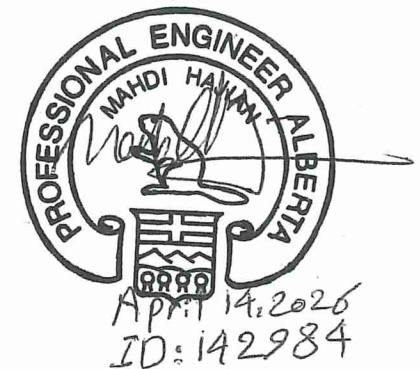
An abstract graphic featuring several glowing, curved lines in shades of blue and orange, set against a dark blue background. The lines appear to be part of a larger, curved structure, possibly representing a transformer or a power line. The graphic is positioned in the upper half of the page, overlapping the light blue background and the dark blue background.

# Transformer Energization Assessment Guideline

# Transformer Energization

## Assessment Guideline



Date of issue: April 14, 2026

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<b>PERMIT TO PRACTICE INDEPENDENT SYSTEM OPERATOR</b>	
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# Executive Summary

## Purpose and Scope

The AESO has developed the Transformer Energization Assessment guideline to address emerging reliability challenges in Alberta Interconnected Electric System (AIES). This guideline:

- Addresses challenges transformer energization poses to grid reliability
- Defines a standardized, risk-based approach for transformer energization assessments, including methodology, inputs, assumptions, performance criteria, reporting requirements and mitigation options
- Helps market participants (MPs) understand the requirements for connecting their facilities to the transmission system

## Rationale

Transformer energization can create several grid reliability challenges including:

- Power quality issues
- Ferroresonance and temporary overvoltages
- Sympathetic interaction
- Protection misoperation
- Current transformer (CTs) and potential transformer (PTs) saturation

## Performance Criteria

When energizing transformer at the point of connection (POC):

- The root-mean-square (RMS) voltage at the POC shall not dip more than four per cent
- Harmonics from transformer inrush current must comply with Institute of Electrical and Electronics Engineers (IEEE) 519 standard

## Application

For high-risk connection projects identified by the AESO, transformer energization requirements and technical assessments will be specified in the functional specification (FS). MPs are expected to apply this guideline when conducting and submitting the required assessments before energizing their facility.

# 1. Transformer Energization Introduction

## 1.1 Background

Transformer energization is an operational requirement new to the industry in Alberta. Transformer energization is currently 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.

The energization of transformers, depending on their size, connection point to the grid and system characteristics (system strength, nearby equipment, etc.), may pose the following reliability issues on the grid:

- **Power quality issues:** the inrush current due to energizing transformers may result in transient voltage fluctuation in the local area
  - This may impact voltage-sensitive load (typically induction motors at industrial facilities), resulting in loss of load and financial impacts
- **Ferroresonance and temporary overvoltages:** The inrush current has a rich harmonic content most significantly the second, third and fourth harmonics
  - The harmonic current may resonate with system impedance in harmonic frequencies leading to temporary overvoltages
  - This could damage equipment at MPs' facilities or the transmission system
  - The harmonic content, especially the third harmonic, could overload nearby alternating current (AC) filters in the transmission system resulting in their protection operation and loss of the AC filter
- **Sympathetic interaction:** the inrush current may interact with nearby transformers, which are already energized causing those transformers to go in saturation
  - This may result in power quality or resonance issues mentioned above
  - This concern is typically present during weak grid conditions
- **Protection misoperation:** the transformer protection, depending on protection settings, may misoperate, treating the inrush current as a fault current and tripping the transformer following the energization
- **Nearby CTs/PTs saturation:** Inrush current may also saturate nearby current transformers (CTs) or potential transformer (PT) cores and lead to undesired protection relay misoperation

The AESO developed this guideline to educate stakeholders about why transformer energization 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 for technical assessment outlined in the AESO's functional specification.

It is noted that this guideline is not authoritative and for information purposes only.

## 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 AESO’s project manager for details.

**Table 1. RACI Chart for Transformer Energization Assessment**

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

Deliverable	AESO	Transmission Facility Owner (TFO)*	Generation Facility Owner (GFO)*	Market Participant (MP)
<b>Applicability and Pre-Screening</b>				
(Earliest Connection Process Stage: Stage 1)				
Determine if the project meets the applicability criteria	A, R	I	I	I
<b>Screening Assessment</b>				
(Earliest Connection Process Stage: Stage 2)				
Provide the required system information (i.e., short circuit level) to perform screening in Engineering Study Result (ESR)	R	I	C	C
Provide the required facility information (i.e. transformer base mega volt-amperes (MVA) rating) to perform screening	C	I	R	R
Perform screening and capture results, including pass/fail, in facility scope	A, R	I	C	C
<b>Hardware Mitigation and/or Detailed Study</b>				
(Earliest Connection Process Stage: Stage 3)				
Include mitigation options in the specification if the screening does not pass	R	I	I	I
Decide which option to pursue	C	I	R	R
Detailed electromagnetic transient (EMT) study (if	C	I	A	A

