Effective Grounding
Assessment Guideline

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Alberta Electric System Operator
3000, 240 4 Avenue SW
Calgary, AB • T2P 4H4
aeso.ca

Effective Grounding for Transmission-Connected Generating Facilities

Assessment Guideline

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	Name	Signature	Date
Author – Lead Engineer, Protection & Control	Lucy Lin, P.Eng.		April 22, 2026
Checked & Approved – Senior Advisor, Operational Reliability	Changling Luo, P.Eng.		April 22, 2026

PROFESSIONAL ENGINEER ALBERTA
LUCY LIN
ID 93491
2026-04-22

PERMIT TO PRACTICE
INDEPENDENT SYSTEM OPERATOR
RM SIGNATURE:
RM APEGA ID #: 98372
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Contents

Executive Summary

Purpose and Scope

The Alberta Electric System Operator (AESO) has developed the Effective Grounding Assessment guideline to support market participants (MPs) in complying with the effective grounding requirement under Section 503.12(1) of the ISO rules, *Grounding and Surge Protection*. This guideline:

- Addresses challenges non-effective grounding poses to grid reliability
- Outlines the AESO's screening process to identify high-risk projects for non effective grounding
- Defines a standardized scope for detailed study, including methodology, inputs, assumptions, performance criteria, reporting requirements and mitigation options
- Explains how the effective grounding assessment fits into the AESO Connection Process

Rationale

Effective grounding is essential to the safe and reliable operation of Alberta's transmission system. Non effective grounding in customer connections can result in transient recovery voltage (TRV), leading to breaker failure and temporary overvoltage (TOV), which can damage transmission equipment and endanger public safety. The rise of inverter-based resources (IBRs) and generation additions at load only facilities has increased the complexity of grounding assessments. This guideline provides a standardized, risk-based approach to support the effective grounding assessment and the compliance.

Performance Criteria

During an unbalanced grounded fault, healthy phase(s) voltage at the point of connection (POC) shall not exceed 0.8 per unit (pu) of system nominal voltage under any operating conditions.

Application

MPs are expected to use this guideline for all applicable projects to assess compliance with effective grounding requirements before energizing their facility. For high-risk connection projects identified by the AESO, detailed effective grounding study and reporting requirements will be included in the functional specification (FS).

1. Effective Grounding Introduction

1.1 Background

Effective grounding is related to subsection 2(1) of Section 503.12 of ISO rules, *Grounding and Surge Protection* (Section 503.12). MPs' projects that have been as high-risk through the applicability, pre-screening criteria or screening steps will be required to conduct detailed study, providing evidence of compliance with the AESO Authoritative Document, which will be documented in a project's functional specification. This guideline is not authoritative and for information purposes only.

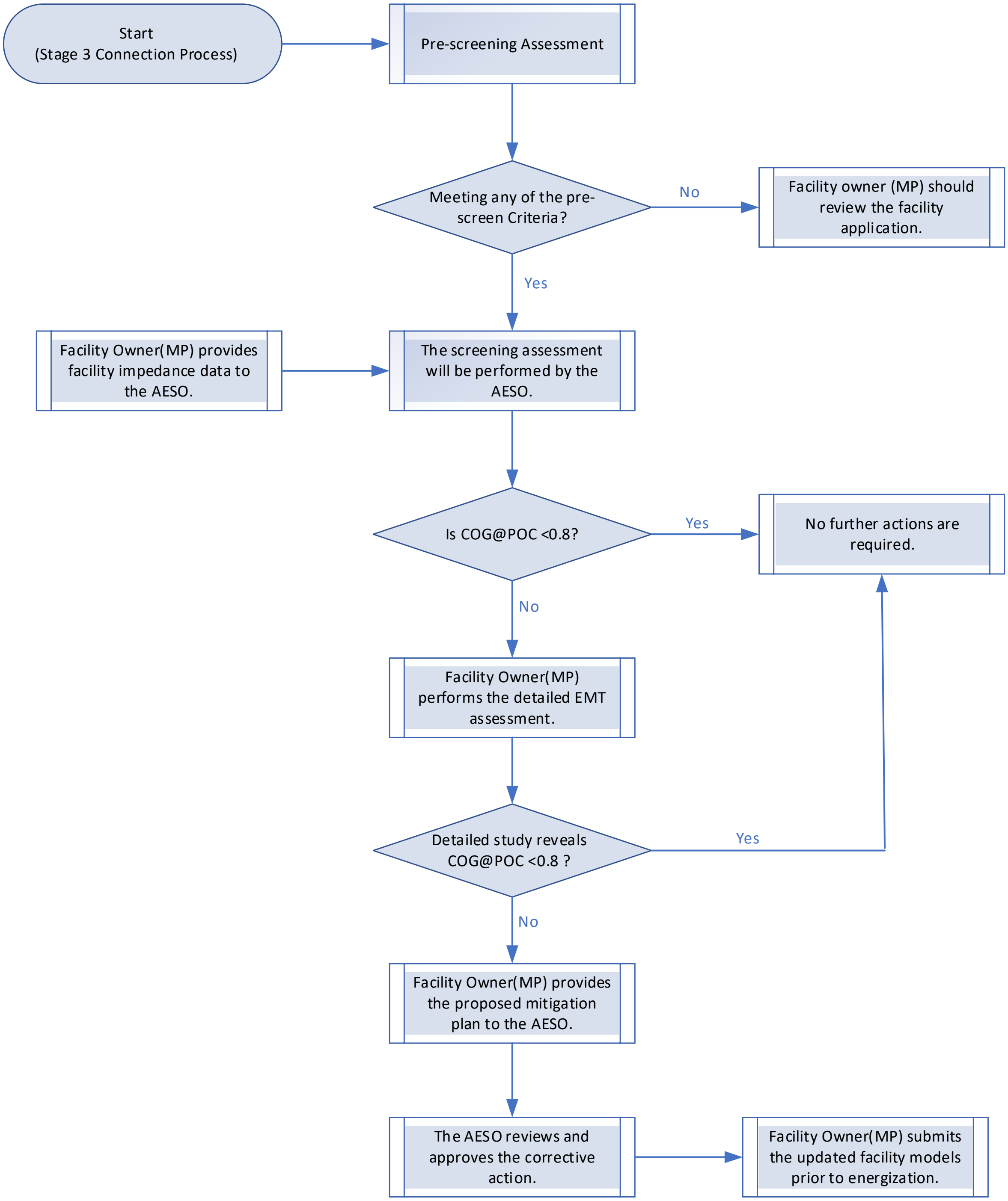
Effective grounding is an important characteristic of the whole electric power systems, affected by the generation sources. The current industry standard practices regarding grounding effectiveness were developed in an era when generation was dominated by conventional rotating machines and IBR penetration levels were negligible. With the increasing penetration of IBRs connected to the AIES, effective grounding has become more critical than ever for system reliability and public safety. Unlike traditional synchronous machine, IBR's responses to ground faults are largely dependent on its control algorithm which are significantly different from synchronous machines. As such, some underlying assumptions related to the sources being rotating machine are no longer valid and need to be revisited. Therefore, it is necessary for the AESO to provide information required in the guideline to properly conduct effective grounding assessment, particularly considering the coordination between IBRs and the transmission system.

