

Sub-Synchronous Oscillations (SSO) Analysis

Assessment Guideline



Alberta Electric System Operator

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Executive Summary

Purpose and Scope

The Alberta Electric System Operator (AESO) has developed the Sub-Synchronous Oscillation (SSO) Assessment guideline to address emerging reliability challenges in the Alberta Interconnected Electric System (AIES). This guideline:

- Addresses the risk of sub-synchronous oscillatory phenomena associated with the increasing integration of power electronic-based technologies in the AIES
- Defines a standardized, risk-based approach for assessing SSO, including assessment scope, study methodologies, inputs, assumptions, performance criteria, reporting requirements and mitigation options
- Helps market participants MPs understand the requirements for connecting and operating their facilities on the transmission system in a manner that does not introduce or exacerbate SSO-related reliability risks

Rationale

Sub-synchronous oscillations are an emerging reliability risk in modern power systems. These issues were once primarily associated with interactions between synchronous generators and series-compensated transmission networks. More recently, the increasing penetration of inverter-based resources (IBRs), HVDC systems, FACTS devices and large power electronic-based loads, has introduced new forms of SSO driven by power electronic device interactions.

SSO phenomena can result in sustained or poorly damped oscillations, increased mechanical and electrical stress on equipment, protection misoperation, and, in severe cases, widespread system disturbances. As the AIES adds more power-electronic-interfaced facilities, a consistent and transparent framework is required to identify, assess, and mitigate SSO risks prior to and during facility operation.

Performance Criteria

The following criteria apply to the Sub-Synchronous Oscillation (SSO) performance:

- The facility shall not introduce or exacerbate any form of sub-synchronous oscillation (SSO) under any credible operating condition. For this assessment, SSO includes both sub-synchronous resonance (SSR) and power electronic device interactions (PEDI).
 - **SSR:** The facility shall not excite or worsen SSR phenomena arising from interactions between the electrical network and mechanical systems of turbine- generators, or from purely electrical resonance in the transmission network, including conditions associated with series-compensated transmission lines
 - **PEDI:** The facility shall not introduce or exacerbate oscillations resulting from interactions involving power electronic devices, including:

- Interaction between a power electronic device and the network
- Interaction between two or more power electronic devices across the network (e.g., IBR–IBR, IBR–HVDC, IBR–FACTS, or large electronic-based loads)
- The facility shall have positive damping impact for all relevant oscillatory modes across the sub-synchronous and near-synchronous frequency ranges, including modes driven by mechanical resonance, electrical network resonance and power electronic control dynamics
- No oscillatory behaviour shall be sustained, growing or poorly damped, nor persist beyond a short transient period following credible disturbances such as faults, switching events or changes in network configuration
- Oscillatory interactions shall not result in excessive electrical, thermal or mechanical stress on other existing facilities in the network, nor lead to protection misoperation, unintended control behaviour or forced disconnection

Application

For connection projects identified by the AESO as having an elevated risk of SSO, SSO assessment requirements and associated technical studies will be specified in the functional specification (FS). Market participants (MPs) must comply with the FS and demonstrate meeting with the SSO performance criteria prior to connection and during operation, as applicable.

MPs are expected to apply this guideline when conducting and submitting SSO assessments to the AESO, and to implement any required mitigation measures.

1. SSO Introduction

1.1 Background

Sub-synchronous oscillations (SSO) is an operational requirement new to the industry in Alberta. The assessment and mitigation requirement for SSO are currently not included in any AESO Authoritative Documents.

This guideline is not authoritative and for information purposes only. It has been developed based on current industry practices and draws extensively from International Council on Large Electric Systems (CIGRE) published guidance on SSO in power systems.¹

SSO has been identified as a major concern in modern power systems. The introduction of power electronic devices such as high voltage direct current (HVDC), flexible alternating current transmission system (FACTS), large electronic-based loads (e.g., hyper scale data centre) and IBRs driven by grid transformation, has escalated SSO related issues². SSO is generally divided into sub-synchronous resonance (SSR) and power electronic device interactions (PEDI). Historically, SSOs in the power grid occur when the electrical network interacts with the mechanical systems of a turbine- generator at frequencies below the system's nominal frequency. In addition, the SSR could be purely electrical due to the resonance in the electrical network when there are series compensation device or it could be due to negative resistance introduced by a generator at a resonance frequency. These oscillations can lead to mechanical wear, equipment damage and, in extreme cases, widespread power outages. Historically, the risk of SSO has been most prevalent in grids that use series compensation for long-distance transmission or HVDC links.

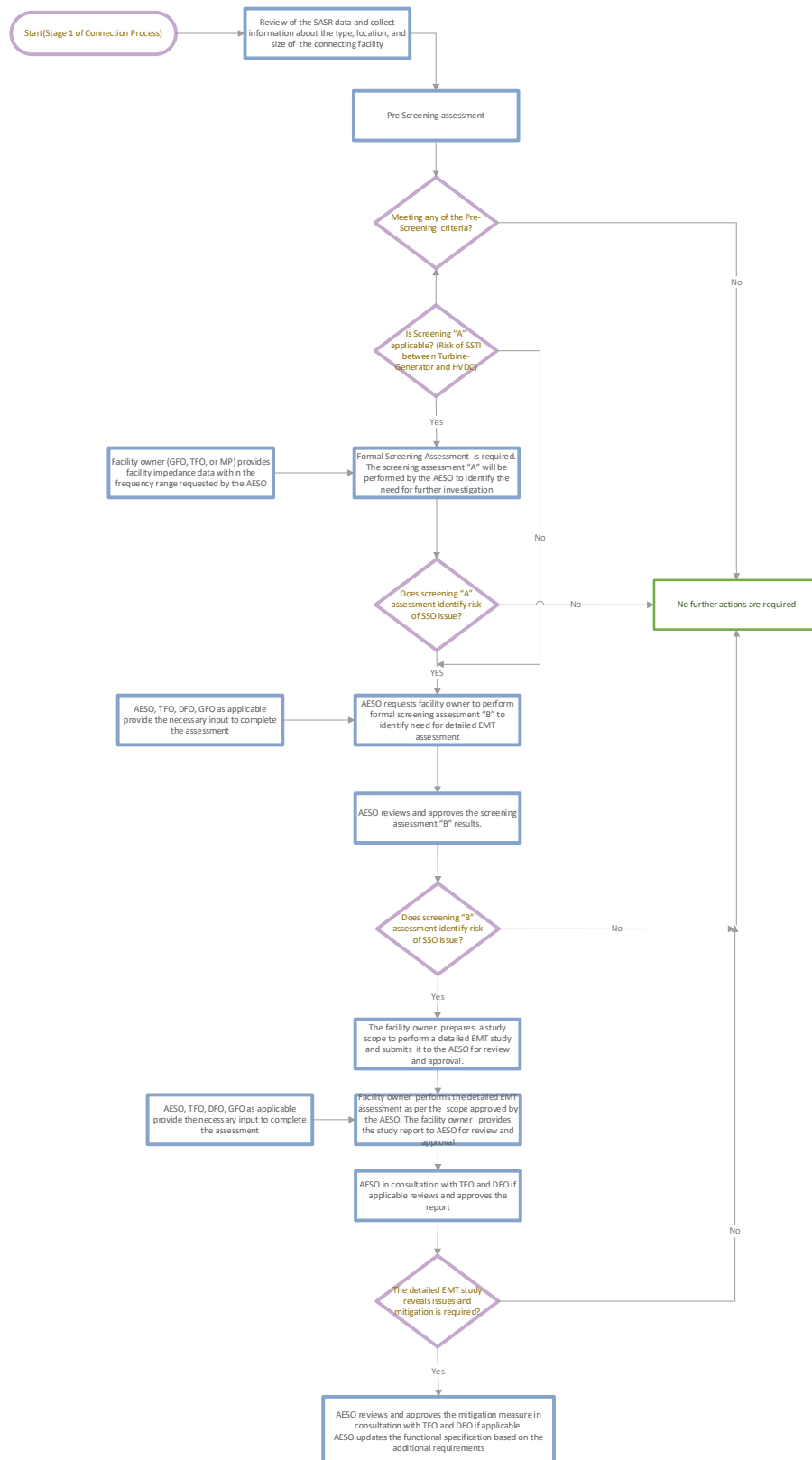
Recently, the growing increase of power electronic based devices in the grid has resulted in PEDI as a new SSO phenomena. This new category of SSO includes two types of interactions. The first type involves interaction of a power electronic device with the network while the second type includes interactions between two or multiple power electronic devices across the network.

A high level of the SSO analysis process flow is shown below in Figure 1.

¹ CIGRE WG C4/B4.52 “Guidelines for Subsynchronous Oscillation Studies in Power Electronics Dominated Power Systems”, TB 909, June 2023.

² CIGRE WG B4.81 “Interaction between nearby VSCHVDC converters, FACTs devices, HV power electronic devices and conventional AC equipment”, TB 934, July 2024.

Figure 1: SSO Assessment Process Flow Visual



1.2 Applicability³

Projects that may be applicable to this guideline include:

- All power electronic based generating facilities, including aggregated generating facilities or energy storage resources (e.g., battery energy storage systems [BESS]), that are directly connected to the transmission system and those situated within an industrial complex directly connected to the transmission system.⁴
- All conventional generating facilities (e.g., synchronous generators), including:
 - Facilities connecting electrically close to series compensated lines or other power electronic based generating facilities
 - All load facilities for which power-electronic-interfaced equipment represents 50% or more of the facility's total connected load, including: Facility connecting industrial load (e.g., large-scale data centre load) to the transmission system.
 - Facility connecting distribution load to the transmission system.
- All transmission facilities owned by the TFO that:
 - Interfaced to the transmission system through power electronic converters (e.g., static synchronous compensator [STATCOM], HVDC or other FACTS devices)

1.3 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 SSO Assessment

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

Deliverable	AESO	Transmission Facility Owner (TFO) *	Generation Facility Owner (GFO) *	Market Participant (MP)
Applicability and Pre-Screening (Earliest Connection Process Stage: Stage 1)				
Performs pre-screening and identifies the need for further investigation	A/R	I	I	I

³ Identifying a project as applicable under this section does not automatically trigger a SSO analysis requirement. Rather, it indicates that the project should proceed through pre-screening and, if necessary, further screening to assess whether further study is required based on its specific design and characteristics.

⁴ Distributed energy resources (DERs) above 5MW (MARF), must adhere and follow the requirements set out by the corresponding distribution facility owner (DFO).

Deliverable	AESO	Transmission Facility Owner (TFO) *	Generation Facility Owner (GFO) *	Market Participant (MP)
Screening Assessment “A” (Earliest Connection Process Stage: Stage 2)				
Provides modeling data for the facility	R	R	R	A/R
Performs the screening assessment and identify the need for further investigation	A/R	I	I	I
Screening Assessment “B” (Earliest Connection Process Stage: Stage 3 but prior to facility energization)				
Provides required data for the study including modeling data and base cases	A/R	R	R	R
Performs screening assessment and identifies the need for detailed electromagnetic transient simulation (EMT) studies	C	I	I	A/R
Detailed Study (Earliest Connection Process Stage: Stage 3 but prior to facility energization)				
Develops study scope for the detailed EMT study	A/R***	R	R	R
Provides study data including modeling data and base cases**	A/R	R	R	R
Performs detailed EMT study based on the study scope and proposes mitigation if applicable	C	R	R	A/R
Result Acceptance and Mitigation Recommendation (Earliest Connection Process Stage: Stage 3 but prior to facility energization)				
Reviews and accepts study results	A/R	I	I	I
Reviews proposed mitigation	A/R	C	R	R

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

** Further details about data requirements are provided in the Table 5.

*** The first draft will be prepared by MP and submitted to AESO for review and approval.

1.4 Pre-Screening

Pre-screening is required when project applicability cannot be directly applied, and engineering judgment need to 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:

Sub-synchronous torsional interaction between HVDC and turbine-generators:

- Electrical proximity to the HVDC converter station and system topology
 - Good engineering judgment needs to be used to exclude a unit from the formal screening process based on electrical proximity and system topology
- Size of turbine-generator is larger than 100 MW⁵
- Type of turbine-generator is steam, gas or combined-cycle

⁵ The 100 MW threshold for turbine-generator size was selected based on insights from prior studies and historical case reviews of sub-synchronous oscillation events. It functions as a practical screening boundary rather than an absolute limit—engineering judgment should prevail, and the threshold may be adjusted to reflect project-specific risk assessments.

Sub-synchronous or super-synchronous control interaction (SSI/SSCI) among power electronic-based facilities including IBRs, battery energy storage system (BESS), HVDC, power electronic-based loads (e.g. large data centres) and FACTS:

- Electrical proximity of such facilities to each other and system topology
 - Good engineering judgment needs to be used to exclude a unit from the formal screening process based on electrical proximity and system topology
 - Since it is difficult to quantify these parameters, they will be refined in the future based on the AESO's experience with SSI phenomena in the AIES and as more of these studies are performed
- Or the facility is in renewable rich areas of AIES (e.g., South region) or in weak parts of the system or remote areas electrically further away from large synchronous generators
- **Note:** If a facility is already subject to a detailed system strength EMT assessment, a separate SSCI study is not required
 - The system strength EMT assessment adequately identifies potential interaction risks, addressing the same concerns evaluated in an SSCI study

Sub-synchronous torsional Interaction between series capacitor compensated lines and turbine-generators;

- Electrical proximity to series compensated line and system topology
 - Good engineering judgment needs to be used to exclude a unit from the formal screening process based on electrical proximity and system topology
 - Since it is difficult to quantify these parameters, they will be refined in the future based on the AESO's experience with SSI phenomena in the AIES and as more of these studies are performed
 - Informed judgment may include past studies, connection voltage level, series compensation level [typically higher than 30%], possibility that the generator of being radial or close to radial to the series compensated line and order of contingencies that could lead to direct connection to the series compensated line)
- Size of turbine-generator is larger than 100 MW⁶
- Type of turbine-generator is steam, gas or combined-cycle

Sub-synchronous control interaction between series capacitor compensated lines and power electronic based facilities:

- Electrical proximity to series compensated line and system topology
 - Good engineering judgment needs to be used to exclude a unit from the formal screening process based on electrical proximity and system topology

⁶ The 100 MW threshold for turbine-generator size was selected based on insights from prior studies and historical case reviews of sub-synchronous oscillation events. It functions as a practical screening boundary rather than an absolute limit—engineering judgment should prevail, and the threshold may be adjusted to reflect project-specific risk assessments.

- Since it is difficult to quantify these parameters, they will be refined in the future based on the AESO's experience with SSI phenomena in the AIES and as more of these studies are performed. Informed judgment may include past studies, connection voltage level, series compensation level (typically higher than 30 per cent), possibility that the generator of being radial or close to radial to the series compensated line and order of contingencies that could lead to direct connection to the series compensated line
- Type of power electronic based facility is Type 3 wind turbine (Doubly Fed Induction Generator [DFIG]) or HVDC (line commutated converter [LCC]) or power electronic-based loads (e.g., large data centre)

1.5 Detailed Study

As outlined in Appendix A: AESO's Risk-Based Assessment Approach, the need for a detailed SSO study is identified if a project meeting the applicability or pre-screening criteria does not pass the screening assessment, which indicates that further assessment is required to ensure that there is no operational or reliability risk to the AIES, or that the risk can be adequately mitigated. As such, the project functional specification will be updated to include the SSO detailed study requirement. The AESO suggests MPs to present the detailed study results using the study report template in Appendix B.

A structured and detailed approach to undertake detailed SSO assessment, covering all necessary steps from data collection to mitigation strategies to ensure power system reliability is outlined in SSO Detailed Study section.

1.6 Result Acceptance and Mitigation Implementation

The MP shall 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:

- shall review the study report within reasonable time
- may comment on the report and ask the market participant to respond prior to our acceptance
- 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.

1.7 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. The AESO encourages the market participant to check with AESO's project manager to fully understand how to meet the energization requirements.

