Harmonic Analysis

Assessment Guideline

MAY 2026

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Assessment Guideline

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April 14, 2026
#213253

Date of issue: April 14, 2026

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RM APEGA ID #: 98372

DATE: April 14, 2026

PERMIT NUMBER: P008200
The Association of Professional Engineers and Geoscientists of Alberta (APEGA)

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Executive Summary

Purpose and Scope

The Alberta Electric System Operator (AESO) has developed the Harmonic Assessment guideline to support market participants (MPs) in demonstrating compliance with power quality and harmonic distortion to address the requirements of subsection 2(b) of Section 503.11 of the ISO rules, *Power Quality*, and subsection 9.2 of the AESO Connection Requirements for Inverter-Based Resources.

Rationale

Harmonic distortion is a power quality issue that can adversely affect both transmission-connected facilities and other equipment connected to the AIES. Elevated harmonic levels may result in increased losses, overheating of equipment, insulation stress, interference with control and protection systems, and the amplification of resonant conditions within the transmission network.

As the AIES continues to evolve with increasing penetration of inverter-based resources and other power electronic–based facilities, the potential for harmonic emissions and resonance has increased. Compliance with subsection 2(b) of Section 503.11 of the ISO rules requires that facilities be assessed to ensure harmonic performance remains within acceptable limits and does not degrade overall system power quality. A structured harmonic assessment framework is therefore required to identify potential issues and to ensure that appropriate mitigation measures are implemented where necessary.

Performance Criteria

The maximum harmonic current and voltage distortions at the point of connection (POC) shall be within the limits set out in:

- Subsection 2(b) of Section 503.11, Power Quality of the ISO rules
- Section 9.2 of the AESO Connection Requirements for Inverter-Based Resources

Application

MPs are expected to use this guideline for all applicable projects during the connection process. For high-risk connection projects identified by the AESO, detailed harmonic study and subsequent mitigation requirements will be specified in the project's functional specification.

1. Harmonic Analysis Introduction

1.1 Background

Harmonics is related to subsection 2(b) of Section 503.11 of ISO rules[1] and subsection 9.2 of the AESO Connection Requirements for Inverter-Based Resources.[2]

For many years, harmonic distortions in power systems have been mainly caused by large nonlinear loads in the system, such as arc furnaces and industrial converters or transmission-connected facilities like high-voltage direct current (HVDC) and flexible alternating current transmission system (FACTS) systems.

In recent years, there has been a growing number of installations of IBR, particularly transmission-connected wind and photovoltaic power plants. These resources are connected to the power system through a power electronic interface. Based on industry experience in different power systems worldwide, voltage harmonic distortion has been trending upwards when there is a general increase in IBR and reduction in synchronous generators. These distortions might lead to a series of adverse impacts to the power system equipment including overheating of electric machines and transformers, equipment and protection system malfunctions, increased losses, etc. As the power quality issues associated with harmonics in power systems are becoming more pronounced, it is paramount to perform detailed analysis during connection process to minimize and mitigate the adverse impacts in a timely manner.

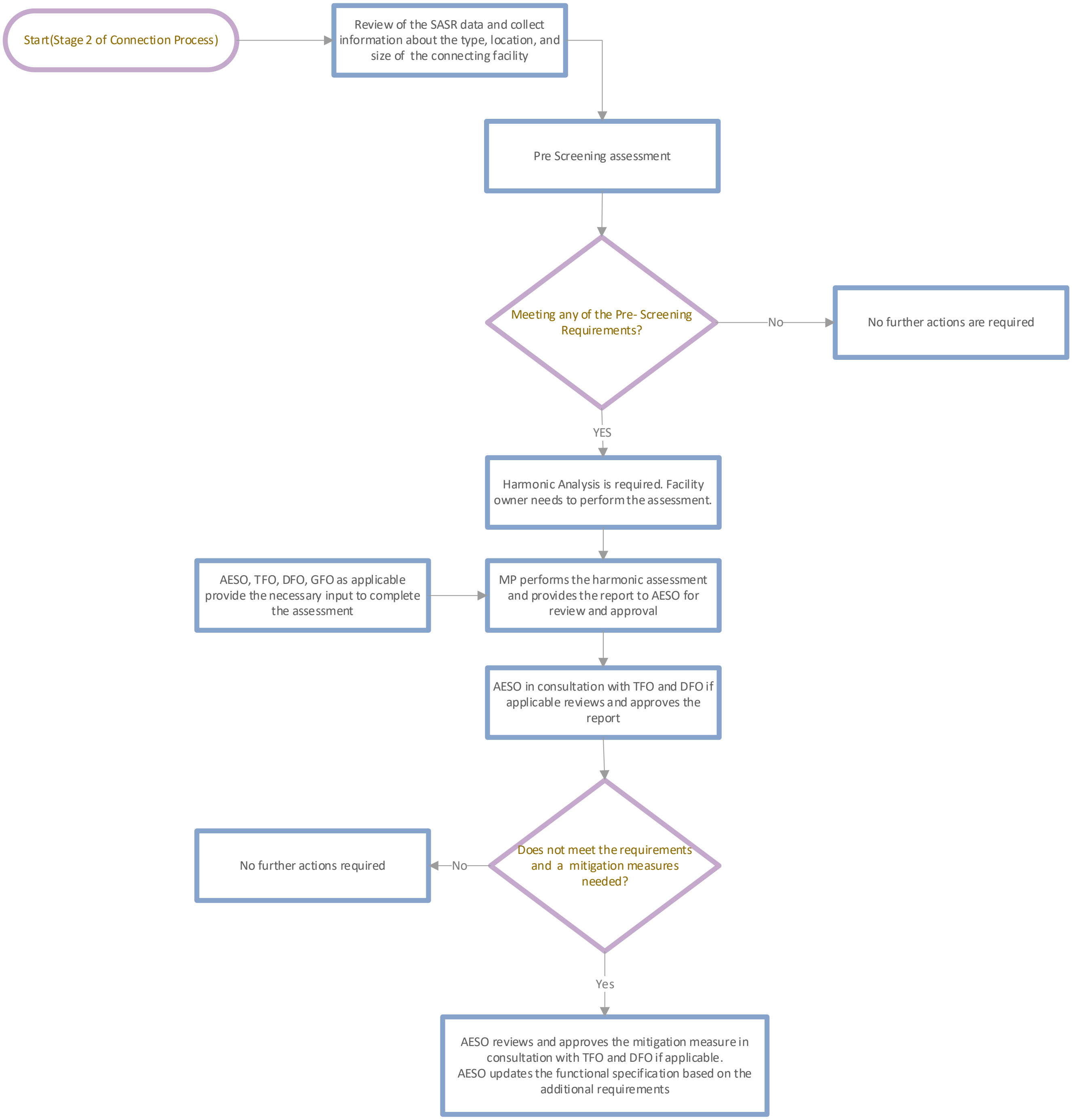
This guideline was developed to educate stakeholders about why Harmonics assessment is required and how a project will be assessed through a standardized approach. It provides transparency and guidance on how to conduct the applicability, pre-screening, screening and detailed study by the responsible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