The primary objective of having an effectively grounded system in the transmission system is to limit the temporary overvoltage (TOV) on unfaulted phase(s) during unbalanced ground faults and enable the protection system to detect high-magnitude ground fault currents and rapidly isolate faults. In an effective grounded system, unbalanced ground faults produce zero-sequence current. Protective relays with ground elements (e.g., ground overcurrent, ground distance), detect zero-sequence currents and initiate appropriate actions to clear the faults. In addition, zero-sequence currents flowing through an effective grounding path limits neutral displacement and the resulting voltage rise on healthy phases, which has a significant impact on insulation coordination within a facility. For example, application of surge arresters for ground-neutral service requires the system to be effectively grounded.

In contrast, an ungrounded or non-effectively grounded system does not experience significant ground fault currents during unbalanced grounded faults. Under such condition, the faulted phase holds at or near ground potential, causing a neutral displacement toward the faulted phase. This displacement will lead to voltage swell on the healthy phase(s). This resulting increase in line-to-ground voltage will impose excessive stress on insulators and surge arresters. If adequate withstand capability is not specified, this condition can lead to equipment failure. Consequently, an ungrounded or non-effectively grounded system may present a higher risk of equipment failure, such as transient recovery voltage (TRV) violation on circuit breakers or equipment damage like TOV on surge arresters.

A high level of the effective grounding assessment process flow is shown below in Figure 2.

Figure 2: Assessment Process Flow Visual



1.2 Roles and Responsibilities

This section outlines the high-level roles and responsibilities of various tasks in the study. All the parties can reach out to the AESO's project manager for details.

Table 1: RACI Chart for Effective Grounding Assessment

Note: R – Responsible; **A** – Accountable; **C** – Consult; **I** – Inform

Deliverable	AESO	Market Participant (MP)	Transmission Facility Owner (TFO)
Applicability and Pre-Screening (Earliest Connection Process Stage: Stage 1/2)			
Performs pre-screening and identifies the need for detailed study	A/R	C	I
Screening Assessment (Earliest Connection Process Stage: Stage 2)			
Provide the required facility information including positive/negative/zero-sequence impedance for each element to perform screening	C	A/R	I
Perform screening and capture results, including pass/fail, in facility scope	A/R	I	I
Hardware Mitigation and/or Detailed Study (Earliest Connection Process Stage: Stage 3 ~ Stage 5			
Propose the mitigation options if the screening does not pass	C	A/R	I
Detailed electromagnetic transient (EMT) study (if selected): Carry out the study and provide the report and simulation files	C	A/R	I
Inputs for the detailed EMT study (if selected): Facility data, EMT Model of IBR facilities, if required and available	R	A/R	I
Result Acceptance and Mitigation Action (Earliest Connection Process Stage: Stage 3 ~ Stage 5**)**			
Provide the mitigation and/or detailed study results	C	A/R	I

Deliverable	AESO	Market Participant (MP)	Transmission Facility Owner (TFO)
Accept the mitigation strategy and update the functional specification (FS) accordingly with related requirements	A/R	C	I
Energization Authorization (Earliest Connection Process Stage: Stage 5)			
Submit the Stage 5 Project Data Update Package (PDUP) with proof of correction action (e.g. hardware installation, original equipment manufacturer [OEM] datasheet)	C	A/R	I

Note:

Responsible (R) = “the doer”. Those who do work to achieve the task. There can be multiple resources responsible. The act of approving a deliverable can be categorized under the responsible party.

Accountable (A) = “the buck stops here”. The resource ultimately answerable for the correct and thorough completion of the task There can only be one “A” specified for each task.

Consulted (C) = “in the loop”. Those whose opinions are sought. Those who have special knowledge or expertise needed to make decisions or solve problem. Two-way communication.

Informed (I) = “in the picture”. Those who are kept up to date on progress and decisions (once made). May be impacted by decision but are not active in final decision. One-way communication.

1.3 Applicability

All new generating facilities as listed below, and load facilities connecting to the transmission system in the connection process are subject to this assessment.

- Synchronous generating facilities (e.g., gas, biomass, hydro, steam)
- Aggregated generating facilities (e.g., industrial CoGen, IBRs including wind, solar and battery energy storage system [BESS] resources)

Distribution energy resources (DERs) and pure load facilities are currently excluded from this guideline, and they are subject to the effective grounding requirement enforced by distribution facility owners (DFO).

1.4 Pre-Screening

The projects listed in the applicability section do not require additional screening. These projects may proceed directly to performing the screening study and providing the necessary deliverables.

At the pre-screening stage, emphasis is placed to ensure the presence of a path in the zero-sequence network. To achieve the grounding effectiveness, proper interconnection transformer winding configuration plays a crucial role in providing zero-sequence path at the proposed facility. Therefore, it is essential to select an interconnection transformer which could provide a closed path for zero-sequence currents so that the protective relays can reliably detect these currents and isolate unbalanced ground faults.

Refer to Appendix B3.2 for the proper transformer winding configurations applied to different generating facilities.

1.5 Screening Assessment

The purpose of the screening assessment is for the AESO to identify potentially high-risk projects. The MP can use the screening to understand the risk of non-compliance. If the screening identifies a potential risk with effective grounding, the AESO will explicitly ask the MP to pursue detailed study.

The MP has option to skip the screening and go directly to a detailed Study or mitigation. The MP is recommended to inform the AESO at the beginning of stage 2 about their preferred option.

Please refer to Appendix B for the screening assessment details.

If the screening is passed but there are changes in the screening inputs during the connection process (e.g., transformer winding configuration change, IBR control change, etc.), then the screening must be reassessed.

1.6 Detailed Study

As outlined in AESO’s Risk-Based Assessment Approach section, the need for a detailed effective grounding study is identified if a project meeting the applicability or screening criteria does not pass the screening assessment, which indicates that further assessment is required to ensure that there is no operational or reliability risk to the AIES, or that the risk can be adequately mitigated. As such, the project functional specification will be updated to include the effective grounding detailed study requirement. A detailed study on effective grounding requires EMT analysis to confirm whether the facility is complying with the effective grounding requirement or effectiveness of the proposed mitigation solution. The study scope and criteria shall be similar with screening assessment but in EMT environment. The AESO suggests market participants to present the detailed study results using the study report template in Appendix A.

A structured and detailed approach to undertake detailed effective grounding assessment, covering all necessary steps from data collection to mitigation strategies to ensure power system reliability is outlined in Appendix C.

1.7 Result Acceptance and Mitigation Implementation

For the high-risk projects selected by the AESO, the MP will be asked to submit the study report and the proposed mitigation solution, which must be accepted by the AESO before the in-service date of project. The AESO will review the study report within reasonable time and may provide comments, requesting the MP to respond prior accepting the report. If the MP decides to change their facilities to meet the effective grounding requirement according to the study result or proposed mitigation solution, the AESO may revise the functional specification of the project. Any delay on the study report submission may result in a delay of project energization. It is noted that some mitigation solutions may require changes on transmission facility impacting the project cost and timeline significantly.