2. SSO Screening Assessment

2.1 Methodology

The screening assessment A (if applicable) is performed by the AESO as part of the connection studies in stage 2 of the AESO connection process to identify the risk of SSO. The screening assessment B (if applicable) will be performed by a market participant in stage 3 or beyond.

2.2 Screening Methods

The primary purpose of screening studies is to assess the SSO risk, ensuring potential issues are not prematurely dismissed while accepting some level of false alarms to avoid misclassifying unsafe situations as acceptable. To achieve this, the studies cover a broad area of the network surrounding the planned or vulnerable devices and evaluate numerous systems operating conditions, including system intact and contingency scenarios.

Screening methods are designed to identify potential risks across various scenarios, often sacrificing some precision for simplicity and feasibility. Once potential risks are flagged, these cases are subjected to more detailed studies. It is important to note that screening methods only indicate the possibility of SSO risk and are not conclusive. Several screening methods are available for assessing different types of SSO risks, but the most commonly used ones are:

1. Unit interaction factor (UIF)
2. Impedance model-based analysis
 - a. Passive frequency scan
 - b. Dynamic frequency scan

Each of these screening methods might be used for screening for SSO issues (e.g., torsional interaction of HVDC with turbine-generators, control interactions of type 3 wind farm with the electrical network due to series compensation, etc.). An overview of each method is provided in the following sections.

2.2.1 Unit Interaction Factor

To investigate the phenomenon of sub-synchronous torsional interactions (SSTI) between HVDC and thermal turbine-generators, and screening methodology known as the UIF was developed by Electric Power Research Institute (EPRI).⁷ The UIF methodology has been established as a preliminary screening tool to check how closely coupled a thermal turbine-generator with the HVDC. The UIF is used as guide to decide whether detailed studies of SSTI are needed.

The UIF method offers a simple and practical way to estimate the extent or severity of the inherent impact an HVDC system may have on the sub-synchronous damping of a turbine-generator. This method is based on an approximate relationship that quantifies the potential level of interaction.

⁷ EPRI, "HVDC System Control for Damping of Sub synchronous Oscillations," EPRI, EPRI EL-2708 report, New York, USA, 1982.

The UIF is calculated as follows:⁸

$$UIF_i = \frac{MVA_{HVDC}}{MVA_{Gen}} * \frac{\partial V_c}{\partial V_{Gen}} * \frac{\partial I_{Gen}}{\partial I_c} \quad \text{Eq.1}$$

Where:

UIF_i = Unit Interaction Factor for i^{th} generator in specific network condition

MVA_{HVDC} = Rating of HVDC (MW)

MVA_{Gen} = Rating of generator (MVA)

V_c = Voltage at converter AC bus

V_{Gen} = sub-transient voltage of generator (voltage behind sub-transient impedance in classical model of synchronous generator)

I_c = Current from converter into AC bus

I_{Gen} = current in generator

To calculate the unit interaction factor between an HVDC terminal and a generator connected in the network, the following quantities need to be calculated:

- Change in the converter bus voltage for a change in the generator internal (behind sub-transient impedance) voltage ($\partial V_c / \partial V_{Gen}$)
- Change in the generator current (when the generator internal bus is grounded) for the change in converter current ($\partial I_{Gen} / \partial I_c$)

It should be noted that under special cases where the generator is radially connected to the HVDC terminal, the above equation can be generally simplified to the below equation to calculate UIF. This is the most commonly used equation of UIF, but it is only applicable to radial connection and should not be used for non-radial systems.

$$UIF_i = \frac{MVA_{HVDC}}{MVA_{Gen}} \left[1 - \frac{SC_i}{SC_{Total}} \right]^2 \quad \text{Eq.2}$$

Where:

UIF_i = Unit Interaction Factor for i^{th} generator in specific network condition

MVA_{HVDC} = Rating of HVDC (MW)

MVA_{Gen} = Rating of generator (MVA)

SC_{Total} = Short circuit capacity at HVDC terminal with i^{th} generator connected

SC_i = Short circuit capacity at HVDC terminal with i^{th} generator disconnected

⁸ CIGRE Technical Brochure 563, "Modelling and Simulation Studies to be performed during the lifecycle of HVDC systems," WG B4.38, www.e-cigre.org, 2013.

2.2.1.1 Limitations

This screening formula was originally developed for LCC-HVDC converter technology, the UIF screening method suggests a risk threshold of 0.1 for SSTI. While SSTI characteristics and risks depend on the type of converter, significant differences exist between LCC and voltage-source converter (VSC)-based HVDC technologies. As such, the threshold value for UIF is not recommended to be used for VSC-HVDC systems.

This method assumes an inductive network and that impedance changes linearly with frequency in the sub-synchronous range. Therefore, the UIF screening method is not suitable for networks containing series compensation.

2.2.2 *Impedance Based Methods*

Impedance-based methods to investigate oscillatory stability issues have been used widely in power systems and the merits of these methods are more pronounced in power electronic converter-dominated power systems. In principle, in these techniques, the electrical impedance of the connecting facility and the impedance of the network seen from the point of connection are determined and used to evaluate the risk of instability. There are several techniques to determine the impedance have been proposed in literature, but the following techniques are commonly used in industry:

- Passive frequency scanning
- Dynamic frequency scanning

2.2.2.1 Passive Frequency Scanning

Passive frequency scanning is a method used to evaluate SSO risks by analyzing network impedance which is obtained across a range of frequencies. Peaks or dips in the impedance magnitude indicate potential resonance conditions.

This method is an established method for formal screening of SSO issues, mainly looking for electrical resonances in the network triggered by series capacitor compensated transmission lines that might be excited by power electronic converter controls used in IBRs or lead to interacting with torsional modes of the mechanical system in thermal plants. For example, if a 40 Hz electrical series resonance is observed (due to the series capacitor) then this could potentially excite 20 Hz mechanical oscillations on the shaft of a thermal machine if the mechanical mass system has a torsional mode at the complementary frequency ($60 \text{ Hz} - 40 \text{ Hz} = 20 \text{ Hz}$ in this case).

This method is widely used due to its simplicity and applicability in linear systems, such as networks with series compensation. However, it does not capture dynamic interactions involving power electronic controllers. This method is computationally efficient and suitable for initial SSO screening, especially in networks with series compensation or other elements that may introduce resonances. However, it has limitations in representing dynamic effects from power electronic controllers or other nonlinear components, making it insufficient for analyzing complex SSO phenomena like sub-synchronous control interactions.

2.2.2.2 Dynamic Frequency Scanning

Dynamic frequency scanning builds on the passive method by incorporating system dynamics, including nonlinear and time-varying effects from power electronic controllers. This approach offers a more accurate representation of real-world behaviour in systems with complex interactions, addressing the limitations of passive scanning.

Dynamic frequency scanning, also referred to as frequency-domain analysis, calculates system impedance over a range of frequencies to detect resonant points. This method is crucial in evaluating the risk of SSO. It helps assess how the impedance of a power electronic system varies with frequency, providing insights into system stability, oscillation damping, and the dynamic interactions between power electronic devices and the grid or other systems. Impedance scanning is essential for small-signal stability analysis and understanding system behaviour across different frequency ranges.

In systems with power electronic components, impedance scanning involves injecting small voltage perturbations at various frequencies and measuring the corresponding current response. Impedance is then calculated for each frequency, allowing for the identification of resonance points or instability risks.

3. Proposed Sub-Synchronous Oscillations Risk Screening Procedure

The following screening procedure is proposed to assess the SSO risk effectively.

3.1 Screening “A” Procedure

3.1.1 *SSTI Between HVDC and Turbine-Generator Units*

For turbine-generator facilities with a SSTI risk, the UIF will be used as the primary screening tool to evaluate the coupling strength between turbine-generators and HVDC systems preliminarily and identify the risk of interactions between a turbine-generator and HVDC system. In this screening process a set of scenarios including different dispatches and network configurations. If the calculated “UIF” for any of the studied scenarios is larger or equal to 0.1, this warrants the need to perform a detailed EMT assessment to further investigate the risks of SSO for those scenarios.

Basic assumptions for conducting the UIF study:

- In general, the UIF is higher when fewer generators are in service and vice versa
 - Therefore, UIF calculations in the AIES should be conducted under summer light load with no export
- The UIF calculation in simple form is based on 3-phase short circuit levels and therefore any short circuit analysis tool can be used (e.g., PSS/E, PSLF, etc.)
- The power flow base case including network data will be used
 - UIF methodology does not require detailed models and data of the turbine-generator shaft system, generator detailed model, excitation system model, governor, HVDC and other control systems
- Sensitivities to the generation availability and dispatch for units in the vicinity of the HVDC station should be considered
- In addition to system normal cases (N-0), the UIF analysis need to cover all transmission single contingency (N-1) scenarios
 - In addition, all second contingencies that cause the turbine- generator to be connected radially or close to radially to the HVDC station need to be considered
 - Therefore, at minimum, the scope of the UIF analysis need to cover (N-0), (N-1), (N-2), (N-1-1), (N-1-2) and (N-2-2), where applicable
- Contingencies which involve outages of more than four transmission elements, for example higher than (N-4), which could result from two or more consecutive contingencies or during system restoration, may be considered
 - However, credible cases only should be considered if the system after the contingencies has a steady state power flow solution without significant voltage or thermal violations

- It is not necessary to consider all permutations and combinations of transmission facilities outages but rather to focus on contingencies that cause the turbine-generator to be connected radially or close to being connected radially with the HVDC
- The following assumptions will be considered while calculating the short circuit levels as an input to the UIF equation:
 - Sub-transient impedance will be used for the generators
 - Flat voltage profile, 1.0 per unit voltage considering nominal voltage of the bus as base value (e.g. 138 kV, 240 kV, 260 kV, etc.) with all the switched shunts and transformer taps locked
 - However, for the time domain simulations of the detailed SSTI studies, use typical voltage profile)

3.2 Screening “B” Procedure

3.2.1 SSCI Interactions Between IBRs, FACTS, BESS, Power Electronic-Based Load (Large Data Centre), HVDC and Electrical Network Including Series Compensated Lines

To identify potential control interactions driven by power electronic-based devices such as IBRs, HVDC systems, FACTS, and the electrical network—including series-compensated lines—the dynamic frequency scanning method will be used as a screening approach. The following sections provide a detailed procedure and key considerations for performing this assessment. Further information about this procedure is provided in sections 4 to 7.

3.2.2 Test System Setup

The facility’s site specific EMT model, will be used to conduct the frequency scan. The model will be scaled to its rated power and connected to the AC grid at the point of interconnection (POI). An infinite voltage source will represent the AC system. A controllable voltage source will be placed in series with the AC source to generate the perturbation waveform during the frequency scan, allowing the system's impedance response across a range of frequencies to be analyzed.

Figure 2: AC System Representation on the Frequency Scan

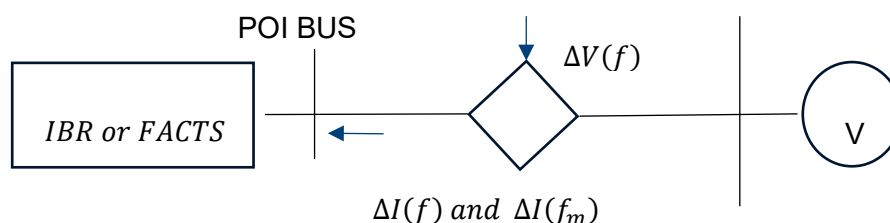


Table 2 lists the possible operational points of an IBR in steady-state conditions. These operating points correspond to different combinations of active power (P_{ini}) and reactive power (Q_{ini}) output

levels that the IBR might experience during normal operation. Each of these operating points affects the system's impedance and, consequently, the results of the frequency scan.

For **non-energy storage IBR devices**, the frequency scan will be conducted based on scenarios 1 through 9. These scenarios cover power injections ranging from full positive injection to zero power, ensuring that system behaviour under typical operating conditions is captured.

For **energy storage IBR devices, such as BESS**, all scenarios from 1 through 15 will be considered. These include both power injection and absorption cases, reflecting the unique ability of storage devices to operate in both modes. This ensures a comprehensive analysis of the system's impedance and stability under both positive and negative power conditions.

For large data centres and other power-electronic-based load facilities, frequency scans shall be performed at representative active-power demand levels, ranging from minimum expected demand to full facility load. These facilities shall be modelled as absorbing active power from the transmission system, with reactive-power demand established based on the facility's expected operating power factor. The selected operating points should reflect the anticipated range of normal operating conditions, including variations in facility loading and power factor, where applicable.

Table 2: Operating Scenarios Considered in Frequency Scan

Scenario No.	Pini*	Qini	Scenario No.	Pini	Qini
1	1.0	0.328	8	0.0	0
2	1.0	0	9	0.0	-0.328
3	1.0	-0.328	10	-0.5	0.328
4	0.5	0.328	11	-0.5	0
5	0.5	0	12	-0.5	-0.328
6	0.5	-0.328	13	-1.0	0.328
7	0.0	0.328	14	-1.0	0
			15	-1.0	-0.328

3.2.3 Frequency Scan Procedure for IBR or FACTS

Once the model is set up, the next step is to conduct a frequency scan to identify potential resonance points in the full power system model. This process involves analyzing how the system's impedance behaves across a range of frequencies, particularly in the sub-synchronous range, to identify potential frequencies where SSO could occur.

To accurately calculate impedance at a specific frequency f , both the positive sequence perturbation at f and its negative sequence response at $f - 2f_0$ (where f_0 is the system base frequency) must be considered.

Frequency Transformation in Converters:

- When a perturbation is applied at frequency f on the AC side of a converter, the resulting frequency observed on the DC side is transformed as $f - f_0$ (where f_0 is the nominal system frequency)
- The frequency $f - f_0$ on the DC side manifests back on the AC side as a negative sequence response at $f_{AC-negative} = (f - f_0) - f_0$
- This interaction leads to the generation of mirror frequencies in the AC domain, which are critical for understanding system stability
- For frequencies below $2f_0$ both the positive sequence response at f and the positive sequence response at $2f_0 - f$ are analyzed
- For frequencies above $2f_0$, both the positive sequence response at f and the negative sequence response at $f - 2f_0$ are analyzed

The frequency scan procedure is applicable to one IBR at a time. This individualized approach ensures precise identification of the dynamic interactions and resonance risks specific to each IBR. By isolating each IBR, the scan avoids overlapping dynamics that could obscure resonance points or damping behaviour, thus providing a detailed analysis of the individual resource's impact on the system stability. Further details are provided in Section 3.

If the facility also includes a voltage regulation device, such as a STATCOM, the frequency scan must be repeated to incorporate the combined dynamics of the STATCOM and the IBR converter. This is essential because the interaction between the STATCOM and the IBR can significantly alter the system's impedance characteristics and resonance points. Including both devices in the analysis ensures that their combined effects on system stability are fully accounted for, particularly in weak grid conditions or areas prone to resonance phenomena.

Procedure

1. Initial Model Setup:

The IBR, and if applicable, the voltage regulation device (e.g., STATCOM), are scaled to their rated power and connected to the AC grid at the POI with an ideal voltage source.

2. Signal Injection:

Perturbation signals, either single-frequency or multi-sine, are applied to analyze the impedance across the frequency range.

3. Frequency Analysis:

Measurements are performed at both the injected frequency (f) and its mirror frequency $f_m = f - 2 * f_0$ to evaluate the system's response.

4. Impedance Calculations:

Frequency-domain transformations (e.g., Fast Fourier Transform [FFT]) are used to extract impedance and admittance data, providing insights into potential resonance points.

5. Critical Considerations:

This procedure is essential for evaluating and mitigating the risk of SSOs in systems with high penetration of IBRs, which often exhibit complex interactions due to their power electronic controls and lack of inertia.

Repeating the scan with voltage regulation devices like STATCOM ensures a realistic evaluation of combined dynamics, reflecting the operational conditions of all installed devices.

