NPCC

Northeast Power Coordinating Council, Inc.

Approaches for Conducting Electromagnetic Transient Studies

Prepared by the NPCC SS-41 Working Group on Electromagnetic Transients.

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1. Introduction

It is the responsibility of NPCC's Members to design and operate an interconnected power system that remains stable as new **resources** and energy-consuming loads are interconnected to the **bulk power system (BPS)**. It has become necessary, due to technological changes in the components behind new **resources** and **loads**, to make use of electromagnetic transient study tools. This is to adequately examine the impacts to reliability of the **bulk power system** under various conditions and system disturbances through the transient state.

This guideline for NPCC Members is to provide recommended approaches to perform electromagnetic transient (EMT) studies for the overall purpose of integrating Inverter Based Resources (IBRs) without adverse impact to reliability of the **bulk power system**. As EMT software is a study tool, rather than a particular study, this guideline document provides recommended study design considerations for several different applications. Certain aspects of the application of EMT are not addressed in this Revision 0; this is to focus first on the essential aspects of reliable IBR integration for the **bulk power system**. Other applications and topics may be added to the guideline in the future (e.g., studies of power electronic loads, etc.).

When available, this guideline uses terms that are defined in the NPCC Glossary of Terms [1] and are shown in bold face type. In addition, it was necessary to provide brief definitions of some terms used commonly with electromagnetic studies. These additional terms are given in the Glossary section of this document and are used for the purpose of giving meaning and understanding to this document.

2. Phenomena Investigated with EMT Studies

This chapter provides an overview of the main phenomena, including power system instability and protection misoperation, that might necessitate the need for EMT studies. Understanding the underlying phenomena provides a clear link between the physical mechanisms of interest and the modeling or simulation approaches applied to study them. This connection ensures that the EMT model structure, time-step resolution, and control system representations are appropriately selected to capture relevant dynamics. Furthermore, it enhances the interpretation and scope of study results by aligning the modeling objectives with the root physical causes of observed transients.

Generally, the system-level EMT studies are used for investigating two main categories, the ones that can be grouped under stability umbrella as per the IEEE classification [2], and the ones associated with the protection misoperation as shown in Figure 1.

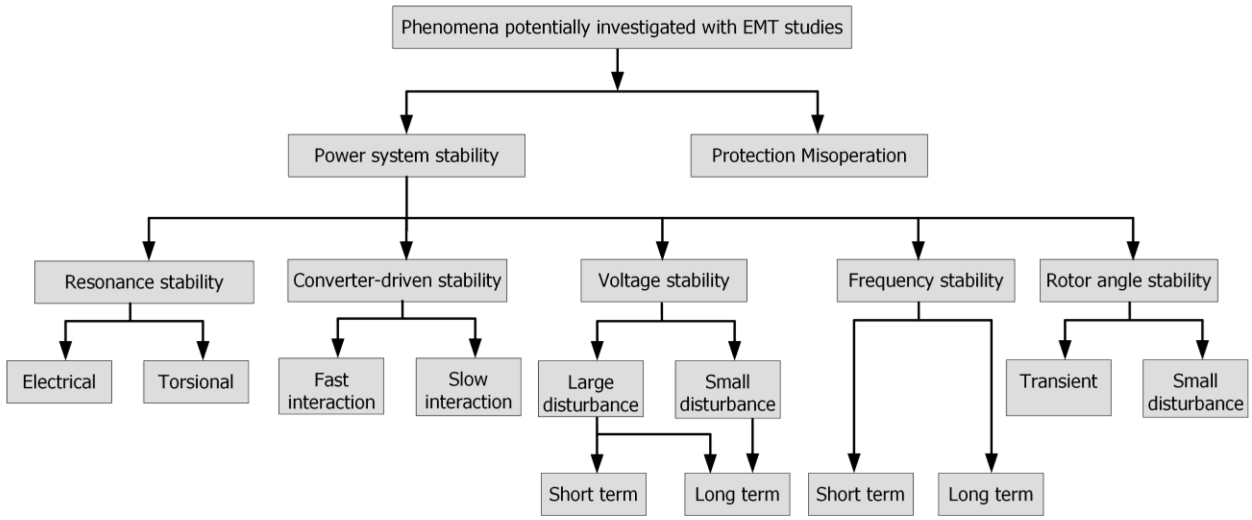


Figure 1: Phenomena Investigated with EMT

Conventional stability phenomena in the synchronous machine dominated grid, namely voltage, frequency and rotor angle stability, have traditionally been studied using non-EMT simulation tools (continuation power flow for long-term voltage stability assessment, phasor-based for dynamic assessment, etc.). The "resonance stability" and "converter-driven stability" were added relatively later to the list of conventional stability phenomena due to increased IBR penetration. The phenomena in these two categories, as well as certain demonstrations of the "traditional" categories when IBRs are involved, would often necessitate EMT studies for capturing the fast, complex, and dynamic behaviors of power electronic IBRs.

IEEE Std 2800™-2022 (herein after referred to as IEEE 2800) Annex C, *Inverter Stability and System Strength*, provides a comprehensive overview of IBR stability issues, including screening methods, illustrative examples, and potential mitigation strategies. IBRs can experience several types of instability that impact power system reliability and performance. Understanding these modes is critical for accurate modeling, analysis, and mitigation during system planning and operation.

Resonance Stability

Resonance in power systems occurs when energy exchanges periodically in an oscillatory manner, leading to magnified voltage, current, or torque oscillations if damping is insufficient. The resonance instability occurs when these magnified quantities exceed their specified threshold. Oscillations in power systems are a result of the energy exchange between different components of electric grid. These oscillations are often damped, but when there is an undamped amplification of normal background low magnitude oscillations, they can negatively impact power systems by degrading power quality, causing outages to generation and transmission equipment, or even damaging system components. As the penetration of IBRs in the BPS increases, the risk of oscillations also rises.

Oscillations can occur over a wide frequency range, and EMT dynamic performance study can be used to detect and analyze those oscillations for the frequency range over which the model is valid (typically from a few Hz to several kHz). Oscillations may occur at integer harmonics, subsynchronous, or super-synchronous (sometimes both denoted as SSO) frequencies and have many possible causes that may involve natural system resonance, control-driven device characteristics or even a faulty equipment. While the first two causes can often be analyzed with different simulations techniques including system-level EMT studies, those caused by faulty equipment in the field cannot be captured with typical models used in planning and operational studies. The Energy System Integration Group "Diagnosis and Mitigation of Observed Oscillations in IBR-Dominant Power Systems" guide [3] and the CIGRE "Guidelines for Subsynchronous Oscillation Studies in Power Electronics Dominated Power Systems" brochure [4] are useful resources on this topic.

Depending on the components involved, IBR-related oscillations can be categorized into the following categories and summarized in Table 1 below.

Table 1: Types of Sub- or Supersynchronous Oscillations Related to IBRs

Types of Synchronous Oscillations			
	Series Capacitors	Power Electronics	Mechanical Components (Steam Turbines, Gas Turbines, etc.)
Power Electronics	SSCI	Control Interaction	SSTI

- **Subsynchronous Torsional Interaction (SSTI):** IBR-related subsynchronous torsional interaction occurs when subsynchronous electrical oscillations originating from inverter-based resources interact with the torsional modes of nearby synchronous generators through the transmission network. Although inverter-based resources do not possess mechanical shafts, their control systems can inject or amplify subsynchronous current components due to interactions with series-compensated lines or resonant network impedance. These subsynchronous currents propagate through the grid and induce electromagnetic torque oscillations in synchronous generators at frequencies coincident with their shaft torsional modes (typically for gas turbines). If the phase relationship between the induced torque and shaft speed deviation results in negative damping, sustained growth of torsional oscillations may occur. In this mechanism, the IBR acts as the source or amplifier of subsynchronous electrical energy, while the mechanical impact is experienced by the synchronous generator shaft system.

