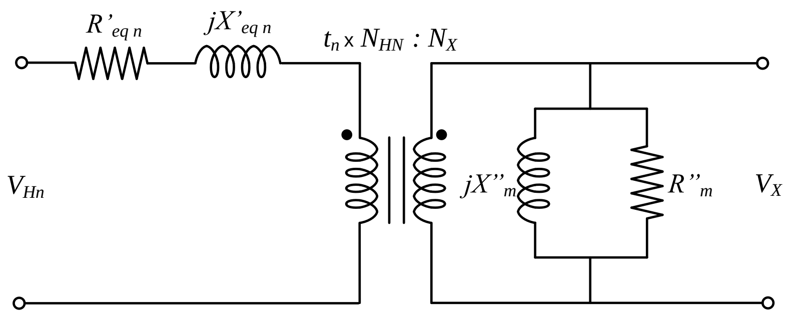

Figure F-6- Transformer equivalent circuit at tap position n with magnetizing branch at the secondary side

Figure F-6 shows the transformer equivalent circuit that operates at tap position, a non-nominal tap setting. The magnetizing branch which had been considered in the secondary side is constant and the tap position does not change its parameters. Now, the magnetizing branch can be transferred to the primary side as shown in Figure F-7, but it should be noted that the excitation voltage in the primary side is not the nominal voltage. Therefore, the magnetizing branch parameters should be calculated according to the tap operating position as follows:

$$R'_{m\,n} = R"_m \times \left(\frac{N_{Hn}}{N_X}\right)^2 = R"_m \times {t_n}^2 \times \left(\frac{N_{HN}}{N_X}\right)^2 = {t_n}^2 \times R_m$$

$$X'_{m\,n} = X"_m \times \left(\frac{N_{Hn}}{N_X}\right)^2 = X"_m \times {t_n}^2 \times \left(\frac{N_{HN}}{N_X}\right)^2 = {t_n}^2 \times X_m$$

These obtained parameters of the magnetizing branch not only do not mean that the magnetizing branch parameters are changed by the tap position, they also guarantee that 100% peak volts per turn is energized.

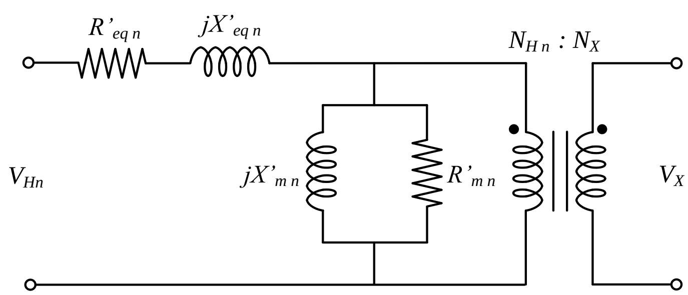

Figure F-7- Transformer equivalent circuit at tap position n with the magnetizing branch at the primary side

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A Practical Example: Two-Winding Transformer

The transformer of Example 1, discussed in Section 2.4.4, is used here to show how it can be modelled at non-nominal tap positions. The load losses test results have been provided for the minimum, maximum, and nominal tap positions. The following table shows the calculated results for the given tap positions.

Table F-1- The Series Impedance Parameters of Transformer Calculated from Test Results

tap n	V_H	P_{LL}	I_Z	Test	I_{Hrated}	Z_{base}	z (pu)	r	Z	R	X
	kV	kW	%	MVA	A	@ MVA	@ Test MVA		Ω	Ω	Ω
1	151.8	39.952	7.5	15	57.05	1536.216	0.075	0.002663	115.216	4.0917	115.143
9	138	41.66	7.68	15	62.76	1269.6	0.0768	0.002777	97.5052	3.5261	97.4415
17	124.2	37.25	7.41	13.5	62.76	1142.64	0.0741	0.002759	84.6696	3.1528	84.6109

The equivalent series impedance parameters are calculated through Approach Two and Approach Three, which were detailed in the numbered list above.

