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System Strength
Assessment Guideline

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System Strength

Assessment Guideline

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Executive Summary

Purpose and Scope

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

- Addresses system strength–related reliability risks associated with the increasing penetration of inverter-based resources (IBRs), power electronic facilities (e.g. high voltage direct current [HVDC] and flexible alternating current transmission system [FACTS]), and changes in network configuration
- Defines a standardized, risk-based approach for assessing system strength, including assessment scope, 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 maintains adequate system strength and reliable system performance

Rationale

System strength is a fundamental characteristic of the power system that reflects the ability of the network to maintain stable voltage and frequency in response to disturbances.

- Declining system strength has become an increasing concern as synchronous generation is displaced by inverter-based resources, particularly in electrically weak areas of the AIES
- Insufficient system strength can result in poorly damped or sustained voltage and power oscillations, reduced fault ride-through capability, increased sensitivity to network changes and an increased risk of protection misoperation

These issues can adversely impact both the connecting facility and the surrounding network. A consistent framework is therefore required to identify system strength risks and ensure that facilities are capable of stable operation under weak grid conditions.

Performance Criteria

The following criteria apply to the system strength performance:

- The facility shall not excite interactions with the network or nearby facilities
- The facility shall demonstrate stable operation, absent of sustained or growing oscillations in voltage, frequency, active power or reactive power following disturbances
- Any oscillatory response following disturbance clearance, switching operations or network configuration changes shall exhibit positive damping

- Following any voltage or frequency disturbance for which the facility is expected to remain in service, the facility shall remain connected, shall not trip shall recover to stable operation following disturbance clearance

Application

For connection projects identified by the AESO as having elevated system strength risk, system strength requirements and associated technical assessments will be specified in the functional specification (FS). MPs must comply with the FS to meet with system strength performance criteria prior to connection.

MPs are expected to apply this guideline when conducting and submitting system strength assessments to the AESO and to implement any required mitigation measures to address identified system strength limitations.

1. System Strength Introduction

1.1 Background

System strength is an operational requirement new to the industry in Alberta. System strength is currently not included in any AESO Authoritative Documents. MPs projects that have been identified as high-risk through the applicability, pre-screening criteria or screening steps will be required to conduct detailed study and provide the AESO with evidence of meeting an operational requirement, which will be documented in a project's functional specification.

The strength of the power grid plays a crucial role in maintaining stability during minor disturbances, such as load variations or equipment switching. A strong grid provides a stable reference for connected resources, ensuring smooth operation. In contrast, a weak grid can pose difficulties, especially when integrating new energy sources like IBRs. These resources rely on adequate grid strength to synchronize effectively.

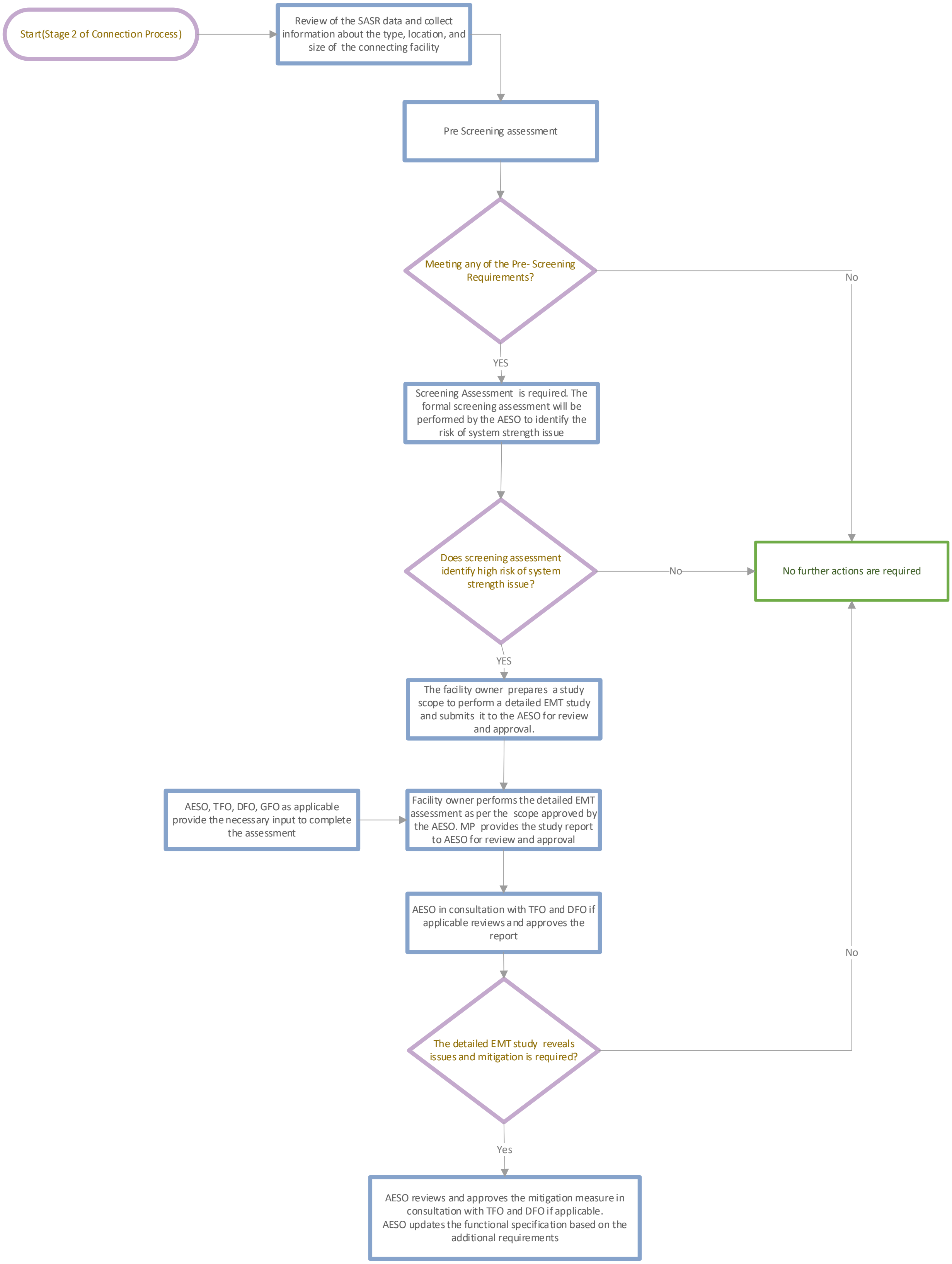
The shift from traditional synchronous generators to increased IBR penetration reduces grid strength and system inertia, posing significant challenges for operators. This decline in system stability functions provided by synchronous generators can lead to issues such as voltage fluctuations, frequency deviations and, in extreme cases, widespread blackouts. As a result, innovative strategies and technologies are needed to maintain grid stability and reliability.

The AESO developed this guideline to educate stakeholders about why system strength 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.

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

Based on the risk-based assessment approach described above, the AESO developed system strength risk-based assessment process flow as seen in Figure 1.

Figure 1: System Strength Risk Based Assessment Process



Review of the SASR data and collect information about the type, location, and size of the connecting facility

Screening Assessment is required. The formal screening assessment will be performed by the AESO to identify the risk of system strength issue

The facility owner prepares a study scope to perform a detailed EMT study and submits it to the AESO for review and approval.

AESO, TFO, DFO, GFO as applicable provide the necessary input to complete the assessment

Facility owner performs the detailed EMT assessment as per the scope approved by the AESO. MP provides the study report to AESO for review and approval

AESO in consultation with TFO and DFO if applicable reviews and approves the report

AESO reviews and approves the mitigation measure in consultation with TFO and DFO if applicable.
AESO updates the functional specification based on the additional requirements

1.2 Roles and Responsibilities

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

Table 1: RACI Chart for System Strength 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 screening assessment	A/R	I	I	I
Screening Assessment (Earliest Connection Process Stage: Stage 2)				
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 EMT simulation studies	A/R	I	I	I
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
Provide study data including modeling data and base cases**	A/R	R	R	R
Perform detailed EMT study based on the study scope provided and proposes mitigation if applicable	C	R	R	A/R
Result Acceptance and Mitigation Recommendation				

Deliverable	AESO	Transmission Facility Owner (TFO)*	Generation Facility Owner (GFO)*	Market Participant (MP)
(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
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 Table 2.

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

1.3 Applicability[1]

Projects that may be applicable to this guideline include:

- All power electronic based generating facilities, including aggregated generating facilities or energy storage resources that are directly connected to the transmission system, and those situated within an industrial complex directly connected to the transmission system.[2]
- All load facilities, including:
  - Facility connecting industrial load to the transmission system
  - Facility connecting distribution load to the transmission system
- All transmission facilities owned by the TFOs that:
  - Interfaced to the transmission system through power electronic converters (e.g., static synchronous compensator [STATCOM], HVDC or other FACTS devices)

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:

- Facility is connecting to areas in the system with a high density of IBR, (e.g., wind, solar or battery energy storage systems [BESS])
- Facility is connecting to an area in the system already identified as a weak area with lack of system strength
- Facility is connecting to the areas in the system where electrically is far from synchronous generators

1.5 Screening Assessment

The screening assessment is performed by the AESO as part of the connection studies in stage 2 of the AESO connection process to identify the risk of system strength shortfall and the reliability issues tied to it.