- **Subsynchronous Control Interaction (SSCI):** IBR-related subsynchronous control interaction is an electrical instability driven by adverse feedback between inverter control systems and the subsynchronous impedance characteristics of the transmission network. At subsynchronous frequencies, network elements such as series compensation or resonant collector systems can create impedance profiles that interact unfavorably with inverter phase-locked loops, current controllers, or voltage regulators. In this environment, the inverter control response may introduce effective negative damping, causing subsynchronous voltage or current oscillations to be reinforced rather than attenuated. The resulting instability develops rapidly and is confined to the electrical and control domains, without involving synchronous machine mechanical dynamics. IBR-SSCI can lead to excessive current oscillations, converter blocking, or protection system operation, and is strongly dependent on control tuning, grid strength, and the aggregate behavior of multiple inverter-based resources.

- **Control Interactions:** Adverse interactions between power electronic devices at both subsynchronous and supersynchronous frequencies, particularly in weak grids.

It should be noted that resonance stability includes phenomena exceeding several Hertz (typically 5Hz) and can go up to 500 Hz or more due to fast IBR controller action. Thus, such phenomena often require EMT modeling. While other lower frequency oscillations, such as related rotor angle stability, can be investigated with the aid of conventional phasor domain simulations as transmission system impedances are reasonably approximated at these frequencies.

Converter Driven Stability

This category covers all the phenomena associated with interaction of IBR control loops with the electromechanical dynamics of power system or with electromagnetic dynamics of power system components including other IBRs. Such phenomena can occur in the subsynchronous frequency range (associated with electromechanical dynamics) to hundreds of kilohertz. These phenomena can be categorized in slow- and fast-interactions instability [5]. Figure 2 illustrates the graphical representation and the associated main causes of each sub-category.

Low frequency oscillations are often associated with the action of outer control loops and phase lock loops (PLLs). System strength has also significant impact on such stability phenomena, as demonstrated in real life examples, such as sustained oscillations in the range of 20-40 Hz in the weak grid-connected Type IV wind park in Xinjiang (China).

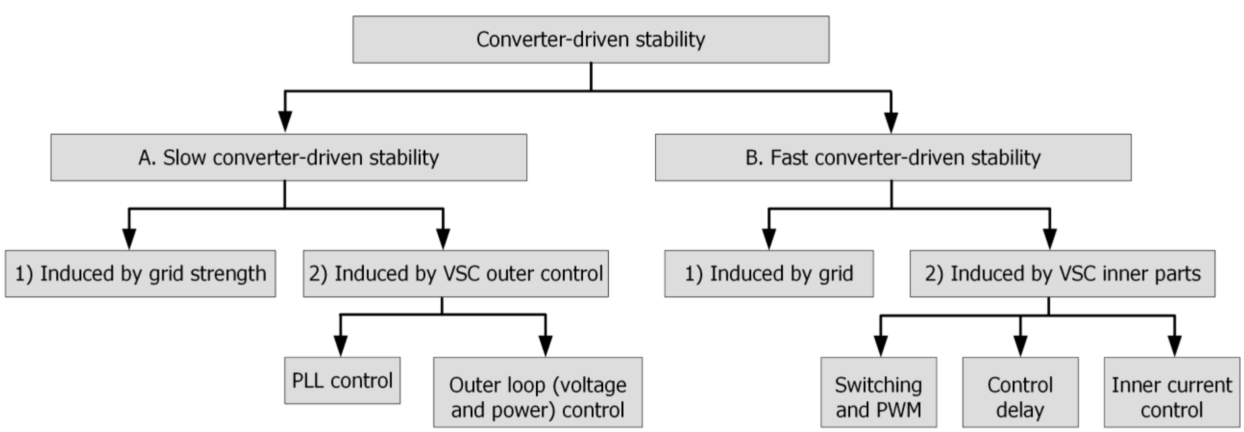


Figure 2: Types of Converter-Driven Stability

Such control instability often involves inadequate control tuning and protection configurations of IBRs. These may involve nonlinear control actions or mode changes that are triggered during system disturbances or external events. Figure 3 illustrates an example of control instability in a wind plant, characterized by a “chattering” behavior. In this case, the wind plant repeatedly enters voltage ride-through mode reducing active power output to support voltage recovery then exits the mode once voltage improves, only for the cycle to repeat. The plot depicted in Figure 3 shows voltage traces at several transmission buses during this event.

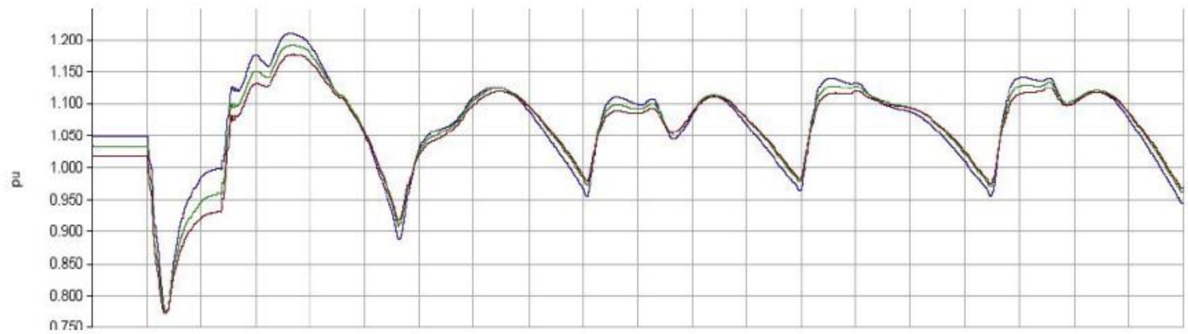


Figure 3: Control Instability (Mode Cycling / Chattering) at Wind Plant Connected to a Weak Grid

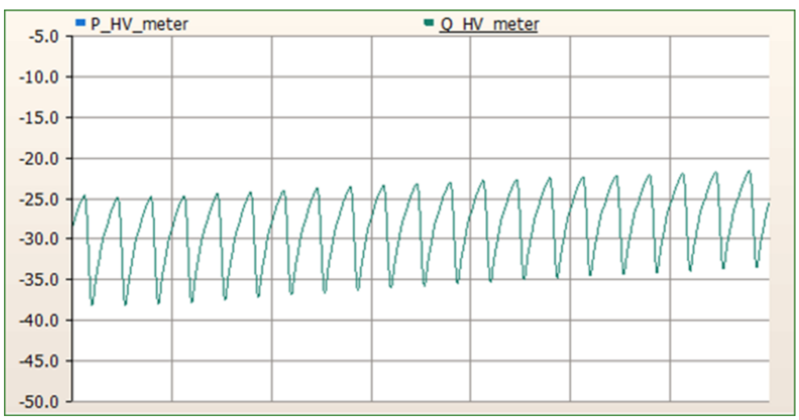


Figure 4: Reactive Oscillations due to Increased Voltage Control Loop Proportional-Integral (PI) Gains (SCR = 3)

Figure 4 above depicts another example of oscillatory instability due to high controller gains. The plot in Figure 4 is of an IBR with a terminal voltage that is at the edge of a low voltage ride-through (LVRT) threshold after fault recovery. If the plant controller is slow to change the reactive power command and was perhaps requesting the inverters to absorb reactive power before the fault, the inverter controls may repeatedly toggle between the power plant controller (PPC) commands and the inverter-level LVRT commands (which would be requiring the inverter to inject reactive power). This type of response is typically not accepted as a stable response, however the severity and duration of oscillation, as well as the potential system impact, should be taken into consideration when making such assessments. This can also be categorized as control mode cycling/chattering.