Deliverable	AESO	Transmission Facility Owner (TFO)*	Generation Facility Owner (GFO)*	Market Participant (MP)
selected): Carry out the study and provide the report and simulation files				
Inputs for the detailed EMT study (if selected): <ul style="list-style-type: none"> <li>• Power flow and dynamic models in PSS/e</li> <li>• EMT Model of IBR facilities in the area, if required and available</li> </ul>	R	I	C	C
Inputs for the detailed EMT study (if selected): Facility data (transformer saturation, surge arrester, etc.)	C	I	R	R
Inputs for the detailed EMT study (if selected): <ul style="list-style-type: none"> <li>• Frequency-dependent transmission line models for required transmission lines</li> <li>• Other transmission system data as required (adjacent transformers' modelling data, surge arrestors, etc.)</li> </ul>	C	R	C	C
<b>Result Acceptance and Mitigation Recommendation</b> (Earliest Connection Process Stage: Stage 3)				
Provide the hardware mitigation and/or detailed study results	C	I	A	A
Accept the mitigation strategy and update functional specification accordingly with related requirements	R	I	C	C
<b>Energization Authorization</b> (Earliest Connection Process Stage: Stage 5)				
Proof of hardware installation (if specified in the functional	C	I	A	A

Deliverable	AESO	Transmission Facility Owner (TFO)*	Generation Facility Owner (GFO)*	Market Participant (MP)
specification): single-line diagram (SLD), vendor information in 100-day energization package at stage 5				
Proof of hardware commissioning (if specified in the functional specification): commissioning reports including event records in stage 6	C	I	R	R
Accept the deliverables	R	I	C	C

**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.

\* If the connecting facility is owned by the TFO or GFO, they will retain their designated roles in this RACI chart and assume the responsibilities assigned to the MP, as they are acting as the owner of the connecting project.

### 1.3 Applicability

This guideline applies to projects including:

- Transmission-connected generation projects
- Transmission-connected load projects

This guideline does not apply to distribution service transformers, i.e., those energized at a nominal primary voltage of 25 kV or less. It is the distribution facility owners' responsibility to assess transformer energization risks in such cases as necessary.

## 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 assessment and providing the necessary deliverables.

## 1.5 Screening Assessment

The purpose of the screening assessment is to identify potentially high-risk projects and discard low-risk projects from the transformer energization perspective. If the screening identifies a potential risk with transformer energization, a subsequent phase involving either, or both, the hardware solution (i.e., equipment installation) or a detailed study will be pursued.

The MP has the option to skip the screening assessment and go directly to a detailed study or hardware mitigation solution. The MP should inform the AESO at the beginning of stage 2 if they would like to skip the screening phase and proceed with the next phase (hardware mitigation and/or detailed study requirements). Please refer to Section 2 for the screening assessment details.

If the screening assessment is passed but there are changes in the screening inputs during the connection process (e.g., increasing MPs' transformer rating), then the screening should be repeated. MPs should be aware of this risk especially if they decide to change their facility design.

If a project does not pass the screening phase, the MP has the following options to mitigate or further assess the risk, which will be documented in the functional specification:

1. **Preferred Option- Hardware Implementation:** the MP should consider equipment addition or modification to mitigate the risk of transformer energization. Depending on the equipment and its implementation, this approach could skip the study and its associated cost. The AESO recommends that MPs contact equipment vendors as soon as possible during facility design and equipment procurement to assess controlled transformer energization for their facility and understand the scope of work. Refer to Section 3 for further details on the requirement and assessment approach.
2. **Conduct Detailed Study:** Conduct an EMT study using the Power Systems Computer Aided Design (PSCAD) software to assess the risk and identify if mitigations, including a Point-On-Wave (POW) controller, are required per the study methodology provided in Section 4 and template report provided in Appendix B.
  - If this option is chosen, the study may need to be carried out in stage 5 when accurate models are available
  - If the study finds issues, mitigations in option 1 may still be required
  - The study has its limitations, as the grid evolves, study assumptions may become invalid in the future, impacting results and risking the MPs facility not meeting the AESO's power quality requirements and requiring mitigations, such as a POW controller
3. **Modify Facility Design:** the MP may choose to modify their facility design, if possible, to energize their transformer(s) from the facility side (as opposed to the transmission system side)

- This assumes the station service load can be supplied through feeds other than the generator step-up transformer (GSU) so that their facility can come online and energize the GSU
- This may be the case for synchronous generation facilities
  - However, IBR projects are typically designed such that GSU must be energized from the system side to provide the station service load and required voltage reference for (grid-following) inverters
  - This option is also not feasible for load facilities

The AESO will update the functional specification based on the selected option by the MP from the above alternatives and will require the deliverables accordingly.

## 1.6 Detailed Study

As outlined above, the need for a detailed assessment is identified if a project meeting the applicability criteria does not pass the screening assessment, and the MP chooses to conduct a detailed study to ensure that there is no operational or reliability risk to the AIES, or that the risk can be adequately mitigated. The TFO will coordinate with the MP to assess the risk of transformer energization by complying with the assessment outlined in this document.

## 1.7 Mitigation

Mitigations for transformer energization are to install equipment. As outlined above, the need for a mitigation is identified if a project meeting the applicability criteria does not pass the screening assessment, and:

- The MP chooses to implement a hardware mitigation; or
- The detailed study result indicates a mitigation is required

## 1.8 Result Acceptance and Mitigation Implementation

The MP shall submit the detailed study report, if applicable, and the proposed mitigation solution, which must be accepted by the AESO before the in-service date of project. The AESO shall review the study report within a reasonable time. The AESO may comment on the report and ask the MP to respond prior to our acceptance. The AESO may revise the functional specification of the project according to the study result or proposed mitigation solution. Any delay on the study report submission may result in a delay in project energization.