A structured approach to undertake system strength screening assessment, covering methodology, data requirements, step by step study procedure, study tools, etc. is provided in Section 2.

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[1] Identifying a project as applicable under this section does not automatically trigger a system strength 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.

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

1.6 Detailed Study

As outlined in AESO’s Risk-Based Assessment Approach in Section 3, the need for a detailed study for system strength 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 system strength 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 system strength study covering all necessary steps from data collection to mitigation strategies to ensure power system reliability is outlined in Section 3.

1.7 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 will review the study report within reasonable time and may provide comments on the report, requesting the MP to respond prior to accepting the report. We may revise the functional specification of the project according to the study result or proposed mitigation solution. Any delay on the study report submission may result in a delay of project energization.

1.8 Energization Requirements

The AESO authorizes the project to connect to the AIES and achieve energization when the project meets all 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. System Strength Screening Assessment

2.1 Methodology

2.1.1 Quantification Indices on Grid Strength

Identifying weak systems is crucial for the reliable planning and operation of the bulk power system (BPS) by pinpointing areas where weak grid issues may emerge. Weak grids present system-specific challenges, making it difficult to apply uniform interconnection standards or requirements in a fair and effective way. Therefore, it is often more practical for system planners to use specialized tools, techniques and approaches to identify weak grids and determine when further detailed analysis is necessary for specific interconnections or areas with high penetration of IBRs. Additionally, it is essential to recognize the system conditions that could lead to weak grid scenarios and associated issues.

The North America Reliability Corporation (NERC) has recommended several "indices" to quantify system strength.[3] These indices can serve as useful screening tools for identifying potential weak grid conditions.

Short Circuit Ratio (SCR):

The SCR is the most basic and widely used index to indicate the relative strength of a power system to a single power electronic device/plant at its connecting point. SCR is defined as the ratio of short-circuit capacity (SCMVA) during a three-phase fault at a specific point in the system to the power rating of the connected power electronic device/plant.

$$SCR = \frac{SCMVA}{P_{rated}}$$

where $SCMVA$ is the short circuit capacity at the connecting bus and P_{rated} is the rated power of power electronic facility.

A higher SCR indicates a stronger grid with more capacity to handle fluctuations in power injection from IBR, meaning the system is less sensitive to changes in power output. Conversely, a low SCR implies a weaker grid, where even small disturbances might lead to voltage instability or other operational issues.

The traditional SCR, as previously defined, becomes less effective for assessing grid strength when multiple IBR are located in close electrical proximity. In such cases, using SCR alone can result in overly optimistic evaluations of system strength. To address this, several alternative methods have been developed to better estimate grid strength when groups of IBR are interconnected. A brief overview of these methods is provided below, with more detailed examples available in the International Council on Large Electric Systems (CIGRE) technical brochure.[4]

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[3] NERC, Integrating Inverter-Based Resources into Low Short Circuit Strength Systems Reliability Guideline, December 2017

[4] WG B4.62, "Connection of Wind Farms to Weak AC Networks," Cigré Technical Brochure 671, December 2016.

Weighted Short Circuit Ratio (WSCR):

WSCR is proposed to address the limitation of the SCR on screening the power system strength to multiple IBRs in the study region. WSCR is defined as:

$$WSCR = \frac{\sum_{i=1}^{N}(SCMVA_i \times Pr_i)}{\left(\sum_{i=1}^{N} Pr_i\right)^2}$$

where $SCMVA_i$ is the short-circuit capacity at bus i, excluding current contributions from non-synchronous generation. Pr_i is the MW rating of non-synchronous generation connected at bus i. N is the number of IBR in the study region and i represents the wind plant index.

WSCR provides a weighted estimate of system strength for regions with multiple interacting IBR.

Composite Short Circuit Ratio (CSCR):

The index CSCR calculates aggregated network impedance at a common medium voltage bus which all the IBRs connect to. The ratio of the short-circuit capacity $CSCMVA$ and the total rating of the IBRs considered is defined as CSCR:

$$CSCR = \frac{CSCMVA}{\sum_{i=1}^{N} Pr_i}$$

Where Pr_i s the MW output of non-synchronous generation connected at bus i. N is the number of IBR in the study region and i represents the IBR index.

Multi-Infeed Short Circuit Ratio (MISCR):

The was proposed as an extension of the traditional SCR for systems with multiple converters. It accounts for the interactions between a specific converter and other nearby converters, analogous to how SCR functions in single-infeed systems. The MISCR helps assess system strength in multi-infeed converter environments.

The index MISCR is empirically defined by the following equation:

$$MISCR_i = \frac{SCMVA_i}{Pr_i + \sum_{i=1\&j\neq i}^{n} (MIIF_{ji} \cdot Pr_j)}$$

where n is the total number of the IBRs in the study region.

The multi-infeed interaction factor (MIIF) is used quantify the voltage interaction between two inverter ac buses and is defined as in (2). $MIIF_{ij}$ is the limiting ratio of voltage change ΔV_i at bus *I* caused by a small voltage change ΔV_j on bus *j*. On a simulator, or in actual networks, the voltage on bus *j* can be perturbed by a small amount with the application of a small inductive fault and the voltage at bus *i* can be measured to yield the MIIF value.

$$MIIF_{ij} = \frac{\partial V_i}{\partial V_j} \approx \frac{\Delta V_i}{\Delta V_j}$$

2.2 Recommended Tools for Screening Assessment

Power System Simulation for Engineering (PSS/E) is recommended for initial SCR screening across the grid, though it is not the only option. Other transient stability (TS) tools can also be utilized for short-circuit current calculations at points of interest.

PSS/E or other TS tools should used for the following tasks:

- **Short Circuit Calculations:** Quickly calculates short circuit currents at select key buses, crucial for determining system strength
- **Power Flow Analysis:** Simulates different load conditions (e.g., light and heavy loads) to understand their effects on SCR values and grid stability
- **Screening Assessment:** Conducts grid-wide SCR scans to highlight weak grid areas in need of more detailed study

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

2.3 Screening Assessment Methodology to Identify System Strength Shortfall Risks

2.3.1 Assumptions

To perform a consistent and realistic assessment of system strength and evaluate system strength shortfall risks effectively, the following assumptions and considerations should be noted:

- **Maximum IBR Penetration:** the operating condition corresponding to maximum penetration level from IBRs should be considered
  - This condition typically represents the grid's weakest possible state, where the share of generation supplied by conventional generators is minimized
  - Given this scenario corresponds to the lowest number of conventional generators, it represents the reduced system strength due to the low inertia and fault current contributions from conventional generators
- **IBR Contribution to Short Circuit Levels:** Short circuit contributions from IBRs are ignored in this assessment to represent a conservative, worst-case scenario
  - This approach helps identify areas that could pose risks even without IBRs' short-circuit support.
- **Focus on Localized Weakness:** This analysis is concentrated in areas with potential IBR clusters or critical network points where contingencies might exacerbate weak conditions, allowing for more accurate flagging of weak points
- **List of Contingencies:** A comprehensive list of N-1 and key N-1-1 contingencies in the study area is developed to model common disturbances, such as the loss of a transmission line or a generator, that could weaken the grid

  - These contingencies help simulate conditions where the grid's resilience is tested under real-world fault scenarios
- **Critical Buses:** Only certain buses in the targeted area are evaluated for system strength, with a focus on those most relevant to IBR connections or grid stability
  - This targeted selection improves the efficiency of the assessment by concentrating on the most impactful points within the network
- **WSCR:** In the WSCR calculation, the focus is on multiple IBRs in the study area
  - The electrical distance between the key bus—the primary high-voltage (HV) bus connecting all IBR points of interconnection (POI) in the study area—and each individual IBR's POI is critical to determine which IBRs need to be included in this study group
  - The transfer path flow should also be considered when determining the group of IBRs
  - This approach offers a conservative view, focusing on the aggregated impact of multiple IBRs on the key bus, which can help in identifying worst-case region from grid stability perspective driven by lack of system strength
- **WSCR Threshold:** A predefined WSCR threshold is set as a benchmark to flag study regions that need further detailed studies
  - If WSCR falls below this threshold, it indicates a higher risk of instability that warrants further examination

2.3.2 Study Procedures

To accurately assess system strength in grids with high penetration of IBRs, a structured approach based on WSCR, and contingency analysis is essential. This method identifies potential weak points and examines how the system performs under various fault scenarios, particularly in regions where synchronous generation is minimized.