Voltage Instability

Voltage stability is defined as the ability of a power system to maintain steady voltages close to nominal value after being subjected to a disturbance. This phenomenon traditionally did not require EMT studies, except in rare cases such as associated with high voltage DC (HVDC) studies. However, large disturbance short term voltage stability often requires EMT studies under weak grid and high IBRs penetration conditions. This category includes unstable interaction between IBR voltage controller and the grid, voltage recovery issues associated with fault-current limitations, current priority setting (active vs reactive), negative-incremental Q-V support, etc.

Weak grids with high source impedance and low short-circuit current exhibit increased sensitivity of voltage to changes in active and reactive power (dV/dip and dV/dQ). This sensitivity can lead to voltage instability or collapse, especially under conditions such as high IBR output, reduced synchronous generation online, large power transfers, or system outages. For example, if the PLL is slow in grid synchronization and provides erroneous phase angle reference during large system disturbances, the resulting current injection may be at a wrong angle (e.g., injecting partly active current instead of required reactive current), resulting in further voltage magnitude degradation and potential instability without any preceding oscillations. Other outer control loops, such as the one responsible for mode switching (e.g., switching between grid forming (GFM) and grid following (GFL)), can also potentially cause instability if not properly coordinated.

Rotor Angle and Frequency Stability

These categories typically do not require EMT studies. However, in certain scenarios IBR penetration might have significant influence on these phenomena, especially if such penetration reduces grid inertia. EMT studies for analyzing rotor angle and frequency stability might be necessitated in such scenarios where a converter could create rapid active-power swings that significantly influence system frequency or machine angles.

Transmission System Protection Misoperation

As inverter-based resources continue to connect to the North American **bulk power system**, transmission protection engineers face growing challenges in ensuring reliable system protection. Traditional protection schemes were developed when synchronous generation dominated the grid and fault current behavior could be reliably predicted using machine impedances and time constants. Protection practices and relay settings were therefore optimized based on the well-understood physics of synchronous generator fault responses.

By contrast, the fault contribution of IBRs is governed primarily by inverter control systems (i.e., power electronics) rather than physical machine characteristics. These controls can produce responses that differ significantly from those of synchronous generators, and the behavior is often manufacturer-specific and less transparent to protection engineers. Documented instances of relay misoperations primarily caused by insufficient or inaccurate fault current injection from IBRs have been thoroughly examined in the study titled *Short Circuit Studies with IBR Penetrations and Distance Protection Application of National Grid Sub-Transmission System* (Ji et al., 2024) [6]. As a result, conventional protection assumptions regarding fault magnitude, duration, and system response may no longer hold in areas with high IBR penetration. This shift has direct implications for the dependability and security of transmission protection systems since misoperations under faulted conditions can threaten system reliability.

Objectives of protection system misoperation EMT studies include:

- Evaluation of the existing protection schemes and settings by determining whether relays and associated protection algorithms continue to operate correctly in systems with significant IBR presence.
- Identify reliability risks by highlighting scenarios where low fault current magnitudes or nontraditional IBR fault responses may compromise relay dependability or security.
- Support interconnection studies by providing criteria and guidance for identifying situations where additional EMT-based fault response analysis is warranted in the study process.
- Guide protection engineers by offering practical insights for transmission protection engineers to evaluate protection performance and consider setting adjustments or alternative schemes as needed.

3. When to Perform an EMT Study

Electromagnetic transient studies have been used to study the integration of bulk IBR plants, HVDC lines, and flexible AC transmission system (FACTS) devices for years. In the past, these studies tended to be limited to project developers and the Original Equipment Manufacturers (OEMs) that provided equipment for the projects. However, recent system events have indicated that relying solely on plant developers to perform these studies may lead to unwanted performance behaviors potentially leading to reliability concerns. Examples include the multiple events where momentary cessation led to several GWs of active power reduction in California and Texas [7].

When combined with a clear set of performance requirements, EMT studies are a powerful tool in IBR plant integration and for identifying reliability risks early on. Further, assessing source impedance strength, commonly referred to as system strength, at the potential points of interconnection (POIs) is critical during the planning and design phase of IBR deployment. Low system strength can adversely affect stability and performance of IBRs.

Here are some examples of what triggers the need to perform EMT simulations and studies by a Transmission Owner (TO) or Transmission Planner (TP).

- Demonstration of performance for a new generator interconnection
- When there is a risk of instability, such as:
    - when the short circuit level is low
    - when an IBR is connected close to another IBR
    - when there is a risk of resonance, such as subsynchronous resonance with a series capacitor compensated line
- Root cause analysis following a disturbance or compare simulation with test results
- To prevent the risk of misoperation of the TO protections or GO protections
- Overvoltage risk following network unintentional islanding
- To validate a phasor domain model by benchmarking it against an EMT model

EMT studies for IBRs may be performed either during their interconnection stage or as part of regular planning assessments. The interconnection process is hereby defined as the period between the initial submission of a new facility application to the planning coordinator all the way until the point where the plant enters commercial operation. The interconnection stage may include studying the IBR plant individually, studying multiple IBR plants collectively as a cluster, re-studies as needed as a project moves closer to final engineering design all the way to its commercial operation date (COD).

EMT studies performed after a plant enters commercial operation fall into the realm of traditional system planning studies.

- **Interconnection studies** aim to assess the impact of the interconnecting IBR(s), identify potential network upgrades, and evaluate the performance of the IBR plant when connected to the system.
- **Planning studies** evaluate the cumulative effect of existing IBRs on system reliability under different dispatch conditions as the grid evolves over time, as well as specific system risks (e.g., NERC TPL and NPCC Directory 1 studies, UFLS studies, restoration studies, etc.).

Screening Methods

While performing EMT studies for every IBR might be the approach used by some entities, other regions may find it challenging or unnecessary to do so. This is due to several reasons, some of which are discussed below:

- IBRs connect to strong grids where Phasor Domain Transient (PDT) studies may be sufficient to determine system impact.
- EMT modeling, validation, and studies can be resource-intensive, and performing them at scale (i.e., hundreds of them) may take a substantial amount of time, computational power, and highly limited engineering resources.
- Limited availability of skilled personnel makes it difficult to perform large numbers of EMT studies in parallel or at once.

- The availability of highly detailed PDT models (often UDM models) can be effective in capturing the true plant behavior and support an accurate assessment of plant stability, reducing the need for EMT studies.

However, PDT models may optimistically predict the ability of an IBR to remain connected and synchronized to the grid during system transients. This can be due to various factors, such as:

- PDT models take the bus phase angle directly from the network solution without using a phase lock loop (PLL) to measure it, as is done in actual plants. This simplified control representation may not adequately capture the plant behavior in PDT studies. Enhancements to PDT models (e.g., the use of user-defined models) can go a long way in the inclusion of PLL controls, current regulators and other OEM specific controls. Highly detailed UDM models can be very effective in capturing IBR plant stability behaviors but may still not be sufficient to capture all details of interest.
- PDT models do not include a detailed representation of the controls that may play an active role in the interaction between IBRs, particularly when interactions occur at higher frequencies (e.g., >20Hz).
- PDT models have an inability to capture network resonant conditions at off-nominal frequencies, such as the ones introduced by series compensation, which prevents their use to evaluate SSR and SSCI phenomena. Therefore, technologies that use line commutated converters or voltage source converters such as HVDC, STATCOM, and other FACTS devices have traditionally been studied using EMT.