## 1.9 Energization Requirements

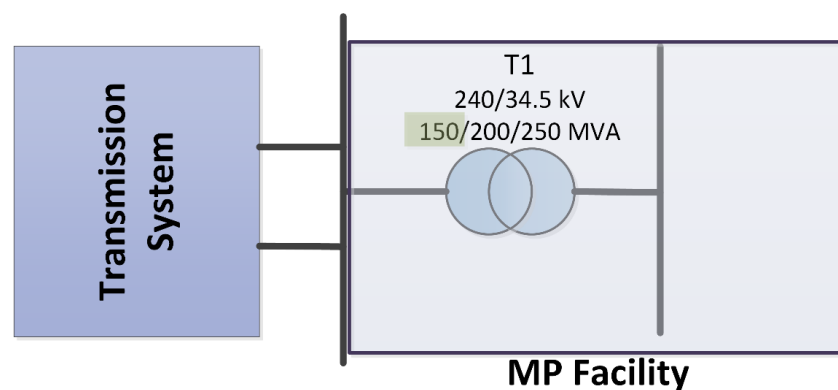
The AESO authorizes the project to connect to the AIES and achieve energization when the project meets all the AESO's energization checklist requirements, outlined in the 100-day and 30-day energization packages. The required study report will be included in the energization checklist, if applicable.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

## 2. Screening Assessment Details

### 2.1 Required Inputs

1. The lowest pre-project short circuit level at the connection point of the transformers
  - a. This information is available from the engineering study results at stage 2
2. Transformer base megavolt-ampere (MVA) rating, also known as oil natural air natural (ONAN) rating
  - a. This information should be provided by MP at stage 2
    - i. Note that the base MVA rating of the transformer is typically the lowest rating out of three ratings which is presented on the proposed facility SLD
    - ii. An example is shown in Figure 1, where the base MVA rating of 150 should be used for the screening

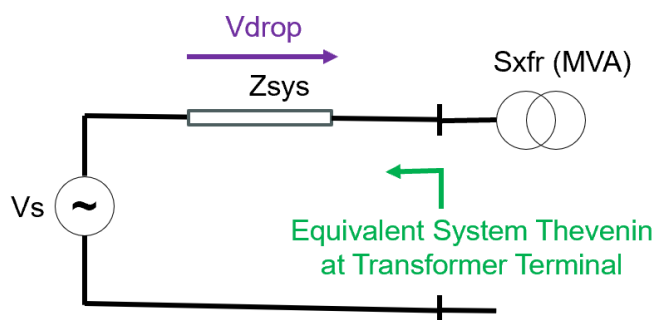
**Figure 1: Example SLD with the Base MVA Rating of the Transformer Highlighted in Green**



### 2.2 Study Methodology

The screening assessment is based on estimating the voltage drop due to transformer energization. The associated methodology and the formula to estimate the voltage drop are shown in Figure 2.

**Figure 2: The Screening Methodology Formula**



$$V_{drop}(pu) = Z_{sys}(pu) * I_{Inrush}(pu)$$

$$I_{Inrush}(pu) = \frac{I_{Inrush}(kA)}{I_{nominal}(kA)} = IF \text{ (Inrush Factor)}$$

$$Z_{sys}(pu) = \frac{Z_{sys}(ohm)}{Z_{base}(ohm)}$$

$$Z_{sys}(ohm) = \frac{V_s^2(kV)}{SCL(MVA)}$$

$$Z_{base}(ohm) = \frac{V_{nom}^2(kV)}{S_{xfr}(MVA)}$$

$$Z_{sys}(pu) = \frac{S_{xfr}(MVA)}{SCL(MVA)}$$

Assuming  $V_s \approx V_{nom}$

$$V_{drop}(pu) = \frac{S_{xfr}(MVA)}{SCL(MVA)} * IF$$

SCL: Short circuit level at transformer terminal

In this formula:

- $S_{xfr}$  (MVA) is the base MVA rating of the transformer
- SCL (MVA) is the lowest available pre-project short circuit level in MVA, which can be calculated by converting the three-phase fault (in kVA) multiplied by the nominal voltage
- Inrush factor (IF): the inrush factor depends on several factors, including the size, design and voltage class of transformers with typical values between 8-10<sup>1</sup>
  - For the screening assessment and based on the AESO's experience with previous projects, IF of 8 is deemed sufficient at this point

If a voltage drops higher than 0.1 (i.e., 10 per cent) is estimated using the above formula, it indicates that the screening has not passed, and further action is required. Otherwise, no further action is required from the risk of transformer energization perspective. The 10 per cent threshold is selected based on the AESO's experience with previous connection projects and a TFO practice.

<sup>1</sup> IEEE C37.91, IEEE Guide for Protective Relay Applications to Power Transformers.