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.

A high level of the harmonic analysis process flow in Figure 1 is developed based on AESO's risk-based assessment approach:

[1] Subsection 2(b) of Section 503.11 of the ISO rules does not prescribe harmonic limits directly. Instead, it requires compliance with the most recent version of IEEE Standard 519, *Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems*, which sets out the applicable harmonic performance specifications.
[2] Published on February 28, 2024(link: https://www.aesoengage.aeso.ca/reliability-requirements-roadmap#folder-131431-30654).

Figure 1: Harmonic Assessment Process Flow



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 Harmonic Analysis

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

Deliverable	AESO	Transmission Facility Owner (TFO)*	Generation Facility Owner (GFO)*	Market Participant (MP)	Distribution Facility Owner (DFO)
Applicability and Pre-Screening (Earliest Connection Process Stage: Stage 1)					
Performs pre-screening and identifies the need for detailed study	A/R	I	I	I	Not Applicable
Detailed Study (Earliest Connection Process Stage: Stage 3 but prior to facility energization)					
Provides modeling data for the facility	R	R	R	A/R	R
Provides other required data for the study including base cases	A/R	R	R	R	R
Performs detailed study and proposes mitigation (if applicable)	C	R	R	A/R	I
Result Acceptance and Mitigation Recommendation (Earliest Connection Process Stage: Stage 3 and prior to facility energization)					
Reviews and accepts study results	A/R	I	I	I	I

Deliverable	AESO	Transmission Facility Owner (TFO)*	Generation Facility Owner (GFO)*	Market Participant (MP)	Distribution Facility Owner (DFO)
Reviews proposed mitigation	A/R	C	R	R	C
Accepts the proposed mitigation[3]	A/R	I	I	I	I
Updates the functional specification	A/R	C	I	I	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.

*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[4]

Projects that may be applicable to this guideline include:

[3] Since proposed mitigations may affect the design and technical scope of the project, many of the activities outlined in the "Result Acceptance and Mitigation Recommendation" step should ideally be agreed upon and resolved during Stage 3.

[4] Identifying a project as applicable under this section does not automatically trigger a harmonic analysis requirement. Rather, it indicates that the project should proceed through pre-screening and, if necessary, further screening to assess whether a harmonic study is required based on its specific design and characteristics.

- All power electronic based generating facilities, including aggregated generating facilities or energy storage resources that are directly connected to the transmission system, and those situated within an industrial complex directly connected to the transmission system.[5]
- All load facilities including:[6]
  – Facility connecting industrial load to the transmission system
  – Facility connecting distribution load to the transmission system
- All transmission facilities owned by a TFO that:
  – Have nonlinear characteristic equipment producing harmonics (e.g., static synchronous compensator [STATCOM], HVDC or FACTS devices)
  – Have equipment shifting/causing system harmonic resonance (e.g., capacitor or alternating current [AC] filter banks, etc.)

1.4 Pre-Screening

Pre-screening is required when project applicability cannot be directly applied, and engineering judgment will be applied to several factors to determine if a connecting facility can be excluded from further analysis. Information that may be used for pre-screening includes, but is not limited to:

Type of load facility

Harmonic assessment will be required if the transmission connecting load comprises a significant[7] portion of power electronic based load or loads with nonlinear characteristics. Common load types belonging to this category include:

- **Variable Frequency Drives (VFDs):** Used in motor controls for adjustable speed, VFDs use switching devices that generate harmonics
- **Uninterruptible Power Supplies (UPS):** Typically used in critical power applications, the inverters in UPS systems can produce harmonics
- **Large-Scale Industrial Equipment with Rectifiers:** Equipment such as furnaces, electrolysis processes, or large welding machines often use rectifiers that convert AC to direct current (DC), generating significant harmonics
- **Arc Furnaces and Industrial Heaters:** These use high currents and are non-linear loads, producing harmonics due to the arcing process
- **High-Power Electric Vehicle (EV) Chargers:** Fast chargers for EVs can inject harmonics, especially in systems with high penetration of EV infrastructure

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[5] Distributed energy resources (DERs) above 5MW (maximum authorized real power [MARP]), will adhere and follow the requirements set out by the corresponding distribution facility owner (DFO).
[6] This excludes residential loads.
[7] Typically, a “significant portion” refers to power electronic or nonlinear loads making up more than 50 per cent of the total connected load. However, this threshold may vary depending on system characteristics such as location, size, and sensitivity of nearby equipment.