A final proof of Effective Grounding Study Report and updated facility model should be presented and shared with the AESO as part of Stage 5 PDUP package and corrective actions should be implemented prior to the project energization.

1.8 Energization Requirements

The AESO authorizes the project to connect to the AIES and achieve energization when the project meets all the AESO's energization checklist requirements, outlined in the 100-day and 30-day energization packages. The required study report will be included in the energization checklist. We encourage the MP to check with AESO's project manager to fully understand how to meet the energization requirements.

2. Effective Grounding Screening Assessment

2.1 Methodology and Criteria

As per IEEE C62.92.1- *IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems--Part I: Introduction*, there are strong economic reasons for adopting effective grounding in systems operating at 115 kV and above, primarily driven by reduced insulation costs and the lower cost per transformer sizing.

In system grounding practice, the term coefficient of grounding (CoG) is defined as the ratio of E_{LG}/E_{LL} expressed as follows

$$CoG = \frac{E_{LG}}{E_{LL}}$$

Where:

E_{LG} *is the highest root-mean-square (rms), line-to-ground voltage on a healthy (un-faulted) phase at a selected location during a line-to-ground fault (i.e. single-line-to-ground [SLG] and phase-to-phase-to-ground [LLG]) affecting one or more phases.*

E_{LL} *is the system nominal line-to-line voltage that would be obtained at the selected location with the fault removed.*

For three-phase system, CoG is calculated from the phase-sequence impedance components, as viewed from the fault location. The CoG is very useful in the selection of a surge arrester rating for a specific location.

The other term earth-fault factor (EFF), to a limited extent, can also be used instead of CoG. At a specific location on a three-phase system, the EFF is the ratio of the highest rms line-to-ground voltage on a healthy (un-faulted) phase to the system nominal line-to-ground voltage during an unbalanced ground fault (affecting one or more phases at any point).

$$EFF = \sqrt{\mathbf{3}} * CoG$$

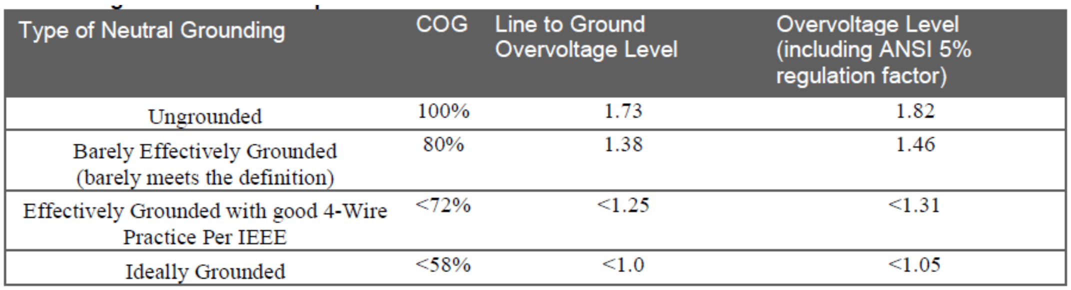
Where:

CoG is the coefficient of grounding expressed as a percentage as defined above.

As per Section 7 of IEEE C62.92.1-2000, effective grounding is defined as a system grounded through a sufficiently low impedance (inherent or intentionally added, or both) so that the CoG does not exceed 80 per cent. To quantify a grounding scheme being effective or not, if CoG is calculated less than or equal to 80 per cent, the grounding scheme is deemed as being effective. If a system's CoG is higher than 80 per cent, then it is non-effectively grounded.

Table 2 summarizes the overvoltage level on healthy (un-faulted) phase for various CoG.

Table 2: Overvoltage Level on Unfaulted Phase for Various CoG[1]



Type of Neutral Grounding	COG	Line to Ground Overvoltage Level	Overvoltage Level (including ANSI 5% regulation factor)
Ungrounded	100%	1.73	1.82
Barely Effectively Grounded (barely meets the definition)	80%	1.38	1.46
Effectively Grounded with good 4-Wire Practice Per IEEE	<72%	<1.25	<1.31
Ideally Grounded	<58%	<1.0	<1.05

IEEE C62.92.1-2000 also states that effective grounding "is obtained approximately when, for all system conditions, the ratio of the zero-sequence reactance to the positive-sequence reactance, (X0/X1) is positive and ≤ 3, and the ratio of zero-sequence resistance to positive-sequence reactance, (R0/X1) is positive and <1." This simplified CoG calculation is based on assumptions of the same positive-sequence and negative-sequence impedances (Z1 = Z2) where synchronous generations are overwhelmingly dominant sources. However, this criterion can not be applied for current-limited power electronic inverter-based resources, which have extremely high positive-sequence impedance Z1 and different values of positive- and negative-sequence impedance Z1 ≠ Z2.[2]

2.2 Recommended Tools for Screening Assessment

Power System Simulation for Engineering (PSS/E) is recommended for initial effective grounding screening for the proposed facility, though it is not the only option. Other steady state short-circuit tools (e.g. PSS/CAPE, ETAP, ASPEN OneLiner) can also be utilized for short-circuit analysis at points of interest.

PSS/E or other Short-circuit tools can be utilized for the following tasks:

- **Short Circuit Calculations:** simulate unbalanced ground faults (i.e. single-line-to-ground and line-to-line-ground) at the point of connection (POC) bus of the proposed generating facility, irrespective of the transmission system influence.
- **Screening Assessment:** observe the phase voltage on healthy phase(s) under the specific fault, calculate the CoG to evaluate the grounding effectiveness at the proposed facility, identify the risks in need of more detailed study.

In case another tool is selected to complete this task, it should still support data export in ".raw" and ".seq" formats to ensure compatibility with other software and facilitate data sharing for further analysis.

2.3 Facility Sequence Network Modelling

As aforementioned, system grounding is essential for protection system to trip and isolate unbalanced ground faults. An unbalanced ground fault is part of unbalanced system operation.

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[1] EPRI- Effective Grounding for Inverter-Connected DER Final Report.

[2] EPRI- Effective Grounding for Inverter-Connected DER Final Report.

Symmetrical components analysis is the easiest method to analyze unbalanced system operation. To perform fault analysis, networks within the facility is usually broken down into three-sequence components known as the positive, negative and zero-sequences.

2.3.1 Type of Generators

In general, there are two types of generators. Their characteristics related to grounding are elaborated as follows.

2.3.1.1 Rotating Generators or Machine-Based Generators

This type of generators includes combined heat & power (CHP), landfill gas, small hydroelectric, simple cycle gas turbine or steam engine.

Synchronous generator reactance is used to describe the behaviour of a generator during certain operating conditions. Since the resistive component in generators is negligible, for practical purposes it may be ignored and only the reactance need be considered.