3.2.3.1 [Signal Selection](#)

Multi-Sine Signals

A voltage perturbation signal can combine multiple sinusoidal frequencies into one, allowing a broad frequency range to be scanned in a single simulation. This minimizes the need for repeated runs.

The formula for a multi-sine signal is:

$$\Delta v(t) = a \sum_{m=m_0}^N \sin(2\pi \cdot f_b \cdot m \cdot t + \delta_m) \quad \text{Eq.3}$$

Where a is the amplitude of each sinusoid, δ_m is the phase, f_b is the frequency resolution, and N is the number of sinusoids.

Single Frequency Signals

Due to the nonlinear characteristics of the converter, a single-frequency excitation signal (at frequency f) can generate system responses at both the injected frequency (f) and the mirror frequency $f_m = f - 2 \cdot f_0$, where f_0 is the base frequency of the system (e.g., 50 Hz or 60 Hz), this makes it essential to observe the system's behaviour at both frequencies.

By measuring responses at both the injected and mirror frequencies, this method ensures a more comprehensive understanding of the system's dynamics, allowing for a detailed evaluation of system performance and stability.

3.2.3.2 [Initial Phase Settings](#)

In frequency scans, especially when using multi-sine signals, managing the phases of the signal components is crucial for achieving accurate and stable system behaviour. The purpose of signal injection is to apply a small perturbation that allows for the calculation of impedance or other frequency-domain characteristics without disrupting the system's normal operation. However, if the phases of the individual sinusoidal components within a multi-sine signal are not appropriately managed, large spikes or peaks may occur in the system's response, which can interfere with its steady-state behaviour.

A multi-sine signal consists of several sinusoidal components at different frequencies. When the phases of these components are aligned (i.e., identical for each frequency), the combined signal can produce large periodic spikes due to constructive interference between the waves. These spikes can temporarily push the system out of its nominal operating range, leading to non-linear behaviour or inaccurate impedance measurements. For instance, if all frequency components are

injected with the same phase, the signal amplitude at certain points may be significantly higher than anticipated. This can obscure the system's true dynamic characteristics, leading to errors in the measurement of impedance or other performance metrics.

To avoid this, the phases of the sinusoidal components are intentionally varied. This phase adjustment ensures that the sinusoidal components do not combine in a way that causes large spikes. Instead, the phase variation results in a more uniformly distributed perturbation, ensuring that the multi-sine signal maintains a consistent amplitude over time rather than generating periodic peaks. This process helps to preserve the system's normal operation and ensures more reliable and accurate results during frequency-domain analysis.

3.2.3.3 Perturbation Magnitude

The magnitude⁹ of the injected signal must strike a balance:

- It needs to be large enough to generate a measurable response but small enough to keep the system within its normal operating range.
- This ensures accurate impedance calculations while avoiding nonlinear or unstable behaviour in the system.

3.2.3.4 Impedance Scan

Before performing the impedance scan, the IBR model must be connected to an ideal voltage source and successfully initialized to the specified operating point. A perturbation voltage source is then connected in series with the ideal voltage source and applied at the POI.

For IBR models, at each frequency, voltage perturbations $\Delta V(t)$ are applied at the selected frequency f and the mirror frequency f_m in separate tests. The corresponding current responses $\Delta i(t)$ is measured during each test to evaluate the system's behaviour at both frequencies.

Use the FFT or an alternative method to convert the time-domain signals $\Delta V(t)$ and $\Delta i(t)$ into their corresponding frequency-domain representations. These methods enable the accurate extraction of the magnitude and phase of the voltage and current signals of positive sequence and negative sequence directly from the time-domain data, ensuring precise frequency-domain analysis:

$$\Delta V^+(f) = FFT(\Delta V(t)) \quad \text{Eq.4}$$

$$\Delta I^+(f) = FFT(\Delta i(t)) \quad \text{Eq.5}$$

$$\Delta V^-(f_m) = FFT(\Delta V(t)) \quad \text{Eq.6}$$

$$\Delta I^-(f_m) = FFT(\Delta i(t)) \quad \text{Eq.7}$$

The admittances of an IBR model can be represented using the following equation:

⁹ It should be noted that small magnitudes of the perturbation (as a rule of thumb, less than 5 per cent) should be used to make sure that the devices stay within the linear operating ranges (i.e., to avoid nonlinearities).

$$\begin{bmatrix} \Delta I^+(f) \\ \Delta I^-(f_m) \end{bmatrix} = \begin{bmatrix} Y_{11}(f) & Y_{12}(f) \\ Y_{21}(f) & Y_{22}(f) \end{bmatrix} \begin{bmatrix} \Delta V^+(f) \\ \Delta V^-(f_m) \end{bmatrix}$$

3.2.3.5 Frequency Range and Precision

The scan typically covers a frequency range from 1 Hz to 119 Hz, although higher ranges, up to 1,000 Hz, may be used for broader analysis. Scanning in smaller subranges (e.g., 1-60 Hz, 61-119 Hz) helps avoid errors due to harmonic interference or sensitivity near the system's fundamental frequency (e.g., 60 Hz).

3.2.3.6 Sequence-Based Impedance Scanning

For three-phase power electronic systems, impedance can be calculated in different reference frames:

- **Sequence Variables:** Scanning can be done separately for positive, negative and zero sequence components, with independent perturbations applied to each
- **DQ Variables:** Scans can also be performed along the direct (D) and quadrature (Q) axes, commonly used in control systems

3.3 Data and Reporting

After completing the frequency scan and related measurements, a report including the following data will be prepared:

Impedance and Admittance Data

- **Frequency-Dependent Results:** For each frequency in the scan range, provide the calculated impedance
- **Real and Imaginary Components:** Present both the real (resistance) and imaginary (reactance) components of the impedance and admittance
 - This breakdown helps in identifying key system characteristics like resonances or potential instabilities
- **Magnitude and Phase:** Report the magnitude and phase angle for impedance and admittance at each frequency
 - This data is critical for evaluating system stability and dynamic responses

Impedance Plots

- **Impedance vs. Frequency:** include plots that show how the system impedance varies with frequency
 - These graphs should highlight peaks that indicate potential resonance points or regions of instability
- **Admittance vs. Frequency:** include plots for admittance to show how the system responds to changes in current with respect to voltage

- **Magnitude and Phase Plots:** Provide separate plots for the magnitude and phase of both impedance and admittance over the frequency range

Simulation and Test Data

The report should include a description of the simulation environment, system model and key parameters/settings, and any assumptions made during the frequency scan.

AESO may request the simulation models/files used for the frequency scan.

3.4 Frequency Scan Procedure of the Grid

The grid frequency scan is performed at POI to evaluate the grid's impedance within the frequency range of 1 to 119 Hz. This process is crucial for identifying potential resonance points and assessing the risk of instability, particularly in systems with IBRs that may exhibit negative damping, as indicated by the frequency scan results. Further details are provided in Section 4.

The same tool used for the frequency scan of IBRs will be utilized to generate sinusoidal voltage signals across the assigned frequency range. At each frequency, the corresponding current into the grid is measured at the POI. The procedure involves measuring the voltage perturbation and the resulting current at each frequency. The signals recorded in the time domain are converted to their frequency-domain representations using the FFT method. This allows for the calculation of grid impedance and admittance, which are key indicators of the system's stability and response at different frequencies. The impedance and admittance values provide insight into how the grid behaves dynamically and are critical for detecting potential sub-synchronous oscillations or other forms of instability.

Consideration of Series-Compensated Lines

In cases where a series-compensated transmission line is located near the POI, different levels of compensation must be considered.

Series compensation can significantly alter the grid's impedance and resonance characteristics. Thus, varying the compensation level (e.g., partial or full compensation) helps identify potential resonance or instability risks that may arise due to these changes in system impedance.¹⁰

3.5 Criteria for SSO Evaluation¹¹

The SSO risk evaluation process utilizes impedance and admittance data from the frequency scan to quantitatively assess system stability. This guideline adopts a well-established industry method

¹⁰ For further details, refer to AESO's guideline "Connection to Series Compensated Line."

¹¹ Formal impedance-based stability assessment is typically performed using established control-theoretic techniques, including the Nyquist stability criterion, generalized Nyquist methods, passivity-based approaches, and modal impedance analysis applied to the interaction between device and grid impedances. These methods enable a rigorous evaluation of

whereby the net impedance is determined by summing the harmonic impedances from both the network side and the generator side.

- **Net Reactance Zero-Crossing:** A zero-crossing in the net reactance curve indicates the emergence of a sub-synchronous mode, signaling a potential resonance condition
- **Net Resistance:** The net resistance reflects how the generator's control system influences sub-synchronous oscillations
 - Negative or low resistance suggests inadequate energy dissipation, which may lead to instability

This impedance-based scanning technique enables rapid analysis across various configurations, efficiently identifying cases with minimal risk of sub-synchronous interactions and thereby streamlining the screening process. By examining the combined impedance characteristics, engineers can swiftly detect potential instability risks and prioritize further detailed studies as needed.

3.6 Limitation

This stability evaluation method proposed in this guideline can also incorporate the positive and negative sequence coupling effects of nearby IBRs, provided that the grid model used for the frequency scan includes those IBRs. By capturing these coupling interactions, the method offers a more comprehensive view of the system's impedance characteristics. However, this approach has its limitations.

The dynamic frequency scan results are highly dependent on the operating points of IBRs. When multiple IBRs are near the scan point, each unit's operational state can significantly affect the frequency-dependent impedance. The vast number of possible operating combinations makes it impractical to consider every scenario, thereby limiting the method's ability to fully capture the complete range of system behaviour. This complexity underscores the need for complementary analyses to ensure robust stability evaluation in highly dynamic and interconnected grid environments.

3.7 Screening “B” Procedure for Electrical and Torsional Interactions Between Turbine-Generator Units and Series Compensated Lines

To identify potential electrical or torsional interactions between by series-compensated lines and turbine-generator units the passive frequency scanning method will be used as a screening

closed-loop stability and associated stability margins; however, they rely on well-defined impedance representations, consistent reference frames, and appropriate treatment of multi-input multi-output (MIMO) system dynamics. The approach adopted in this report represents a simplified and reduced form of the formal impedance-based framework and is intentionally applied as a screening-level assessment. Rather than conducting a full source-load stability analysis or applying formal stability criteria, the analysis focuses on qualitative frequency-domain indicators to identify potential interaction risks. This approach is intended to flag operating conditions that may warrant further detailed investigation, rather than to provide a definitive determination of small-signal stability.

approach. The following sections provide a detailed procedure and key considerations for performing this assessment. This approach identifies three distinct interactions:

- Induction generator effect (IGE) results from the apparent negative resistance characteristic of generators at frequencies below the system synchronous frequency
 - At a resonant electrical frequency defined by the combined inductance and capacitance characteristics of the system, this apparent negative resistance may exceed the network resistance
 - Such a condition will result in self-excitation of oscillatory currents at the natural frequency
- Torsional interaction (TI) may occur when the electrical resonant frequency driven by series compensated line is near the complement of a torsional resonant frequency of a turbine-generator torsional mode f_m (i.e., $f_n = f_0 - f_m$)
 - Under these conditions, a small voltage induced in the armature by rotor oscillation can result in a large sub-synchronous current
 - When the net circuit resistance is positive, this current will produce an oscillatory component of rotor torque which is phased to enhance the rotor oscillation
 - When this torque is larger than that resulting from mechanical damping, the coupled electro-mechanical system will experience growing oscillations
- Torque amplification (TA) analysis is the study of the response of turbine-generator shaft systems to large amplitude disturbances such as faults in the transmission system
 - When the transmission system contains series capacitors, the transient electrical torque may contain large amplitude frequency components close to resonant frequencies of the shaft system
 - This can result in high shaft torques which may seriously damage the turbine-generator unit

Passive frequency scanning is performed to determine the total impedance of the network seen from the neutral point of the turbine-generator stator circuit. This impedance data can estimate the damping in the electrical system to identify risk of IGE or TA interactions. If combined with damping data of the turbine-generator's mechanical system can determine the risk of TI interactions.

3.7.1 Test System Setup

The power flow base case with anticipated network topology based on the projected in-service data of the proposed project will be selected. This includes the positive sequence network data including transmission lines data, switched shunts, generators, etc. The network data (*.raw data file) in a positive sequence-based platform (e.g. PSS/E) will be converted to a time-domain simulation platform (i.e., PSCAD).

3.7.2 Data and Modeling Requirements

The following factors regarding the modeled network used to be frequency scanning should be considered:

- **Transmission Line Modeling:** If the frequency range of interest is limited to sub-synchronous frequencies, transmission lines can be represented using a lumped parameter model (e.g., PI sections)
 - However, for higher-frequency studies, frequency-dependent models are required
- **Series Capacitor Representation:** All series capacitors within a relevant electrical distance should be modeled without metal-oxide varistor (MOV) protection
- **Transformers Representation:** All transformers are represented by the leakage impedance between the two buses
- **Loads Representation:** The load characteristics (constant megavolt-amperes [MVA] or constant impedance) generally follow the representation used in power flow study
- **Network Reduction Approach:** For large systems, a reduced network model can be used to focus on the devices of interest
 - Given that this is an analytical method, a relatively large portion of the network can be retained in the reduced model, while the rest of the system is represented using static equivalents
 - It is crucial to validate the reduced model against the original system
 - If the full network is too large for frequency scanning, results from the reduced model should be compared against a model at least one level larger to ensure accuracy

In addition to electrical system representation, this assessment requires detailed turbine-generator data, including:

- Torsional modes of the mechanical system (or multi-mass shaft model)
- Fatigue life expenditure data (i.e., S-N curve)

As part of a turbine-generator purchase contract, manufacturers should provide a detailed spring-mass model, natural frequencies, mode shapes of the torsional system, generator electrical models, and fatigue life expenditure data for each shaft. These models can be used to develop rotor circuit representations or classical stability models for different frequency ranges.

3.7.3 Study Procedure

Once the model is setup, the frequency scanning is performed at selected buses in the network that turbine-generator units are connected to. The unit being investigated is represented by an induction generator equivalent at sub-synchronous frequencies.¹² The induction generator impedance of the machine can be represented approximately by a series combination of stator resistance, sub transient reactance, and effective rotor resistance divided by slip.

The frequency scanning for a broad range of network configuration (e.g., contingencies) and operating conditions (e.g., low and high system strength conditions) will be performed within the sub synchronous range (e.g., 5 Hz to 55 Hz). These following sensitivities should be considered:

¹² L. A. Kilgore, D. G. Ramey and M. C. Hall, "Simplified transmission and generation system analysis procedures for subsynchronous resonance problems," *IEEE Transactions on Power Apparatus and Systems*, Vols. PAS-96, no. 6, pp. 1840-1846, 1977.

- Switched shunt status
- Series capacitor staging/bypass status
- Status of nearby generators

3.8 Criteria for SSO Evaluation

The frequency scanning results will be used to screen out the SSO issues (e.g. TI, IGE, and TA).

- **“IGE” Risk Criteria:** if the impedance data shows a negative resistance (or impedance angle beyond ± 90 degrees) at a reactance crossover of zero ohms (or a dip or saddle point in the impedance magnitude) from negative to positive with increasing frequency, then the scenario is considered to have IGE vulnerability
 - This point relates to a resonance point
- **“TI” Risk Criteria:** The electrical damping of the resonance can be estimated from the value of the resistance at that frequency in the impedance characteristic
 - If the sum of electrical damping (De) plus mechanical damping (Dm) resulting in a negative value indicates TI vulnerability
 - Considering uncertainties associated with the mechanical mode, Dm at ± 1 Hz of the modal frequency is utilized to compare to De
- **“TA” Risk Criteria:** If impedance data shows a 5 per cent reactance dip occurring within a ± 3 Hz complement of the torsional mode frequency indicates a potential TA vulnerability

3.9 Data and Reporting

After completing the passive frequency scan, a report including the following data will be prepared:

Impedance Data

- **Frequency-Dependent Results:** For each frequency in the scan range, provide the calculated impedance
- **Real and Imaginary Components:** Present both the real (resistance) and imaginary (reactance) components of the impedance for all selected turbine-generator units and all studied scenarios
 - This breakdown helps in identifying key system characteristics like resonances or potential instabilities
- **Magnitude and Phase:** Report the magnitude and phase angle for impedance at each frequency for all the selected turbine-generator units and all the studied scenarios
 - This data is critical for evaluating system stability and dynamic responses

Impedance Plots

- **Impedance vs. Frequency:** include plots that show how the system impedance varies with frequency
 - These graphs should highlight peaks or dips that indicate potential resonance points or regions of instability

- **Magnitude and Phase Plots:** Provide separate plots for the magnitude and phase of impedance for all selected turbine-generator units and all the studied scenarios

Simulation and Test Data

The report should include a description of the simulation environment, system model, studied scenarios, contingencies, and any assumptions including sensitivity tests made during the frequency scan.