Step 1: Obtain Power Flow and Dynamic Data Provided in " .raw " and " .dyr " Format

The assessment begins by collecting comprehensive data in " .raw" and ".dyr" formats. The .raw files should represent both light and peak load conditions with high IBR penetration, reflecting scenarios where the system is most vulnerable. Light load scenarios are critical as they typically include synchronous generator support, revealing potential system weaknesses. The ".dyr" files contain the dynamic models for key components, including conventional generators and control elements associated with IBRs, ensuring the analysis can account for transient behaviour.

Step 2: Define Study Area and Select Critical Buses

The study area is chosen based on regions with significant IBR integration or known weak grid characteristics. Within this area, certain buses are selected for detailed analysis. These buses are strategically important as they represent critical points where IBRs or power electronic based facilities are connected or where the system strength might be compromised due to distance from synchronous sources. Focusing on these critical buses allows for a targeted and efficient assessment of system stability.

Step 3: Create Contingency List

A list of N-1 and key N-1-1 contingencies is developed to simulate common single-component failures, such as line outages, transformer trips, or generator shutdowns. Each contingency is selected based on its potential impact on system strength. For example, the loss of a critical transmission line or generator could significantly weaken system resilience, making it important to assess how these events affect the WSCR at key buses.

Step 4: Switch Off IBRs or Power Electronic Based Facilities in the Power Flow Case (i.e., .raw File) for Short Circuit Scan

For an accurate assessment of the underlying grid strength, fault contributions by these facilities are ignored by switching off these facilities models in the power flow case. This step simulates a worst-case scenario by focusing on the system's natural short circuit capacity, provided mainly by synchronous generators. Ignoring short circuit contributions from these facilities reveals any areas that may be overly reliant on these facilities for stability, highlighting weak spots that might not be apparent if their contributions were included.

Step 5: Calculate WSCR for the Contingencies

The WSCR is calculated for each key bus under the N-1 and N-1-1 contingencies identified in Step 3. The calculation follows the method described in Section 2.1.

Step 6: Sort WSCR Results and Flag Low-Threshold Cases

After calculating WSCR values for each contingency, the results are sorted from lowest to highest. This sorting highlights cases where system strength is especially low. A predefined threshold is applied to flag cases that fall below acceptable WSCR levels, typically around 3.0 or lower. These flagged cases represent scenarios where the system may struggle to maintain stability, indicating the need for further investigation (i.e., detailed EMT studies) and potential intervention.

2.3.3 Threshold WSCR

The WSCR is an essential metric for determining grid strength and identifying when detailed EMT studies are necessary.

WSCR Above 3 (Strong Grid): A WSCR above 3 indicates a robust grid with sufficient short circuit capacity, meaning it can generally support high levels of IBR penetration with minimal risk of instability. Under these conditions, the grid is stable against voltage and frequency fluctuations and EMT studies are typically not required unless unusual risk factors are present.

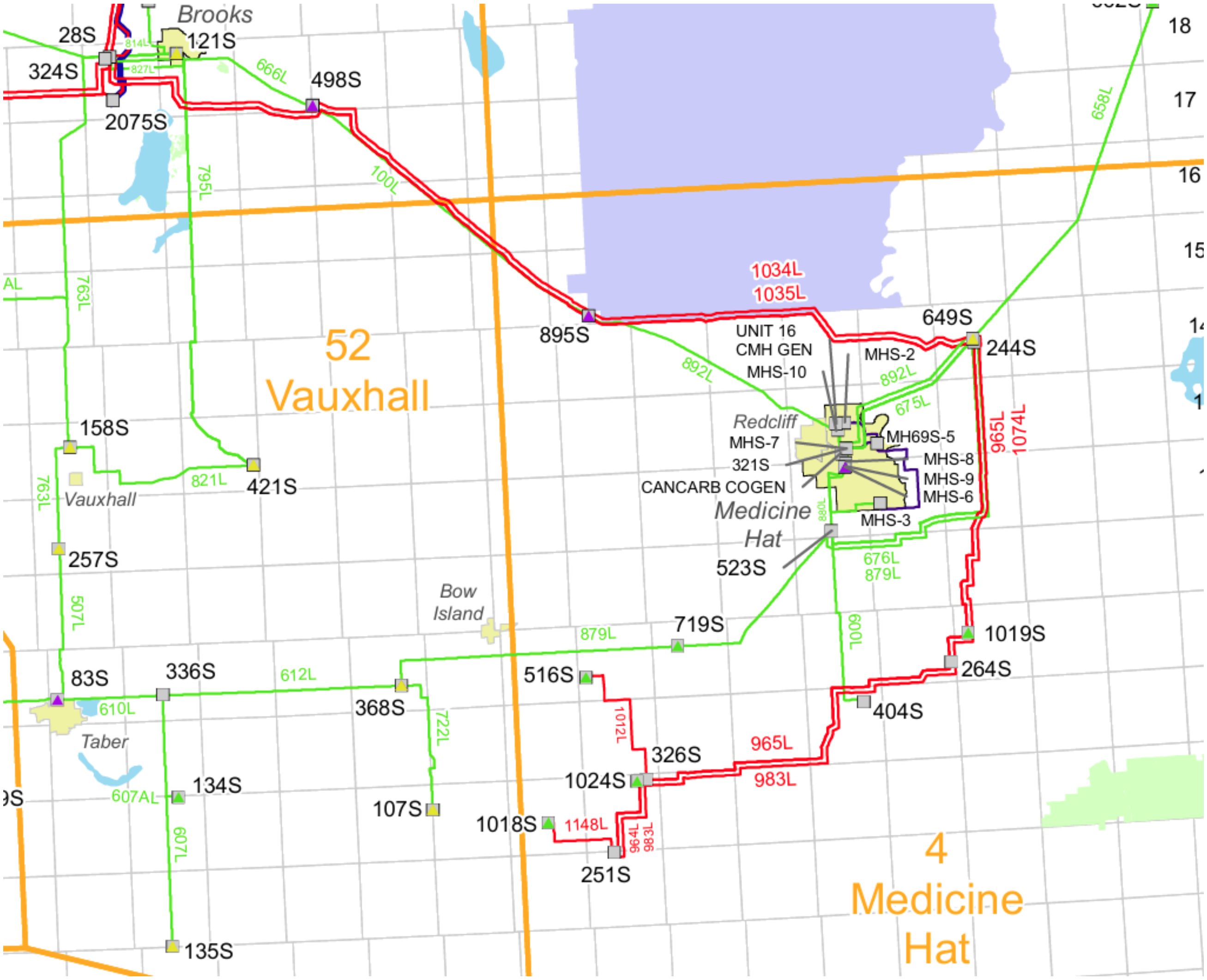
WSCR Below 3 (Marginal to Weak Grid): A WSCR below 3 suggests increasing sensitivity to IBR power variations, with stability risks that grow as the WSCR decreases. For grids with WSCR close to 3, periodic stability assessments may suffice. However, as WSCR values decline further, particularly below 2.5, the grid becomes more prone to voltage and frequency instability and detailed EMT studies become essential to evaluate system resilience under disturbances.

This WSCR threshold of 3 helps prioritize stability measures and determine when EMT studies are necessary, supporting reliable grid operation as IBR penetration increases.

2.4 Example of WSCR Calculation

This example illustrates WSCR calculation procedure as described in the Study Procedures section. This study uses Bowmanton region as an example.

Figure 2: AC System Representation in the SCR Test



Step 1: Obtain Power Flow and Dynamic Data Provided in ".raw" and ".dyr" Format

In this step, it is assumed that the ".raw" and ".dyr" data files have been collected and ready to be used.

Step 2: Obtain Study Area and Select Key Buses

In this example, the selected study area is Area 4 – Medicine Hat and the selected key bus is the 240 kV bus at Bowmanton 244s. The following IBRs are grouped for WSCR calculation:

- I-1019S Woolchester (P2122)
- 264S Elkwater (Wild Rose)
- I-516S Forty Mile
- I-1024S Granlea
- 1018S Shamrock

Step 3: Create Contingency List

The selected N-1 contingency at the vicinity of Bowmanton 244S is listed below.

Ctg No.	Description
1	1034L (Bowmanton 244s – Cassils 324S)
2	1035L (Bowmanton 244S – Newell 2075S)
3	965L (Bowmanton 244S – Murray Lake 326S)
4	1074L (Bowmanton 244S – Elkwater 264S)

Step 4: Disable IBRs in ".raw" File for Short Circuit Scan

This step can be combined with Step 5 below to calculate the short circuit capacity for each individual IBR.

Step 5:

This step is to calculate the WSCR for each N-1 contingency using the equation below. The results are summarized in the next step.

$$WSCR = \frac{\sum_{i=1}^{N}(SCMVA_i \times Pr_i)}{\left(\sum_{i=1}^{N} Pr_i\right)^2}$$

Where $SCMVA_i$ is the short-circuit capacity at bus i, excluding current contributions from non-synchronous generation. Pr_i is the MW rating of non-synchronous generation connected at bus i. N is the number of IBR in the study region and i represents the wind plant index.