Positive-sequence Impedance

In power system modelling, a typical rotating generator is characterized as a voltage source behind a relatively low positive-sequence impedance. This impedance is represented as saturated sub-transient impedance *Xd”*. Saturated sub-transient impedance *Xd”* is a parameter that describes the behaviour of a synchronous generator during a line-line-line (LLL) fault at its terminal. It is used to calculate the maximum available short circuit current to select circuit breakers with adequate interrupting rating. *Xd”* typically value ranges from 0.15 to 0.3 per unit (pu). In general, rotating generators have sufficient capability to withstand large over-currents (e.g., 4–6 times rated) for several cycles (3~5 cycles).

Negative-sequence Impedance

Due to the physics of tiny difference between two different rotating directions (clockwise and counterclockwise), the negative-sequence impedance is equal or very close to its positive-sequence impedance.

Zero-sequence Impedance

Rotating generator zero-sequence reactance has the lowest value. In this case, a generator might have a higher initial ground-fault current than a three-phase fault current if a generator has a solidly grounded neutral.

According to National Electrical Manufacturers Association (NEMA), synchronous generator is required to withstand only the three-phase current level unless it is otherwise specified. To limit the line-to-ground fault current, a high-impedance grounding (e.g., grounding resistor, grounding reactor) is typically connected to the generator neutral, which makes generator zero-sequence impedance practically infinite. Therefore, its equivalent zero-sequence impedance is modelled as a neutral grounding impedance behind a generator zero-sequence impedance.

2.3.1.2 Inverter-Based Resources (IBRs)

IBRs include solar photovoltaic (PV) power, BESS, Type 3 doubly fed induction generator (DFIG) and type 4 full-scale converter (FSC) wind turbine generators (WTGs).

Unlike conventional synchronous generators, the fault response of an IBR is largely determined by the inverter control system, which has been programmed to respond to its terminal conditions. Because the power electronic devices used in inverters are highly sensitive to overcurrents, they may be subject to failure due to even a sub-cycle exposure to excessive currents. To protect the inverter hardware, high-speed switches at kilohertz (kHz) speeds, are implemented to effectively limit maximum output current from the inverter to slightly above its rated value. In general, the short circuit current from an IBR is low magnitude, highly controlled by fast-switching of power electronics devices dependent upon OEM-specific control algorithm.

Positive-Sequence Impedance

In power system modelling, most IBRs are controlled for constant-power output with current limiting functionality, so they can be represented by a voltage controlled current source with parallelled a positive-sequence impedance (i.e., a Norton impedance instead of Thevenin one). After injecting current onto a set of physical 3-phase inductors, the constant current (or power) inverters would be able to output a synthetic ac voltage.

Negative-Sequence Impedance

In contrast to the rotating generators, negative and zero-sequence impedance of IBRs need extra attention.

DFIG WTGs, similar to synchronous generators, provide a low impedance path for the circulation of negative-sequence current. However, the apparent negative-sequence impedance of FSC WTGs and solar PV inverters varies widely depending on the inverter’s control design. In some cases, it may be fully suppressed, while in others it may take a finite value dictated by the control logic. In most existing designs with full converter interface, the IBR only injects positive-sequence current under all operating conditions including balanced and unbalanced faults.

Zero-Sequence Impedance

IEEE C62.92.6-2017- *IEEE Guide for Application of Neutral Grounding in Electrical Utility Systems,* Part VI-*Systems Supplied by Current-Regulated Sources* details the zero-sequence impedance of three-wire inverters and four-wire inverters, respectively. A three-wire inverter is a three-phase inverter without neutral connection, with no path for zero-sequence currents and infinity zero-sequence impedance. In contrast, a four-wire inverter is a three-phase inverter with neutral connection. Despite appearing as a neutral, the fourth wire is only meant for sensing but not rated for carrying fault current.

To date, most IBRs are 3-wire ungrounded. Sequence impedance datasheets from OEMs often show zero-sequence impedance being infinity as 9999 ohms.

2.3.2 *Interconnection Transformers*

The interconnection transformer between the sources and the grid could complicate the ground effectiveness within a facility. The selection of the interconnection transformer winding configurations plays a significant role on over-voltage mitigation for unbalanced grounded faults. Typically, transmission systems are effectively grounded through the wye winding of a transformer or an autotransformer.

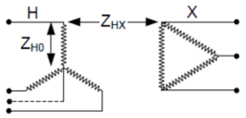
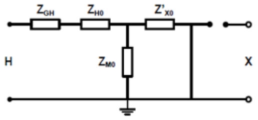
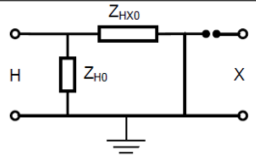
2.3.2.1 Two-Winding YN/D Transformer in Synchronous Generating Facilities

The synchronous generator step-up transformer high-voltage to low-voltage windings are normally specified with wye-grounded to delta connections. This is the most common generator step-up transformer configuration.

The primary side of the transformer is typically connected in wye configuration due to its electrical and mechanical advantages (e.g., low insulation costs of the windings, simple insulation design for the on-load tap changer). When grounded, the wye connection establishes a defined ground reference and enables the flow of zero-sequence current during ground faults. The delta winding connected to the generator side provides a closed circulating path for zero-sequence magnetizing currents, thereby preventing zero-sequence currents flowing into the generating facility.

For this connection, zero-sequence current will flow through a grounded Y-delta connected transformer; however, the total zero-sequence current flowing through the secondary terminals is zero and no zero-sequence voltage appears on the terminal of secondary windings, as shown in Table 3.

Table 3: Zero-Sequence Equivalent Circuit of YN-Delta Transformer[3]

Symbol	Connection Type	T-Model	Π- Model
YN-Delta			

In PSS/E, winding connection codes are indicating the connections and ground paths to be used in modelling the transformer in the zero-sequence network. The Connection Code 12 as Table 4 is to represent a two-winding Wye-Delta transformer zero-sequence network in PSS/E.

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[3] Table 2-5 Zero-Sequence Equivalent Circuit of Y-Delta-connected Transformers in AESO Transformer Modelling Guide.

Table 4: YN-Delta Transformer Seq Data Configuration in PSS®E[4]

YN-d without earthing transformer	CC	12
	RG1, XG1	RGH, XGH
	R01, X01	R0, X0
	RG2, XG2	Not Used
	R02, X02	Not Used

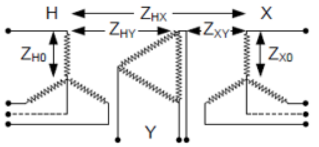
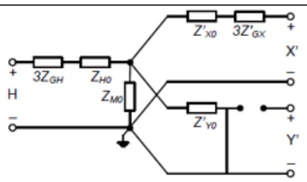
Which:

R0,X0: zero-sequence impedance measured from 'H' winding

2.3.2.2 Three-Winding YN/yn/D Transformer for Inverter-Based Generating Facilities

To incorporate the advantage of a wye winding and the advantage of delta winding, a three-winding YN/yn/Delta transformer is commonly employed as an interconnection transformer at an IBR facility. With this transformer winding configuration, the primary grounded wye winding is connected to the transmission side and the secondary wye winding is connected to IBR medium-voltage side, and the delta tertiary winding is buried into the two-winding Y-Y transformer. This transformer offers a zero-sequence path, which allows zero-sequence elements quantities to provide reliable operation for unbalanced ground faults. Table 5 shows Zero-sequence Equivalent Circuit of this YN/yn/Delta Transformer.