Approach Two: To estimate from interpolation, the impedance and resistance values shown in Figures F-7 and F-8 have been drawn in MS- Excel, and from Excel's curve-fitting feature a second-order polynomial equation versus tap position has been obtained for impedance and resistance as follows, in which n is the tap position (1-17):

$$Z = 2.4376 \times n^2 - 25.024 \times n + 137.8$$
$$R = 0.0015015625 \times n^2 - 0.085728125 \times n + 4.1758265625$$
$$X = \sqrt{Z^2 - R^2}$$

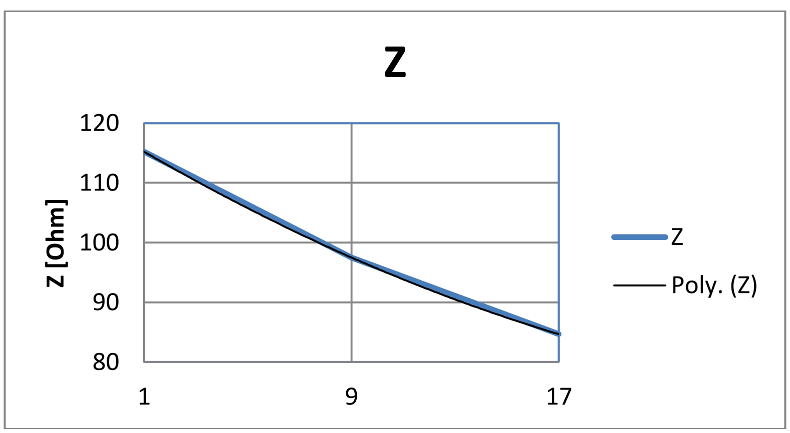

Figure F-7- The equivalent series impedance versus three given tap positions

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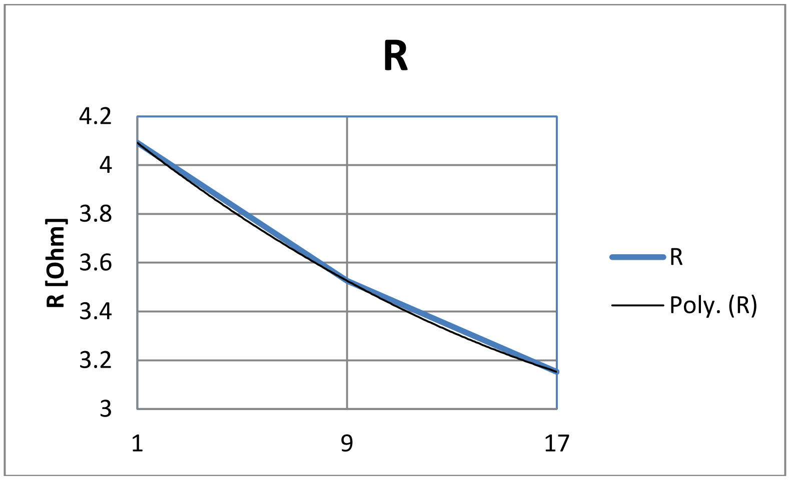

Figure F-8- The equivalent series resistance versus given three tap positions

Figures F-9 to F-11 show the estimated values of the series impedance. The results have been listed in the Table F-2.