- **Data Centres and IT Equipment:** Due to extensive use of switch-mode power supplies (SMPS) and UPS system, data centres and IT loads can inject harmonics

Type of transmission connected facility

- HVDC and FACTS devices
- AC filter or transmission capacitor banks
- Renewable Energy Resources: Solar photovoltaic (PV), wind farms and battery energy storage systems (BESS)
- Transmission system developments including series compensation transmission development

1.5 Screening

Harmonics assessment doesn’t require screening. Applicable project will move into detailed study directly.

1.6 Detailed Study

As outlined in AESO’s Risk-Based Assessment Approach section, a detailed harmonic study is required if a project that meets the applicability or pre-screening criteria does not pass, indicating that further assessment is necessary to confirm that the project poses no operational or reliability risk to the AIES, or that any identified risk can be adequately mitigated. For high-risk projects selected by the AESO, the project functional specification may be updated to include the Harmonic Detailed Study requirement and study report submission requirement. The TFO will coordinate with the MP to assess the risk of harmonics by complying with the harmonic analysis guideline outlined in this document. The AESO suggests MPs to present the detailed study results using the study report template in Appendix B.

1.7 Result Acceptance and Mitigation Implementation

The MP must 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. We 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 of project energization.

1.8 Energization Requirements

The AESO authorizes the project to connect to the AIES and achieve energization when the project meets all our 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. Harmonic Detailed Study Requirements

As the number of harmonic-generating devices connecting to power systems grows, conducting detailed assessments of their impact on the grid becomes increasingly important. This includes evaluating potential adverse effects on network equipment and other customers. Accurate modelling of each network component and non-linear device is a crucial part of harmonic analysis. Practical considerations such as assumptions, inputs, result interpretation and data exchange are also essential. This section offers guidelines and discussions on key aspects to consider when performing harmonic studies related to the connection of new non-linear installations. Given the drivers and objectives of harmonic assessment can vary, this leads to different modelling requirements.

2.1 Study Methodology

Harmonic analysis can be performed in either frequency or time domain, or a hybrid combination depending on the study requirements. Each method has its own benefits and drawbacks from an implementation and accuracy perspective. As part of this assessment, voltage and current distortions at specific network nodes, commonly the point of connection, will be calculated. The results will be compared against the set-out limits outlined in the Harmonic Performance Calculation, Criteria and Limits section to ensure limits are not exceeded or any mitigation is required to stay within them. However, frequency domain methods, mainly frequency scans and harmonic penetration studies, are widely accepted in industry and most used in the available commercial simulation platforms. Therefore, the AESO prefers the harmonic analysis in frequency domain methodology and the recommendations here are mainly targeting the frequency domain analysis approach.

2.2 Software

Harmonic analysis in power systems requires specialized software tools capable of accurately modelling and analyzing the complex interactions of electrical components and harmonics. Each of these software platforms offers unique strengths and capabilities, making them suitable for different types of harmonic analysis studies in power systems. The choice of software depends on the specific requirements of the analysis, the complexity of the power system and the expertise of the users for the purpose of the harmonic assessment required here. The AESO does not have any specific requirements regarding the type of software to use.

2.3 Data Requirements

Conducting a thorough harmonic analysis requires the collection of a wide range of data to accurately assess the power system's harmonic conditions and determine the sources, impact and appropriate mitigation measures. The following outlines the critical data required to proceed with harmonic analysis:

1. **Facility**

This includes single-line diagrams of the connecting facility showing the electrical layout of the system including all main equipment, such as power transformers, generating units including inverters, feeders/cables, grounding transformers, etc. Technical specifications of key components within the facility footprint, including rating and impedance data for main transformer data, cable/feeder data, grounding transformers, harmonic filters, etc.

   a. Harmonic sources:
      i. As mentioned in the former section, power converters and technologies using them (e.g., wind, solar, HVDC, FACTS, variable speed drives, arc furnaces, etc.) are significant sources of harmonic distortion and function as frequency-dependent impedances, which can influence network resonance frequencies
      ii. The nonlinear characteristics of these technologies are mainly design-specific, therefore, to model these harmonic sources accurately, the corresponding modelling data needs to be provided by the equipment manufacturer

2. **Network Data Beyond Point of Connection (POC)**
   a. Transmission line geometry/cable layout and conductor/cable data needed to accurately represent the frequency dependency of the impedances within the desired frequency spectrum
   b. The PSS/E base power flow cases (.sav files) and data, including:
      i. Transmission system model including data for key transmission elements (e.g., generators, loads, shunt capacitor banks, power transformers, etc.) in the vicinity of POC
   c. Distribution system model, if required, depending on the relative location of DERs in the distribution system; (Point of Common Coupling [PCC])
      i. Detailed Power System Computer Aided Design (PSCAD) models of existing power electronic based facilities in the vicinity of the project (if available)[8]
   d. Background harmonic voltage measurements at the POC, if available

The following table shows the accountability among the main parties involved (i.e., AESO, TFOs, GFOs and DFOs) for providing the required data to complete the harmonic analysis.

[8] This data covered by the NDA will be provided solely upon AESO's determination that it is essential for completing the assessment.