Table 5: Zero-Sequence Equivalent Circuit of YN/yn/Delta Transformer[5]

Symbol	Connection Type	T-Model	Π- Model
YN-yn-d			-

In PSS®E, it is strongly recommended to use Connection Code 12 to represent a three-winding Wye-Wye-Delta transformer zero-sequence network. Equivalent zero-sequence impedance ZHX0, ZHY0 and ZXY0 used in (CC 12) zero-sequence network as shown in Table 6 are aligned with zero-sequence in-between winding test data defined in IEEE Std C57.12.90.

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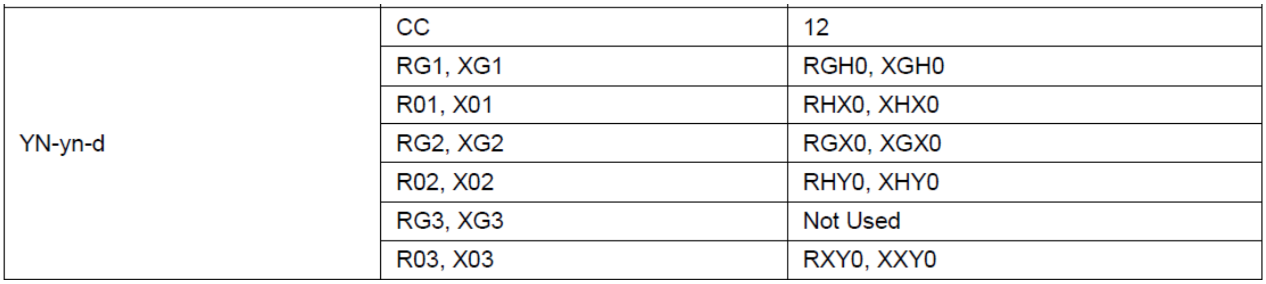
[4] Table A-7-3 PSSE Seq Data Source in AESO- Transformer Modelling Guide.

[5] Table 3-4 Zero-Sequence Equivalent Circuit of Wye-wye-delta-connected Three-Winding Transformers in AESO Transformer Modelling Guide.

Table 6: YN/yn/Delta Transformer Seq Data Configuration in PSS/E [6]



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

Which:

- *ZHX0: zero-sequence leakage impedance measured from 'H' winding, with 'X' winding shorted and delta-winding closed;*
- *ZHY0: zero-sequence leakage impedance measured from 'H' winding, with 'X' winding open and delta-winding closed;*
- *ZXY0: zero-sequence leakage impedance measured from 'X' winding, with 'H' winding open and delta-winding closed.*

2.4 Initial Screening Process

Based on the Stage 0 (for cluster projects) PDUP model submission from the MP, an initial screening will be performed using PSS/E to conduct steady-state (i.e., 60 HZ) analysis on CoG as defined in IEEE C62.92.1-2000.

To perform a consistent and realistic assessment of grounding effectiveness at the proposed facility, the approach of evaluating grounding effectiveness at a particular generating facility is elaborated as follows:

Step 1: Validate power flow and sequence data provided in .raw and .seq format

The assessment begins by validating comprehensive data in ".raw" and ".seq" formats. To determine whether facility grounding is effective or not needs accurate model to simulate unbalanced ground faults. The key components within the facility, including generators, transformers, conductors and etc., should be properly represented in both ".raw" and ".seq" files. Equivalent positive, negative and zero-sequence impedance for each component in ".seq" file should be validated for the short-circuit analysis.

It is highly recommended to apply typical parameters for facility components, considering most of OEMs' data are not available at the project early stages.

Step 2: Island the proposed facility from the system in the power flow case (i.e., .raw file) for short circuit calculation

To more accurately evaluate the grounding effectiveness at the proposed facility, the fault currents will be contributed exclusively from the facility itself. This step simulates a worst-case scenario by

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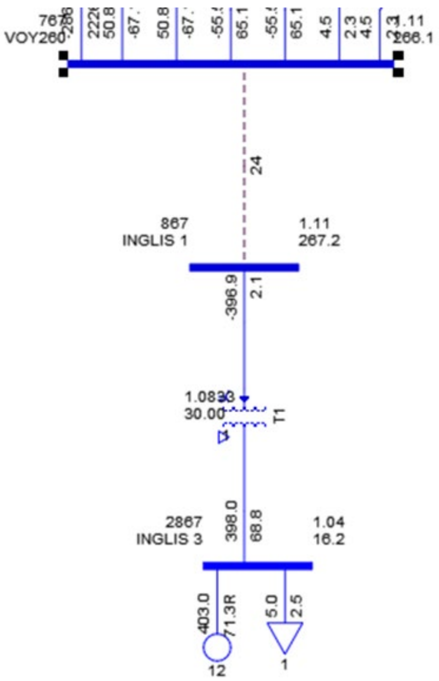
[6] Table A-7-3 PSSE Seq Data Source in AESO- Transformer Modelling Guide in AESO Transformer Modelling Guide.

islanding the facility (i.e., switch off the connection line between POC bus and TFO bus, as shown in Figure 3) and ignoring short circuit contribution from the system, which reveals that any generating facility is operated as an effectively grounded system and is therefore, not overly reliant on the transmission system for grounding effectiveness.

Acknowledging the limitation of PSS/E (e.g., current version 35 in 2025) short-circuit algorithm, which always treats a generator as a linear machine with a constant internal EMF in series with a constant shunt sub-transient impedance. Therefore, it is acceptable to model IBRs as a conventional synchronous generator during the subtransient period (about two cycles after the fault inception) for the initial assessment.

Figure 3: Island the Proposed Generating Facility



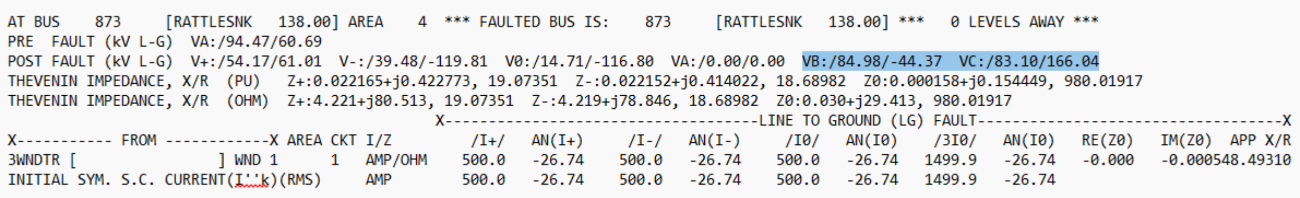
Step 3: Simulate the unbalanced ground faults at POC bus

The unbalance grounded faults (i.e., SLG fault and LLG fault, respectively) will be applied on islanded POC bus, then observe the phase voltage of healthy phase(s) in the output report.

Step 4: Calculate the CoGs

As per the methodology and criteria detailed in B.1, CoGs are calculated by dividing line-to-ground voltage on a healthy phase under unbalanced grounded faults (i.e., SLG and LLG faults at islanded POC bus) to system nominal line-to-line voltage.