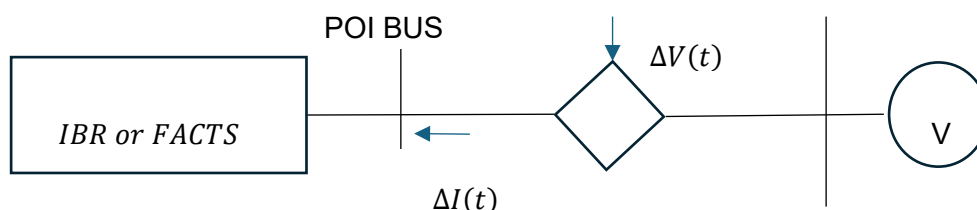
AESO may request the simulation models/files used for the frequency scan.

4. Frequency Scan Procedure of IBR or FACTS Model

4.1 Model Setup

The model will be scaled to its rated power and connected to the AC grid at the POI. An infinite voltage source will represent the AC system. A controllable voltage source will be placed in series with the AC source to generate the perturbation waveform during the frequency scan, allowing the system's impedance response across various frequencies to be analyzed. The model is initialized to the required operation point:

Figure 3: AC System Representation in the Frequency Scan



4.2 Y11 and Y21 Calculation

1. Injection of Voltage Perturbation:

Inject a three-phase positive sequence sinusoidal voltage perturbation at the POI of the device under test at chosen frequency f .

2. Frequency Domain Conversion:

Use the **Fast Fourier Transform (FFT)** or an equivalent method to extract the positive-sequence voltage $\Delta V^+(f)$ and current $\Delta I^+(f)$ components at f , and the negative sequence current $\Delta I^-(f_m)$ components at f_m ($f_m = f - 2f_0$ when $f < 2f_0$) or $\Delta I^+(-f_m)$ when $2f_0 < f$.

Please note that $\Delta I^-(f_m) = \Delta I^+(-f_m)$. This is because a negative frequency in the negative sequence corresponds to the mirrored positive frequency in the positive sequence.

3. Calculation of Y11 (f)

Use the following equation to get Y11(f):

$$Y_{11}(f) = \frac{\Delta I^+(f)}{\Delta V^+(f)} \quad \text{Eq.8}$$

4. Calculation of Y21 (f)

When $f < 2f_0$, the following equation is used to calculate the Y21(f):

$$Y_{21}(f) = \frac{\Delta I^+(2f_0 - f)}{\Delta V^+(f)} \quad \text{Eq.9}$$

When $f > 2f_0$, the following equation is used to calculate the Y21(f):

$$Y_{21}(f) = \frac{\Delta I^-(f_m)}{\Delta V^+(f)} \quad \text{Eq.10}$$

4.3 Y12 and Y22 Calculation

1. Injection of Voltage Perturbation:

Inject a three-phase positive sequence sinusoidal voltage perturbation at the POI of the device under test at chosen frequency $f_m = f - 2f_0$.

2. Frequency Domain Conversion:

Use the **Fast Fourier Transform (FFT)** or an equivalent method to extract the positive-sequence voltage $\Delta V^-(f_m)$, negative current $\Delta I^-(f_m)$ components at $f - 2f_0$ when $f > 2f_0$ or the positive sequence current $\Delta I^+(2f_0 - f)$ components at $2f_0 - f$ when $f < 2f_0$ and the positive sequence current $\Delta I^+(f)$ components at f .

3. Calculation of Y12 (f)

$$Y_{12}(f) = \frac{\Delta I^+(f)}{\Delta V^-(f_m)} \quad \text{Eq.11}$$

4. Calculation of Y22 (f)

When $f < 2f_0$, the following equation is used to calculate the Y22(f):

$$Y_{22}(f) = \frac{\Delta I^+(-f_m)}{\Delta V^-(f_m)} \quad \text{Eq.12}$$

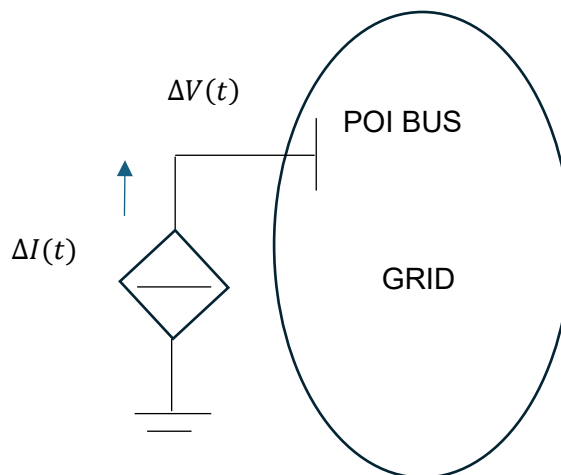
When $f > 2f_0$, the following equation is used to calculate the Y22(f):

$$Y_{22}(f) = \frac{\Delta I^-(f_m)}{\Delta V^-(f_m)} \quad \text{Eq.13}$$

5. Frequency Scan Procedure of Grid

5.1 Model Setup

The grid model is created in the EMT program. A controllable current source will be connected to the AC grid at the POI to generate the perturbation waveform during the frequency scan, allowing the system's impedance response across various frequencies to be analyzed.



5.2 Y11 and Y21 Calculation

1. Injection of Voltage Perturbation:

Inject a three-phase positive sequence sinusoidal current perturbation at the POI of the device under test at chosen frequency f .

2. Frequency Domain Conversion:

Use the **Fast Fourier Transform (FFT)** or an equivalent method to extract the positive-sequence voltage $\Delta V^+(f)$ and current $\Delta I^+(f)$ components at f , and the negative sequence current $\Delta I^-(f_m)$ components at $f_m = f - 2f_0$ or $\Delta I^+(-f_m)$ when $2f_0 < f$ $\Delta I^-(f_m) = \Delta I^+(-f_m)$

3. Calculation of Y11 (f)

Use the following equation to get Y11(f):

$$Y_{11}(f) = \frac{\Delta I^+(f)}{\Delta V^+(f)} \quad \text{Eq.14}$$

4. Calculation of Y21 (f)

When $f < 2f_0$, the following equation is used to calculate the Y21(f):

$$Y_{21}(f) = \frac{\Delta I^+(-f_m)}{\Delta V^+(f)} \quad \text{Eq.15}$$

When $f > 2f_0$, the following equation is used to calculate the Y21(f):

$$Y_{21}(f) = \frac{\Delta I^-(f_m)}{\Delta V^+(f)} \quad \text{Eq.16}$$

5.3 Y12 and Y22 Calculation

1. Injection of Voltage Perturbation:

Inject a three-phase positive sequence sinusoidal current perturbation at the POI of the device under test at chosen frequency $f_m = f - 2f_0$.

2. Frequency Domain Conversion:

Use the **Fast Fourier Transform (FFT)** or an equivalent method to extract the positive-sequence voltage $\Delta V^-(f_m)$, negative current $\Delta I^-(f_m)$ components at $f_m = f - 2f_0$ when $f > 2f_0$ or the positive sequence current $\Delta I^+(-f_m)$ components at $2f_0 - f$ when $f < 2f_0$ and the positive sequence current $\Delta I^+(f)$ components at f .

3. Calculation of Y12 (f)

$$Y_{12}(f) = \frac{\Delta I^+(f)}{\Delta V^-(f_m)} \quad \text{Eq.17}$$

4. Calculation of Y22 (f)

When $f < 2f_0$, the following equation is used to calculate the Y22(f):

$$Y_{22}(f) = \frac{\Delta I^+(-f_m)}{\Delta V^-(f_m)} \quad \text{Eq.18}$$

When $f > 2f_0$, the following equation is used to calculate the Y22(f):

$$Y_{22}(f) = \frac{\Delta I^-(f_m)}{\Delta V^-(f_m)} \quad \text{Eq.19}$$

6. Stability Evaluation Method

6.1 Combined Impedance Calculation

Assuming the following admittance matrix of an IBR plant at each frequency is acquired following the procedure listed in Section 4.:

$$Y_{IBR}(f) = \begin{bmatrix} Y_{IBR_{11}}(f) & Y_{IBR_{12}}(f) \\ Y_{IBR_{21}}(f) & Y_{IBR_{22}}(f) \end{bmatrix} \quad \text{Eq-20}$$

Assuming the following admittance matrix of the grid at each frequency is acquired following the procedure listed in Section 5:

$$Y_{GRID}(f) = \begin{bmatrix} Y_{GRID_{11}}(f) & Y_{GRID_{12}}(f) \\ Y_{GRID_{21}}(f) & Y_{GRID_{22}}(f) \end{bmatrix} \quad \text{Eq-21}$$

When the IBR plant connects to the grid, the system can be represented by the following admittance relationships (with the frequency variable f omitted for simplicity):

$$\begin{bmatrix} Y_{IBR_{11}} & Y_{IBR_{12}} \\ Y_{IBR_{21}} & Y_{IBR_{22}} \end{bmatrix} \begin{bmatrix} V^+ \\ V^- \end{bmatrix} = \begin{bmatrix} I_{IBR}^+ \\ I_{IBR}^- \end{bmatrix} \quad \text{Eq-23}$$

$$\begin{bmatrix} Y_{GRID_{11}} & Y_{GRID_{12}} \\ Y_{GRID_{21}} & Y_{GRID_{22}} \end{bmatrix} \begin{bmatrix} V^+ \\ V^- \end{bmatrix} = \begin{bmatrix} I_{GRID}^+ \\ I_{GRID}^- \end{bmatrix} \quad \text{Eq-24}$$

Where V^+ and V^- represent the positive sequence and coupled negative sequence voltages at the Point of Coupling (POC), respectively. I_{IBR}^+ is the positive sequence current into the IBR, I_{IBR}^- is the coupled negative sequence current into the IBR. I_{GRID}^+ is the positive sequence current into the grid, I_{GRID}^- is the coupled negative sequence current into the grid.

In the absence of a negative sequence voltage/current source, the following constraint must hold for the negative sequence currents:

$$I_{IBR}^- + I_{GRID}^- = 0 \quad \text{Eq-25}$$

Equation Eq.23 can be rewritten as follows:

$$I_{IBR}^+ = Y_{IBR_{11}} V^+ + Y_{IBR_{12}} V^- \quad \text{Eq-26a}$$

$$I_{IBR}^- = Y_{IBR_{21}} V^+ + Y_{IBR_{22}} V^- \quad \text{Eq-26b}$$

Equation Eq.24 can be rewritten as follows:

$$I_{GRID}^+ = Y_{GRID_{11}} V^+ + Y_{GRID_{12}} V^- \quad \text{Eq-27a}$$

$$I_{GRID}^- = Y_{GRID_{21}} V^+ + Y_{GRID_{22}} V^- \quad \text{Eq-27b}$$

Using the constraint (Eq.25) together with Equations (Eq-26b) and (Eq-27b):

$$Y_{IBR_{21}} V^+ + Y_{IBR_{22}} V^- + Y_{GRID_{21}} V^+ + Y_{GRID_{22}} V^- = 0 \quad \text{Eq-28}$$

Grouping the terms gives:

$$(Y_{IBR_{22}} + Y_{GRID_{22}})V^- = -(Y_{IBR_{21}} + Y_{GRID_{21}})V^+ \quad \text{Eq-29}$$

Thus, we can express V^- in terms of V^+ :

$$V^- = -\frac{Y_{IBR_{21}} + Y_{GRID_{21}}}{Y_{IBR_{22}} + Y_{GRID_{22}}} V^+ \quad \text{Eq-30}$$

Substitute this expression into the equation for the positive sequence current for the IBR:

$$I_{IBR}^+ = Y_{IBR_{11}} V^+ - Y_{IBR_{12}} \frac{Y_{IBR_{21}} + Y_{GRID_{21}}}{Y_{IBR_{22}} + Y_{GRID_{22}}} V^+ \quad \text{Eq-31}$$

This simplifies to:

$$I_{IBR}^+ = (Y_{IBR_{11}} - Y_{IBR_{12}} \frac{Y_{IBR_{21}} + Y_{GRID_{21}}}{Y_{IBR_{22}} + Y_{GRID_{22}}}) V^+ \quad \text{Eq-32}$$

The equivalent impedance of the IBR, accounting for the negative sequence effects, is given by:

$$Z_{IBR}(f) = \frac{V^+}{I_{IBR}^+} = \frac{1}{Y_{IBR_{11}} - Y_{IBR_{12}} \frac{Y_{IBR_{21}} + Y_{GRID_{21}}}{Y_{IBR_{22}} + Y_{GRID_{22}}}} \quad \text{Eq-33}$$

If the coupling effect in the grid is absent or can be ignored, then $Y_{GRID_{21}} = 0$. In this case, the equivalent impedance of the IBR becomes:

$$Z_{IBR}(f) = \frac{V^+}{I_{IBR}^+} = \frac{1}{Y_{IBR_{11}} - \frac{Y_{IBR_{12}} Y_{IBR_{21}}}{Y_{IBR_{22}} + Y_{GRID_{22}}}} \quad \text{Eq-34}$$

The impedance of the grid can be calculated as:

$$Z_{GRID}(f) = \frac{1}{Y_{GRID_{11}}(f)} \quad \text{Eq-35}$$

The sum of the impedance of the grid and the IBR – $Z_{equ}(f)$ is used to evaluation overall stability of the IBR and the grid at each frequency:

$$Z_{equ}(f) = Z_{GRID}(f) + Z_{IBR}(f) \quad \text{Eq-36}$$

Equation Eq-36 is primarily used to evaluate the positive sequence stability because most instabilities in power systems tend to manifest in the positive sequence. This is largely since the majority of the network dynamics, including voltage control and frequency regulation, are governed by the positive sequence components.

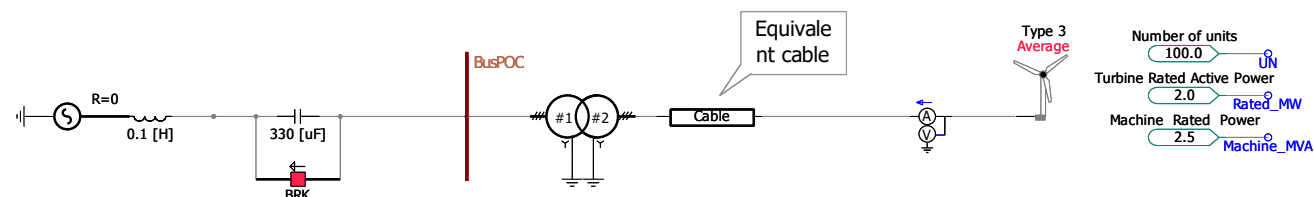
However, this method can be extended to the negative sequence as well. In cases where system unbalance is significant or when negative sequence coupling becomes non-negligible—such as in scenarios involving faults, asymmetrical loads, or specific inverter control dynamics—a similar approach can be adopted.

7. Example

7.1 Test Case

The average model of a generic type 3 wind turbine is used in Figure 4 as an example:

Figure 4: Generic Type 3 Wind Turbine Model



The AC system in the original model was removed and replaced with a modified AC system with selected parameters. This modified AC system exhibits a 20 Hz oscillation when connected to the POC (Point of Connection) bus of this 200 MW wind turbine model.