In essence, depending on the type of concern and risks that need to be studied, an EMT study may be unnecessary, or it may be the only appropriate option. As a result, screening methods are commonly applied to determine the need for EMT studies during the interconnection process. These may include one or more of the following:

- **Plant MVA rating:** A simple way to screen IBR plants, HVDC converters or FACTS devices for the need of an EMT study can simply look at the size of the plant or converter interconnecting to the grid. For instance, a region may choose to perform an EMT study for any IBR plant rated for a generic 'X' MVA or larger. That doesn't mean that an EMT study is not needed for plants below 'X' MVA, but that other factors will also need to be considered. For example, the interconnection of very large plants (e.g. ~1GW) will likely lead to EMT studies being performed because the impact of those plants on the system is significant and therefore using high fidelity EMT models, regardless of other factors, is of interest. Alternatively, a smaller plant (e.g., 80MVA) may not trigger the need for an EMT study, especially if it is known to interconnect to a strong system and there are no other known risk factors nearby (e.g., presence of other IBR plants, series capacitor compensated lines, etc.).

- **Short-Circuit Ratio (SCR) Screening:** Traditional SCR is defined as the ratio of available short-circuit MVA at the point of interconnection to the plant's rated MW capacity. Low SCR (e.g., <3) typically indicates a weak grid, where EMT studies are recommended to evaluate the IBR plant stability. The formula for SCR is given in Appendix 1.

- **Emerging Alternative-SCR screening methods:** SCR screening method loses its effectiveness in networks with high levels of IBR penetration. Multiple variants of the traditional SCR metrics have been proposed to address those limitations, such as the Composite SCR method and the Weighted SCR method. This is due to the fact that the SCR method was proposed at a time when the majority (or all) of the short circuit MVA contribution would come from synchronous generators. Not only have short circuit MVA levels gone down, but a significant amount is now provided by grid following IBRs, which still rely on a network reference frame for power injection and cannot establish the network voltages themselves. This will affect the ability of traditional SCR methods to remain accurate and effective in those regions. Upcoming grid forming technology (GFM) may help maintain traditional SCR metrics relevant since they operate as a voltage source, similar to synchronous machines. That will largely depend on the ratio of GFM and Synchronous Generation versus GFL IBRs. Variations of SCR (i.e., Weighted SCR, Composite SCR) represent an important evolution in the way that projects are screened for the need of time domain EMT studies. The formulas for Weighted and Composite SCR are given in Appendix 1. Additional metrics related to system strength and stability are detailed in IEEE 2800 Annex C [8].

- **Presence of Other Devices Near the Project**: Some interactions between IBRs and other devices cannot be captured using PDT studies. Examples include:
  - Control interaction between multiple IBRs or between IBRs and other inverter-based devices such as HVDC and FACTS
  - Subsynchronous Control Interaction (SSCI) with series-compensated lines
  - Subsynchronous Torsional Interaction (SSTI) with nearby thermal units

- **Screening with impedance-based methods:** Some regions may use impedance-based methods (i.e., frequency scan) to screen for the risk of certain types of subsynchronous oscillation issues. One example of an impedance-based method that can be applied to evaluate SSR and SSTI risks uses electrical damping torque (De) plots to evaluate the impact of new IBR plants, converters or series capacitors near existing synchronous thermal power units pre- and post-project [9]. As shown in Figure 5**Error! Reference source not found.**, if significant dips in De are observed, or if De becomes negative for a frequency range, or if De dips align with torsional mode frequencies, the risk for adverse torsional interactions increases. This method, when applied in conjunction with available torsional models (spring-mass models) and mechanical damping (Dm) and net damping (Dnet) torque values, can be effective in determining risks of SSR and SSTI. If risks are found to exist, time domain EMT studies can be used to complement the method and to evaluate and design mitigation alternatives.

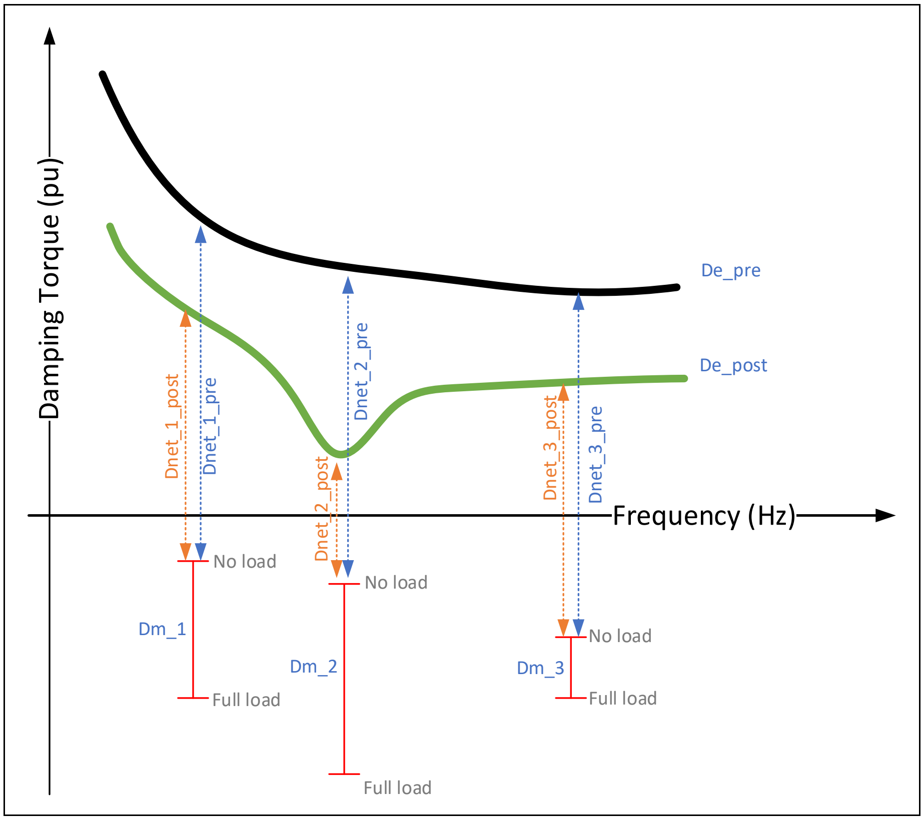


Figure 5: Illustration of Electrical, Mechanical and Net Damping Torques for a Synchronous Generator over the Subsynchronous Frequency Range

Timing of EMT Studies in the Interconnection Process

There is no industry consensus of when to perform EMT studies for new projects interconnecting to the system. Some entities request EMT models early on in their interconnection study process, others request EMT models later, after the initial cluster studies are completed.

In general, obtaining accurate EMT models in the early phases of a project is difficult. It is not uncommon for projects to have not yet signed equipment contracts with their OEM suppliers until they have an idea of whether they can accept cost allocations for system upgrades. The specific product line to be used may not yet be defined or may still be under design by the OEM. Similarly, the electric design (balance of plant design) may not yet be finalized at early stages of the cluster study period. Practical experience indicates that project updates are rather the norm than the exception. Last, adjustment to plant controller settings during commissioning to meet performance requirements may lead to the need for model updates.