Below is the example for CoG calculation for a SLG fault at a 138 kV bus.



```
AT BUS    873     [RATTLESNK   138.00] AREA    4  *** FAULTED BUS IS:    873     [RATTLESNK   138.00] ***   0 LEVELS AWAY ***
PRE  FAULT (kV L-G)  VA:/94.47/60.69
POST FAULT (kV L-G)  V+:/54.17/61.01  V-:/39.48/-119.81  V0:/14.71/-116.80  VA:/0.00/0.00  VB:/84.98/-44.37  VC:/83.10/166.04
THEVENIN IMPEDANCE, X/R  (PU)   Z+:0.022165+j0.422773, 19.07351  Z-:0.022152+j0.414022, 18.68982  Z0:0.000158+j0.154449, 980.01917
THEVENIN IMPEDANCE, X/R  (OHM)  Z+:4.221+j80.513, 19.07351  Z-:4.219+j78.846, 18.68982  Z0:0.030+j29.413, 980.01917
                                                  X-------------------------------------LINE TO GROUND (LG) FAULT-------------------------------------X
X----------- FROM ------------X AREA CKT I/Z         /I+/   AN(I+)     /I-/   AN(I-)     /I0/   AN(I0)    /3I0/   AN(I0)   RE(Z0)    IM(Z0)  APP X/R
3WNDTR [                 ] WND 1      1   AMP/OHM    500.0   -26.74    500.0   -26.74    500.0   -26.74   1499.9   -26.74   -0.000   -0.000548.49310
INITIAL SYM. S.C. CURRENT(I''k)(RMS)      AMP        500.0   -26.74    500.0   -26.74    500.0   -26.74   1499.9   -26.74
```

V*b* = 84.98 kV **CoG @ B-Phase** = 84.98 kV/ 138 kV =0.61

V*c* = 83.10 kV **CoG @ C-Phase**= 83.10 kV/ 138 kV =0.6

Step 5: Compare CoG results and complete the initial assessment

Comparing the results from Step 4, if the highest CoG at POC bus ≤ 0.8, implies that the facility is designed as an effectively grounded system.

However, for the facility with the highest CoG at POC bus exceeding 0.8, an EMT study is needed to accurately and more realistically quantify the risk of the grounding effectiveness, and the screening results should only be treated as an indication of the need for further assessment.

3. Effective Grounding Detailed EMT Study and Mitigation Plan

3.1 Recommended Tools for Detailed EMT Assessment

PSCAD, in conjunction with E-Tran or PRISM, is the primary tool recommended for electromagnetic transient (EMT) modelling due to its robustness in handling high-fidelity transient studies and detailed model compatibility with power electronic systems.

PSCAD is widely regarded as the industry standard for EMT simulation, especially for power systems that include IBRs and power electronic converters. It enables detailed analysis of transient behaviour, which is essential for evaluating transient overvoltage under unbalanced ground faults at the transmission level.

E-Tran and PRSIM are tools used specifically to convert transient stability models, such as those in “. Raw” and “.Seq “formats, into EMT-compatible models.

Other EMT (e.g., ElectroMagnetic Transients Program - Restructured Version [EMTP-RV]) tools can be used if they meet the following criteria:

- Model Building from transient stability (TS) Data: The tool should support importing or building models from TS data (such as “.raw” and “.seq” formats), ensuring compatibility with existing TS datasets.
- Co-Simulation Support with PSCAD Models: The tool needs to facilitate co-simulation with existing EMT models and OEM models or allow synchronized data exchange, enabling combined EMT and TS analyses for system-wide studies.

3.2 EMT Model and Detailed EMT Studies

The detailed study on effective grounding is using EMT analysis to demonstrate whether the facility is complying with the effective grounding requirement or effectiveness of the proposed mitigation solution.

A detailed EMT assessment becomes essential following the initial screening assessment when specific indicators reveal potential non-effective grounding risks within the proposed facility. While the initial screening—commonly using a PSS®E test—offers a preliminary evaluation of the facility performance during unbalanced ground faults, it has limitations and may not adequately observe the complex transient voltage behaviours which need to be coordinated with TOV withstand capability of facility equipment. Therefore, if the screening result in Screening Assessment Methodology section indicates some results exceed CoG threshold—further detailed EMT studies become necessary. Especially where there is an IBR integration, it is strongly recommended to go beyond the PSS®E test and conduct more detailed EMT studies. The detailed study scope, assumptions, methodology and scenarios shall be similar with screening assessment. Through the detailed EMT studies, the MP is responsible to ensure the proposed facility is effectively grounded on transmission voltage level and performing within limits during all scenarios.

This holistic approach of the detailed EMT assessment is expected to deliver a very comprehensive analysis of facility dynamic responses and behaviours during transient events, to allow system planners and operators to identify and mitigate potential reliability and operational risks. By thoroughly examining transient stability, control interactions, fault ride-through (FRT) capabilities, and protection coordination, these detailed studies are critical for supporting grid stability, particularly in challenging conditions that the initial effective grounding screening cannot fully address.

3.3 Study Scenarios

At a minimum, unbalanced ground faults (i.e., SLG and LLG faults) should be applied in study scenarios considering the fault location at both far end and near end of connection between the proposed facility and transmission system. The breakers at both far and near end of connection together with fault clearing time should be included in the study scenarios, if applicable.

For example, a facility connects with transmission network through a radial line with line breakers on both ends. The following scenarios should be included in the detailed study:

- Apply different types of unbalanced ground fault at far-end line and island the proposed facility with far-end breaker open (i.e., TFO’s breaker open)
- Apply different types of unbalanced ground fault at near-end line and island the proposed facility with near-end breaker open (i.e., MPs high voltage side breaker)

Additional scenarios may be required for sensitivity analysis and assumptions based on engineering judgment.

3.4 EMT Model and Data Requirements

To ensure consistency, accuracy and high fidelity in EMT, all EMT models used for the study need to strictly adhere to the comprehensive requirements outlined in the AESO Facility Modelling Data document. Appendix 3,[7] present the whole facility including all the components with consideration of adjacent TFO owned substation, which matter to the effective grounding detailed study.

3.5 Mitigation Plan

As aforementioned, a non-effective grounding system can result in elevated temporary overvoltage, increased risks of equipment damage during unbalanced ground faults, which can cause significant operational and safety issues. When effective grounding analysis reveals that maximum CoG on the unfaulted phase(s) exceeds acceptable limit, implementing the mitigation strategies becomes crucial to ensure system reliability, safety and compliance with requirements.