## 2.3 Screening Assumptions and Limitations

The screening methodology is a high-level assessment to flag a potential risk with the energization of transformers. Similar to other screening methodologies, it has its own limitations, such as:

- It is based on fundamental frequency calculations, and no harmonic is included
- Impacts of saturation and remnant flux are not considered
- It does not consider potential resonance with the transmission system
- Breaker closing time is not considered

An EMT study is needed to accurately and more realistically quantify the risk of the transformer energization, and the screening results should only be treated as an indication of the need for further assessment.

The screening assessment should be repeated for changes to the above inputs during the connection process. MPs should be aware of this risk, especially if they decide to change (i.e., increase) the size of their transformers.

### 2.3.1 Screening Output

The screening results will be captured in the AESO's facility scope document in stage 2. If the screening needs to be repeated later in the connection process as mentioned above, the results will be shared by the AESO via email.

### 3. Equipment Addition and Requirements for Transformer Energization Mitigation

There are a few hardware mitigations to address the risk of inrush current for transformer energization as follows:

1. The POW controller is the most common mitigation. It controls the closing time of each phase of the transformer breaker (also known as controlled energization) to reduce the inrush current. The POW controller determines the optimum point on a voltage sine wave to close the breaker, considering the residual flux in the transformer.
2. Pre-insertion resistor (PIR): This temporarily inserts a resistor into the circuit breaker for a short period (typically half to the third quarter of the cycle) during closing operation to minimize transformer inrush current. The required size and duration of the PIR need to be determined through a PSCAD study.

The AESO preference is the POW controller; however, if MPs decide to go with PIR, a PSCAD study is required to demonstrate its effectiveness per the study objectives in Section 4 and the required configuration (resistor size and insertion period). Other hardware mitigations may be accepted and need to be evaluated on a case-by-case basis. The remainder of this section covers the considerations and requirements for the POW controller.

#### 3.1 Equipment Requirements for POW Controller

To fully minimize the inrush current and achieve the full capability of POW controller, two major pieces of equipment are typically needed for the installation of POW controller:

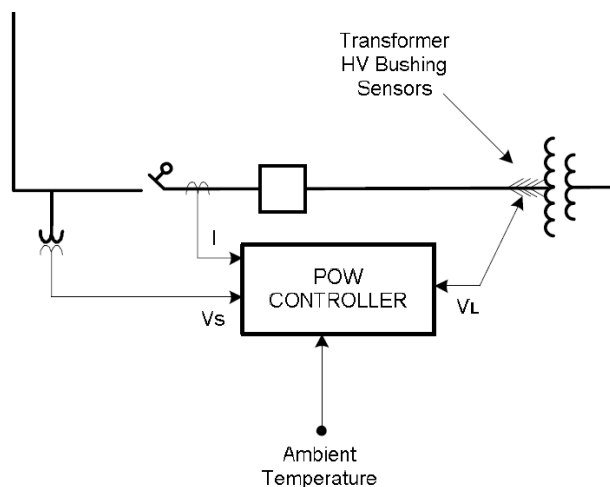
- Single-pole breakers to independently control the closing time of each pole within a three-phase breaker
- Voltage measurement between transformer breakers and transformer<sup>2</sup>
  - This is to allow calculating and memorizing the residual flux when transformer breakers are opened to de-energize the transformer
  - The undistorted voltage measurement could be provided by magnetic PTs or voltage sensors on transformer bushings; however, capacitive voltage transformers (CVTs) cannot generally be used for this purpose
  - Note that a voltage measurement on the hot side of the transformer breaker is also needed for the POW controller to determine the closing time based on sine wave; any measurement apparatus, including CVTs could provide this voltage measurement
- All instrument transformers and voltage sensing devices shall provide three-phase measurements for event recording

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<sup>2</sup> Per the AESO's experience, some POW controller vendors require the voltage measurement on one winding only. For example, a voltage measurement on the secondary or tertiary winding can be used for a POW controller implementation on the primary side of the transformer.

Figure 3 illustrates the conceptual design example with POW controller, where in this example, the voltage measurement on the transformer side is provided by bushing sensors.

**Figure 3: Conceptual Design with POW Controller**



Without the above equipment, POW controllers can still be installed and it will reduce the inrush current to some extent; however, it will not fully minimize the inrush current. Specifically:

- If there are three-phase ganged breakers (typically on 138 kV and below), the POW controller addition is still possible if transformer side voltage measurement is available
- Without transformer side voltage measurement, POW controller vendors may be able to estimate (as opposed to calculate) residual flux
  - However, the effectiveness of this approach might be affected by the application (e.g., the location and size of the transformer) and needs to be assessed by the vendor

To address the imperfect (i.e., non-optimal) situations where the inrush current cannot be fully minimized by the POW controller (e.g., there are no single pole breakers or residual flux cannot be accounted for), a PSCAD study should be conducted to prove the imperfect solution meets AESO's power quality requirements per the study objectives in Section 4.