7.2 Dynamic Frequency Scan in the Screening Assessment “B”

In this stage, the EMT model meeting the AESO’s model requirement needs to be used to conduct the SSO screening assessment, which includes the following steps:

Step 1: Model setup for the dynamic frequency scan of the facility model

The model should accurately represent the electric and control system of the facility. The model should be initialized to steady-state operating points listed in Table 2. An infinite bus (voltage source at rate voltage with no impedance) is used to simulate the AC grid and a controllable voltage source is connected in series with the AC source to apply perturbations. In the frequency scan procedure, the perturbation signal is applied through the controllable voltage source.

Step 2: Y11 and Y21 Calculation

1. Voltage Perturbation Injection:

- Inject a positive-sequence sinusoidal voltage (i.e., $\sin(x)$ function) perturbation at the chosen frequency
(use $f=30\text{Hz}$ as an example)

2. Frequency Domain Conversion:

- Extract the following quantities:
 - Positive-sequence voltage at 30 Hz, $\Delta V^+(30\text{Hz}) = V_{30}^+ e^{j\theta_{30}^+}$
 - Positive-sequence current at 30 Hz, $\Delta I^+(30\text{Hz}) = I_{30}^+ e^{j\theta_{30}^+}$
 - Negative-sequence current at -90 Hz, $\Delta I^-(-90\text{Hz}) = I_{90}^+ e^{j(\pi-\theta_{90}^+)}$

3. Admittance Calculations:

- Calculate the following quantities:

- $Y_{11}(30 \text{ Hz}) = I_{30}^+ e^{j\theta_{30}^+} / V_{30}^+ e^{j\theta_{30}^+}$
- $Y_{21}(30 \text{ Hz}) = I_{90}^+ e^{j(\pi - \theta_{90}^+)} / V_{30}^+ e^{j\theta_{30}^+}$

Step 3: Y12 and Y22 Calculation

1. Voltage Perturbation Injection:

- Inject a negative-sequence sinusoidal voltage perturbation at the frequency of $f - 2f_0 = 30 - 120 = -90 \text{ Hz}$

2. Frequency Domain Conversion:

- Extract the following quantities:
 - Negative-sequence voltage at -90 Hz, $\Delta V^-(90 \text{ Hz}) = V_{90}^+ e^{j(\pi - \theta_{90}^+)}$
 - Positive-sequence current at 30 Hz, $\Delta I^+(30 \text{ Hz}) = I_{30}^+ e^{j\theta_{30}^+}$
 - Negative-sequence current at -90 Hz, $\Delta I^-(-90 \text{ Hz}) = I_{90}^+ e^{j(\pi - \theta_{90}^+)}$

3. Admittance Calculations:

- Calculate the following quantities:
 - $Y_{12}(30 \text{ Hz}) = I_{30}^+ e^{j\theta_{30}^+} / V_{90}^+ e^{j(\pi - \theta_{90}^+)}$
 - $Y_{22}(30 \text{ Hz}) = I_{90}^+ e^{j(\pi - \theta_{90}^+)} / V_{90}^+ e^{j(\pi - \theta_{90}^+)}$

The above steps 2 and 3 should be repeated for every frequency within the range of 1 Hz to 119 Hz to generate a comprehensive frequency-impedance profile. Table 2 shows the frequency scan result for the 200 MW type 3 wind farm model shown in Figure 4.

Step 4: Model setup for the Dynamic frequency scan of the AC system

In this step, the model setup is designed to perform a dynamic frequency scan of the AC system, ensuring an accurate assessment of the system's impedance behaviour across a specified frequency range. The objective is to capture detailed system dynamics. A controllable current source is incorporated at the point of connection (POC) bus to apply targeted perturbations to the system. This current source is used to simulate a wide range of scenarios and test conditions, enabling the evaluation of the AC system's response to inject current disturbances. The current perturbations are typically small to ensure the system remains within its normal operating range while still generating measurable results.

Step 5: $Y_{GRID_{11}}$ Calculation

1. Current Perturbation Injection:

- Inject a positive-sequence sinusoidal current perturbation at the chosen frequency (use $f=30 \text{ Hz}$ as an example)

2. Frequency Domain Conversion:

- Extract the following quantities:
 - Positive-sequence voltage at 30 Hz, $\Delta V^+(30 \text{ Hz}) = V_{30}^+ e^{j\theta_{30}^+}$

- Positive-sequence current into the grid at 30 Hz, $\Delta I^+(30 \text{ Hz}) = I_{30}^+ e^{j\theta_{30}^+}$

3. Admittance Calculations:

- Calculate the following quantities:
 - $Y_{GRID_{11}}(30 \text{ Hz}) = I_{30}^+ e^{j\theta_{30}^+} / V_{30}^+ e^{j\theta_{30}^+}$

Step 6: $Y_{GRID_{22}}$ Calculation

1. Current Perturbation Injection:

- Inject a negative-sequence sinusoidal current perturbation at the frequency of $f - 2f_0 = 30 - 120 = -90 \text{ Hz}$

2. Frequency Domain Conversion:

- Extract the following quantities:
 - Negative-sequence voltage at -90 Hz, $\Delta V^-(90 \text{ Hz}) = V_{90}^+ e^{j(\pi - \theta_{90}^+)}$
 - Negative-sequence current at -90 Hz, $\Delta I^-(-90 \text{ Hz}) = I_{90}^+ e^{j(\pi - \theta_{90}^+)}$

3. Admittance Calculations:

- Calculate the following quantities:
 - $Y_{GRID_{22}}(30 \text{ Hz}) = I_{90}^+ e^{j(\pi - \theta_{90}^+)} / V_{90}^+ e^{j(\pi - \theta_{90}^+)}$

The above steps 5 and 6 should be repeated for every frequency within the range of one Hz to 119 Hz to generate a comprehensive frequency-impedance profile. Figure 5 shows the frequency scan result for the AC system at the POC bus shown in Figure 4.

Step 7: $Z_{equ}(f)$ Calculation

1. $Z_{GRID}(f)$ calculation:

- Calculate the impedance of Z_{GRID} at each frequency using the following equation:
 - $Z_{GRID}(f) = \frac{1}{Y_{GRID_{11}}(f)}$

2. $Z_{IBR}(f)$ calculation:

- Calculate the equivalent impedance of the IBR/DER/plant at each frequency using the following equation:
 - $Z_{IBR}(f) = \frac{1}{Y_{IBR_{11}}(f) - \frac{Y_{IBR_{12}}(f) * Y_{IBR_{21}}(f)}{Y_{IBR_{22}}(f) + Y_{GRID_{22}}(f)}}$

3. $Z_{equ}(f)$ calculation:

- Calculate the sum of the impedance of the grid and the IBR/DER/Plant – $Z_{equ}(f)$ is used to evaluate the overall stability of the IBR and the grid at each frequency:
 - $Z_{equ}(f) = Z_{GRID}(f) + Z_{IBR}(f)$

Step 8: $Z_{equ}(f)$ Plot and SSO Risk Evaluation

The equivalent impedance $Z_{equ}(f)$ is represented in terms of its real and imaginary components, which correspond to resistance (R) and reactance (X), respectively. This representation provides a clearer understanding of the system's dynamic characteristics.

Steps for Plotting:

- Frequency Range:
 - Use a frequency range relevant to the study (e.g., one Hz to 119 Hz or broader, depending on the scope)
- Resistance (R):
 - Plot the real part of $Z_{equ}(f)$ (R) against the frequency
- Reactance (X):
 - Plot the imaginary part of $Z_{equ}(f)$ (X) against the frequency

Criteria to Evaluate Stability Based on R and X Behaviour

1. Key Indicators of Stability

The stability of the system can be evaluated by analyzing the resistance (R) and reactance (X) components of the equivalent impedance $Z_{equ}(f)$. The behaviour of R and X at critical frequencies to determine the likelihood of resonance or instability.

2. Criteria for Stability Assessment

Negative or Low Resistance (R):

- Description:
 - Resistance represents the system's ability to dissipate energy
 - A negative R-value indicates energy amplification instead of dissipation, which can lead to oscillatory growth
 - Low R values imply insufficient damping to mitigate oscillations
- Stability Implication:
 - Negative R: Indicates instability, as oscillations are likely to grow instead of being damped
 - Low R: Suggests the system is marginally stable, with a high risk of sustained oscillations if disturbed
- Actionable Insight:
 - Points with negative or small R should be flagged for detailed SSO study, such as retuning controls or enhancing system damping

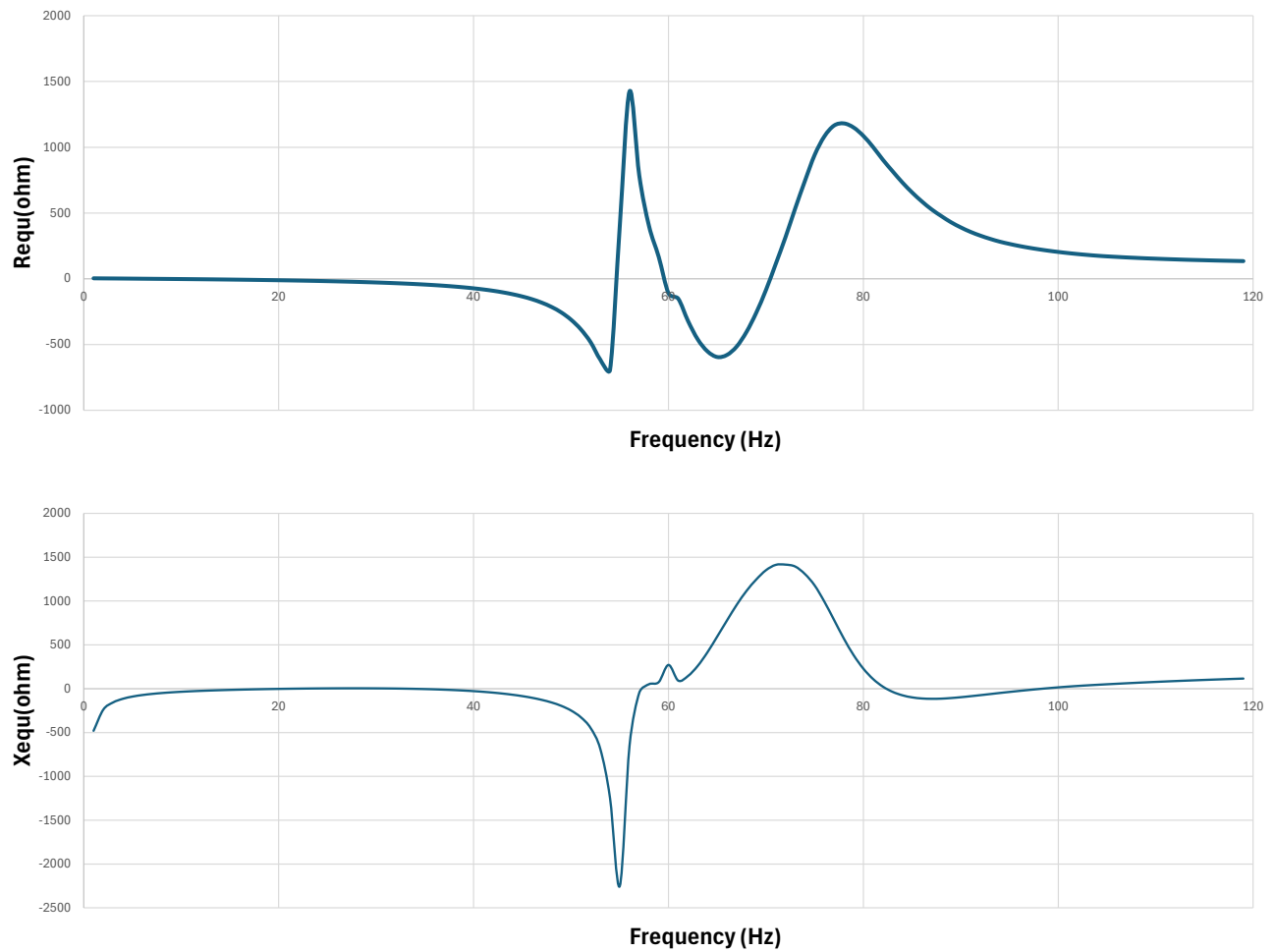
Crossings of Zero in Reactance (X):

- Description:
 - Reactance represents the system's reactive characteristics, and zero-crossings of X indicate resonance frequencies where inductive and capacitive effects balance
- Stability Implication:
 - At these frequencies, the system is highly sensitive to disturbances, increasing the risk of oscillations
 - The behaviour of R at these points becomes critical; low or negative R in combination with zero-crossing X amplifies the risk of resonance
- Actionable Insight:
 - Monitor all zero-crossings of X and evaluate R values at these frequencies to assess the risk of instability

By systematically applying these criteria to evaluate R and X across the frequency range, the system's stability can be effectively assessed, enabling identification of high-risk conditions and the implementation of targeted mitigation strategies. Table 4 lists the results of $Z_{\text{equ}}(f)$ of the test system shown in Figure 4.

To evaluate the overall stability of the AC system and the wind turbine model, the R (R_{equ} in the plot) and X (X_{equ}) of $Z_{\text{equ}}(f)$ are plotted as follows:

Figure 5: Plot of $Z_{\text{equ}}(f)$



The above plot shows the trace of Xequ has a zero-crossing point at 21Hz and 33Hz, at which the Requ has negative value. This is strong proof that shows this test system may have a SSO issue at this frequency. The EMT simulation results also show the test system has ~20Hz oscillation.