IBRs	Pr (MW)	SCMVA				
		Normal (N-0)	Ctg. 1	Ctg. 2	Ctg. 3	Ctg. 4
1019S Woolchester (P2122)	247.2	1590.3	1221.0	1217.8	1483.6	669.9
Wild Rose	192	1541.1	1191.5	1188.5	1412.1	686.2
Shamrock	406.8	1209.9	982.1	979.8	866.6	865.9
Forty Mile	415.3	1113.9	917.7	915.7	763.6	868.8
Granlea	475	1321.4	1054.5	1052.0	861.9	983.2

Note: N-0 condition is also calculated for reference.

Step 6: Sort WSCR Results and Flag Low-Threshold Cases

The WSCR results are sorted and flagged in this step. The results indicate that under normal operating conditions (N-0), the calculated WSCR is higher than the weak system threshold of 3.0. Under any of the N-1 conditions, the calculated WSCR is lower than 3.0. In other words, all these N-1 contingencies need further investigation (i.e., detailed EMT studies).

Ctg. No.	Description	WSCR	Lower Than Threshold (<=3)
1	1034L (Bowmanton 244s – Cassils 324S)	2.74	Yes
2	1035L (Bowmanton 244S – Newell 2075S_	2.73	Yes
3	965L (Bowmanton 244S – Murray Lake 326S)	2.60	Yes
4	1074L (Bowmanton 244S – Elkwater 264S)	2.23	Yes
-	N-0, normal operation condition	3.43	No

3. System Strength Detailed EMT Study

3.1 Instability of IBRs and Power Electronic Based Facilities in Weak System

3.1.1 Control Related Instability

Nowadays, the majority of the IBRs or FACTS are based on grid-following (GFL) type control, which replies on phase-locked loops (PLLs) to synchronize with the grid. PLLs are crucial components in IBRs, used to lock the inverter's output frequency and phase to the grid. Under certain conditions, can lead to instability. This is especially true in weak grids characterized by low SCRs, where PLL performance is highly sensitive to grid disturbances and impedance fluctuations.[5]

Key Factors in PLL-Induced Instability:

- **Impact of PLL Parameters:** The performance and stability of converters, especially in weak grids with low SCRs, are strongly influenced by PLL gains
  - The study reveals that the maximum power transfer capability of a converter is constrained by both the SCR and the PLL's dynamic response
  - Low SCR values, which indicate weaker grids, heighten the system's sensitivity to PLL tuning, making the system more prone to instability if the PLL parameters are not appropriately adjusted
- **Negative Damping Effect:** In weak grids (low SCR), PLLs can introduce a negative damping effect, which aggravates system oscillations
  - It was demonstrated through eigenvalue analysis that when SCRs fall below 1.32, systems become more susceptible to instability due to high PLL gains
  - This negative damping can exacerbate oscillations, making the system difficult to stabilize

3.1.2 Voltage Instability in Weak Power System

Voltage instability is a major concern in weak power grids, particularly those with a high penetration of IBRs. In these grids, maintaining stable voltage levels becomes increasingly difficult as the voltage at the point of connection (POC) becomes more sensitive to fluctuations in load and generation. This sensitivity makes it challenging to maintain voltage stability, as even small changes in power demand or supply can cause significant voltage variations, leading to instability, especially when power flows through high-impedance lines.

Traditional synchronous generators provide inherent inertia, which helps naturally stabilize voltage and frequency fluctuations on the grid. In contrast, IBRs like solar panels and wind turbines lack inherent inertia, primarily because most modern IBRs utilize grid-following control. This lack of inertia, especially in weak grids, increases the risk of voltage instability as the system becomes less

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[5] J. Z. Zhou, H. Ding, S. Fan, Y. Zhang and A. M. Gole, "Impact of Short-Circuit Ratio and Phase-Locked-Loop Parameters on the Small-Signal Behavior of a VSC-HVDC Converter," in IEEE Transactions on Power Delivery, vol. 29, no. 5, pp. 2287-2296, Oct. 2014.

capable of absorbing and dampening disturbances. Consequently, rapid voltage fluctuations can occur when there is an imbalance between supply and demand, further compromising grid stability. Weak grids typically exhibit higher impedance, which increases the voltage's sensitivity to power flow changes. In stronger grids with low impedance, changes in demand or generation result in smaller voltage variations. However, in weak grids, the higher impedance amplifies these variations, causing larger voltage fluctuations. This presents significant challenges for maintaining voltage stability, especially as the number of IBRs in remote areas increases, where they are connected to the grid via long transmission lines. In such grids, the responsibility for voltage regulation increasingly falls on IBRs. However, most IBRs are not designed to provide the same level of voltage support as traditional generators. Many rely on power plant control (PPC) systems to regulate the voltage at the POC. In weak systems, the effectiveness of PPC settings may diminish, leading to voltage oscillations or instability. This reduced effectiveness of PPC in weak grids can exacerbate voltage control issues and increase the risk of instability.

Voltage instability in weak grids can manifest in several ways, including voltage oscillations, over-voltages, under-voltages and even complete voltage collapse.

3.2 Recommended Tools for Detailed EMT Assessment

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

PSCAD/EMTDC is widely regarded as the industry standard for EMT simulation, especially for power systems that include IBRs and power electronic converters. It enables detailed analysis of transient behaviour, which is essential for evaluating system stability and control performance under weak grid conditions.

E-Tran and PRSIM are tools used specifically to convert TS models, such as those in ". Raw" and ".dyr "formats, into EMT-compatible models.

Other EMT (e.g., EMTP-RV) tools can be used if they meet the following criteria:

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

3.3 EMT Model and Detailed EMT Studies

A detailed EMT assessment becomes essential following the initial screening assessment when specific indicators reveal potential instability or interaction risks within the grid. While the initial screening—commonly using a SCR test—offers a preliminary evaluation of the facility performance under weak grid conditions, it has limitations and may not detect complex stability challenges and interactions that can emerge in grids with significant IBR penetration.

The AESO may request detailed EMT assessments under the following conditions, beyond instances where the WSCR falls below the threshold:

- **High IBR Penetration and Proximity of IBRs:** In areas with dense concentrations of IBRs, especially where multiple plants are in close electrical proximity, the likelihood of control interactions and harmonic resonance issues rises
  - The standard SCR test does not account for the intricate dynamics in multi-IBR settings, where the control systems of individual IBRs may interact in unpredictable ways, potentially destabilizing the grid
  - Detailed EMT analysis is necessary in these scenarios to identify, analyze and mitigate potential control interactions and stability risks
- **Presence of Compensation and Power Electronic Devices:** Systems with compensated alternating current (AC) lines or other power electronic devices, such as STATCOMs or SVCs, can introduce significant additional complexity, particularly in weak grid environments
  - These devices impact voltage stability, reactive power support and fault responses in ways that traditional screening assessments may not adequately capture
  - A detailed EMT study allows for a comprehensive evaluation of these interactions, ensuring that the compounded effects of compensation devices and IBRs on system stability and performance are thoroughly understood
- **Identified Areas with Voltage and Frequency Stability Risks:** When specific areas are identified as having potential risks related to voltage or frequency stability—especially under conditions of high IBR penetration—detailed EMT studies become essential
  - These studies provide insight into potential voltage dips, frequency deviations and reactive power imbalances under various operational scenarios, thereby informing strategies to enhance system stability

The purpose of the detailed EMT assessment is to deliver a comprehensive analysis of facility dynamic responses and surrounding network interactions during transient events, allowing system planners and operators to identify and mitigate potential stability and operational risks. By thoroughly examining TS, control interactions, harmonic resonance, Fault Ride-Through (FRT) capabilities voltage and frequency stability, these detailed studies are critical for supporting grid stability, particularly in challenging conditions that the initial SCR screening cannot fully address.

3.3.1 SCR Test

The SCR test, as outlined in Section 4, is designed as a basic procedure to evaluate the robustness of the control systems of IBRs when operating in weak grid conditions. The test is meant to ensure that the control systems can maintain stability across a range of predefined scenarios. However, while useful for initial assessments, this test has limitations and may not identify deeper, more complex risks that weak systems can pose.

One major shortfall of this test is its inability to fully capture potential control interactions between multiple IBR plants or between IBRs and compensated AC lines, which are common in weak grids. These interactions can lead to unforeseen instabilities, particularly in regions with a high penetration of renewable energy and power electronic devices. For example, control systems designed for individual IBRs may behave unpredictably when interacting with the controls of nearby plants, leading to phenomena like harmonic resonance, oscillations or other destabilizing effects.

3.3.2 The Detailed EMT Studies

In weak system interconnections, especially where there is high IBR integration, it is strongly advised to go beyond the SCR test and conduct more detailed EMT studies. These detailed studies provide a much more comprehensive analysis of the potential system behaviours under various conditions and contingencies.