## 3.2 POW Controller Performance Requirements

### 3.2.1 Capability and Performance Requirements

- POW controller device, unless otherwise specified, shall be capable of controlled single pole closing of the breaker to minimize the inrush current and resulting voltage dip during transformer energization

- The POW controller shall be capable of automatically calculating breaker closing time considering applicable variations, including ambient temperature and circuit breaker operation time<sup>3</sup>
- The POW controller shall be implemented such that it is always active to control its breaker(s) used to energize the associated transformer
- In case of breaker and half schemes or bus loop configuration, the POW controller capability to control both breakers is desired (but not required) to create flexibility in case of unavailability/maintenance on the other breaker
  - If the MP chooses to install a POW controller on a single breaker only, the MP should be aware of the potential risks such as the unavailability of the associated breaker and potential delays with transformer energization until the breaker becomes available
  - Further, the MP shall have appropriate procedures and/or adequate indications in the operator's displays, such that MP operators are aware and trained on which breaker to use to energize the transformer
  - Failure to carry out such actions will pose the risk of MP noncompliance with the AESO's power quality requirements
- The POW controller shall be capable of memorizing the residual flux when the transformer is de-energized with voltage decay as a trigger (in addition to breaker opening)
  - A voltage drop below a certain threshold shall be used as a trigger for the POW controller to realize the transformer is de-energized such that the residual flux is measured and memorized
  - If this capability is not provided or cannot be implemented, the AESO, through engagement with vendor(s), is required to understand the expected range of inrush current without this capability
- The capability of the controlled opening of the breaker during transformer de-energization to minimize the residual flux is desired but not required

### 3.2.2 *Event Records*

Transformer energization records during POW controller commissioning and for all energization events of the transformer following any outage shall be reviewed to ensure the POW controller properly operates as expected and identify corrective actions if needed. The commissioning records shall be provided to the AESO as part of the post-energization package submission. The energization records post commissioning shall be submitted if requested by the AESO.

The following requirements apply for event records:

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<sup>3</sup> Breaker operations time may be dependent on ambient temperatures which should be considered in the POW controller settings. Typically, this can be achieved by the information provided by the breaker vendor; if this information is not available, breaker closing may need to be conducted in various ambient temperatures based on POW controller vendor recommendations.

- Three-phase voltages and currents must be recorded on the side that the transformer is energized; the voltage records must show the voltage on the system side of the transformer prior and after the energization in order to show voltage dip/impacts (if any)
- Event recording must be triggered when the close command is issued to the transformer breaker.
- Sequence of event recording (SER) data, including breaker closing command and closing time shall be provided
- Event record(s) must include a pre-trigger record length of at least two cycles and a total record length of at least 30 cycles for the same trigger point
- A minimum recording rate of 16 samples on event records is required
- Event data must be synchronized to Coordinated Universal Time with clock accuracy within  $\pm 2$  milliseconds
- POW controller records, including the target closing angle(s) versus the actual closing angles of the breaker and the resulting error
- Event data must be provided in .CSV format as the preferred format
  - Alternatively, the event data could be provided in Common Format for Transient Data Exchange (COMTRADE) in conformance with IEEE C37.111 Standard

### 3.2.3 Redundancy

The AESO does not mandate POW redundancy at this point, however, MPs may consider planning for redundancy based on their business practices and operational needs. This can be achieved through a redundant POW controller as an optimal solution or by incorporating staggered pole closing within the breaker's control circuit, which can provide limited improvement in managing inrush current.

Table 2 and Table 3 provide commonly used pole staggering timings for transformer energization and de-energization, respectively.<sup>4</sup> Table 2 summarizes the optimum controlled closing times for energizing the transformer based on winding configuration. This table assumes an A-B-C counterclockwise rotation, with A-ph (or A and another phase) being energized first. The columns labelled A-ph, B-ph and C-ph show the close angle relative to the A-phase voltage positive-going, zero-crossing.

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<sup>4</sup> D. Goldsworthy, T. Roseburg, D. Tziouvaras and J. Pope, "Controlled Switching of HVAC Circuit Breakers: Application Examples and Benefits," 2008 61st Annual Conference for Protective Relay Engineers, College Station, TX, USA, 2008, pp. 520-535, doi: 10.1109/CPRE.2008.4515078.

**Table 2: Transformer Energization Timings for Staggered Breaker Closing**

Transformer Configurations	A-Ph (Deg)	B-Ph (Deg)	C-Ph (Deg)
Yg – Yg	90	210	150
Yg-D or Yg-Yg-D	90	180	180
Y-D	60	60	150
D-D, D-Yg or D-Y	60	60	150

Table 3 lists natural current zero timing while de-energizing a transformer.<sup>5</sup> The columns labelled A-ph, B-ph, and C-ph show the phase angle of the current zeros relative to the A-phase voltage positive-going zero-crossing.

**Table 3: Transformer De-energization Timings for Staggered Breaker Opening**

Transformer Configurations	A-Ph (Deg)	B-Ph (Deg)	C-Ph (Deg)
Yg – Yg	90	210	150
Yg-D or Yg-Yg-D	90	210	120
Y-D	90	180	180
D-D, D-Yg or D-Y	90	180	180

<sup>5</sup> This is intended for manual de-energization and not a protection trip.

## 4. Detailed PSCAD Study

### 4.1 Driver

As indicated previously, the detailed PSCAD study is required for either of the following drivers:

- MP decides to perform the detailed study as option 2
- The implemented hardware has limitations or needs to be parameterized; this may include the following cases:
  - The POW controller is planned to be implemented on a three-phase ganged breaker thus it cannot fully minimize the inrush current
  - The POW controller is planned to be implemented without considering residual flux thus it cannot fully minimize the inrush current
  - Pre-insertion resistor is implemented and the size and/or the insertion period need to be determined

### 4.2 Objectives and Criteria

The purpose of the PSCAD study is required to demonstrate compliance with the following requirements outlined below. The requirements apply to all projects per the applicability criteria of this guideline, i.e., transmission-connected generation and all transmission-connected load projects.