Table 2: The Frequency – Impedance (Magnitude and Angle) of the Wind Farm Model in the Test Case

Frequency	YM11	YA11	YM21	YA21	YM12	YA12	YM22	YA22
1	0.30527	-0.26638	0.00976	-2.83213	0.00035	0.19082	0.00706	0.32383
2	0.33209	-0.60017	0.01044	3.11631	0.00059	0.5361	0.00703	0.2991
3	0.3111	-0.91729	0.00963	2.80295	0.00098	0.37984	0.00699	0.27417
4	0.28079	-1.17704	0.00856	2.54769	0.00132	0.19333	0.00694	0.24907
5	0.24166	-1.39674	0.00726	2.33215	0.00169	0.01655	0.00688	0.2237
6	0.20837	-1.56114	0.00617	2.17088	0.00174	-0.12079	0.00682	0.19765
7	0.17917	-1.67665	0.00522	2.05703	0.00188	-0.21795	0.00675	0.1707
8	0.15702	-1.76173	0.00451	1.97167	0.00201	-0.29094	0.00666	0.14287
9	0.14026	-1.83056	0.00396	1.90017	0.00215	-0.35233	0.00657	0.11427
10	0.12719	-1.89133	0.00353	1.83367	0.00231	-0.40938	0.00646	0.08501
11	0.11664	-1.94815	0.00318	1.76732	0.00248	-0.46558	0.00635	0.05518
12	0.10784	-2.00291	0.00288	1.69832	0.00265	-0.52228	0.00621	0.0249
13	0.1003	-2.05641	0.00263	1.62496	0.00283	-0.57994	0.00607	-0.00576
14	0.09372	-2.10908	0.0024	1.5455	0.00301	-0.63865	0.00591	-0.03664
15	0.08791	-2.16125	0.0022	1.45821	0.0032	-0.6985	0.00575	-0.06762
16	0.08273	-2.21329	0.00201	1.36096	0.00339	-0.75962	0.00557	-0.09853
17	0.07806	-2.26564	0.00184	1.25124	0.00358	-0.82224	0.00537	-0.12917
18	0.07382	-2.31879	0.00169	1.12607	0.00378	-0.88664	0.00517	-0.15931
19	0.06993	-2.37322	0.00156	0.98222	0.00398	-0.95311	0.00496	-0.1887
20	0.06631	-2.42954	0.00146	0.81533	0.00418	-1.02198	0.00474	-0.21706
21	0.06291	-2.48758	0.00135	0.62673	0.00437	-1.09322	0.00451	-0.24402
22	0.05967	-2.54815	0.00129	0.413	0.00456	-1.16714	0.00427	-0.26931
23	0.05652	-2.61119	0.00126	0.17942	0.00474	-1.24362	0.00403	-0.29256
24	0.05343	-2.67669	0.00126	-0.06528	0.00491	-1.32248	0.00379	-0.31342
25	0.05037	-2.74447	0.0013	-0.3103	0.00505	-1.40339	0.00355	-0.33163
26	0.04731	-2.8142	0.00138	-0.5451	0.00517	-1.48585	0.00332	-0.34685
27	0.04425	-2.88542	0.00149	-0.76345	0.00527	-1.56924	0.00308	-0.35882
28	0.04119	-2.95751	0.00162	-0.9631	0.00534	-1.65282	0.00285	-0.36731
29	0.03814	-3.02981	0.00176	-1.14458	0.00537	-1.73577	0.00263	-0.37201
30	0.03512	-3.10158	0.0019	-1.30961	0.00537	-1.81724	0.00241	-0.37256

Frequency	YM11	YA11	YM21	YA21	YM12	YA12	YM22	YA22
31	0.03215	3.11104	0.00205	-1.46047	0.00534	-1.8964	0.0022	-0.36841
32	0.02927	3.04241	0.00219	-1.59886	0.00529	-1.97247	0.00199	-0.35876
33	0.02649	2.97632	0.00232	-1.72642	0.00521	-2.04478	0.0018	-0.34242
34	0.02386	2.91327	0.00244	-1.84442	0.0051	-2.11277	0.00161	-0.31775
35	0.02137	2.85369	0.00256	-1.95393	0.00499	-2.17603	0.00143	-0.28238
36	0.01905	2.79787	0.00266	-2.05585	0.00486	-2.23427	0.00126	-0.23316
37	0.0169	2.74606	0.00275	-2.15093	0.00473	-2.28735	0.0011	-0.16584
38	0.01492	2.69841	0.00282	-2.23985	0.0046	-2.33526	0.00096	-0.07499
39	0.01311	2.65503	0.00289	-2.32323	0.00448	-2.3781	0.00083	0.04556
40	0.01147	2.61601	0.00295	-2.40164	0.00435	-2.41607	0.00073	0.20113
41	0.00999	2.58139	0.003	-2.47561	0.00424	-2.44949	0.00066	0.3921
42	0.00866	2.55125	0.00304	-2.5456	0.00414	-2.47875	0.00062	0.60892
43	0.00746	2.52564	0.00307	-2.61207	0.00405	-2.50434	0.00061	0.8315
44	0.00638	2.50462	0.0031	-2.67543	0.00398	-2.52678	0.00063	1.03857
45	0.00543	2.48826	0.00312	-2.73608	0.00392	-2.54668	0.00067	1.21799
46	0.00458	2.47661	0.00313	-2.79438	0.00388	-2.56467	0.00073	1.3685
47	0.00382	2.46967	0.00313	-2.85066	0.00385	-2.58137	0.00079	1.49494
48	0.00315	2.46735	0.00313	-2.90528	0.00384	-2.59743	0.00086	1.60379
49	0.00255	2.4693	0.00312	-2.9586	0.00385	-2.61346	0.00092	1.70111
50	0.00201	2.47468	0.00309	-3.01098	0.00387	-2.63005	0.00099	1.79195
51	0.00153	2.48142	0.00306	-3.0629	0.00392	-2.64773	0.00107	1.88049
52	0.0011	2.48391	0.00301	-3.1149	0.00399	-2.66702	0.00115	1.97018
53	0.00069	2.46261	0.00294	3.11536	0.00409	-2.68841	0.00124	2.06399
54	0.00031	2.29409	0.00283	3.06006	0.00423	-2.71249	0.00135	2.1647
55	0.00017	0.32342	0.00268	2.99926	0.00443	-2.7402	0.00149	2.27553
56	0.00062	-0.14689	0.00245	2.92489	0.00474	-2.77353	0.00171	2.40175
57	0.00126	-0.17039	0.00206	2.80988	0.00525	-2.81718	0.00208	2.55176
58	0.0024	-0.14806	0.00126	2.48095	0.00626	-2.88461	0.00292	2.72594
59	0.00566	-0.18863	0.00199	0.12687	0.00924	-3.04419	0.00589	2.83165
60	0.00422	-2.57234	0.00422	-0.56172	0.00404	0.41452	0.00404	2.71953
61	0.00589	-2.83165	0.00924	3.04419	0.00199	-0.12687	0.00566	0.18863
62	0.00292	-2.72594	0.00626	2.88461	0.00126	-2.48095	0.0024	0.14806

Frequency	YM11	YA11	YM21	YA21	YM12	YA12	YM22	YA22
63	0.00208	-2.55176	0.00525	2.81718	0.00206	-2.80988	0.00126	0.17039
64	0.00171	-2.40175	0.00474	2.77353	0.00245	-2.92489	0.00062	0.1469
65	0.00149	-2.27553	0.00443	2.7402	0.00268	-2.99926	0.00017	-0.32342
66	0.00135	-2.1647	0.00423	2.71249	0.00283	-3.06006	0.00031	-2.29409
67	0.00124	-2.06399	0.00409	2.68841	0.00294	-3.11536	0.00069	-2.46261
68	0.00115	-1.97018	0.00399	2.66702	0.00301	3.1149	0.0011	-2.48391
69	0.00107	-1.88049	0.00392	2.64773	0.00306	3.0629	0.00153	-2.48142
70	0.00099	-1.79195	0.00387	2.63005	0.00309	3.01098	0.00201	-2.47468
71	0.00092	-1.70111	0.00385	2.61346	0.00312	2.9586	0.00255	-2.4693
72	0.00086	-1.60379	0.00384	2.59743	0.00313	2.90528	0.00315	-2.46735
73	0.00079	-1.49494	0.00385	2.58137	0.00313	2.85066	0.00382	-2.46967
74	0.00073	-1.3685	0.00388	2.56467	0.00313	2.79438	0.00458	-2.47661
75	0.00067	-1.21799	0.00392	2.54668	0.00312	2.73608	0.00543	-2.48826
76	0.00063	-1.03855	0.00398	2.52678	0.0031	2.67544	0.00638	-2.50462
77	0.00061	-0.8315	0.00405	2.50434	0.00307	2.61207	0.00746	-2.52564
78	0.00062	-0.60892	0.00414	2.47875	0.00304	2.5456	0.00866	-2.55125
79	0.00066	-0.3921	0.00424	2.44949	0.003	2.47561	0.00999	-2.58139
80	0.00073	-0.20113	0.00435	2.41607	0.00295	2.40164	0.01147	-2.61601
81	0.00083	-0.04556	0.00448	2.3781	0.00289	2.32323	0.01311	-2.65503
82	0.00096	0.07499	0.0046	2.33526	0.00282	2.23985	0.01492	-2.69841
83	0.0011	0.16584	0.00473	2.28735	0.00275	2.15093	0.0169	-2.74606
84	0.00126	0.23318	0.00486	2.23427	0.00266	2.05585	0.01905	-2.79787
85	0.00143	0.28238	0.00499	2.17603	0.00256	1.95393	0.02137	-2.85369
86	0.00161	0.31775	0.0051	2.11277	0.00244	1.84442	0.02386	-2.91327
87	0.0018	0.34242	0.00521	2.04478	0.00232	1.72642	0.02649	-2.97632
88	0.00199	0.35876	0.00529	1.97248	0.00219	1.59887	0.02927	-3.04241
89	0.0022	0.36841	0.00534	1.8964	0.00205	1.46047	0.03215	-3.11104
90	0.00241	0.37256	0.00537	1.81724	0.0019	1.30961	0.03512	3.10158
91	0.00263	0.37201	0.00537	1.73577	0.00176	1.14458	0.03814	3.02981
92	0.00285	0.36731	0.00534	1.65282	0.00162	0.96309	0.04119	2.95751
93	0.00308	0.35882	0.00527	1.56924	0.00149	0.76345	0.04425	2.88542
94	0.00332	0.34685	0.00517	1.48585	0.00138	0.5451	0.04731	2.8142

Frequency	YM11	YA11	YM21	YA21	YM12	YA12	YM22	YA22
95	0.00355	0.33163	0.00505	1.40339	0.0013	0.3103	0.05037	2.74447
96	0.00379	0.31346	0.00491	1.32248	0.00126	0.06537	0.05343	2.67669
97	0.00403	0.29256	0.00474	1.24362	0.00126	-0.17942	0.05652	2.61119
98	0.00427	0.26931	0.00456	1.16714	0.00129	-0.413	0.05967	2.54815
99	0.00451	0.24402	0.00437	1.09322	0.00135	-0.62673	0.06291	2.48758
100	0.00474	0.21703	0.00418	1.02182	0.00143	-0.81771	0.06632	2.42917
101	0.00496	0.1887	0.00398	0.95311	0.00156	-0.98222	0.06993	2.37322
102	0.00517	0.15931	0.00378	0.88664	0.00169	-1.12607	0.07382	2.31879
103	0.00537	0.12917	0.00358	0.82224	0.00184	-1.25124	0.07806	2.26564
104	0.00557	0.09853	0.00339	0.75961	0.00201	-1.36095	0.08273	2.21329
105	0.00575	0.06762	0.0032	0.6985	0.0022	-1.45821	0.08791	2.16125
106	0.00591	0.03664	0.00301	0.63865	0.0024	-1.5455	0.09372	2.10908
107	0.00607	0.00576	0.00283	0.57994	0.00263	-1.62496	0.1003	2.05641
108	0.00621	-0.02489	0.00265	0.52228	0.00288	-1.69838	0.10784	2.00291
109	0.00635	-0.05518	0.00248	0.46558	0.00318	-1.76732	0.11664	1.94815
110	0.00646	-0.08501	0.00231	0.40938	0.00353	-1.83367	0.12719	1.89133
111	0.00657	-0.11427	0.00215	0.35233	0.00396	-1.90017	0.14026	1.83056
112	0.00666	-0.14287	0.00201	0.29091	0.00451	-1.97168	0.15702	1.76173
113	0.00675	-0.1707	0.00188	0.21795	0.00522	-2.05703	0.17917	1.67665
114	0.00682	-0.19765	0.00174	0.12079	0.00617	-2.17088	0.20837	1.56114
115	0.00688	-0.2237	0.00169	-0.01478	0.00726	0.83022	0.24159	-1.72407
116	0.00694	-0.24907	0.00132	-0.19339	0.00856	-2.54769	0.28079	1.17704
117	0.00699	-0.27417	0.00098	-0.37984	0.00963	-2.80295	0.3111	0.91729
118	0.00703	-0.2991	0.00059	-0.5361	0.01044	-3.11631	0.33209	0.60017
119	0.00706	-0.32383	0.00035	-0.15872	0.00974	-0.27497	0.30466	-2.8407

Table 3: The Frequency – Impedance of the AC System in the Test Case

Frequency	YM11	YA11	YM21	YA21	YM12	YA12	YM22	YA22
1	0.00208	1.57079	0	1.50699	1.00E-05	1.60473	0.01414	1.57072
2	0.00417	1.5708	0	1.24038	0	1.55746	0.01427	1.57081
3	0.00629	1.5708	0	1.5358	0	1.55053	0.01441	1.57073
4	0.00847	1.5708	0	1.57356	0	1.6116	0.01455	1.57033
5	0.01072	1.5708	0	1.55158	3.00E-05	1.59158	0.01469	1.57091
6	0.01305	1.5708	0	1.64382	0	1.57433	0.01484	1.5709
7	0.0155	1.5708	0	1.4462	0	1.59118	0.01499	1.57095
8	0.0181	1.5708	0	1.66319	0	1.55779	0.01514	1.57096
9	0.02086	1.5708	0	1.69346	0	1.58207	0.01529	1.57079
10	0.02384	1.5708	0	1.47076	0	1.55897	0.01545	1.57071
11	0.02708	1.5708	0	1.61007	0	1.58233	0.01561	1.57075
12	0.03063	1.57079	0	1.5042	0	1.51128	0.01577	1.57064
13	0.03457	1.5708	0	1.67185	0	1.56525	0.01594	1.57094
14	0.03898	1.5708	0	1.54258	0	1.56311	0.01612	1.5709
15	0.044	1.5708	0	1.4988	0	1.543	0.01629	1.57097
16	0.04978	1.5708	0	1.63346	0	1.60294	0.01647	1.57122
17	0.05653	1.57081	0	1.67833	0	1.58066	0.01666	1.57091
18	0.06458	1.57078	0	1.51699	0	1.61083	0.01685	1.57094
19	0.07437	1.57078	0	1.57552	0	1.49295	0.01704	1.57071
20	0.0866	1.57106	0	1.64443	0	1.56849	0.01724	1.57082
21	0.10234	1.57086	0	1.77027	0	1.57772	0.01744	1.57068
22	0.12347	1.57085	0	1.56413	0	1.56413	0.01765	1.57069
23	0.15343	1.57081	0	1.59457	0	1.58016	0.01787	1.57086
24	0.19939	1.57103	0	1.67021	0	1.55376	0.01809	1.57054
25	0.27907	1.57094	0	1.52575	0	1.60076	0.01831	1.57056
26	0.45191	1.57139	0	1.57007	0	1.56741	0.01854	1.57064
27	1.11395	1.57145	0	1.54871	0	1.55892	0.01878	1.57077
28	2.7163	-1.56839	0	-1.51209	0	1.54647	0.01903	1.57045
29	0.6286	-1.57129	0	-1.57958	0	1.56804	0.01928	1.57069
30	0.36067	-1.56971	0	-2.43463	0	1.56537	0.01954	1.57074
31	0.25509	-1.57078	0	-1.57255	0	1.53239	0.0198	1.57079

Frequency	YM11	YA11	YM21	YA21	YM12	YA12	YM22	YA22
32	0.19865	-1.57033	0	-1.49139	0	1.61034	0.02008	1.57057
33	0.16341	-1.57071	0	-1.57604	0	1.56372	0.02036	1.57078
34	0.13932	-1.57068	0	-1.55561	0	1.54963	0.02065	1.57074
35	0.12177	-1.57091	0	-1.42533	0	1.56262	0.02095	1.57106
36	0.10845	-1.57035	0	-1.55631	0	1.46908	0.02126	1.57085
37	0.09792	-1.57057	0	-1.54213	0	1.56226	0.02158	1.57086
38	0.08941	-1.57078	0	-1.58619	0	1.59123	0.02191	1.57113
39	0.08239	-1.57072	0	-1.55135	0	1.57622	0.02225	1.57092
40	0.07648	-1.5708	0	0.85698	0	1.56188	0.0226	1.57155
41	0.07144	-1.57086	0	-1.56242	0	1.55952	0.02297	1.57088
42	0.0671	-1.57026	0	-1.60653	0	1.57533	0.02335	1.57084
43	0.06329	-1.57064	0	-1.57266	0	1.54984	0.02374	1.57069
44	0.05992	-1.57127	0	-1.33641	0	1.5368	0.02415	1.57081
45	0.05696	-1.57062	0	-1.57753	0	1.58193	0.02457	1.57127
46	0.05429	-1.57079	0	-1.51063	0	1.57915	0.02501	1.57077
47	0.0519	-1.57079	0	-1.56996	0	1.57058	0.02547	1.57071
48	0.04972	-1.57095	0	-1.5654	0	1.58111	0.02595	1.57079
49	0.04774	-1.57083	0	-1.62319	0	1.57863	0.02644	1.57084
50	0.04594	-1.5703	0	-1.56272	0	1.5701	0.02696	1.57009
51	0.04427	-1.57119	0	-1.56013	0	1.57502	0.0275	1.57076
52	0.04274	-1.5708	0	-1.96745	0	1.93793	0.02806	1.57147
53	0.04132	-1.57074	0	-1.56381	0	1.58911	0.02865	1.57102
54	0.04	-1.57079	0	-1.55991	0	1.58558	0.02927	1.5703
55	0.03878	-1.57024	0	-1.57399	0	1.56526	0.02993	1.57019
56	0.03764	-1.57034	0	-1.57657	0	1.56299	0.0306	1.57039
57	0.03656	-1.5706	0	-1.55345	0	1.56753	0.03132	1.57048
58	0.03556	-1.57031	0	-1.54983	0	1.57717	0.03208	1.57049
59	0.03461	-1.57047	0	-1.55249	0	1.59451	0.03287	1.57123
60	0.00735	-0.21976	0.00735	2.9256	0.00735	-0.22354	0.00735	2.92182
61	0.03287	-1.57123	0	-1.59452	0	1.55249	0.03461	1.57047
62	0.03208	-1.57049	0	-1.57717	0	1.54983	0.03556	1.57031
63	0.03132	-1.57048	0	-1.56753	0	1.55345	0.03656	1.5706