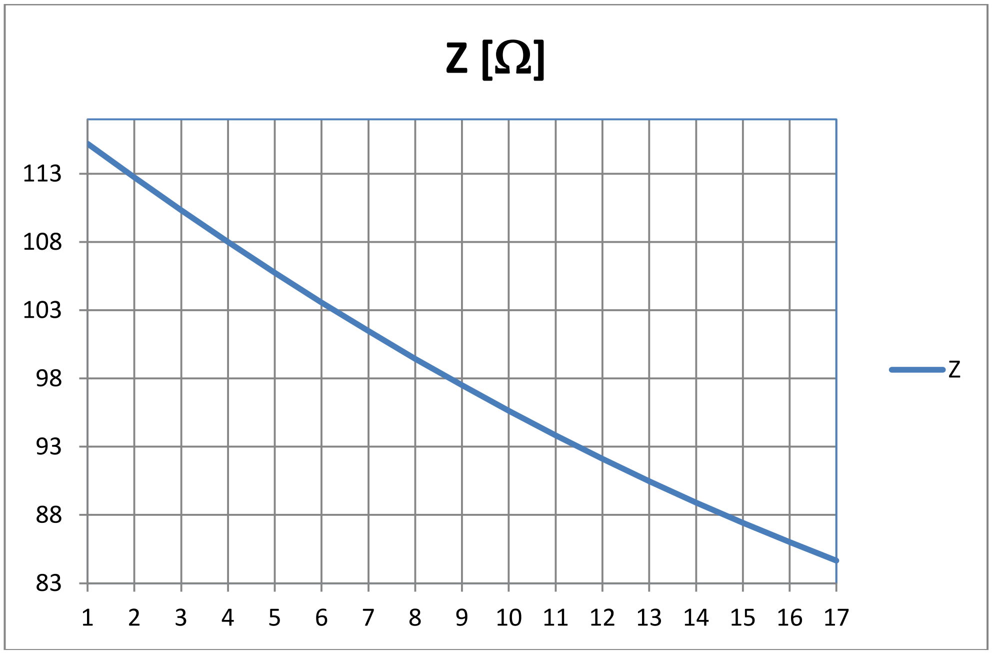

Figure F-9- The estimated equivalent series impedance versus tap positions through approach Two

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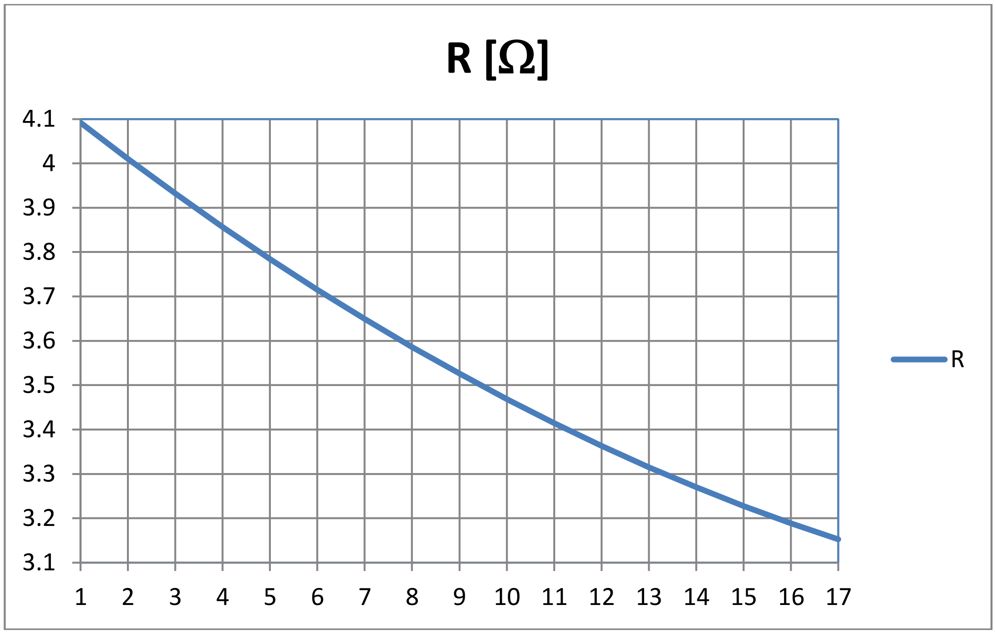

Figure F-10- The estimated equivalent series resistance versus tap positions through approach Two