1. the transformer energization shall not cause transmission voltage changes (delta V) greater than the allowable limit of 4% (subsection 3(1)(b) of Section 503.11 of ISO rules [Power Quality])
2. the harmonics during transformer energization must comply with the specifications set out in the IEEE-519 Standard (subsection 2(b) of Section 503.11 of ISO rules [Power Quality])

Per IEEE 519-2022, very short time harmonic values are assessed over a 3-second interval based on an aggregation of 15 consecutive 12-cycle windows for 60 Hz power systems.<sup>6</sup>

Individual frequency components are sampled every 200 ms and aggregated using a root mean square (RMS) calculation as shown below, where  $V_{h,i}$  represents rms voltage in the  $i^{\text{th}}$  harmonic order. The subscript vs in dictates “very short.”

$$V_{vs,h} = \sqrt{\frac{1}{15} \sum_{i=1}^{15} V_{h,i}^2}$$

Then, the individual harmonic distortion (IHD) and total harmonic distortion (THD) for harmonic orders between the 2<sup>nd</sup> and 15<sup>th</sup> are calculated as follows:

<sup>6</sup> The AESO recognizes that the requirements in IEEE 519-2022 are intended for measurements; however, for the purpose of the PSCAD study, the intent is to replicate such calculations in PSCAD.

$$IHD_h = \frac{V_{vs\_h}}{V_{vs\_1}}$$

$$THD = \sqrt{\sum_{h=2}^{15} \left( \frac{V_{vs\_h}}{V_{vs\_1}} \right)^2}$$

Per IEEE Standard 519-2022, daily 99th percentile very short time values should be less than 1.5 times the values given in Table 4. For example, for the 240 kV voltage, the acceptable limits are 1.5% for each IHD and 2.25% for THD. This table applies to each line-to-neutral voltage within the three-phase voltage at the point of transformer connection to the grid.

**Table 4: Voltage Distortion Limits per IEE 519-2022**

Bus voltage $V$ at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
$V \leq 1.0$ kV	5.0	8.0
$1$ kV $< V \leq 69$ kV	3.0	5.0
$69$ kV $< V \leq 161$ kV	1.5	2.5
$161$ kV $< V$	1.0	1.5 <sup>a</sup>

<sup>a</sup>High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal whose effects will have attenuated at points in the network where future users may be connected.

### 4.3 Study Scenarios

At a minimum, two study scenarios should be considered as follows:

- Maximum short circuit level at the point of transformer connection to the grid
- Minimum short circuit level corresponding to:
  - light loading conditions (thus having synchronous machines in the area offline) and
  - most impactful N-1 transmission topology from a short circuit level perspective measured at the point of transformer connection to the grid

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

## 4.4 Study Inputs and Models

The following inputs, models and tools are required to perform the PSCAD study:

- The power flow base case and dynamic model corresponding to each study scenario
  - This is used as a starting point to create the corresponding PSCAD case
  - The power flow case and dynamic model from the connection study provided by the AESO can be used as a starting point
- A frequency-dependent transmission line model is the preferred and most accurate model to represent transmission lines that are required to be modelled in the PSCAD case
  - Alternatively, a Bergeron model may be used based on engineering judgment and the length of transmission lines in the area
  - Refer to the Network Equivalencing section below
  - The frequency-dependent models in PSCAD or the required information to create such models shall be provided by the TFOs
- Transformer models including saturation data (air core reactance, magnetizing current, knee voltage, tap changer position) for the PSCAD case
  - The remanent (residual) flux should be represented in the transformer model; typically, the remanent flux of +60%, 0, -60% corresponding to each transformer core is assumed
  - The tap changer position is typically represented in the nominal position for on-load tap changers or in the fixed position for off-load tap changers, as determined by other studies. Higher tap positions usually reduce the inrush current and modelling a higher tap position is not recommended unless it can be demonstrated by providing other relevant studies that it is the permanent transformer tap position.
- To ensure capturing sympathetic interaction<sup>7</sup> of the transformer under study and other adjacent transformers, other adjacent transformers should also be modelled, including their saturation data
  - Engineering judgment applies to selecting the number, type and location of the adjacent transformers
  - Generic parameters may be used to model the saturation data of the adjacent transformers if actual data is not available
- EMT model of adjacent generation facilities in the area (see also Network Equivalencing section below) as needed
  - These models can be created in PSCAD using the PSS/e dynamic model for synchronous machines
  - For IBRs, the AESO may be able to provide such models if available, assuming non-disclosure agreements (NDA) can be arranged between the MP and other parties; otherwise,

<sup>7</sup> CIGRE TB 568, Transformer Energization in Power Systems: A Study Guide, February 2014.

generic models may be used with sound engineering judgment in consultation with the AESO as required

- Generally, based on the AESO’s experience, dynamic equivalencing is not a concern from a transformer energization perspective
- This is because the main driver for potential resonance is passive network elements
- Hence, representation of detailed nearby PSCAD models such as inverters and power electronic-based facilities excluding passive elements like filters may not be necessary
- Surge arrester data at the facility and surrounding transmission facilities as needed, including manufacturer, types, and V-I profiles provided by TFOs
  - Generic parameters may be used to model the saturation data of the adjacent transformers if actual data is not available.<sup>8</sup>
- After the PSCAD model is created, a PSSE to PSCAD validation should be carried out by comparing three-phase and phase-to-ground short-circuit levels at the transformer terminal

Refer to Table 1 for a summary of roles and responsibilities to provide the required data for the detailed PSCAD study.