If the screening result in Screening Assessment Methodology section indicates some results fall below the threshold WSCR—further detailed EMT studies become essential. These studies provide an in-depth analysis of the dynamic behaviour of IBRs and the surrounding network during transient events. They help in identifying potential instability, control interaction and system performance risks. EMT studies focus on the following aspects:

- **TS and Control Interaction:** EMT studies allow for the precise modelling of fast transients that occur in IBRs and their control systems
  - This includes analyzing interactions between the IBRs' control loops (e.g., voltage, frequency and current control) and the network, particularly in weak grid conditions
  - The study evaluates whether the IBRs' control strategies maintain stability or trigger undesired oscillations or instability by simulating disturbances like faults, line switching, or other events
- **Harmonic Resonance and Distortion:** In grids with multiple IBRs, especially under weak conditions, there is a higher risk of harmonic interactions and resonance between the inverter controls and the grid impedance
  - Detailed EMT simulations are necessary to identify and mitigate harmonic resonance issues that may compromise system performance, particularly in grids with high levels of non-synchronous generation
- **FRT Performance:** EMT studies evaluate the IBRs' ability to remain connected and operational during and after fault conditions
  - This includes simulating voltage dips, fault clearance times and post-fault recovery, to ensure compliance with grid code requirements and reliable system operation during contingencies or other faults
  - Detailed FRT analysis helps in designing appropriate controls to prevent tripping and ensure smooth recovery after disturbances
- **Voltage and Frequency Stability:** In weak or marginal grids, EMT studies provide detailed insight into voltage and frequency stability under various operational scenarios
  - By simulating different levels of IBR penetration and grid configurations, these studies help identify potential issues such as voltage collapse, uncontrolled frequency excursions and reactive power imbalances

  - EMT analysis can also guide the design of voltage support systems like STATCOMs, synchronous condensers or other voltage control devices
- **Protection Coordination and Interaction:** Traditional protection systems may not respond correctly in grids with high levels of IBRs due to differences in fault current characteristics
  - EMT simulations are crucial for assessing how IBRs interact with protection systems during faults
  - This includes evaluating relay settings, fault detection sensitivity and the timing of protection devices, to ensure proper coordination and prevent malfunctions or unnecessary tripping
- **Impact of Power Electronic Interfaces:** EMT studies focus on the detailed behaviour of power electronic converters in IBRs, including their response to transient events, switching actions and control logic.
  - By modelling these interfaces accurately, EMT simulations help assess the impact of converter behaviour on the overall system stability, especially under weak grid conditions or during dynamic events such as faults, load changes or grid disturbances

Key aspects of these detailed EMT studies include:

- **Site-Specific IBR Models:** The EMT study should incorporate detailed, site-specific IBR models supplied directly by the OEM
  - These models are critical as they reflect the actual control and protection algorithms used in the IBRs deployed at the site, including dynamic responses to disturbances and interactions with the grid
- **Models of Nearby IBR Plants:** In addition to the site-specific models, the study should include models of other nearby IBR plants
  - This is because neighbouring plants can introduce control system interactions, which are difficult to capture in more simplified screening processes like the SCR test
  - Including these models ensures that the study reflects real-world operational conditions where multiple IBRs are interacting
- **Other Key Electrical Device Models:** The study should also include models of any other relevant electrical devices, such as compensated transmission lines, synchronous condensers and FACTS devices, which are often present in weak systems
  - These devices can introduce additional complexity, such as voltage support issues, and need to be included in the simulation to fully understand the grid dynamics

The AESO may also deem it necessary to include specific equipment models to ensure that all significant electrical interactions are captured. This holistic approach to modelling in EMT studies helps ensure that the entire electrical environment around the IBR plant is represented, leading to a more accurate understanding of potential risks.

3.3.3 EMT Model and Data Requirements

To ensure consistency, accuracy and high fidelity in EMT, all EMT models used for the study need to strictly adhere to the comprehensive requirements outlined in the AESO Facility Modelling Data document. Appendix 3,[6] 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 2.

Table 2: Required Data for Weak System Detailed

Data Requirement	Accountable to Provide	Comment
Facility Data		
Facility Model	**GFO**	Detailed, site-specific simulation models reflecting facility control and protection algorithms
Control/Protection Settings		Specific control/protection settings with detailed instructions
Network Data		
Compensated Transmission Lines	**TFO/AESO**	Detailed surge arrester data, bypass circuit details, and protection settings
Models of Nearby IBR Plants (if available)	**AESO**	Required to account for potential control interactions with adjacent IBRs
FACTS Devices (e.g., STATCOM, SVC) (if available)	**AESO/TFO**	Detailed, site-specific models are 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 needed in special cases.
Transformer Data	**AESO**	Transformers data, including winding configuration, grounding data, saturation data, etc.

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[6] 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.

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

3.3.3.1 Procedure for Detailed EMT Studies

Detailed EMT studies are essential for analyzing the dynamic stability of systems with high IBR integration, especially in weak grid areas. 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

The first step in a detailed EMT study is to identify the specific study area where the analysis is to be focused. This area is chosen based on factors like high IBR penetration, known stability issues, or points of interconnection that may be susceptible to instability. Clearly outline the geographical and electrical boundaries of the study area and document all buses within this area, particularly those associated with IBR connections, key transmission nodes and other critical points. This list of buses will help in configuring the internal and external network representations. It is worth mentioning that key prior outages in the study area might need to be considered. This might require developing multiple power flow cases representing different network configurations and topologies in this step.

Step 2: Define Internal Area and Detailed Modelling of Buses

Once the study area and relevant buses are identified, these buses form the "internal area" where detailed modelling is required. All equipment within this internal area should be represented with high fidelity to capture dynamic behaviour accurately. Each component within the internal area—such as transformers, transmission lines, synchronous condensers and IBRs—should be represented in detail. Include specific parameters for transformers (e.g., saturation characteristics), transmission lines (frequency-dependent parameters) and other devices critical to accurately simulate transient behaviours. Ensure that all control systems, including voltage control, frequency control and protection schemes, are configured according to site-specific settings.

Step 3: Representation of External Network

While the internal area requires detailed EMT modelling, the surrounding external network can be represented with a simplified, equivalent model. This approach reduces simulation complexity without significantly impacting the accuracy of results. Model the external network as an equivalent impedance or simplified representation, reflecting the primary characteristics of the surrounding grid. The external network should be configured to provide realistic boundary conditions for the internal area, such as the expected short circuit strength and voltage levels. Though simplified, the external network still needs to provide a stable and realistic environment for the internal area to interact with, ensuring the focus remains on internal dynamics.

Step 4: IBR Models Integration

Accurate integration of IBR models is critical for the EMT study, as these components are often the focal point of stability analysis in weak grids. IBR models should be sourced from the OEM and configured according to the exact specifications of the equipment on-site. Integrate detailed, site-specific IBR models, including all control loops (inner and outer loops), protection settings and FRT features. These models should replicate the actual control systems and protection schemes implemented in the field. Include models of neighbouring IBRs if they are electrically close to the study area. Ensure that the IBR models are validated against real operational data, where possible, to confirm that they accurately replicate the equipment's behaviour.

Step 5: Model Initialization and Power Flow Check

Before proceeding with transient simulations, it is essential to initialize the model and confirm that power flow and voltage conditions match expected steady-state values. This step ensures that the model setup is correct and provides a stable starting point for further analysis. Initialize the model to establish a steady-state condition, confirming that voltage, frequency and power flows are consistent with normal operating levels. Perform a power flow analysis to verify that all components, especially IBRs, are operating within their specified limits. If there are discrepancies between expected and actual values, adjust model settings (e.g., droop controls, voltage setpoints) until the model achieves a stable steady state.

Step 6: Fault Setup and Simulation

With the model initialized, the next step is to configure fault scenarios for transient analysis. Faults are simulated to assess the grid's stability and the IBRs' response under disturbance conditions. Define fault scenarios relevant to the study area, including N-1 and key N-1-1 contingencies such as line faults, transformer faults and bus faults. These scenarios are chosen based on the likelihood of occurrence and their potential impact on grid stability. Set up the fault parameters, such as fault type (e.g., single-line-to-ground, three-phase), fault duration and fault location. This configuration should align with typical system disturbances and be based on expected operating conditions. Run transient simulations to observe the IBRs' response to each fault scenario, focusing on parameters like voltage stability, frequency deviation, current injection and fault ride-through capability.

Step 7: Results Analysis

The final step in detailed EMT studies is to analyze the simulation results to assess grid stability, control interactions and potential risks associated with IBRs under weak grid conditions. 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 IBR controls, especially in multi-IBR setups where neighbouring IBRs may exhibit coupled or synchronized responses. Harmonic resonance or oscillatory behaviours should be flagged for further mitigation. Evaluate the IBRs' 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 IBR response characteristics. Based on the analysis, provide recommendations for any required adjustments to control settings, protection schemes or network reinforcements to ensure stable IBR operation in weak grid conditions.