Frequency	YM11	YA11	YM21	YA21	YM12	YA12	YM22	YA22
64	0.0306	-1.57039	0	-1.56299	0	1.57657	0.03764	1.57034
65	0.02993	-1.57019	0	-1.56525	0	1.57399	0.03878	1.57024
66	0.02927	-1.5703	0	-1.58559	0	1.5599	0.04	1.57079
67	0.02865	-1.57102	0	-1.58911	0	1.5638	0.04132	1.57074
68	0.02806	-1.5708	0	-1.93726	0	1.96744	0.04274	1.57079
69	0.0275	-1.57076	0	-1.57501	0	1.55934	0.04428	1.5704
70	0.02696	-1.57149	0	-1.57151	0	1.56272	0.04594	1.5703
71	0.02644	-1.57084	0	-1.57863	0	1.62318	0.04774	1.57083
72	0.02595	-1.57079	0	-1.58111	0	1.5654	0.04972	1.57095
73	0.02547	-1.57071	0	-1.57058	0	1.56997	0.0519	1.57079
74	0.02501	-1.57077	0	-1.57915	0	1.51063	0.05429	1.57079
75	0.02458	-1.57032	0	-1.58097	0	1.57753	0.05696	1.57062
76	0.02415	-1.5708	0	-1.53679	0	1.33587	0.05994	1.57073
77	0.02374	-1.57069	0	-1.54984	0	1.57266	0.06329	1.57064
78	0.02335	-1.57084	0	-1.57533	0	1.6076	0.06708	1.57132
79	0.02297	-1.57088	0	-1.55951	0	1.56243	0.07144	1.57086
80	0.0226	-1.57155	0	-1.56188	0	-0.85699	0.07648	1.5708
81	0.02225	-1.57092	0	-1.57622	0	1.55135	0.08239	1.57072
82	0.02191	-1.57113	0	-1.59123	0	1.58619	0.08941	1.57078
83	0.02158	-1.57086	0	-1.56226	0	1.54214	0.09792	1.57057
84	0.02126	-1.57057	0	-1.4688	0	1.55675	0.10843	1.5708
85	0.02095	-1.57106	0	-1.56263	0	1.42536	0.12177	1.57091
86	0.02065	-1.57074	0	-1.54963	0	1.55561	0.13932	1.57068
87	0.02036	-1.57078	0	-1.56373	0	1.57604	0.16341	1.57071
88	0.02008	-1.57057	0	-1.61034	0	1.49139	0.19865	1.57033
89	0.0198	-1.57079	0	-1.53239	0	1.57255	0.25509	1.57078
90	0.01954	-1.57074	0	-1.56537	0	2.42833	0.36067	1.56971
91	0.01928	-1.57069	0	-1.56804	0	1.57958	0.6286	1.57129
92	0.01902	-1.57127	0	-1.54729	0	1.52303	2.70733	1.57933
93	0.01878	-1.57077	0	-1.55892	0	-1.5487	1.11395	-1.57145
94	0.01854	-1.57064	0	-1.5674	0	-1.57007	0.45191	-1.57139
95	0.01831	-1.57056	0	-1.60076	0	-1.52575	0.27907	-1.57094

Frequency	YM11	YA11	YM21	YA21	YM12	YA12	YM22	YA22
96	0.01809	-1.57054	0	-1.55376	0	-1.67021	0.19939	-1.57103
97	0.01787	-1.57086	0	-1.58016	0	-1.59454	0.15343	-1.57081
98	0.01765	-1.57069	0	-1.56413	0	-1.56412	0.12347	-1.57085
99	0.01744	-1.57068	0	-1.57771	0	-1.77027	0.10234	-1.57086
100	0.01724	-1.57107	0	-1.56874	0	-1.64398	0.08659	-1.57062
101	0.01704	-1.57071	0	-1.49297	0	-1.57553	0.07437	-1.57078
102	0.01685	-1.57094	0	-1.61083	0	-1.51699	0.06458	-1.57078
103	0.01666	-1.57091	0	-1.58066	0	-1.67832	0.05653	-1.57081
104	0.01647	-1.57122	0	-1.60294	0	-1.63344	0.04978	-1.5708
105	0.01629	-1.57097	0	-1.543	0	-1.4988	0.044	-1.5708
106	0.01612	-1.5709	0	-1.56311	0	-1.54255	0.03898	-1.5708
107	0.01594	-1.57094	0	-1.56525	0	-1.67184	0.03457	-1.5708
108	0.01577	-1.57102	0	-1.51166	0	-1.50423	0.03063	-1.57081
109	0.01561	-1.57075	0	-1.58233	0	-1.61008	0.02708	-1.5708
110	0.01545	-1.57071	0	-1.55897	0	-1.47077	0.02384	-1.5708
111	0.01529	-1.57079	0	-1.58208	0	-1.69346	0.02086	-1.5708
112	0.01514	-1.57096	0	-1.55779	0	-1.6632	0.0181	-1.5708
113	0.01499	-1.57095	0	-1.59118	0	-1.44622	0.0155	-1.5708
114	0.01484	-1.5709	0	-1.57433	0	-1.64381	0.01305	-1.5708
115	0.01469	-1.57091	3.00E-05	-1.59158	0	-1.5516	0.01072	-1.5708
116	0.01455	-1.57131	0	-1.61258	0	-1.57356	0.00847	-1.5708
117	0.01441	-1.57073	0	-1.55053	0	-1.5358	0.00629	-1.5708
118	0.01427	-1.57081	0	-1.55746	0	-1.24038	0.00417	-1.5708
119	0.01414	-1.57072	1.00E-05	-1.60473	0	-1.507	0.00208	-1.5708

Table 4: The Zequ(f) in the Test Cast

Frequency (HZ)	1	2	3	4	5	6	7	8	9	10
R(ohms)	3.161247	2.481383	1.949455	1.360127	0.708162	0.036799	-0.60116	-1.22221	-1.84721	-2.49592
X(ohms)	-479.907	-238.109	-156.434	-114.781	-89.2168	-71.84	-58.9795	-49.012	-41.0675	-34.507

Frequency (HZ)	11	12	13	14	15	16	17	18	19	20
R(ohms)	-3.18089	-3.90868	-4.68346	-5.50494	-6.3736	-7.28967	-8.2564	-9.27561	-10.3528	-11.5
X(ohms)	-28.9831	-24.2558	-20.1409	-16.5268	-13.3135	-10.4471	-7.8841	-5.58645	-3.53501	-1.712

Frequency (HZ)	21	22	23	24	25	26	27	28	29	30
R(ohms)	-12.7045	-13.9907	-15.3659	-16.8392	-18.418	-20.1225	-21.96	-23.9484	-26.1118	-28.4652
X(ohms)	-0.10622	1.284711	2.467977	3.440301	4.196379	4.731147	5.031019	5.081575	4.863934	4.351948

Frequency (HZ)	31	32	33	34	35	36	37	38	39	40
R(ohms)	-31.0541	-33.8878	-37.035	-40.5015	-44.388	-48.7333	-53.6487	-59.2521	-65.6655	-73.05
X(ohms)	3.521996	2.333796	0.746479	-1.28996	-3.82984	-6.9583	-10.7492	-15.324	-20.793	-27.314

Frequency (HZ)	41	42	43	44	45	46	47	48	49	50
R(ohms)	-81.6171	-91.6262	-103.573	-117.956	-135.046	-156.041	-182.21	-214.708	-256.384	-311.623
X(ohms)	-35.0551	-44.2518	-55.2572	-68.4779	-84.2203	-103.37	-127.113	-156.664	-195.162	-248.167

Frequency (HZ)	51	52	53	54	55	56	57	58	59	60
R(ohms)	-384.329	-481.929	-615.147	-693.707	398.8209	1424.296	785.6507	401.2851	165.5357	-110.119
X(ohms)	-324.707	-446.871	-685.861	-1247.53	-2251.27	-651.176	-46.299	51.50744	75.76926	271.6381

Frequency (HZ)	61	62	63	64	65	66	67	68	69	70
R(ohms)	-151.861	-320.514	-461.075	-552.439	-595.399	-579.643	-515.522	-405.195	-259.69	-86.2172
X(ohms)	92.41827	144.9714	260.5981	416.1047	595.4549	778.317	957.1565	1114.936	1245.166	1351.623

Frequency (HZ)	71	72	73	74	75	76	77	78	79	80
R(ohms)	111.3147	314.1323	533.9677	743.6033	941.5191	1082.862	1165.232	1181.259	1149.968	1086.138
X(ohms)	1412.478	1415.539	1393.903	1308.339	1177.929	992.3805	782.7657	571.0041	382.6883	228.6899

Frequency (HZ)	81	82	83	84	85	86	87	88	89	90
R(ohms)	1000.97	904.6504	817.1014	732.1092	655.9444	587.908	527.3515	476.3741	429.2654	390.1073
X(ohms)	110.1859	23.85759	-35.5807	-74.7195	-98.4851	-111.054	-114.774	-113.03	-106.012	-96.6381

Frequency (HZ)	91	92	93	94	95	96	97	98	99	100
R(ohms)	356.1137	327.824	303.2528	281.8213	264.5073	248.9977	235.5401	223.6983	213.0314	203.6343
X(ohms)	-85.2862	-73.3145	-60.8298	-48.2605	-36.4392	-24.8693	-13.824	-3.33011	6.57458	15.74782

Frequency (HZ)	101	102	103	104	105	106	107	108	109	110
R(ohms)	195.1949	187.6231	180.9971	174.9666	170.0654	165.997	162.01	158.5856	155.1573	152.4084
X(ohms)	24.21224	31.77785	38.5844	44.91729	50.90585	56.66957	62.32566	67.76451	72.96557	78.00436

Frequency (HZ)	111	112	113	114	115	116	117	118	119	
R(ohms)	149.5934	147.1573	144.6819	142.5962	140.7112	138.7851	137.1424	135.6001	134.0636	
X(ohms)	82.83997	87.48456	91.93068	96.26189	100.4788	104.4704	108.3718	112.1728	115.8129	

8. SSO Detailed Study

8.1 Methodology

In assessing and mitigating SSO, several analytical methods can be employed to identify potential risks and design appropriate countermeasures. These methodologies help to evaluate the stability of power systems, particularly as they integrate more renewable energy sources and series-compensated transmission lines.

Below is an overview of the commonly used methodologies used in SSO studies. However, this may not be comprehensive given that several methods are proposed and being used in industry to study SSO phenomena.

8.1.1 *Small Signal Stability/Eigenvalue Analysis*

Eigenvalue analysis is a traditional and widely used technique for assessing the small-signal stability of power systems. In this method, the dynamic equations governing the system are linearized around a specific operating point. By solving for the eigenvalues of the system matrix, engineers can assess the system's stability:

- Eigenvalues with negative real parts: Indicate stable modes where oscillations will naturally decay over time
- Eigenvalues with positive real parts: Indicate unstable modes where oscillations will grow, potentially leading to instability or system failure

Eigenvalue analysis is particularly effective in detecting sub-synchronous modes in power systems, especially in those with series compensation, where electrical and mechanical interactions may occur at frequencies below the nominal system frequency. By identifying these sub-synchronous modes, grid operators can predict potential SSO events and take preventive measures.

Limitations

While eigenvalue analysis is effective for small-signal stability studies, it has limitations in systems with significant non-linearities, such as those found in grids with high penetration of IBRs like wind and solar plants. In such systems, the complex non-linear behaviors introduced by power electronic converters and their control systems may not be fully captured by the linearization process used in eigenvalue analysis. This can result in an incomplete or inaccurate understanding. Additionally, small-signal modelling of IBRs presents challenges for original equipment manufacturers (OEMs). Accurately modelling the dynamic responses and control systems of IBRs often requires access to proprietary control algorithms. Due to concerns over intellectual property (IP), OEMs may not be willing to provide “open box” models that reveal the internal workings of their equipment. This lack of detailed information can further complicate eigenvalue analysis, as certain dynamic behavior. In cases where these non-linearities and proprietary limitations hinder effective analysis, complementary methods, such as EMT, are required to gain a more detailed understanding of system dynamics.

8.1.2 Detailed EMT Studies

EMT simulations are a powerful tool for modelling the detailed time-domain behavior of electrical systems. These simulations capture the fast, non-linear interactions between power system components, including the dynamics introduced by power electronic converters, series compensation and renewable energy sources.

EMT simulations are particularly effective for:

- **Capturing non-linearities:** Unlike eigenvalue or frequency-domain analyses, which may assume linearity, EMT simulations provide high-fidelity models that reflect the actual behaviour of non-linear components such as power electronic converters in wind and solar plants
- **Transient analysis:** These simulations help understand how the system behaves during and immediately after disturbances, such as faults, switching events, or sudden changes in generation or load
 - By modelling events in real-time, EMT simulations provide insights into the system's dynamic response and identify potential SSO events that may arise from specific operating conditions

EMT simulations are a crucial and definitive tool for analyzing complex power systems that incorporate significant renewable energy integration. These simulations allow engineers to study the detailed interactions between the mechanical and electrical components of the grid, enabling the identification of potential sub-synchronous oscillations. Additionally, EMT simulations are used to test and refine mitigation strategies, such as control system adjustments, to ensure system stability under various operating conditions.

8.2 Detailed EMT Studies Procedure and Mitigation

Given the limitations of the small signal stability study, the AESO requires an EMT study as an acceptable detailed study methodology to evaluate the risk of SSO if deems necessary.

8.2.1 EMT Model Requirement and Setup

To ensure consistency, accuracy, and high fidelity in EMT, all EMT models must strictly adhere to the comprehensive requirements outlined in the AESO Facility Modelling Data document. The reference¹³ presents requirements for model acceptance applicable to all IBR and high-voltage power electronic based equipment interfacing with the Alberta grid.

The data required to conduct these EMT studies, along with the parties responsible for providing it, are outlined in Table 5.

¹³ Facility Modelling Data and List of Electrical and Physical Parameters for Transmission System Model (2010-001R), <https://www.aeso.ca/assets/Information-Documents/2010-001R-Facility-Modelling-Data-2024-04-19.pdf>.

Table 5: Required Data for SSO Detailed EMT Studies

Data Requirement	Accountable to Provide	Comment
Facility Data		
IBR Models (if applicable)	GFO	Detailed, site-specific Power Systems Computer Aided Design (PSCAD) models reflecting IBR/Power Plant Control and protection algorithms
Voltage regulation device (e.g., STATCOM, SVC - if applicable)	TFO/AESO	Detailed, site-specific PSCAD models
Generator/Turbine Data (if applicable) Excitation Data (if applicable)	GFO	Detailed electrical dynamic data, mechanical data including multi-mass shaft data, shaft fatigue life expenditure curves (if available)
Control/Protection Settings	GFO	Specific control/protection settings with detailed instructions
Models of Nearby IBR Plants (if needed)	AESO	Required to account for potential control interactions with adjacent IBRs.
Network Data		
Compensated Transmission Lines	TFO/AESO	Detailed surge arrester data, bypass circuit details, and protection settings
FACTS Devices (e.g., STATCOM, SVC)	TFO/AESO	Detailed, site-specific models needed if such devices are in the study area
Protection System Data	TFO	Models of protection devices and relay settings for typical faults may be required in special cases
Transformer Data	TFO/AESO	Transformers with winding configuration, impedance data, saturation characteristic, and grounding data may be needed
Conductor Data and Tower/Pole Geometry	TFO	Detailed transmission line data is needed if a frequency-dependent line model is required in the EMT study

Data Requirement	Accountable to Provide	Comment
Power Flow and Dynamic Data	AESO	Large or reduced-scale network model, including impedance, load profiles and interconnection points

When setting up a full EMT model, it is essential to ensure that all critical components of the power system are accurately represented to capture the system's dynamic behaviour.