When non-effective grounding risks are identified in the full EMT simulation, the following proposed mitigation solutions can be applied to address this risk effectively, based on the nature of the facility:

1. Selection of the proper interconnection or generator step-up transformer winding configuration which could provide a zero-sequence continuity path for proposed generating sources. This

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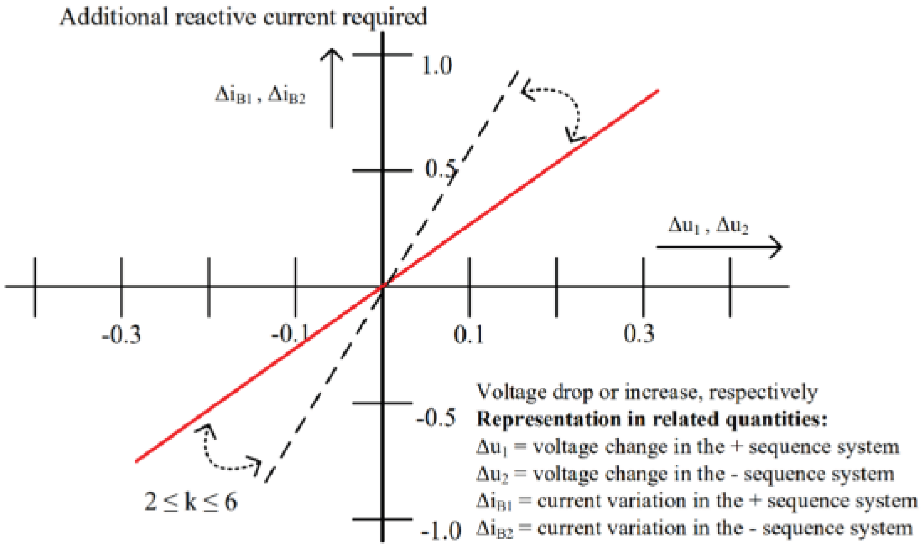
[7] Facility Modelling Data and List of Electrical and Physical Parameters for Transmission System Model (2010-001R), https://www.aeso.ca/assets/Information-Documents/2010-001R-Facility-Modelling-Data-2024-04-19.pdf.

objective can be obtained through the main transformer embedded with a grounding source (e.g. delta winding) or a supplemental grounding source (e.g. grounding transformer, zigzag transformer). Details of selection depend on facility design and generation characteristics.

2. For an IBR facility, another key strategy is to retune the inverter controls. As per AESO's Connection Requirements for Inverter-Based Resources Section 8.1.3.2, each generating unit shall have the capability to inject negative-sequence reactive current up to 50 percent of its maximum current rating when the negative-sequence voltage at its terminal is at or above 25 per cent of the nominal voltage and the unit is operating in reactive current priority mode. K factor, which represents the proportionality between the negative-voltage deviation (pu) at its terminal and the resulting incremental negative-current injection (pu) in ride-through mode, can be configured to achieve the aforementioned requirement, as show in Figure 4.

Figure 4: Characteristic Curve for Negative-Sequence Current Injection of IBRs Based on VDE-AR-N 4120 Technical Connection Rules[8]



Typically, $K = 2$ is taken by default, as long as it does not counteract with any protection scheme. So far, there is no specific guidance of best suitable *K* factor. However, the facility owner can perform EMT studies to test the suitability of the K factor and other fault response settings and adjust the OEM parameters as needed to achieve grounding effectiveness at the proposed facility under all scenarios.

When the study results show noncompliance to the required threshold, a detailed plan for implementing proposed mitigation measures should be provided and the effectiveness of this mitigative measure should be demonstrated.

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[8] EPRI - Impact of Inverter-Based Resources on Protection Schemes Based on Negative Sequence Components.

Appendix A: GRIP Overview

Introduction

The Alberta Interconnected Electric System (AIES) is undergoing a period of grid transformation driven by multiple factors, including the increasing integration of inverter-based resources (IBRs) such as wind and solar, changes in system topology, and evolving operating conditions. Collectively, these factors present the following challenges to the Alberta Electric System Operator (AESO):

- High penetration of IBRs, which can reduce system capability to manage and maintain frequency stability, system strength and operational flexibility
- Restrictions on the availability of reliability support through interties due to weak connectivity with the Western Interconnection, where excessive reliance on external resources increases the risk of intertie tripping
- Increasing operational limitations associated with newly energized facilities
- An increase in reliability-related phenomena observed during real-time operations

As a result of these emerging AIES reliability challenges, the AESO has identified several areas where performing Grid Readiness, Integration and Performance (GRIP) Requirements would be beneficial. System reliability is also heavily dependent on how market participants (MPs) conduct technical assessment and design the facility accordingly to meet connection requirements prior to energization. Therefore, we have created standard guidelines on how to conduct GRIP. We have adopted a risk-based approach, which considers the risk to the reliability of the AIES using project information, beginning with high-level screening assessments for all active connection projects and, where necessary, proceeding to more detailed studies. These studies may identify potential mitigation measures to be implemented during the connection process. This approach seeks to strike the right balance between moving efficiently through the connection process and exercising the due diligence required to ensure system reliability.

Background and Purpose

These topics addresses the issue that the assessment aims to resolve as it relates to a subsection of an ISO rule or is an operational requirement new to the industry in Alberta and not included in any AESO Authoritative Documents. MPs projects that have been identified as high-risk through the applicability, pre-screening criteria or screening steps will be required to conduct detailed study and provide the AESO with evidence of meeting an operational requirement, which will be documented in a project’s functional specification.

This guideline was developed to educate stakeholders about why an assessment is required and how a project will be assessed through a standardized approach. It provides transparency and guidance on how to conduct the applicability, pre-screening, screening and detailed study by the responsible entity and how to provide the detailed study report to the AESO, demonstrating adherence to the requirements in the AESO’s functional specification.

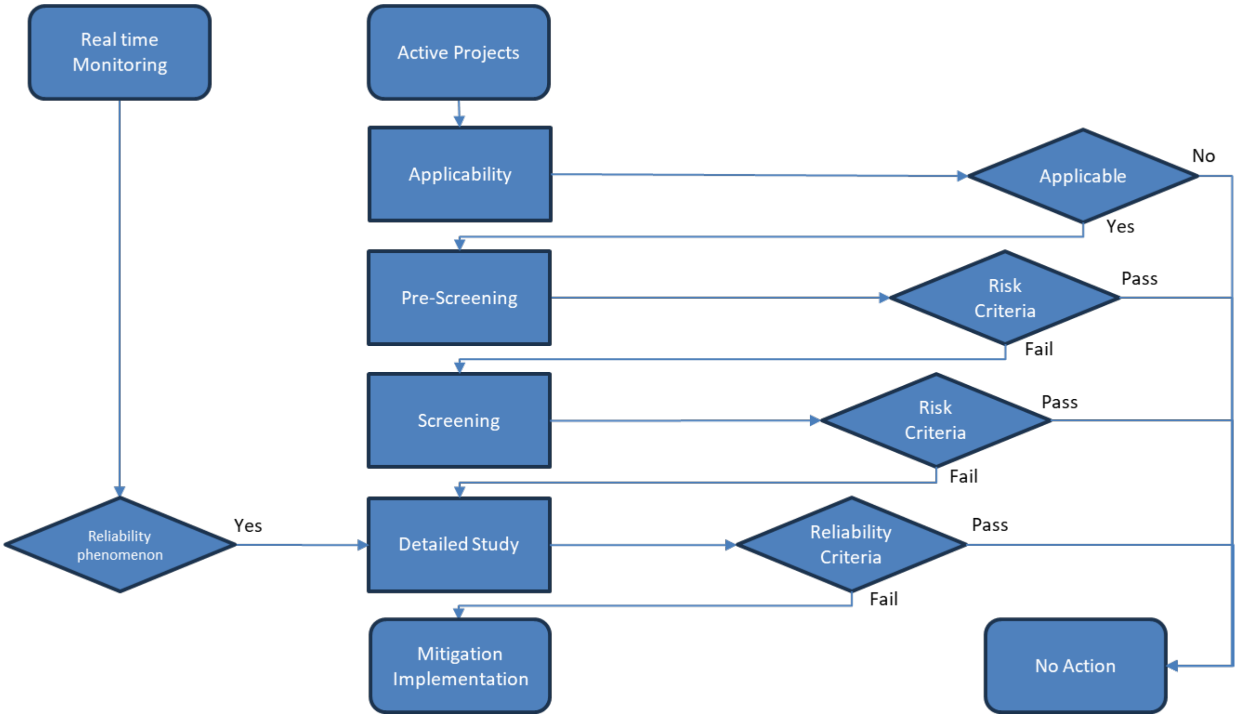
This guideline is not authoritative, for information purposes only and has been developed based on current industry practices.