Table 1: Accountabilities for the Required Data for Harmonic Analysis

Data Requirement	Accountable to Provide	Comment
Facility Data		
Single-line diagram of connecting facility including the electrical layout and main equipment like, power transformers, feeders, generating units, inverters, reactive compensating equipment, capacitor banks and harmonic filters, etc.	GFO	This data will be used to implement harmonic modelling of the facility
Technical specification of main equipment within the facility (rating, impedance, ratio, winding configuration of main transformers, cable data, rating and impedance of static reactive power compensating devices, etc.)		Detailed manufacturer datasheets and test reports including electrical characteristics of the main pieces of plant, such as cables, transformers, generators, reactors, capacitors, harmonic filters, etc., will be used for harmonic modelling of the facility
Manufacturer data, including detailed electrical characteristics of harmonic resources (e.g., inverters, power electronic converters, HVDC, FACTS, etc.) including modelling data, impedance and harmonic characteristics, ratings, etc.		Detailed manufacturer datasheets and test reports of harmonic generating sources within the facility need to be used. The provided data will be used to represent harmonic modelling and frequency-dependent characteristics of such sources accurately
Network Data		
Transmission line geometry/cable layout, earth resistivity, conductor/cable data	TFO	This information will be used to represent frequency dependency characteristics of transmission lines more accurately by accounting for factors, such as skin and proximity effects, earth-resistivity, long-line effects, inter-circuit coupling, sheath bonding for cables

Data Requirement	Accountable to Provide	Comment
The Power System Simulation for Engineering (PSS/E) base power flow cases (.sav files) and data	**AESO**	PSS/E based case provided by the AESO contains the transmission elements, generation, and load profile in the vicinity of POC along with key electrical data The provided PSS/E base case, along with other data provided by TFO and DFO, can be used by the study engineer to derive network equivalent impedance seen from POC at different harmonic orders (network harmonic impedance loci and envelopes) while considering key contingencies and outages within the area
Distribution system model (if applicable)	**DFO**	
Detailed PSCAD models of existing power electronic based facilities in the vicinity of the project (if available)	**AESO**	This information will be required only where it is determined to be necessary for the study and contingent upon the existence of such models.
Background harmonic voltage measurements at the POC (if available)	**TFO/DFO**	

2.4 Modelling Requirements

Modelling requirements for harmonic analysis in power systems are critical to assess and mitigate the effects of harmonic distortion accurately. Effective harmonic analysis necessitates the precise representation of various system components, including classical network elements like power transformers, transmission lines and cables, loads and synchronous generators, as well as non-linear and power electronic based network elements like HVDC, FACTS devices, variable speed drives and IBRs. Accurate impedance modelling of transformers and transmission lines/cables, considering frequency-dependent characteristics, is essential to understanding the propagation and interaction of harmonics throughout the network.

Additionally, the inclusion of network resonance points, which can amplify harmonic levels, requires careful analysis of system configurations and component interactions. Capacitors, reactors and harmonic filters need to be modelled with their exact electrical characteristics to assess their impact on harmonic distortion levels. Moreover, accurate representation of non-linear devices connected to power systems acting as main sources of harmonic distortion is key to capturing any harmful interactions in the system. Ultimately, comprehensive and accurate modelling is foundational to identifying potential harmonic issues and developing effective mitigation strategies to ensure the stability and reliability of the power system. In general, the AESO requires the modelling of various network elements for harmonic analysis to be aligned with the recommendation of *CIGRE-TB 766-Network modelling for harmonic studies*.

2.5 IBR Harmonic Modelling Considerations

Power converters are significant sources of harmonic distortion and function as frequency-dependent impedances, which can influence network resonance frequencies. To thoroughly evaluate the impact of converter-based generation on the grid's harmonic performance, it is crucial to model both the harmonic emissions and impedance characteristics of the power converters accurately. It is advisable to represent converter-based generation using a Norton or Thevenin equivalent circuit at relevant frequencies (typically 2nd to 50th harmonic order) as specified by IEC 61400-21-3 - *Wind energy generation systems – Part 21-3: Measurement and assessment of electrical characteristics – Wind turbine harmonic model and its application*.

This equivalent circuit includes an equivalent voltage/current source and a harmonic impedance that reflects the power converter’s impedance characteristics. This impedance should account for passive components within the plant, such as the main reactor impedance, passive filters and turbine transformers; otherwise need to be modelled separately. The harmonic emission and impedance characteristics vary with the operating point of the resource, and the worst-case operating point for each harmonic order should be used to obtain conservative results.

2.6 Aggregation of Harmonic Sources

One of the difficulties in combining multiple non-linear devices is the uncertainty of the phase angles between harmonic sources. These unknown angles can cause the harmonic effects from different sources to either amplify or neutralize each other. There is significant conjecture with respect to how harmonic emissions from identical non-linear devices that operate within a single installation should be aggregated.

Due to similarities and symmetry of design, it may be reasonable to suggest that two identical devices operating within proximity of each other are likely to emit harmonic currents with very little diversity in phase angle or time of emission and, thus, should add arithmetically. Studies investigating such phenomena suggest that such an assumption may be pessimistic, particularly for higher-order harmonics. Incorrect assumptions regarding the aggregation of harmonic emissions in such a scenario are capable of leading to further error in the evaluation of the impact of the plant. In literature, different approaches to aggregate different harmonic sources have been proposed. As each method has limitations, the AESO proposes to apply caution and consult with the manufacturers when aggregation of harmonic emissions from multiple sources is assumed in the analysis.