3.4 Mitigation

To mitigate instability in weak systems, a combination of approaches targeting both grid infrastructure and the control systems of IBRs is essential. Below are some key mitigation measures with more detailed explanations:

3.4.1 Advanced Control Strategies for IBRs

Grid-Forming Inverters:

- Traditional IBRs are grid-following, meaning they rely on the grid for synchronization
    - In weak grids, switching to grid-forming inverters can improve stability
- Grid-forming inverters actively regulate voltage and frequency, thus providing inertia-like responses and supporting the grid during disturbances

Improved PLL Design:

- A weak grid’s low SCR can cause instability in the PLL used by IBRs for grid synchronization
- To mitigate this, IBRs can adopt advanced PLL algorithms that are more robust under weak grid conditions or switch to control methods that reduce the reliance on PLLs for grid synchronization

Droop Control Tuning:

- Adjusting the frequency and voltage droop settings of IBRs can help improve system stability. Properly tuned droop control enables better sharing of reactive and active power among IBRs, reducing control interaction problems in weak grids

3.4.2 Grid Support Devices

Synchronous Condensers:

- Installing synchronous condensers can provide additional reactive power support and increase the short-circuit strength of the grid
- This enhances voltage stability and reduces the impact of IBR-related control instability. Synchronous condensers also provide inertial response and help stabilize frequency variations

Static VAR Compensators (SVCs) or STATCOMs or E-STATCOMs:

- E-STATCOM, STATCOMs and SVCs can be used to dynamically inject reactive power into the grid, helping to maintain voltage stability and reduce fluctuations caused by weak grids

- E-STATCOMs with an energy storage system, enabling both dynamic reactive power support and limited active power injection.
  • By providing fast voltage control and, where required, short-duration active power support, E-STATCOMs can enhance effective system strength and mitigate weak-grid stability issues such as voltage oscillations and poor damping associated with low SCR conditions. These devices are fast-acting and can mitigate voltage dips during disturbances or faults, improving overall system reliability

Dynamic Reactive Power Compensation:

- In areas with varying load or IBR penetration, dynamic reactive power devices such as STATCOMs can automatically adjust reactive power injection to maintain voltage stability, particularly in weak grids with low reactive power margins.

1.1.1 Grid Reinforcement

Transmission Line Upgrades:

- Reinforcing the transmission network, such as upgrading transmission lines to reduce impedance or building new lines, can significantly increase the grid’s short-circuit strength, mitigating the impacts of weak grids
- Grid reinforcement improves overall grid resilience and reduces the dependence on complex control strategies at the IBR level

Energy Storage Systems (ESS):

- ESS (especially fast-acting systems like Grid Forming BESS) can be used to provide grid services such as frequency regulation and voltage support
- Energy storage can also help smooth out power fluctuations and provide inertia, improving grid stability in weak systems

3.4.3 Operational Flexibility

Dynamic Power Curtailment:

- In weak grids, especially during periods of high IBR penetration or system stress, reducing the active power output of IBRs can help maintain stability
- Dynamic power curtailment involves adjusting the IBR output based on real-time grid conditions, such as voltage fluctuations or frequency instability
- This approach can be especially effective in weak systems where rapid fluctuations in power generation from renewable energy sources (e.g., solar or wind) may exacerbate instability
- Curtailment is typically done temporarily to prevent the grid from becoming further destabilized during periods of low system strength or high operational stress

Remedial Action Scheme (RAS) for Tripping IBRs:

- In cases of severe instability or when specific contingencies are detected, a RAS can be employed to trip IBRs
- RAS is an automated system designed to detect potential instability conditions and take predefined corrective actions to prevent cascading failures or system blackouts
- In weak grid conditions, RAS can be configured to trip certain IBRs if the system detects critical instability, such as voltage collapse, frequency deviation beyond safe limits or excessive power swings
- By tripping selected IBRs, RAS helps alleviate stress on the grid, reducing the risk of widespread outages and restoring operational stability
- However, this approach is typically a last resort, as tripping generation can reduce overall system capacity and lead to power shortages, so it needs to be carefully planned and coordinated with other mitigation strategies

3.4.3.1 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 behavior 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 Association of Professional Engineers and Geoscientists of Alberta (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

3.4.3.2 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

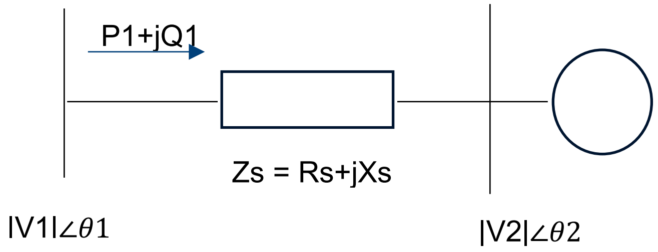
4. Single IBR Model System Strength Performance Test Procedure (SCR Test)

To evaluate the performance of an IBR under different SCRs at the Point of Connection (POC), a simple EMT study is commonly performed. The SCR is a measure of the system's ability to support voltage stability and maintain stable operation of the IBR during grid disturbances.

4.1 Test Platform Setup and Model Requirements

All tests are typically required for both PSS/E and PSCAD models.

Figure 3: AC System Representation in the SCR Test



4.2 Test Procedures

4.2.1 Initial Power Settings for the IBR and test procedure

The IBR's real power (P) should be set to 1.0 pu (per unit) at the POC.

The reactive power (Q) should include three values:

- Q=0.328pu (injecting reactive power)
- Q= 0pu (neutral, no reactive power injection or absorption)
- Q =−0.328pu (absorbing reactive power)

Once the IBR's operating condition reaches to the steady state values according to the initial conditions, a solid three phase to ground fault is applied at POC followed by reducing SCR (adjusted by impedance, Zs, value representing equivalent AC system) after fault clearance.

4.2.2 X/R Ration Configurations

IBR: This ratio plays a crucial role in determining how the system responds to short circuits and affects the overall voltage stability at the POC. The table below provides the X/R ratio used in the SCR test, corresponding to the voltage level at the POC:

Table 3: X/R Ratio in Different Voltage Level (Typical)

Voltage Level (kV)	X/R Ratio
Vr≤33 kV	4
33 kV≤ Vr≤ 69 kV	5
69 kV≤ Vr≤ 138 kV	6
138 kV≤ Vr≤ 240 kV	8
240 kV≤ Vr≤ 500 kV	10

4.2.3 Equivalent AC System Parameterization

The Equivalent System Parameters Calculation section outlines the method for parameterizing Zs and V2 for the SCR test. The magnitudes and angles of Zs and V2 should be adjusted according to the SCR and the initial active and reactive power (Q) set points (refer to Appendix C and Appendix D). Table 4 provides a list of all the tests performed in the SCR test.

Table 4: SCR Tests Performed

Test No.	Pini	Qini	Fault Duration[7]	SCR
1	1.0	0.328	0.4s	10->5->3->2->1.5->1.2
2	1.0	0	0.4s	10->5->3->2->1.5->1.2
3	1.0	-0.328	0.4s	10->5->3->2->1.5->1.2

Extra tests for BESS and other ESS:

Test No.	Pini	Qini	Fault Duration	SCR
4	-1.0	0.328	0.4s	10->5->3->2->1.5->1.2
5	-1.0	0	0.4s	10->5->3->2->1.5->1.2
6	-1.0	-0.328	0.4s	10->5->3->2->1.5->1.2

4.2.4 Acceptance Criteria

The following criteria are used to examine the SCR test results:

- Stability: Any unstable performance at a SCR of 3 or above need to be corrected
- Model Settings Transparency: All settings for the models used in the test need to be provided, with explanations for any differences from other proposed performance standards

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[7] The fault clearing times provided here are provided as an example and might need to be adjusted if neccassary.

- Stable fault ride through (FRT) Performance: FRT does not cause oscillations, instability, uncontrolled disconnection, or uncontrolled behaviour during or after a disturbance
- No Low Voltage Ride Through (LVRT) Retriggering (control mode cycling): Performance must not lead to repeated triggering of LVRT (or switching between LVRT and high voltage ride through [HVRT])
- No Tripping under Normal Conditions: The IBR should not trip
- FRT Mode Termination: The connection must not remain in FRT mode indefinitely unless conditions are outside stability limits
- Voltage Controller Activation: The voltage controller at the connection level needs to be enabled
- Frequency Controller Activation: The frequency controller at the connection level needs to be enabled
- Starting Conditions: Tests need to start at 1.0 pu voltage at POC with no more than 2 per cent deviation from nominal unless specific conditions for low SCR operations are specified
- Minimum Simulation Time: Simulations need to run for at least 15 seconds after the fault clears or the event completes to ensure the model gets to steady state
- Reporting Requirements: A detailed report will be provided with simulated results for all tests
- Plot Resolution: PSCAD/EMTDC simulation plots need to have a resolution no worse than 1 millisecond

Appendix A: GRIP Overview

Introduction

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

- High penetration of IBR, which can reduce system capability to manage and maintain frequency stability, system strength and operational flexibility
- Restrictions on the availability of reliability support through 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