8.2.2 EMT Transient Simulation

This section outlines the step-by-step methodology for performing detailed EMT studies, from defining the study area and configuring the model to executing simulations and analyzing results.

Step 1: Identify the Study Area and List All Buses

- Define the geographical and electrical boundaries of the study area with a focus on regions with high IBR penetration, known stability issues, or points of interconnection prone to instability
- Include buses associated with:
 - IBR connections
 - Generator-turbine units (critical for SSTI studies)
 - HVDC links and FACTS devices
 - Compensated Transmission Lines (series capacitors)
- Document all buses, particularly those critical for dynamic analysis, as these will determine the configuration of internal and external network representations

Step 2: Define Internal Area and Detailed Modelling of Buses

- Identify the internal area where detailed modelling is essential
- Develop high-fidelity representations of components, including:
 - Generator-Turbine Systems: Include detailed shaft models that account for torsional modes, damping characteristics, and shaft dynamics critical for SSTI studies
 - IBRs: Incorporate site-specific models, including site-specific parameters for control systems, protection settings and fault ride-through (FRT) features
 - HVDC Systems: Model both line-commutated and VSC HVDC systems, ensuring accurate representation of control systems and interactions with nearby devices
 - FACTS Devices: Include STATCOMs, SVCs or other FACTS equipment, ensuring their control dynamics and interaction with the grid are captured
 - Transformers: Model detailed transformer saturation characteristics and their impact on transient and steady state behaviour
 - Transmission Lines: Use the frequency-dependent line model to accurately represent transient behaviours if possible

- For series-compensated lines, include detailed models of compensation levels (e.g., series capacitors with arresters and bypass logic) and their dynamic interactions, especially with generator-turbine and IBR systems
- Configure all control and protection schemes to reflect site-specific settings

Step 3: Representation of External Network

- Simplify the external network for computational efficiency while maintaining sufficient accuracy for boundary conditions:
 - Represent the external network as equivalent impedances or simplified models reasonably reflecting the primary characteristics of the grid

Step 4: Integration of IBR, Generator-Turbine, HVDC, FACTS, and large electronic-based load Models

- IBR Models:
 - site-specific models of the facility, ensuring they include detailed inner and outer control loops, protection systems and FRT capabilities
- Generator-Turbine Models:
 - Develop detailed shaft models to capture torsional dynamics for SSTI studies, including multiple masses and coupling spring-damping effects between shaft sections
 - Include excitation and governor systems to represent dynamic interactions during faults and disturbances
- HVDC Systems:
 - Integrate nearby HVDC links, ensuring accurate modelling of control systems, filters and their interactions with the AC network
- FACTS Devices:
 - Include models for devices like STATCOMs or SVCs in the study area, ensuring their dynamic response to system disturbances is represented
- Large electronic-based loads:
 - Include detailed models for large electronic-based loads like data centres ensuring accurate modeling of load profile, power electronic converter systems (e.g. UPS) with associated controls and protections
- Incorporate nearby IBRs, HVDC and FACTS systems in the model if they are electrically close to the study area to capture control and system-level interactions

Step 5: Model Initialization and Power Flow Check

- Initialize the model under steady-state conditions:
 - Verify that all voltage, frequency and power flow values align with expected operating conditions

- Ensure components, such as generator-turbine units, HVDC systems and FACTS devices, are operating within their specified limits
- Perform a flat run to establish a stable operating point and match the power flow result from other transient stability programs (e.g., PSS/E power flow case)

Step 6: Fault Setup and Simulation

- Configure fault/contingency/switching/operating mode change (e.g. power ramp) scenarios to test grid stability and the response of components like IBRs, generator-turbine systems, HVDC and FACTS devices:
 - Include the selected worst scenario where the SSO may occur
 - Define parameters such as fault type (e.g., single-line-to-ground, three-phase), location and duration
- Run transient simulations to assess:
 - Generator-turbine shaft torsional interactions
 - IBR responses, including control interactions and FRT performance
 - HVDC and FACTS device responses, focusing on their contributions to system stability

Step 7: Results Analysis

The final step in detailed EMT studies is to analyze the simulation results to assess grid stability. Review voltage and frequency stability during and after each fault scenario, noting any signs of instability, such as oscillations, voltage dips or frequency excursions. Identify interactions between different device's controls. Harmonic resonance or oscillatory behaviours should be flagged for further mitigation. Evaluate different devices FRT response to verify compliance with grid codes, ensuring that they remain connected and recover smoothly after disturbances. If harmonics or resonance issues are detected, perform additional harmonic analysis to determine the source and design solutions to mitigate their impact. Assess the performance of protection systems during faults, confirming that relays operate correctly, and protection devices are coordinated with nearby device's response characteristics. Based on the analysis, provide recommendations for any required adjustments to control settings, protection schemes or network reinforcements to ensure stable operation and minimize reliability risks.

- Review simulation results to evaluate:
 - SSTI/SSR Risks: Assess generator-turbine shaft torsional oscillations, damping levels and resonance conditions to ensure the oscillations are positively damped and the magnitude of the transient oscillations remain within the capability of the generator (e.g., generator shaft fatigue curve)
 - Control Interactions: Analyze interactions or poorly damped oscillations between IBRs, HVDC systems, and power electronic-based loads, and FACTS devices, particularly under weak grid conditions
 - Voltage and Frequency Stability: Monitor system behaviour during and after faults, noting any instability such as oscillations, voltage dips or frequency excursions

- Oscillatory interactions will not result in excessive electrical, thermal or mechanical stress on other existing facilities in the network, nor lead to protection misoperation, unintended control behaviour or forced disconnection
- Provide recommendations for:
 - Adjusting control settings (e.g., damping controllers or phase-locked loops [PLL] parameters)
 - Modifying protection schemes or improving coordination

8.2.3 *Reinforcing the Network to Enhance Stability SSO Mitigation*

If SSO risks are identified in the full EMT simulation, a range of mitigation methods can be applied to address these risks effectively. Each method aims to enhance the grid's stability by improving the damping of oscillations and preventing the propagation of SSO within the system. Below is an expanded explanation of potential mitigation approaches:

One key strategy is **tuning the inverter controls**. IBRs rely on control systems to regulate voltage, current, and frequency. By adjusting these controllers, especially the PLLs, current control loops and other control parameters, the system's response to sub-synchronous frequencies can be improved. Better-tuned controls will enhance the system's natural damping, reducing the likelihood of oscillations growing unchecked. In many cases, retuning these controllers involves modifying control loop gains and response times to ensure the inverter behaves more like a traditional synchronous machine with inherent damping characteristics.

Sub-synchronous damping controllers (SSDCs) are another effective tool for mitigating SSOs. These controllers are specifically designed to detect sub-synchronous oscillations and dynamically adjust the inverter's power output to counteract them. SSDCs continuously monitor the system for signs of oscillation and respond in real-time by applying corrective control actions. This proactive damping ensures that oscillations are suppressed before they can destabilize the system. SSDCs are particularly useful in weak grid conditions, where IBRs are more susceptible to SSO due to lower grid strength and insufficient natural damping from the network.

Grid-forming converters represent a more advanced and comprehensive solution. Unlike traditional grid-following inverters, which depend on the grid for synchronization, grid-forming converters establish their own voltage and frequency reference, making them more resilient to disturbances. These converters can provide synthetic inertia, mimicking the behaviour of conventional synchronous generators. Synthetic inertia is essential in stabilizing frequency fluctuations and providing a buffer against power imbalances that could lead to SSOs. Additionally, grid-forming converters can operate autonomously in weak grid conditions, maintaining stability even when system strength is low. By providing both inertia and voltage support, these converters help improve overall system damping and reduce the risk of SSO.

Synchronous condensers offer another effective approach by increasing the system's inertia and providing reactive power support. Synchronous condensers are rotating machines that do not generate real power but instead provide inertia and voltage stability, which is critical in reducing the likelihood of oscillations. In systems with high penetrations of IBRs and limited synchronous generation, the addition of synchronous condensers can help balance the grid and provide the necessary damping to suppress sub-synchronous resonances. Their ability to improve grid strength

makes them an asset in mitigating SSO, particularly in networks with significant renewable energy integration.

Modifying protection schemes is also a critical step in addressing SSOs. Protection systems, such as relays and fault-detection devices, can be configured to detect the early signs of sub-synchronous oscillations and initiate corrective actions, such as tripping problem-causing equipment or isolating faulted sections of the grid. By updating the settings of protection devices to recognize sub-synchronous frequencies, the grid can respond quickly to suppress oscillations before they become harmful. Protection schemes may also be integrated in damping control.

In addition to these methods, real-time monitoring and adaptive control strategies can be employed to continuously assess the system's health and prevent SSOs. Phasor measurement units (PMUs) and other monitoring tools can provide real-time data on grid conditions, allowing operators to detect oscillations early and adjust controls pre-emptively. Adaptive controls can dynamically change their settings in response to fluctuating grid conditions, offering a flexible and responsive solution to SSO risks.

By implementing these mitigation strategies, ranging from control tuning and damping controllers to grid-forming converters and advanced protection schemes, the grid can effectively manage and suppress SSOs. These measures ensure the system remains stable, even in the face of increasing integration of inverter-based resources and help prevent the damaging effects of SSOs on power system equipment and overall grid performance.

8.2.4 Study Outputs

Upon completion of the detailed EMT analysis, the MP should provide the following:

- Detailed study report, which at a minimum includes:
 - A thorough explanation of the study methodology and assumptions used in the assessment, including their justification
 - A detailed description of the simulation model scenarios and assumptions, models, and references to the simulation tools employed in the assessment, including PSCAD or other EMT tools, network topology, component models (e.g., inverter-based resources, synchronous machines, HVDC systems) and operating conditions considered
 - List of all data inputs, including detailed equipment parameters (transformer impedances, transformer saturation, inverter control settings, series compensation details, etc.) and external factors like network data representation and equivalencing assumptions
 - Tables, plots and summaries illustrating facility response, including time-domain simulation results for different disturbances and contingencies as per the study scope, and system behaviour under various operational conditions (e.g., fault ride-through performance, oscillation growth or decay)
 - Proposed mitigation actions (e.g., control setting adjustments, damping controllers, synchronous condensers) with an assessment of each option's effectiveness, including simulation results demonstrating the impact of mitigation measures on system stability

- Following the AESO's approval, the finalized report will be authenticated by a professional engineer registered, and in good standing, with the APEGA
- Full PSCAD case file(s) used in the EMT assessment, including all configurations, setup parameters, model versions and input data to facilitate validation and reproducibility of results

8.2.5 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: GRIP Overview

Introduction

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

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

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

Background and Purpose

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

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

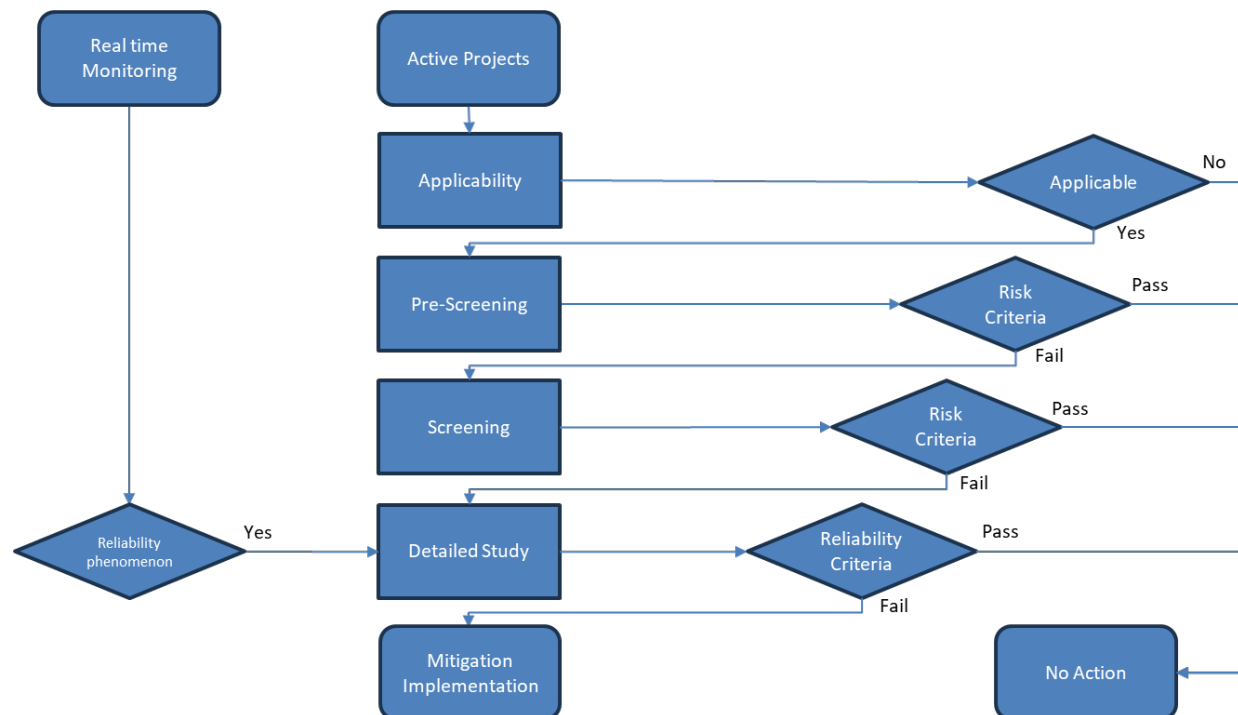
This guideline is not authoritative, for information purposes only and has been developed based on current industry practices.

AESO's Risk-Based Assessment Approach

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

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

Figure A1: Risk-Based Assessment Approach



The phases of this process occur at different points throughout the AESO's Connection Process. For topics related to AESO Authoritative Documents, MPs are responsible for completing applicability, pre-screening and screening steps independently, and are encouraged to use the approach and methodology outlined in this guideline. In all other cases, the AESO will conduct these initial steps. These steps will determine whether a facility requesting system access can be excluded from further analysis or requires further study as a high-risk project. Projects identified as

high risk will include a detailed study requirement in the project's functional specification. This guideline provides details on the recommended approach for conducting detailed studies. Upon receiving the detailed study, the AESO will work with MPs to review and comment on the report in accordance with this guideline. We may revise project's functional specification if the report results in changes to a project's scope of work.

Applicability

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

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

Pre-screening

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

Screening

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

Detailed Study, Report and Submission

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

Mitigation

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

As indicated above, a responsible entity has the option to skip the screening steps and proceed directly to the detailed study. Further, if the responsible entity is aware the detailed study will

indicate a reliability issue or potential non-compliance, the responsible entity may proceed with proposing a mitigation solution to the AESO.

Result Acceptance

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

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

Appendix B: Detailed Study Report Template

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

1.0 Title Page

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

2.0 Executive Summary

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

3.0 Table of Contents

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

4.0 Introduction/Objective

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

5.0 Methodology and Scenarios

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

6.0 Criteria (if applicable)

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

7.0 Inputs Data and Assumptions

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

8.0 Simulation Results Analysis

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

9.0 Mitigation/Correction Actions (if applicable)

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

10.0 Conclusion

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

11.0 References

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

12.0 Appendices

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

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