2.7 Network Representation Beyond POC

A significant challenge in conducting a harmonic study lies in determining the extent of the network that need to be modelled in detail and how to represent the rest of the network with equivalent models accurately. This task requires balancing the accuracy required for the analysis with the available data and the computational resources needed. The extent of the network to be modelled should account for the following:

- The system configuration should include the existing network topology as well as future upgrades driven by transmission system developments and connection projects that meet the AESO's certainty criteria and might have an impact on harmonic impedances near the POC
- Different demand levels might lead to changes to resonances and damping in the system driven mainly by changes in the generation profile, status of reactive compensation equipment, etc. Therefore, as a minimum, both peak and off-peak demand levels should be considered
- A number of credible outages and contingencies in the vicinity of POC should be considered and the retained network beyond POV should accommodate them, including key N-1, N-1-1 and N-2 contingencies in the area
- Key passive and active reactive power compensating equipment (e.g., capacitor banks, static volt-ampere reactive [VAR] compensator [SVC], HVDCs, etc.) electrically close the POC should be represented in detail as the different configurations of AC filters associated with these technologies might introduce resonances at different harmonic frequencies
- As a minimum, the network should be represented in detail up to three substations away from the POC
  - However, this number might need to increase further as the accuracy of this representation is highly dependent on the specific characteristics of the network in the vicinity of POC
  - The progressive approach proposed in Cigre working group C4.307[9] can be used to determine the minimum critical distance from POC

2.8 Network's Harmonic Impedance Loci and Envelopes

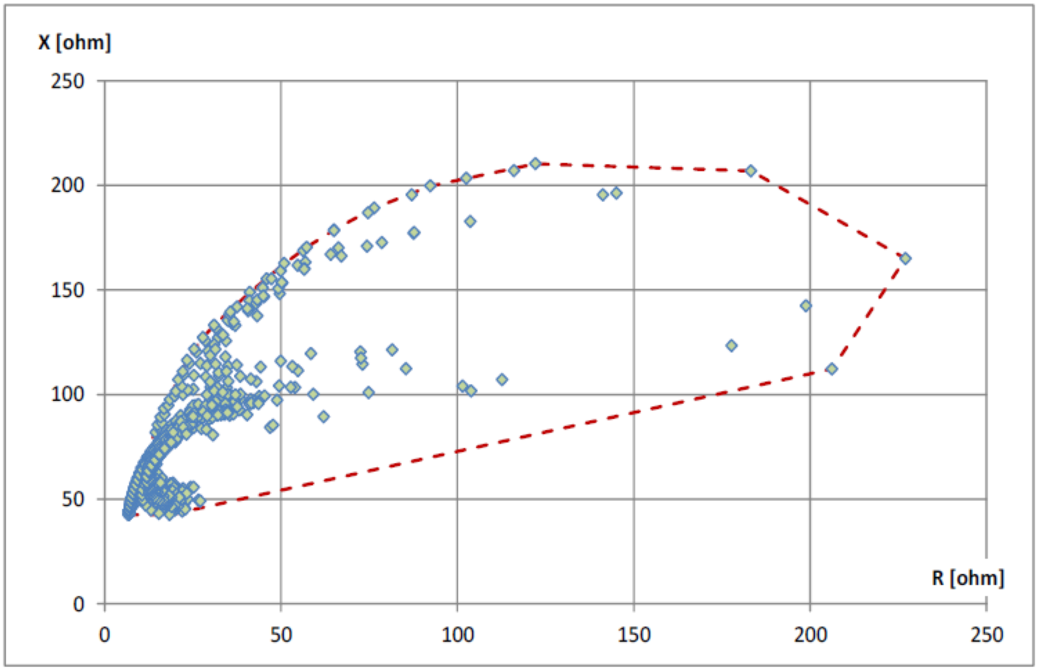
Once the extent of the network beyond POC was determined and all the elements within the retained network were represented by their corresponding harmonic models, the impedance of the retained network, as seen from the POC, will be calculated. Frequency scanning up to the 50th harmonic order with a suitable frequency step resolution will be performed to calculate the harmonic impedance of the retained network at each frequency.

Given this harmonic impedance is subject to continuous change driven by varying network configuration, generation and demand profile, etc., a range of variability for each harmonic impedance needs to be determined. Harmonic impedance loci and envelope is a commonly used approach in industry to represent the range of harmonic impedance. An impedance locus is a set of diagrams defining the range of possible transmission system impedances in the R-X plane for the

[9] CIGRE TB 568. "Transformer Energization in Power Systems: A Study Guide", WG C4.307, February 2014.

harmonic orders that are subject to limits, i.e., from the 2nd up to the 50th harmonic order. The transmission system may operate at any impedance value inside the loci. Figure 1 shows an example.

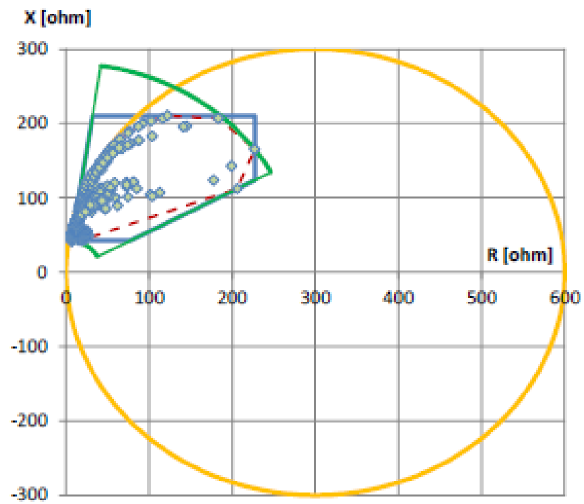
Figure 1: Locus of the 5th to 7th Harmonic Impedance[10]



In literature, there are different methods to represent impedance loci (e.g., circle, sector and polygon). Figure 2 compares the fit of different envelopes for a set of calculated harmonic impedance values in a defined frequency range.

[10] Source: Cigre C4/B4 TB Ref: 766.

Figure 2: Different Harmonic Impedance Envelope Representation[11]



Harmonic impedance envelopes: Circle, Sector, Basic Polygon, Convex-Hull Polygon

The AESO recommends the use of individual or narrow frequency band impedance for each harmonic. The use of a single envelope encompassing impedance for all harmonic orders should be avoided.