In the interconnection study process, EMT models are requested at various points in time and EMT studies are performed over a period of time. The recommended interaction between developer, OEM, and planning entities as an interconnection project matures is presented in Figure 2.2 of a NERC Reliability Guideline on Recommended Model Requirements [10]. The scope of each EMT study may also grow or evolve over time, ranging from a reduced scope at the beginning (where there is a high chance that the EMT model will have to be updated) to a more detailed (and in-depth scope) as the plant nears its COD. Before commercial operation, plant owners and OEMs should have defined the final equipment settings and configuration and can develop EMT models that closely reflect those settings. The use of those EMT models can lead to more definitive study conclusions. A summary of advantages and disadvantages of each approach is provided below in Table 2.

Table 2: Considerations for When to Perform an EMT Study

Considerations for When to Perform EMT Study in the Interconnection Process		
	Early	Late
Advantage	Potential system upgrades are identified early, allowing more time for mitigation, evaluation and deployment.	Uses more realistic equipment settings, leading to studies that tend to provide more actionable results.
Disadvantage	Often there are changes to the IBR control design for project specific locations that typically are not available when the interconnection request is submitted.	Developer may not know the total upgrade cost until later phases of the project

Regardless of when an entity may choose to perform EMT studies during the IBR interconnection process, performing the studies before the project enters commercial operation is strongly recommended as it helps reduce project risk and ensures potential issues are identified and addressed before IBR plant energization.

EMT Studies in System Planning

Certain planning studies, while not mandatory at the current time, are beneficial to enhance or maintain the reliability of the **bulk power system**, due to the nature of power electronic converter technology that is used by IBRs. With the increasing penetration of IBRs displacing synchronous generation, some regions have found increased risk of stability concerns because traditional Phasor Domain Transient studies are insufficient to monitor and evaluate system reliability. It is recommended that EMT study tools be utilized to perform (1) post-disturbance studies of unwanted IBR events such as reduction of IBR plant output, IBR facility trips, or persistent oscillations, and (2) verification of protection scheme function.

Each region should periodically assess its system to identify areas where EMT studies may be required now or in the future, particularly in weaker network areas with large concentrations of IBRs that may be online under certain seasonal or load conditions.

Post-Disturbance Studies

The main purpose of performing EMT studies during interconnections and system planning timeframes is to maximize reliability by reducing the chances of unwanted IBR plant events, such as reduction of total plant output, plant trips, or persistent oscillatory behavior.

While EMT studies are effective in reducing the number of IBR events, it is difficult to completely eliminate the risk for unwanted IBR plant trips and other behaviors. Post-disturbance event studies are sometimes performed to identify root cause of the event and help identify and evaluate corrective actions to be implemented. For example, some oscillatory events cannot be recreated in phasor-domain simulation and require EMT simulation studies, especially if the PDT models do not include the controls that play a role in oscillatory behavior. Many EMT tools provide ways to import COMTRADE files directly for use in play-in tools or for event visualization. Additionally, EMT tools contain a data signal toolbox that allows the filtering and processing of field measurements, making them a powerful tool for event replication and simulation of high-fidelity equipment models. Overall, EMT studies combined with field recordings from fault recorders, event recorders, or phasor measurement units (PMUs) can be a powerful tool to help identify issues and mitigation in a post-disturbance timeframe.

Verification of Protection Scheme

Accurate inverter models may not be available in short circuit and relay coordination programs, such as ASPEN one-liner or CAPE. Using EMT models and simulation can be useful to verify the accuracy of ASPEN or CAPE protection models, or to allow the detailed evaluation of protective functions in EMT studies. The voltage and current analog information from IBR models in EMT can also be exported to COMTRADE files and re-played back in the relay testing apparatus. COMTRADE files from relay recordings can also be imported into EMT tools for play-in simulation. Therefore, using EMT models and studies can be a good complement to more widely used tools for protection studies.

Voltage and current outputs from IBRs are different from conventional synchronous generators under fault conditions and primarily driven by the control logic used in the converter controls. Inverter response under unbalanced fault conditions vary among the different OEMs and unless there are requirements specifying the fault response characteristics, it is likely that wide variation may be observed. For instance, inverters may prioritize the injection of active or reactive currents during faults, especially when current limits are hit.

Inverters may or may not generate negative sequence current (I2) and the phase angle between V2 & I2 is not predictable. The IEEE 2800 standard has established requirements for negative sequence current injection from IBR plants during faults, but the standard has no enforceability unless adopted by a governing body. If adopted, it can help specify the requirements for negative sequence response characteristics from IBR plants, among other fault condition requirements (i.e., IBR plant response during abnormal voltage conditions). Some regional organizations have adopted IEEE 2800 indirectly but created their own local or regional reliability rules. For instance, in NY state, the New York State Reliability Council (NYSRC) has adopted reliability rule B5, which in essence adopts various clauses of IEEE 2800 standard including a clause that specifies the ability for TOs to define the level of negative sequence current contributions from IBRs.

Some of the protective functions available in modern digital protective relays can use negative sequence current (I2) information for the fault directional detection and faulted phase identification/selection. Examples of protective functions that can require negative sequence currents and voltages include:

- Negative Sequence Overcurrent
- Negative Sequence Voltage
- Directional Elements for Unbalanced Faults
- Out-of-Step Protection
- Generator and Motor Protection

Digital relays may not operate or may misoperate under certain unbalanced faults due to lack of I2 or improper phase angle relationship between V2 & I2 from inverter sources. For a close-in three-phase fault, the distance elements of the relay would have no polarization or voltage reference and would not operate without pre-fault memory voltage that is designed in digital distance relays.

Performing EMT studies can help with identifying potential protection misoperation in the presence of IBRs and help protection engineers design a reliable protection system.

4. EMT Model Acceptability

Model acceptability is the process taken to make sure that the EMT model is sufficiently accurate and useful for the facility it represents, in consideration of how far developed the facility is. Following this, acceptability is divided into two themes:

- Verification that the model meets the modeling requirements (checklist) and that the model is specifically configured for the project.
- Validation that the model represents the IBR as accurately as possible.

To ensure that TOs/TPs/Planning Coordinators (PCs) have the ability to accept EMT models as part of the interconnection process, it is recommended for entities to require a software setup from Generator Owners (GOs), OEMs and for themselves to run the needed studies. For example, an installation of PSCAD 5.02 or later (5.02 is the latest as of drafting), EMTP 4.5.0 or later (4.5.0 is the latest as of drafting) or other comparable EMT software. Additionally, if compiling is required, then GOs should ensure their models compile with a Fortran Compiler that is compatible with the software version being used (commonly used is the Intel Fortran Compiler 2021 32 Bit). Models should also be compatible with a common Fortran one API version (commonly prescribed is 2021 or later). Also, they should ensure the correct version (x32 vs. X64) is provided.

EMT Model Design Choices

Different practices exist in designing and building EMT models for IBRs and the model accuracy varies depending on the design choice. The extensiveness of the validation process can depend on these design choices and as such it is important to understand the difference between these and when possible, requesting a more accurate design can save on validation efforts.

Real Control Code Model

Certain model design practices ensure good model representativeness, particularly simulations using "real control code models." In this case, the EMT model uses exactly the same control algorithms as the control equipment.