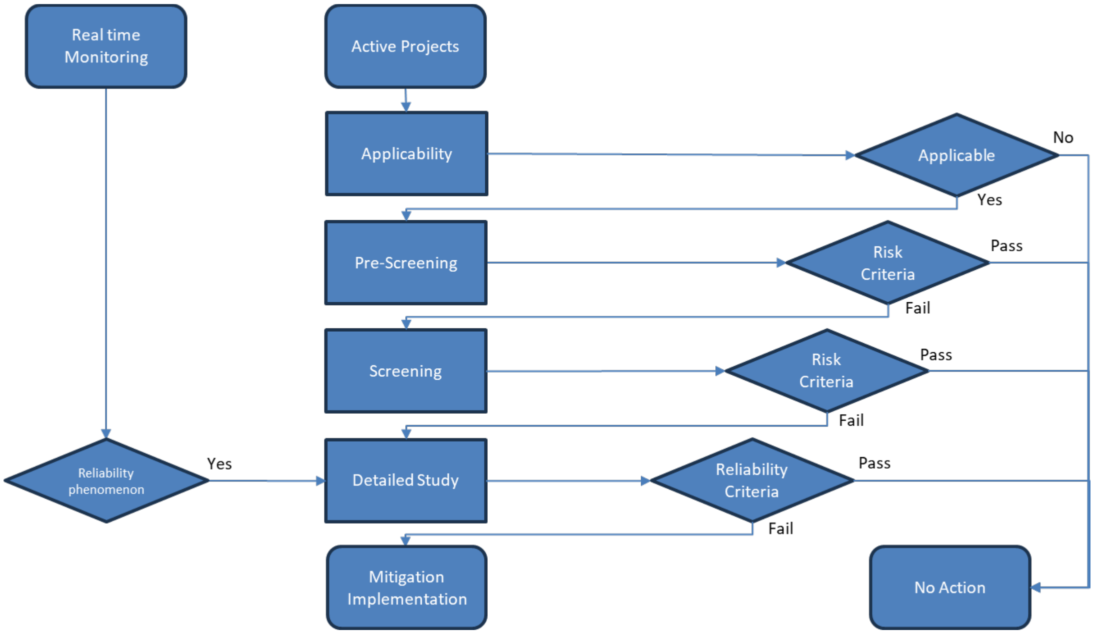
As a result of these emerging AIES reliability challenges, the AESO has identified several areas where performing Grid Readiness, Integration and Performance (GRIP) Requirements would be beneficial. The AESO also realized that the system reliability is heavily dependent on how market participants (MPs)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

AESO’s Risk-Based Assessment Approach

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

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

Figure A1: Risk-Based Assessment Approach



The phases of this process occur at different points throughout the AESO's Connection Process. For topics related to AESO Authoritative Documents, MPs are responsible for completing applicability, pre-screening, and screening steps independently and are encouraged to use the approach and methodology outlined in this guideline. In all other cases, the AESO will conduct these initial steps. These steps will determine whether a facility requesting system access can be excluded from further analysis or requires further study as a high-risk project. Projects identified as high risk will include a detailed study requirement in the project's functional specification. This guideline provides additional details on the recommended approach for conducting those detailed studies. Upon receiving the detailed study, the AESO will work with market participants 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 is to identify projects requiring further assessment using applicability criteria based on accessible project information available early in the customer connection process such as, facility size, type and technology.

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

Pre-Screening

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

Screening

The objective of screening is to conduct a further assessment when more detailed technical information on market participant'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.

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 electromagnetic transient (EMT) simulation outlined in this guideline prior to project energization. To conduct this work, the responsible entity will require detailed project information and models and is usually conducted in the later stages of the customer connection process. The AESO will include the detailed study and report submission requirements in the functional specification for the high-risk projects.

Mitigation

The 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 to the AESO, the AESO will follow this guideline to review and comment on the report within a timely manner. The responsible entity of the detailed study will be responsible to address all comments from the AESO and authenticate the study report. The detailed study must be completed 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, the AESO will work with the market participant on the mitigation measures in real time. Furthermore, project changes, accepted through the AESO's Project Change Proposal process may trigger the need for additional applicability, pre-screening, screening, and detailed study.

Appendix B: Detailed Study Report 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.

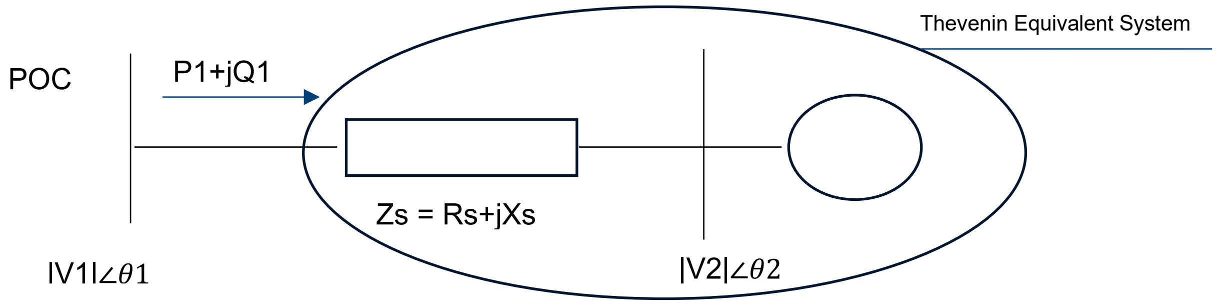
12.0 Appendices

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

Appendix C: Thevenin Equivalence in the SCR Test

For simplicity, the grid is modelled as a single-port Thevenin equivalent circuit at the point of connection (POC). This equivalent circuit consists of a voltage source in series with an impedance. Typically, the impedance is calculated using the following equation, with the assumption that the magnitude of the equivalent voltage source is approximately 1.0 pu. However, this approximation can introduce significant errors when the SCR falls into the “weak” range.

Figure 5: The Grid Equivalence at the POC



Assuming the power sending into the grid at the POC is P1+jQ1 and the rms voltage V1 at the POC is 1.0pu with phase angle 0 deg. The equivalent impedance is Zs = Rs + j Xs. The voltage at bus 2 can be calculated using the following equation:

$$V2 = (1 - P1 * R_s - Q1 * X_s) + j(P1 * X_s - Q1 * R_s)$$

The following equation is used here to get the approximate value of the SCR:

$$SCR = \frac{Vr^2}{Zs * Pr}$$

Where Vr is the rated rms voltage at the POC bus and Pr is the nominal power rating of the converter connecting to the POC.

Figure 6 illustrates the relationship between SCR and the magnitude of V2, taking into account different X/R ratios with P1 = 1.0pu and Q1 =0pu. As SCR increases, the magnitude of V2 decreases for all X/R ratios. For lower values of SCR (closer to 1), |V2| is larger than 1 pu. For example, at SCR = 1, |V2| is around 1.35 pu for X/R=10and 1.15 pu for X/R=4. As SCR increases to values closer to 5, |V2| approaches 1.0 pu for all X/R ratios. Higher X/R ratios (such as X/R = 10) result in larger |V2| values, while lower X/R ratios (such as X/R = 4) result in smaller |V2| values.

When Q1=0 pu, the system is only influenced by the active power P1 and the impedance of the system. Lower SCR values represent weaker systems, which leads to higher |V2|, as the voltage drop across the impedance becomes larger. Higher SCR values represent stronger systems, resulting in |V2| being close to |V1| (1.0 pu) since there is less voltage drop across the impedance.

Figure 6: |V2| vs SCR for Different X/R Ratios (P1 = 1.0pu, Q1 = 0pu)

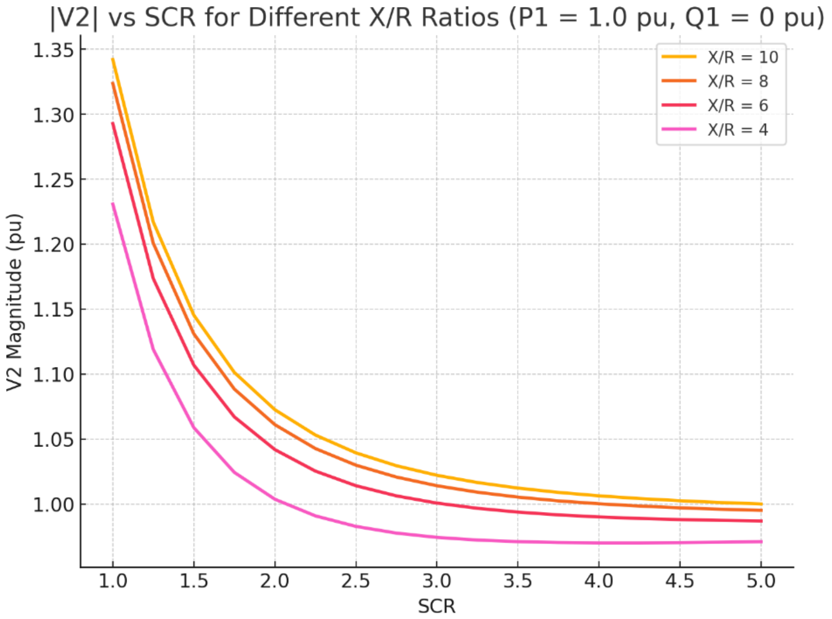


Figure 7 shows the relationship between SCR and the magnitude of V2 with different X/R ratios. The reactive power at the POC bus was changed to 0.328 pu, representing inductive reactive power, the voltage magnitude V2 will decrease further for a given SCR and X/R ratio compared to the Q1=0 case.