2.9 Harmonic Performance Calculation, Criteria and Limits

Once the data collection and harmonic modelling setup are complete, the voltage and current harmonic distortions at the POC need to be calculated and demonstrate that the calculated results are within acceptable bounds already set out by the AESO. For each harmonic order, the maximum and total voltage and current harmonic distortions at the POC will be calculated, and the compliance with the limits and requirements set out in the following documents will be evaluated:

- Subsection 2(b) of Section 503.11, *Power Quality* of the ISO rules
- Section 9.2 of the AESO Connection Requirements for Inverter-Based Resources

As an example, Figure 3 and Figure 4 show a simplified calculation procedure in frequency domain which assumes a current source (**Ih** = representing the harmonic currents generated by the connecting facility) and parallel harmonic impedances (representing all possible system Zs and facility harmonic impedance **Zf** at each harmonic order for a broad possible operating conditions).

[11] Source: Cigre C4/B4 TB Ref: 766

Figure 3: Simplified Circuit to Calculate Voltage Harmonic Distortions by a Harmonic Source

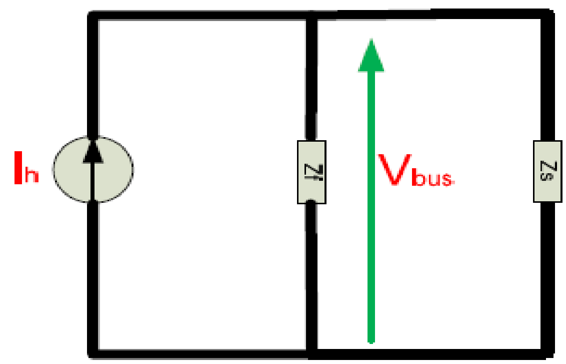
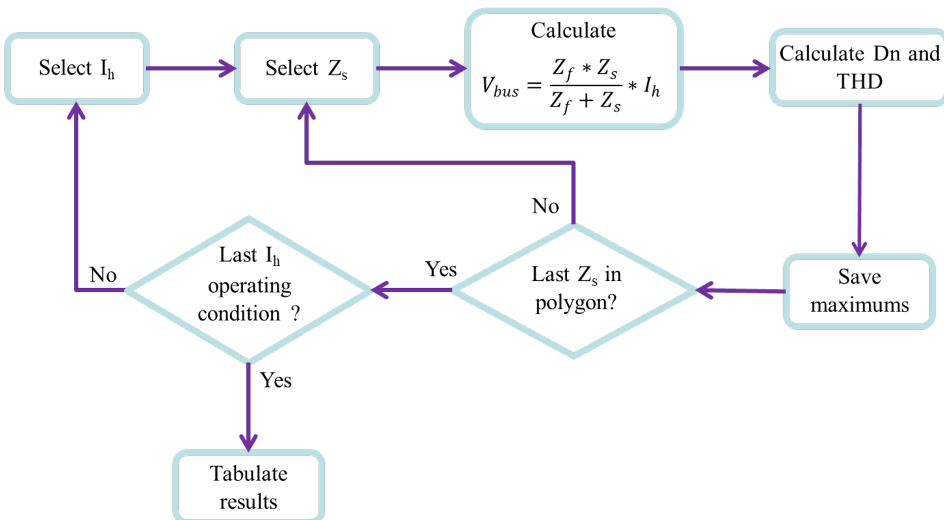


Figure 4: Harmonic Voltage Distortion Procedure



Where:

U_1 is the rated fundamental voltage at the bus

I_h is the n[th] order harmonic current generated by the connecting facility

Z_f is connecting facility's harmonic impedance at each harmonic order

Z_s is system's harmonic impedance at each harmonic order

Individual harmonic voltage distortion:

$$D_n = \frac{U_n}{U_1} * 100\% \quad \text{Eq. 1}$$

Total harmonic voltage distortion:

$$THD = \frac{1}{U_1} * \sqrt{\sum_{n=2}^{N=50} U_n^2} \quad \text{Eq. 2}$$

2.10 Background Harmonic

Background harmonics are typically considered during harmonic performance analysis when connecting a new harmonic-generating facility to the power grid. Background harmonics[12] refer to the existing harmonic distortions present in the grid before the connection of the new facility. These pre-existing harmonics can interact with the harmonics generated by the new facility, potentially amplifying harmonic levels and leading to compliance issues or operational problems.

Therefore, if background harmonic measurements are available at the POC, it is recommended that the harmonic analysis include:

- the combined effect of new harmonic contribution generated by the harmonic-generating facility and amplification, or
- modification of the background harmonic voltage distortion caused by interaction between the connecting facility and the system impedance.

The amplification factor (K) of the background harmonic voltage distortion, as well as incremental contribution to harmonic voltage distortion at the POC following facility connection need to be calculated and provided.

$$K = \frac{Vh(post-connection)}{Vh(pre-connection)} = \left|\frac{Z_f}{Z_f+Z_s}\right| \qquad \text{Eq. 3}$$

The incremental harmonic voltage distortion at POC (ID_n) at each harmonic order attributed to the connecting facility will be calculated as:

$$ID_n = (K-1) * Vh_n(pre-connection) + D_n \qquad \text{Eq. 4}$$

Figure 5 show the simplified representation of the connecting facility and the system to calculate amplification factor of the background harmonic voltage distortions at the POC:

$$K = \frac{Vh(post-connection)}{Vh(pre-connection)} = \left|\frac{Z_f}{Z_f+Z_s}\right| \qquad \text{Eq. 5}$$

[12] CIGRE TB 596, "Guidelines for Power Quality Monitoring: Measurement Locations, Processing and Presentation of Data". Joint Working Group CIGRE/CIRED C4.112. October 2014.