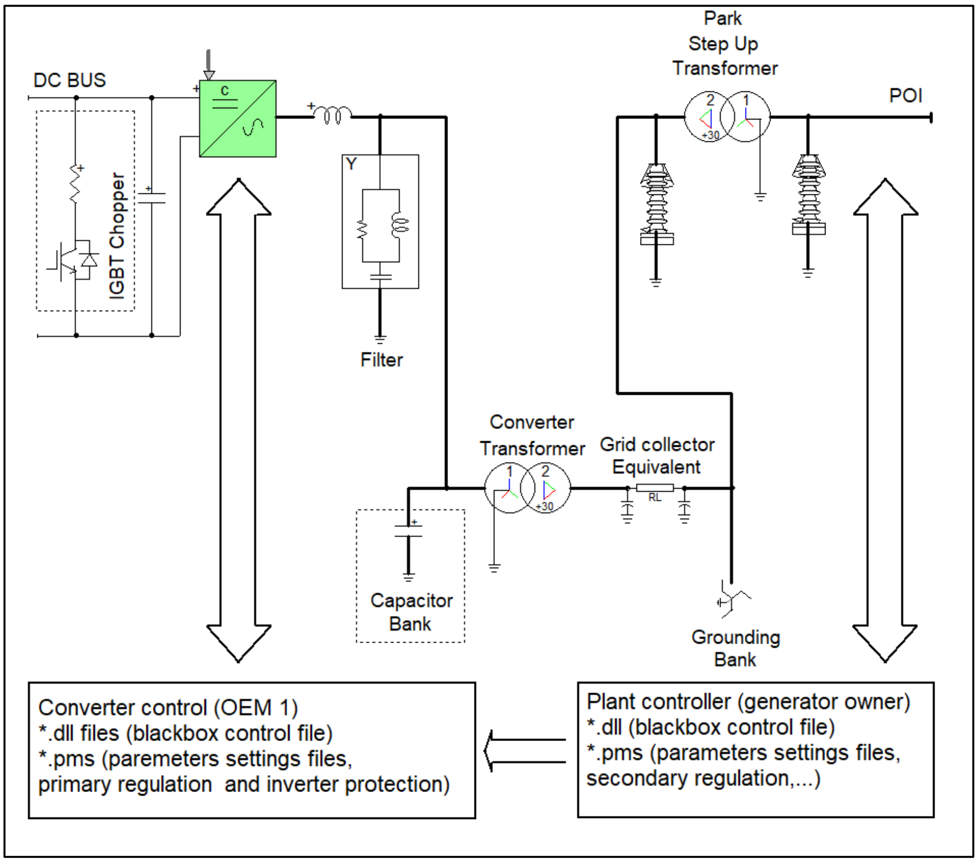


Figure 6 below presents a typical diagram of a producer connected via inverters to illustrate this principle of using blackbox control (.dll) and associated control and protection parameter files.

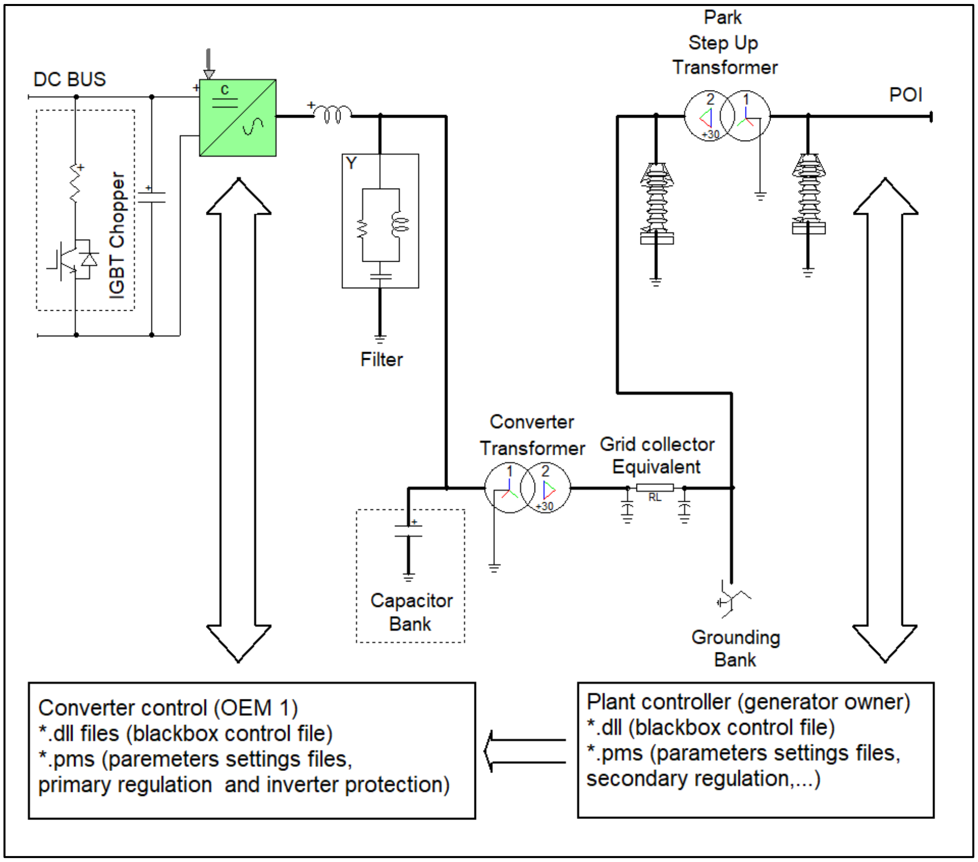


Figure 6: Typical IBR Plant Model Using Real Control Code

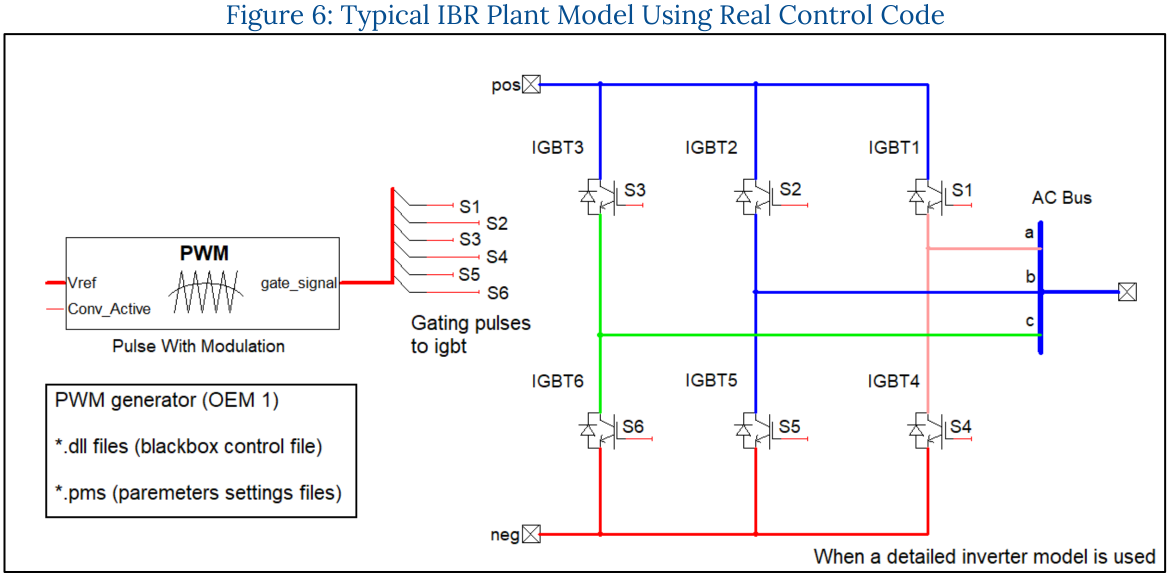


Figure 7: Detailed Inverter Model Using Pulse Width Modulation (PWM) Control Code

The control part, to respect intellectual property, could be a "blackbox" type (e.g. .dll file). In this regard, compliance with standards such as CIGRE TB 958 allows blackbox control files (.dll) that can be independent of the simulation software used. Using "real control code models" also saves validation time when updating parameters or converter firmware, ensuring that the model accurately reflects the control code deployed in the equipment. The model must still be validated, particularly for its behavior when using different parameters. Nonetheless, the validation of the control algorithms itself could be less detailed when real code models are supplied.