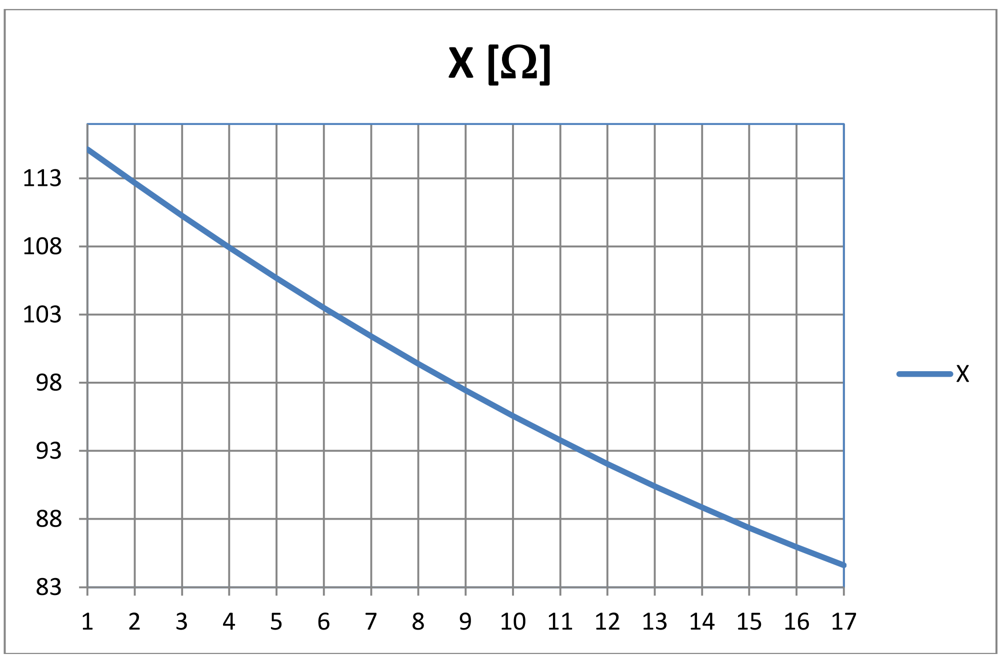

Figure F-11- The estimated equivalent series reactance versus tap positions calculated from estimated impedance and resistance through approach Two

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Approach Three: As described above, the series ac resistance and leakage reactance of a transformer obtained from the load-losses test at the nominal tap position are referred to the related tap setting voltage from nominal voltage as follows:

$$R'_{eq\ n} = {t_n}^2 \times R_{eq\ N}$$

$$X'_{eq\ n} = {t_n}^2 \times X_{eq\ N}$$

And also:

$$Z'_{eq\ n} = {t_n}^2 \times Z_{eq\ N}$$

The calculated parameters through both methods are listed in Table F-2. As can be seen, the results from both methods are close; however, the Approach Two is more accurate than Approach Three.

Table F-2- Transformer Impedance Table for all Tap Positions

Tap	V_H kV	V_X kV	t_n	From Interpolation (Approach Two)			From Off-nominal Turns Ratio (ApproachThree)		
				Z [Ω]	R [Ω]	X [Ω]	Z [Ω]	R [Ω]	X [Ω]
1	151.800	26.5	1.1000	115.21360	4.09160	115.14092	117.98139	4.26658	117.90422
2	150.075	26.5	1.0875	112.73309	4.01038	112.66173	115.31523	4.17017	115.23980
3	148.350	26.5	1.0750	110.32875	3.93216	110.25866	112.67954	4.07485	112.60584
4	146.625	26.5	1.0625	108.00059	3.85694	107.93170	110.07432	3.98064	110.00232
5	144.900	26.5	1.0500	105.74860	3.78473	105.68085	107.49957	3.88753	107.42926
6	143.175	26.5	1.0375	103.57279	3.71551	103.50612	104.95529	3.79552	104.88664
7	141.450	26.5	1.0250	101.47315	3.64931	101.40751	102.44148	3.70461	102.37448
8	139.725	26.5	1.0125	99.44969	3.58610	99.38501	99.95815	3.61481	99.89276
9	138.000	26.5	1.0000	97.50240	3.52590	97.43863	97.50528	3.52610	97.44150
10	136.275	26.5	0.9875	95.63129	3.46870	95.56836	95.08288	3.43850	95.02069
11	134.550	26.5	0.9750	93.83635	3.41451	93.77421	92.69096	3.35200	92.63033
12	132.825	26.5	0.9625	92.11759	3.36331	92.05617	90.32950	3.26660	90.27042
13	131.100	26.5	0.9500	90.47500	3.31513	90.41424	87.99852	3.18231	87.94096
14	129.375	26.5	0.9375	88.90859	3.26994	88.84844	85.69800	3.09911	85.64194
15	127.650	26.5	0.9250	87.41835	3.22776	87.35874	83.42796	3.01702	83.37338
16	125.925	26.5	0.9125	86.00429	3.18858	85.94516	81.18838	2.93603	81.13528
17	124.200	26.5	0.9000	84.66640	3.15240	84.60769	78.97928	2.85614	78.92762