Figure 5: Simplified Circuit for Background Harmonic Amplification Factor Calculation Driven by Facility Connection

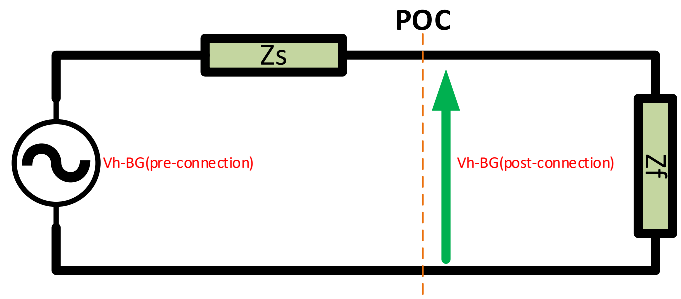
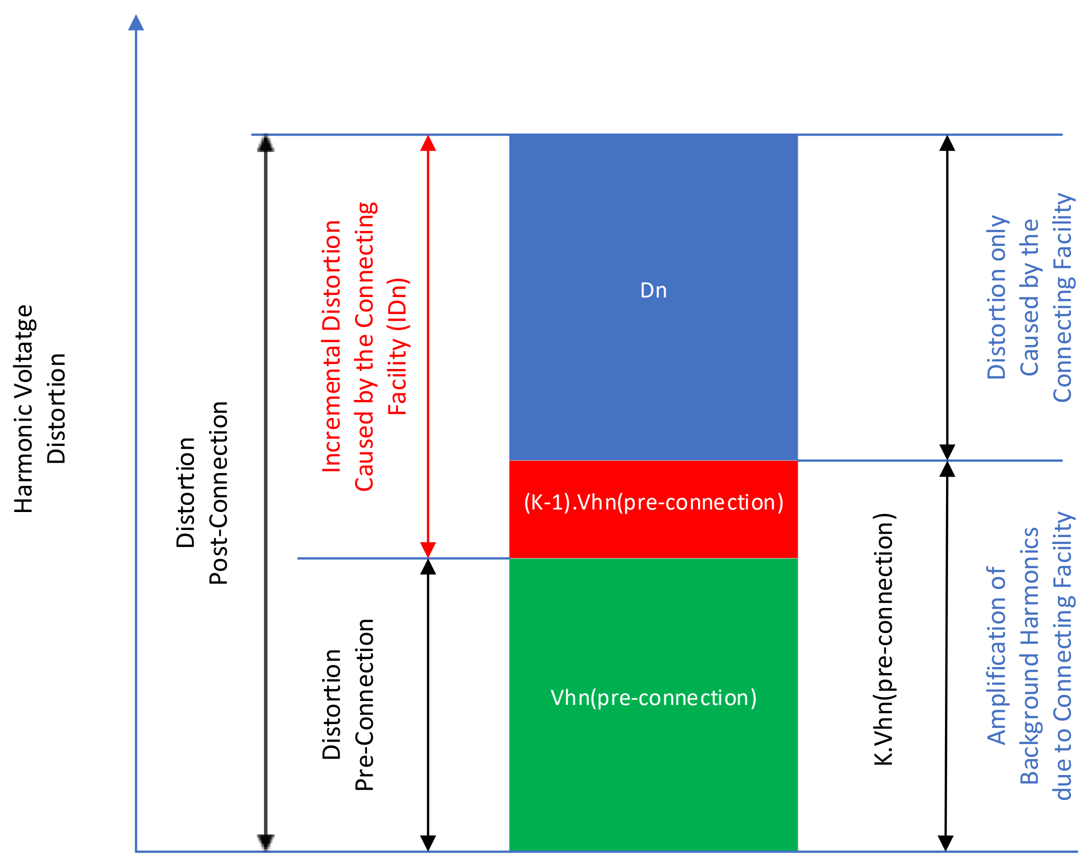


Figure 6 provides an overview of the incremental harmonic voltage distortion at POC by the connecting facility in the presence of background harmonics. The calculated incremental harmonic voltage distortion needs to be equal or lower than the set out limits to meet compliance requirements.

Figure 6: Incremental Harmonic Voltage Distortion



2.11 Mitigation Plan

When harmonic analysis reveals that harmonic distortions exceed acceptable limits, implementing harmonic mitigation strategies becomes essential to ensure system reliability, efficiency and compliance with requirements. Excessive harmonics can lead to overheating of transformers and motors, malfunctioning of sensitive electronic equipment, increased losses in the power system and potential resonance conditions, which can cause significant operational and safety issues. Harmonic mitigation can be approached through various methods, including the installation of passive or active filters, equipment upgrades, network reconfigurations, etc. In some cases, using phase-shifting transformers to spread harmonic currents across different phases or improving system grounding practices can also contribute to reducing harmonic levels.

Therefore, in case the study results show noncompliance to the required limits, a detailed plan for implementing proposed mitigation measures will be provided and the effectiveness of this mitigative measure will be demonstrated.