Another advantage of using a real control code model is that it allows the producer to adjust converter parameters according to the project (weak network, transformer impedance, saturation representation, etc.) and to have greater confidence in the system's proper functioning for demonstrating compliance with grid codes.

Furthermore, for all other conventional equipment (transformers, surge arresters, asynchronous machines, etc.) in the plant model, it is recommended that all parameters (electrical characteristics, saturation curves, etc.) be open and fully accessible to the users. This also facilitates the use of the same models on different software platforms (EMTP, PSCAD, Opal-RT/Hypersim, RTDS, etc.), and the sharing of information between utilities or different stakeholders.

Using open models for conventional power equipment, where the equipment limits are clearly identified and modeled, would greatly facilitate discussions between OEMs, GOs, and NPCC members, particularly during event analyses, but also to facilitate model acceptance.

Approximate Blackbox Models

In these models the control logics and equipment components are built using EMT tool components to represent the inverter behavior. The logic blocks are often placed in blackbox components that are not visible to the user. This type of model requires a more extensive validation to evaluate the representativeness of the model of the actual inverters.

In real code models, some high-level validation can show if the code used in the EMT model is similar to inverter code and once that is established, more extensive testing can be skipped. In the approximate blackbox model, more extensive validation testing is required to make sure the model response is similar to the inverter response under different scenarios and grid conditions.

Relaxed Real Code Models

A model can partially include the real code and partially can be built using blackbox components. This type of the model falls between the two different types in terms of accuracy and need for exhaustive validation.

Generic Models

Generic models can be built by anyone that can represent inverter switching and some generic control and protection logic, but they are not representative of any specific OEM's actual inverters. These types of models may be used for some legacy plants where obtaining actual models may be difficult but should be avoided for all new projects. Some model validation may be useful for these models to tune the accessible parameters to better represent the legacy plants.

Models for Legacy/Operational IBRs

For IBRs that have already commenced commercial operation without an EMT model, it is necessary to request the facility owner to have one created. There will likely be challenges of either technical or resource availability in the supply chain for owners to have EMT models developed. All model options and the associated production times should be assessed between the owner and Transmission Planner. For cases when the OEM exists, one possible approach is to use a new EMT model (for newer equipment) but modified to match, to the extent possible, the protection settings at the facility.

Model Verification

EMT Model Checklist and Attestation

High quality EMT models are critical when performing tests (specifically but not limited to tests on performance requirements and subsynchronous interactions). Bearing this in mind, it is imperative that, at a minimum, TPs and PCs require high quality EMT models for interconnection projects (even if current penetration is low). To maintain consistency in

EMT models provided by various GOs/OEMs, TP/TO organizations have and should develop a model quality checklist for the respective GOs to complete and submit along with the EMT models, attestation and documentation as part of the interconnection process. Many member utilities and ISOs already have their own model acceptance checklists for general EMT model acceptance. Additionally, NERC provides an example checklist in Chapter 1, Table 1.1 of the NERC Reliability Guideline *Electromagnetic Transient Modeling for BPS-Connected Inverter-Based Resources – Recommended Model Requirements and Verification Practices* (March 2023) [10] that is TO/TP agnostic. The checklist should provide focus at the minimum on these key categories:

- Plant and model documentation
- Model verification and validation documentation
- Model components and level of detail
- Model construction, accuracy, usability, and efficiency
- Model Key Points of Contact
- Model Required Settings and Parameters

What follows are recommended features to be included in a model acceptance checklist.

Documentation/Instructions for Model Setup

- **Ability to setup model in voltage control, reactive power control, etc.** A model should have the capability to set the IBR unit up in voltage control, reactive power control, or constant power factor mode. This can be in the form of input parameter in model component, a three-way switched input inside model details, or any other easily identifiable way. Voltage control mode is usually the default mode of operation, but an IBR should be able to operate in all three modes of operation without sacrificing performance.

- **Specifics on units provided/output.** The models such as Power Plant Controller (PPC) must have inputs to pass along as reference to the main generation unit for target power, voltage and frequency at point of interconnection. The units for these inputs should be clear. Some possible units are MW, kV, Hz for power, voltage and frequency. It can also be in per unit (pu). In such cases, the base value for all the quantities should be clearly mentioned in model documentation and/or in text box instruction inside software.

- **Required ancillary files, file directory structures.** Model documentation should specify the hierarchy of files required for successful EMT simulation and testing of the unit. The folder structure and the model files including main EMT software file and ancillary inputs like .dlls, .lib files etc. if any and their order of placement in folder as well as sequence of reading them in EMT software for successful simulation should be mentioned in documentation and briefly in the form of text box content in EMT software if feasible.

- **Description of state values as part of the model, including unit trip indication, which protection trips during fault, etc**. EMT software usually does not have well defined property of component (generator) to indicate its online or offline status etc. They also do not generate a systemic log file during simulation like in RMS based programs. So, the model should ideally have an output parameter to indicate its status of in service or out of service and if it has tripped, a parameter to indicate which protection or feature caused it including the time stamp. This will assist with evaluating the simulation output and distinguishing it from other behaviors like momentary cessation where the IBR unit may have ceased to produce output but has not tripped.

- **If applicable, list minimum SCR at inverter terminal in order to ride-through.** Model documentation should have a clearly defined set of short circuit ratio conditions at POI when the model EMT simulation is expected to run smoothly. Usually testing of an EMT model includes testing it under various contingencies with potentially different SCRs at POI and any inherent limitation in submitted model should be clearly mentioned.

Model Components

The model shall accurately and transparently represent the as-built generating facility performance, with some considerations for ensuring model accuracy as follows:

- **Aggregation and equivalencing**. Aggregated inverter, collector system, and inverter-GSU equivalencing methods are fully documented, with ratings, assumptions, and limitations visible to the end user. Scaling techniques and their impact on dynamic accuracy are clearly stated. In most cases, aggregate models of the same inverter type are sufficient to reduce computational burden when studying the **bulk power system.**

- **Electrical network representation**. Main power transformers, substation components, generator tie lines, filters, specialized transformers, and shunt capacitor/reactor banks are modeled explicitly. Transformer magnetizing curves are included. Transformer nameplate data matches test reports, and winding configurations match site design.

- **Plant-level and advanced controls**. All inverter-level and plant-level control features and operating modes are included, such as:
    - Detailed fast control loops of power electronics are implemented as installed in the field
    - Approximate or reduced-order transient stability representations are not permitted
    - Models are created by embedding actual hardware firmware into EMT software components, either as source code or compiled binaries/DLLs when source code is confidential
    - If master library blocks are used by the software, validation against actual hardware performance is required
    - External voltage and plant controllers
    - Customized PLLs
    - Ride-through controls
    - Grid forming controls, if available
    - Subsynchronous control interaction (SSCI/SSO) damping controllers
    - Common controllers and hybrid plants (e.g., PV/BESS) are fully represented

- Hardware and software filters and limiters are modeled in detail

- **Mechanical effects.** Mechanical features that affect electrical performance (e.g., gearboxes, pitch controllers) are included.