Refer to Information Document, ID #2010-001R “Facility Modelling Data and List of Electrical and Physical Parameters for Transmission System Model,” for further information on the AESO’s EMT modelling requirement, which applies to the detailed PSCAD study here.

## 4.5 Network Equivalencing

One of the concerns regarding transformer energization is the potential harmonic resonance with the transmission system, so the adjacent transmission system must be explicitly modelled in PSCAD. While it is required to equivalence the power flow network to create the PSCAD case, it is not acceptable to use an equivalent Thevenin network of the grid at the point of transformer connection. A few adjacent substations and transmission lines need to be explicitly modelled in the PSCAD case. To determine the boundary of “kept buses” in the PSCAD case (and thus where the rest of the network can be converted to equivalent Thevenin source[s]), the following approach is recommended:<sup>9</sup>

1. Start from the transformer’s connection bus to the grid and include 2 substations back on the system side.
2. Use the PSCAD harmonic impedance component to plot the harmonic impedance vs. frequency and save this frequency response.<sup>10</sup>
3. Repeat step 1 by translating a larger network (e.g., 4 substations back). Plot and save the frequency response.

<sup>8</sup> Refer to the link below as an example of generic data: [https://www.pscad.com/knowledge-base/download/metal\\_oxide\\_surge\\_arrester.pdf](https://www.pscad.com/knowledge-base/download/metal_oxide_surge_arrester.pdf).

<sup>9</sup> E-TRAN User’s Manual.

<sup>10</sup> The PSCAD harmonic impedance component outputs a table with frequencies and impedances, which can be used in a graphical analysis tool (such as excel) to produce a plot.

4. Compare the frequency response from step 2 and step 3. The larger network will include more shunt capacitors, line capacitance, etc., so the larger network plot should show more peaks at harmonic frequencies.
5. Keep translating larger and larger networks until the frequency response no longer changes. Once the frequency response no longer changes in the range of interest, there is no need to make the kept network any bigger. For the purpose of this study, it is recommended to ensure the frequency plot up to and including the 5<sup>th</sup> harmonic given that the harmonic content in the transformer inrush current is typically high up to the 5<sup>th</sup> harmonic.

## 4.6 Study Methodology

- The created PSCAD models shall be benchmarked against the power flow solution to ensure the PSCAD simulations start from a valid power flow solution
- The transformer energization shall reflect how the transformer is energized, including any implemented (or to be implemented) hardware mitigations. The following general guidelines apply:
  - For uncontrolled energization (e.g., no POW controller or when PIR is present), the energization of the transformer shall be performed at least for 50 different breaker closing times, which are evenly spread over a cycle
  - For the cases where an imperfect POW controller is implemented (e.g., ganged breaker, or no residual flux consideration), the PSCAD simulation shall mimic how the controller will function in reality per vendor's input.
  - For example, if a peak voltage strategy is implemented<sup>11</sup> (as one approach in the lack of residual flux consideration), then the closing of each phase shall be implemented based on how the first phase will close at peak voltage, followed by the other phases within the specified time delay at a zero crossing of the first phase voltage
  - Such control strategies should be obtained from the vendor and implemented in the PSCAD model
- In each simulation, the following signals shall be measured and recorded:
  - the pre-energization voltages at the system buses where the transformer is connected and adjacent substations
  - the maximum RMS voltage dips for the system buses
  - the peak inrush current of the transformer for each phase
  - the maximum voltage IHD and THD for each phase of the system buses
- Determine and report if the maximum voltage dip for all simulations meets the 4% criterion
- Determine and report the individual and total harmonic distortion for all simulations that meet the harmonic requirements
- If required, assess and if mitigation methods (e.g., POW controller or PIR) are needed

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<sup>11</sup> CIGRE TB 757, Guidelines and best practices for the commissioning and operation of controlled switching projects, February 2019.

Table 5 could be used as an example of how simulation results could be documented in the report for each simulation scenario.

**Table 5: Example of Reporting PSCAD Results for Each Simulation Scenario**

Voltage Dip Analysis (Based on RMS Value)								
Substation 1			Substation 2			Substation 3		
Vpre(pu)	Maximum absolute Vdip (pu)	DeltaV (%) Highlight Delta v≥4% in red for better visibility	Vpre(pu)	Maximum Vdip (pu)	DeltaV (%) Highlight Delta v≥4% in red for better visibility			
<b>Maximum Inrush Current Peak, IHD, THD</b>								
<b>(based on individual phase, report maximum among three phases)</b>								
<b>I mag (A)</b>			<b>IHD (%)</b>			<b>THD (%)</b>		
			Highlight values exceeding the limits per Table 4 in red for better visibility			Highlight values exceeding the limits per Table 4 in red for better visibility		

## 4.7 Study Outputs and Reports

The detailed PSCAD study should provide the following deliverables:

- A draft report in Microsoft Word format for the AESO’s review and approval. The draft report at a minimum shall include the following information:
  - A summary of study scenarios, inputs and equivalent network in PSCAD
  - Whether the detailed study and if applicable the hardware mitigation (e.g., imperfect POW controller, PIR) meet the power quality requirements
  - If applicable, the hardware mitigation parameters (e.g., PIR parameters) as determined in the study
- Following the AESO’s approval, the finalized report shall be submitted, which shall be certified by a professional engineer registered, and in good standing, with the Association of Professional Engineers and Geoscientists of Alberta (APEGA).
- The developed PSCAD models and any other supporting data shall be provided to the AESO with the finalized report.