2.12 Study Outputs

Upon completion of the Harmonic analysis, the MP should provide the following:

- Detailed study report, which at a minimum includes:
  - A thorough explanation of the methodology and assumptions used in the assessment of maximum disturbance levels from the facility, including their justification
  - A detailed description of the simulation scenarios and assumptions, models and references to the simulation tools employed in the assessment
  - List all data sources and their relevance to the analysis not limited to key electrical parameters of the main equipment within the facility (e.g., cables, harmonic filters, power transformers, motors, etc.)
  - Manufacturer data detailing harmonic emission and impedance characteristics of harmonic-producing equipment within the facility (e.g., inverters, FACTS, variable speed drives, etc.). This includes any assumed aggregation for the entire facility
  - The network's harmonic impedance loci (R-X) calculated and used for the assessment
  - Detailed tables, including maximum harmonic current sources, maximum harmonic current and voltage distortion levels, maximum amplification factors, background harmonic voltage distortions (if available) and comparison with limits
  - Identification of resonance conditions and any potential risks to system components
- Following the AESO's approval, the finalized report will be authenticated by a professional engineer registered, and in good standing, with the APEGA

If MP decides to prove the effectiveness of a preferred mitigation implementation, the following shall be provided:

- Deliverable timing, within the connection process (if applicable)

- A detailed overview of the mitigation measures and their influence on distortion levels, including any proposed operating conditions or limitations

2.13 Study Report

The AESO provides the report template in Appendix B that can be used to present detailed study results. Using the template can help the AESO review the report in an efficient and productive way.

Appendix A: APSA 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

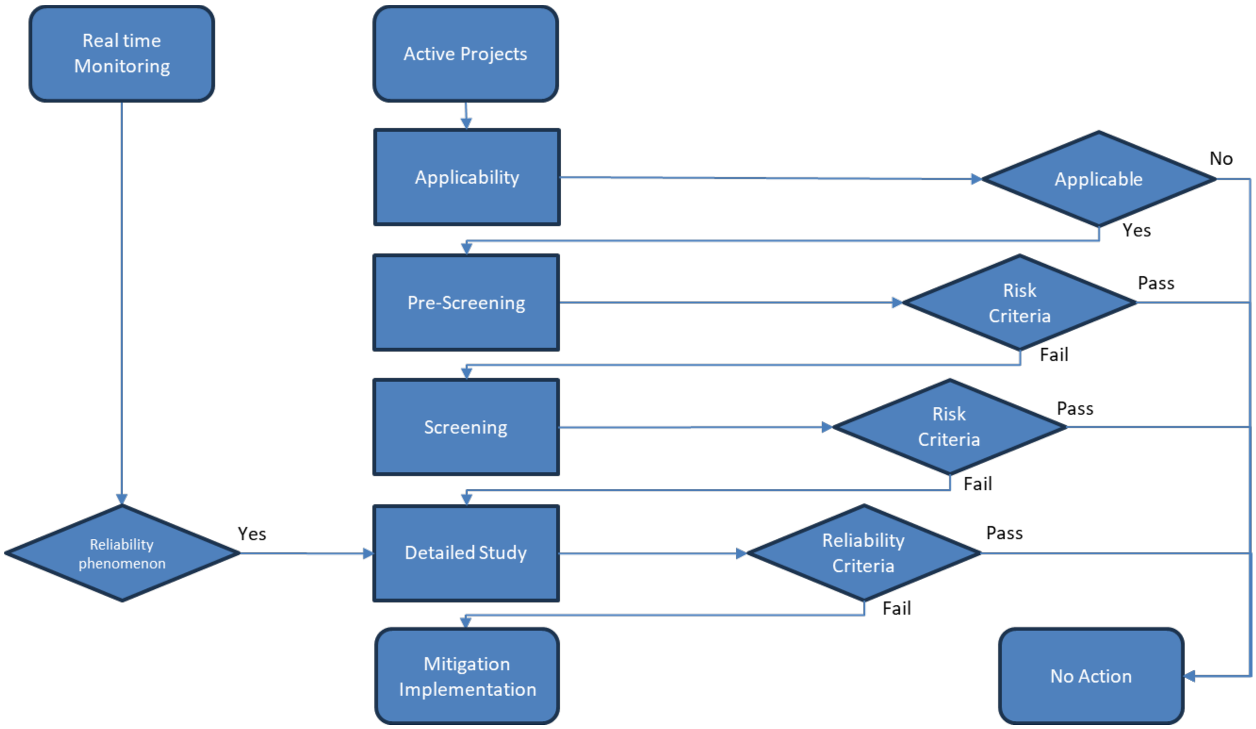
As a result of these emerging AIES reliability challenges, the AESO has identified several areas where performing Advanced Power System Assessments (APSA) would be beneficial. System reliability is also heavily dependent on how market participants (MPs) conduct technical assessment and design the facility accordingly to meet connection requirements prior to energization. Therefore, we have created standard guidelines on how to conduct the APSA. 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.

AESO's Risk-Based Assessment Approach

The AESO's process for the APSA 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. As this topic relates to the AESO Authoritative Documents, the guidelines applicability aligns with that of the relevant AESO Authoritative Documents.

Once a project meets the applicability criteria it will move to the next relevant step following the guideline. MP's 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 by the AESO. This information helps the MP and the AESO understand the risk of meeting harmonic 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 for the AESO to assess whether a project qualifies as high-risk. Projects identified as high-risk move to the detailed study stage and the AESO may add detailed study and report review requirement in the functional specification.

Detailed Study, Report and Submission

The objective of the detailed study is to demonstrate compliance with the AESO's Authoritative Document. If a project does not meet these requirements, it may create reliability risks to the AIES. The study aims to identify potential reliability issues through advanced calculations or simulations outlined in this guideline prior to project energization. To conduct this work, the responsible entity will require detailed project information and models, which usually occurs 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.

The detailed study report may show that the MP cannot fully demonstrate compliance with the AESO's Authoritative Document. When this happens, the MP must propose a solution to address the potential non-compliance and consult the AESO on the proposed solution. The detailed study will then need to be revised to confirm the effectiveness of the proposed mitigation.

Mitigation

The detailed study report may show that the MP cannot fully demonstrate compliance with the AESO's Authoritative Document. When this happens, the MP must propose a solution to address the potential non-compliance and consult the AESO on the proposed solution. 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 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, 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 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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06/2026