AESO's Risk-Based Assessment Approach

The AESO's process for GRIP uses a risk-based framework, as shown in Figure A1, which consists of:

- Applicability
- Pre-screening
- Screening
- Detailed study, report and submission
- Result acceptance
- Mitigation implementation

Figure A1: Risk-Based Assessment Approach



The phases of this process occur at different points throughout the AESO's Connection Process. For topics related to AESO Authoritative Documents, MPs are responsible for completing applicability, pre-screening and screening steps independently, and are encouraged to use the approach and methodology outlined in this guideline. In all other cases, the AESO will conduct these initial steps. These steps will determine whether a facility requesting system access can be excluded from further analysis or requires further study as a high-risk project. Projects identified as high risk will include a detailed study requirement in the project's functional specification. This guideline provides details on the recommended approach for conducting detailed studies. Upon receiving the detailed study, the AESO will work with MPs to review and comment on the report in accordance with this guideline. We may revise project's functional specification if the report results in changes to a project's scope of work.

Applicability

The objective of applicability phase identifies projects requiring further assessment using applicability criteria based on accessible project information available early in the customer connection process such as, facility size, type and technology.

Once a project meets the applicability criteria it will move to the next relevant step following the guideline. MPs have the option to skip the pre-screening or screening steps and move directly to the detailed study or mitigation steps.

Pre-screening

The objective of pre-screening is to conduct a further assessment once the preferred connection alternative is selected. At this stage, the project details such as point of connection, nearby facilities and project scope are known, which are used to help identify potential high-risk projects. This information helps the MP and the AESO understand the risk of meeting operational requirements.

Screening

The objective of screening is to conduct a further assessment when more detailed technical information on MPs proposed facility becomes known. This guideline introduces a technical evaluation to assess whether a project qualifies as high-risk. Projects are identified as high-risk move to the detailed study stage. The AESO will include screening and detailed study requirement and report submission in the functional specifications for high-risk projects.

Detailed Study, Report and Submission

The objective of the detailed study is to demonstrate compliance with the AESO's operational requirements through advanced calculations or simulation outlined in this guideline prior to project energization. To conduct this work, the responsible entity will require detailed project information and models, usually in the later stages of the customer connection process. The AESO will identify and include the detailed study and report submission requirements in the functional specification for the high-risk projects.

Mitigation

The detailed study report may identify a reliability issue. When this occurs, the MP must consider a mitigation solution and consult with the AESO on the proposed approach. The detailed study will then need to be revised to confirm the effectiveness of the proposed mitigation.

As indicated above, a responsible entity has the option to skip the screening steps and proceed directly to the detailed study. Further, if the responsible entity is aware the detailed study will indicate a reliability issue or potential non-compliance, the responsible entity may proceed with proposing a mitigation solution to the AESO.

Result Acceptance

Upon submission of the detailed study report, the AESO will follow this guideline to review and comment on the report within a timely manner. The responsible entity of the detailed study will be responsible to address all AESO comments and authenticate the study report. The detailed study must be completed prior to the project energization, preferably 100 days prior to the project energization.

It is important to note that this guideline is meant to assist the AESO in understanding and mitigating the risks to reliability of the AIES. This risk-based assessment is not conclusive and if the reliability phenomenon is observed in real-time, we will work with the MP on real-time mitigation measures. Furthermore, project changes, accepted through the AESO's Project Change Proposal process may trigger the need for additional applicability, pre-screening, screening and detailed study.

Appendix B: Detailed Study Report Template

It is encouraged that a study report will be written based on the template below to present your relevant study, analysis, or findings for a specific study topic. Following AESO's study guidelines on the specific study topic can help the AESO to review your study report in an efficient and effective manner. This template can also be used for the report to present screening results if required.

1.0 Title Page

This section shall include report title, project number, author/reviewer/approvers names, date of submission and Association of Professional Engineers and Geoscientists of Alberta (APEGA) authentication.

2.0 Executive Summary

This section will provide a summary of the study report, including main objectives, study methodology, key findings, recommendations, mitigation if required, etc.

3.0 Table of Contents

This table will list sections and subsections with page numbers in the report.

4.0 Introduction/Objective

This section will outline the background information on a specific topic, and study purpose, objective and its scope.

5.0 Methodology and Scenarios

This section will elaborate the study approach and list the scenarios to study. Other key information such as simulation software and its version, data collection methods, analysis or evaluation techniques should be included. Please check with AESO's corresponding study guideline to use the recommended methodology and scenarios.

6.0 Criteria (if applicable)

This section will define the basis for judgement and decision-making in the report, including applicable standards, justification for selecting these criteria, application of criteria, etc.

7.0 Inputs Data and Assumptions

This section will define the information, variables and underlying assumptions in the report, including raw data and key variables, credible assumptions made in the study. Please check with AESO's corresponding study guideline to use the recommended inputs and assumptions.

8.0 Simulation Results Analysis

This section will demonstrate the key outcomes from the study, including overview of the simulation, data presentation using tables, graphs or charts, and interpretation of expected or unexpected results. Please check with AESO's corresponding study guideline to use the recommended way to present simulation results if defined.

9.0 Mitigation/Correction Actions (if applicable)

This section will explore solutions or measures to address risks identified in the study report and proposes the mitigation/corrective actions which shall be implemented prior to the project energization. If the mitigation requires another study to confirm the effectiveness, the separate study report can be submitted to the AESO.

10.0 Conclusion

This section will summarize the main takeaways, interpret the implications of the findings and provide the final thoughts to support the decision-making.

11.0 References

The section will list all sources cited in the study report.

12.0 Appendices

This section will provide some additional information that supports the study report. It can include raw data, diagrams, detailed calculations, etc.

Alberta Electric System Operator

3000, 240 4 Avenue SW
Calgary, AB • T2P 4H4
aeso.ca

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