The AESO provides the report template in Appendix B you can consider using to present your detailed study. Using the template can help the AESO review your report in an efficient and productive way.

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

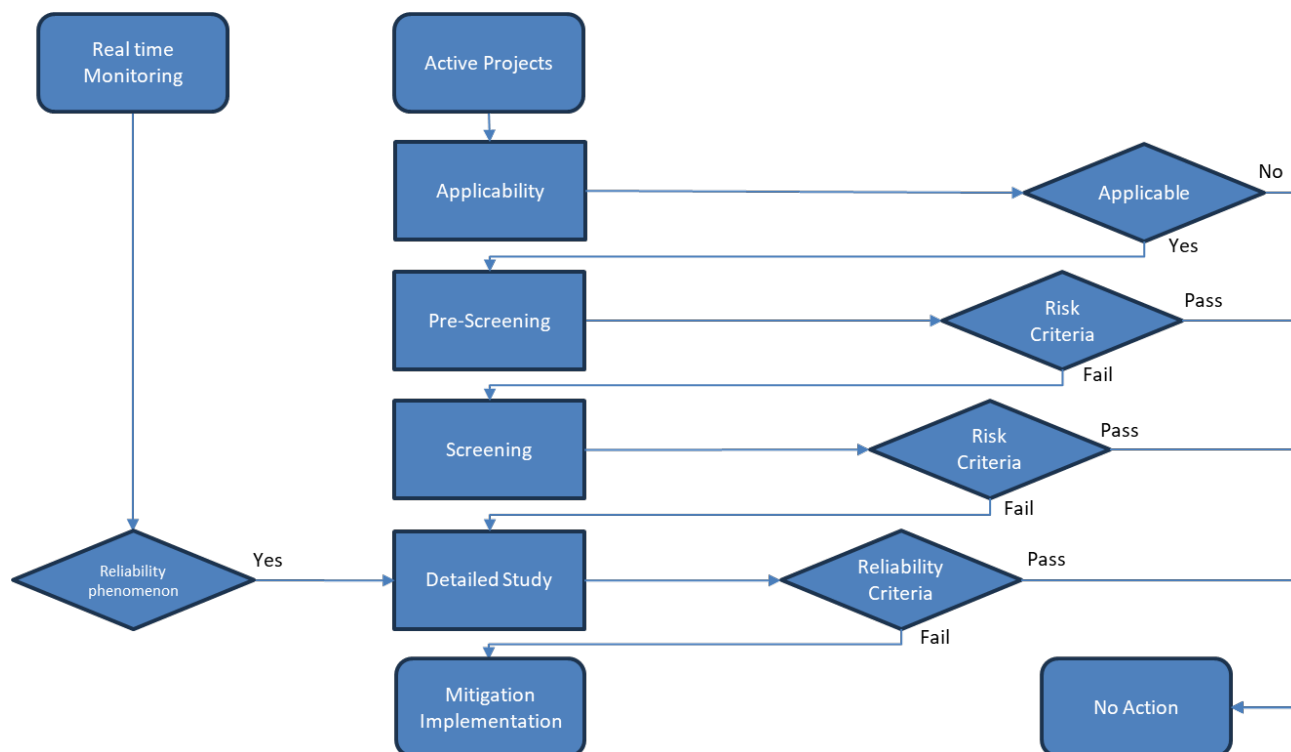
As a result of these emerging AIES reliability challenges, the AESO has identified several areas where performing Grid Readiness, Integration and Performance (GRIP) Requirements would be beneficial. The AESO also realized that the system reliability, due to issues/reasons mentioned in the next section, is heavily dependent on how market participants (MPs) conduct technical assessment and design the facility accordingly to meet AESO's connection requirements prior to their energization. Therefore, the AESO has created standard guidelines on how to conduct the APSA. The AESO has 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.

### AESO's Risk-Based Assessment Approach

The AESO's process for GRIP utilizes 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 result in the AESO including a detailed study requirement in the project’s functional specification. This guideline provides additional details on the recommended approach for conducting those 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. The AESO 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 is to identify 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 applicable 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 and/or mitigation.

### *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 and is usually conducted in the later stages of the customer connection process. The AESO will include the detailed study and report submission requirements in the functional specification for the high-risk projects.

### *Mitigation*

The screening and/or detailed study report may demonstrate 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 to the AESO, 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 comments from the AESO and authenticate the study report. The detailed study must be completed 100 days and 30 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, the AESO will work with the MP on the mitigation measures in real time. 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 Structure

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.

### 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 on 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 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.

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