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Appendix G. Definitions

MMF: Magnetomotive Force
EMF: Electromotive Force
OCTC: Off-Circuit Tap Changer
OLTC or **LTC :** On Load Tap Changer
CT: Current Transformer
PT: Potential Transformer
N: Number of winding turn if it is a parameter and neutral point of the winding set if it represents a node.

Off-Nominal Turn Ratio: When the Vbase ratio of both sides of the transformer's terminals is not the same as the winding-rated voltage ratio, it is called the off-nominal turn ratio or the tap ratio.

Impedance Voltage: The impedance voltage of a transformer is the voltage required to circulate rated current through one of the two specified windings when the other winding is short-circuited with the winding connected as for rated operation.

Short-Circuit Impedance: The short-circuit impedance is the ratio of voltage and current under impedance voltage conditions.

Current Tap Ratio: The transformer's present off-nominal turns ratio.

Minimum Tap Ratio, Maximum Tap Ratio: Minimum and maximum allowable off-nominal tap ratios for the LTC transformer. Typical values are 0.9 and 1.1.

Tap Step Size: Transformer off-nominal turns ratio increment. The off-nominal turns ratio is either incremented or decremented from 1.0 in integer multiples of this value.

Impedance Correction Table: Specifies the number of the transformer's corresponding transformer impedance correction table. Transformer impedance correction tables are used to specify how the impedance of the transformer should change with the off-nominal turns ratio. If this number is 0, no impedance correction table is associated with the transformer, and the impedance of the transformer will thus remain fixed as the tap ratio changes.

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Table G-8 - Designations and Descriptions of the Cooling Classes Used in Power Transformers

IEEE/IEC Designation	Previous Designation (1993)	Description
ONAN	OA or ONS	Oil Natural/Air Natural, Oil-air (self-cooled)
ONAF	FA or ONF	Oil Natural/Air Forced, Forced-air
ONAN/ONAF/ONAF	OA/FA/FA	Oil Natural Air Natural/Oil Natural Air Forced/Oil Natural Air Forced, Oil-air (self-cooled), followed by two stages of forced-air cooling (fans)
ONAN/ONAF/OFAF	OA/FA/FOA	Oil Natural Air Natural/Oil Natural Air Forced/Oil Forced Air Forced, Oil-air (self-cooled), followed by one stage of forced-air cooling (fans), followed by 1 stage of forced oil (oil pumps)
ONAF/ODAF	OA/FOA	Oil Natural Air Forced/Oil Direct Air Forced, Oil-air (self-cooled), followed by one stage of directed oil flow pumps (with fans)
ONAF/ODAF/ODAF	OA/FOA/FOA	Oil Natural Air Forced/Oil Direct Air Forced/Oil Direct Air Forced, Oil-air (self-cooled), followed by two stages of directed oil flow pumps (with fans)
OFAF	FOA	Oil Forced Air Forced Forced oil/air (with fans) rating only—no self-cooled rating
OFWF	FOW	Oil Forced Water Forced Forced oil/water cooled rating only (oil/water heat exchanger with oil and water pumps)—no self-cooled rating
ODAF	FOA	Oil Direct Air Forced Forced oil/air cooled rating only with directed oil flow pumps and fans—no self-cooled rating
ODWF	FOW	Oil Direct Water Forced Forced oil/water cooled rating only (oil/water heat exchanger with directed oil flow pumps and water pumps)— no self-cooled rating

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