The curves will shift downwards, meaning |V2| will be lower than in the case where Q1=0. For lower SCR values, the drop in |V2| will be more noticeable since the system is weaker and the addition of reactive power will cause a larger drop in voltage. At higher SCR values, |V2| will still converge closer to 1 pu, but with a slightly lower value compared to the Q1=0 case.

Positive reactive power (inductive) increases the voltage drop across the impedance, leading to a reduction in |V2|.The overall system's ability to support the active and reactive power leads to a lower voltage magnitude when the system is weaker (lower SCR).

Figure 7: |V2| vs SCR for Different X/R Ratios (P1 = 1.0pu, Q1 = 0.328pu)

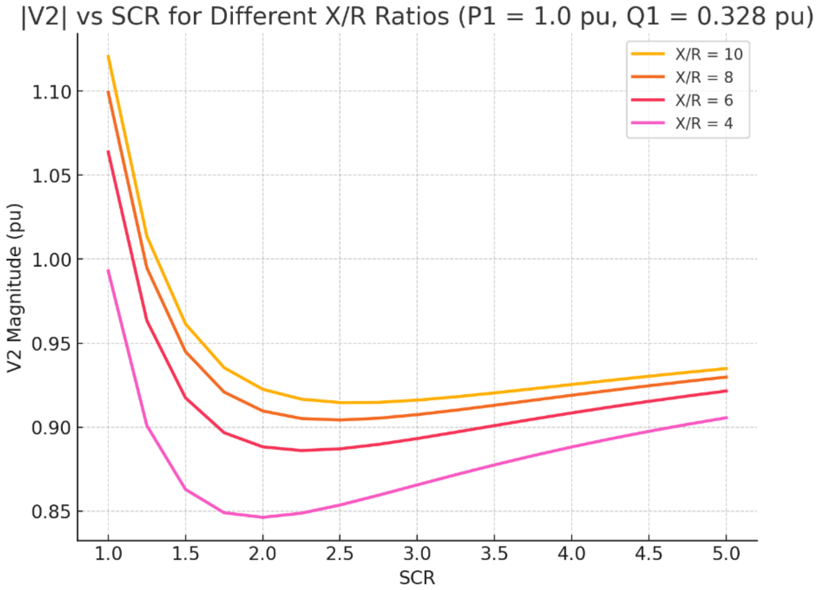
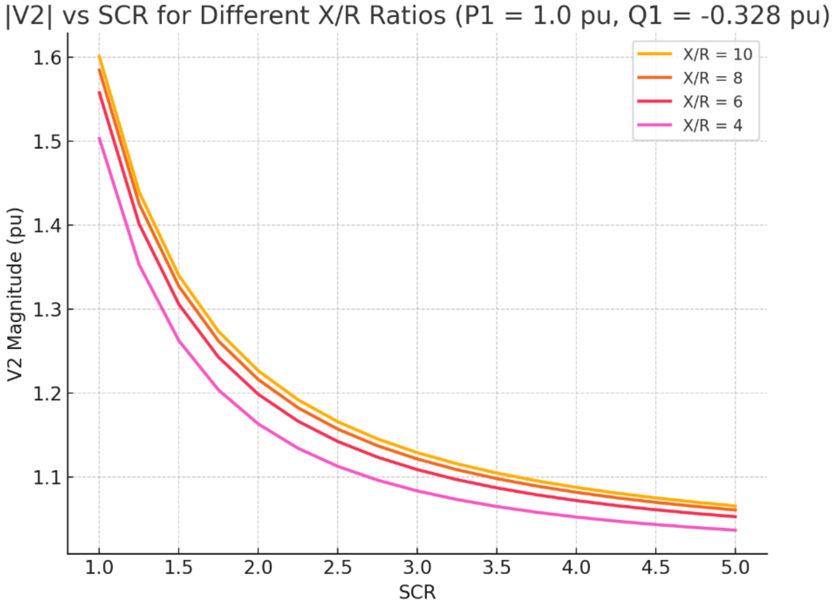


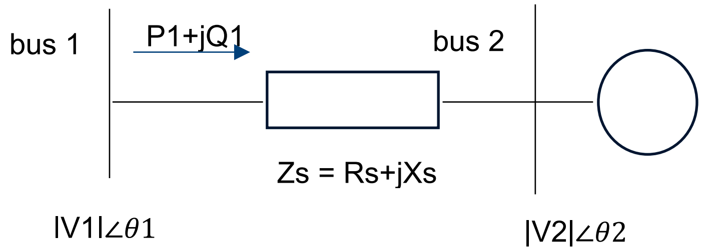
Figure 8 demonstrates the relationship between SCR and the magnitude of V2 with different X/R ratios while the reactive power at the POC bus was changed to -0.328pu, representing capacitive reactive power, the voltage magnitude V2 will increase for a given SCR and X/R ratio compared to the above two cases. The curves will shift upwards, meaning |V2| will be higher than in the cases where Q1=0 and Q1=0.328. Negative reactive power (capacitive) effectively increases the voltage drop across the impedance, leading to an increase in the magnitude of |V2|. In weaker systems (lower SCR), the effect of capacitive reactive power is more pronounced, causing a higher increase in |V2|.

Figure 8: |V2| vs SCR for Different X/R Ratios (P1 = 1.0pu, Q1 = -0.328pu)



Appendix D: Equivalent System Parameters Calculation

Figure 9: The Equivalent System



SCMVA at bus 1 is calculated using the following equation:

$$SCMVA = I_{sc} * |V1| = \frac{|V2|}{|Zs|} * |V1|$$

Where I_{sc} [8] is the short circuit current at bus 1 in per-unit and |V1| is the nominal voltage at bus 1 (assumed to be 1.0 pu in this context, although the pre-fault voltage can also be used). |V2| is the voltage magnitude (in pu) at bus 2. |Zs| is the equivalent impedance in per-unit.

1. Initial Assumptions:

SCR= 1.2, |V2| = 1.0 pu, V1 = 1.0pu$\angle 0$, Pr = 1.0pu, P1+jQ1 = 1.0-j0.2pu, Xs/Rs = 5, α=atan(Xs/Rs)= 78.69∘. All the variables are per-united based on the rated power and voltage at POC point.

2. Calculate Zs:

$$SCR = \frac{SCMVA}{P_r} = \frac{|V1||V2|/|Zs|}{P_r}$$

$$|Zs| = \frac{|V1||V2|}{P_r * SCR}$$

$$|Zs| = \frac{1.0^2}{1.0 * 1.2}$$

$$|Zs| = 0.833$$

$$Rs = |Zs| * \cos(78.69^\circ) = 0.1634$$

$$jXs = j|Zs| * \sin(78.69^\circ) = j0.8168$$

---

[8] This assumes the facility is disconnected.

3. Calculate New V2:

V2 can now be calculated as:

$$V2 = (1 - P1 * R_s - Q1 * X_s) - j(P1 * X_s - Q1 * R_s)$$

$$V2 = (1 - 0.1634 + 0.2 * 0.8168) - j(0.8168 + 0.2 * 0.1634)$$

$$V2 = 1 - j0.8495$$

$$V2 = 1.31\angle{-40.348°}$$

4. Update SCR and Zs:

With the updated $V2 = 1.31\angle - 40.348°$, the new SCR can be recalculated:

$$SCR = \frac{SCMVA}{P_r} = \frac{\frac{|V2|}{|Zs|} * |V1|}{1.0} = \frac{\frac{1.31}{0.833} * 1.0}{1.0} = 1.57$$

So, the new SCR is 1.57, indicating that the system is stronger than initially assumed. Since the SCR has increased to 1.57, the impedance Zs needs to be updated. The new value of Zs is recalculated using the updated V2. Specifically:

$$|Zs_{new}| = \frac{1.31}{P_r * SCR} = 1.31 * Zs_{old}$$

5. Recalculate V2:

With the updated Zs_{new}, the process is repeated to calculate a more accurate V2. Using the updated Zs_{new} and P1+jQ1 = 1.0-j0.2pu, the new V2 is calculated again, and the value will change based on the updated impedance.

6. Iteration Process:

The process continues iteratively: after each calculation of V2, the new SCR is calculated and then Zs is updated accordingly. This iterative loop continues until the difference between successive values of SCR falls below a predefined error threshold (e.g., 0.001 pu), ensuring that the system has converged to a stable, accurate solution.

After the iterations, the final parameters of equivalent system is as following:

$$V2 = 1.3123\angle{-40.36°}$$

$$Zs = 0.2145 + j1.0724\,pu$$

This example demonstrates why iteration is necessary. The interaction between V2 and Zs requires multiple adjustments to accurately represent the system's behaviour, especially when starting with an assumption that doesn't reflect the true system conditions.

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