- **Protection systems.** All relevant inverter-level and plant-level protection functions are included for balanced and unbalanced faults, including voltage, frequency, DC bus, and overcurrent protections. Protection features influencing ride-through or dynamic behavior are implemented using actual firmware code. SSO mitigation and/or protection functions are included with enable/disable capability.

Model Usability Features

Model Usability features are important to improve study efficiency and model compatibility with the software utilized by planning organizations. These features aid in ensuring cohesion across system studies performed with EMT models. Many planning coordinators publish planning guidelines that discuss the usability of models and settings to be implemented in EMT. While modeling guidelines vary based on the planning coordinator's control area, key model features include, but are not limited to:

- Ability to run for a range of timesteps (i.e. 10-20μs), with a common minimum being 10μs. This allows for integration of multiple EMT models that may vary in timestep.
- Capability to initialize itself to full output without external input from the engineer performing the simulation
- Accessibility to control and protection (trip) settings relevant to the study objectives
- Model acceptance of external reference values, with specific control at initialization and runtime of active and reactive power and voltage setpoint
- Active power is scalable and dispatchable
- The IBR model does not use global variables to avoid interfering with other variables
- Model supports multiple instances of its own definition in the same simulation case

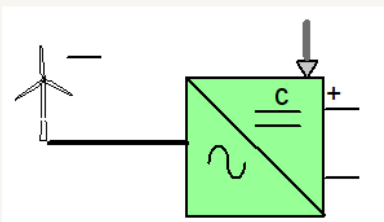
Examples of model usability features are referenced in various planning guidelines, such as NYISO's "UG 28 NYISO Electromagnetic Transient (EMT) Modeling Guideline", ISO-NE's "Planning Procedures PP05-6 Appendix C-1", "NSPI-TPR-015-3 PSSE and PSCAD Model Requirements" in Nova Scotia for PSCAD; [11] – [13], respectively. Similarly, example model usability features for EMTP are in Hydro Quebec's "Functionality and conception analysis of IBR EMTP models" [14].

Information on Internal System Behind the Converter

The representation of the system behind the converter is essential in the model. That source can be modeled with varying levels of detail; however, the model must include key limits allowing the simulation of internal system faults and the operation of protections (e.g., DC current and DC voltage protections).

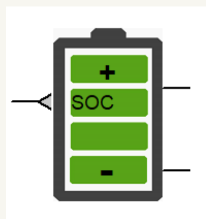
Before demonstrating that internal system protections (such as DC protection) do not operate for a network event, it is good practice to first demonstrate their correct operation for an internal fault where they are expected to act. Using an open model can help identify limits that may appear during large-scale events and assist GO in validating and studying system behavior by also simulating internal plant faults. OEM testing methods depend on these limits, as network stability is also influenced by them. Currently, there is no clear requirement to demonstrate internal system fault operation prior to ride-through demonstration by simulation.

The OEM's choice of model design, often a blackbox approach, makes such validations impractical. At a minimum, the model documentation should include a list and descriptions of the internal system protections that are implemented in the model.



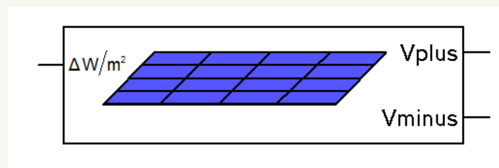
Wind Generation

Asynchronous wind machines with AC/DC inverter



Battery

Battery cells, connected in series or in parallel, with limits represented for the state of charge



Photovoltaic Solar

PV solar cell with connections, representation of their limits and any other specific control strategy(ies)

Figure 8: Different Sources of Energy Behind the Inverter

Validation of Model Representativeness

Validating an EMT model is important because it enhances confidence in its representativeness and hence the consequent study results. To validate the EMT model, different approaches can be undertaken at various stages of a project:

- Comparing the model with commissioning test results
- Fault tests results compare to simulation
- Comparing the model against hardware-in-the-loop simulation tests using real equipment (type tests)
- Simulating a real event and comparing the model response with the event recorders

The more comprehensive the validation, the higher the associated cost and complexity. There is a balance to be struck between the tests conducted and the credibility gain we achieve for the representativeness of the EMT model. In this regard, some tests, such as fault tests, could be carried out as part of a qualification process covering multiple projects, while other tests should be systematically performed for each project.

Commissioning Tests

Commissioning tests allow the assessment of system performance and compliance with grid codes for normal operating conditions. Comparing these test results with simulation results helps validating a part of the model.

Certain tests, such as power or MVAR setpoint changes and step response tests, would allow the validation of EMT and phasor domain models for certain normal operating conditions and the adjustment of controls.

Load shedding tests with no load (or a small load) could also be considered during commissioning. This would validate post-event voltage behavior in simulations and during tests. Indeed, this is a case that can be severe for the plant equipment, and this test should give a good indication of the plant's behavior during network separation with little load and the risk of transient overvoltage that could occur. A load shedding test during commissioning helps to parametrize some IBR control and protection strategy, as loss of the PLL, DC voltage or control limiters and associated protections has observable impact on the behavior of the IBR.

Fault Tests

A load bank can be used to test a wind farm unit for low-voltage ride-through (LVRT) requirements. Balanced and unbalanced loads, calculated for different voltage dips, can be applied to simulate the voltage drop during various fault conditions. This type of equipment qualification test confirms that the system meets connection requirements during faults.

Transformer energization tests can be also interesting and similar to a fault test for validating control and protection functionalities and parameters such as voltage or current limiters and protection settings.

Comparing these results with simulation results helps confirm system performance and model quality.

This is not the type of test that one wishes to perform systematically for every project. A fault test container (load bank) can be used when employing new technology or new equipment, especially when no manufacturer test results are available.

Hardware-in-the-Loop Testing

In the absence of a "real code model" or to confirm that there is no difference between the model and the control equipment, it is possible to connect the control and protection equipment of the converters to a simulated park and run real-time tests (RTDS or Hypersim) and compare the EMT simulation results with the behavior of the real controller.

This type of simulation allows the reproduction of more complex network phenomena that are difficult to achieve during on-site tests. It allows testing of control for network events that are more difficult to achieve during commissioning, such as frequency variations, voltage variations, the addition of harmonic content, operation in the presence of a negative sequence voltage, operation under different network conditions such as a strong network and a weak network, phase angle jumps, etc. Those events are practically impossible to test on-site. The power components must be very well modeled.

A variant of this approach is the use of a complete system replica that includes both the power and control parts adding complexity to the test set-up.

Fast Transient Recorder and Event Analysis

Post-event analysis requires the deployment of fast transient recorders. The advantage of this method is that it confirms the representativeness of the entire IBR park model during that event. The disadvantage is that normally at this point the model had been accepted, and it is harder to get an updated model if discrepancy is found between the model response and the event recording. This approach is recommended in some NERC event reports and will require staff to compare simulation results to those events. Please see Post-Disturbance Event Analysis section for more details in section 6 of this guideline.

5. Grid Code Compliance Through EMT Simulation

Before progressing to detailed grid-wide EMT or RMS simulations, it is standard practice to conduct studies on a simplified Thevenin equivalent of some system considering varying strength/SCR. These provide a simplified but powerful framework to evaluate the core dynamic and control capabilities of the IBR under controlled and repeatable test conditions.

Studies using Thevenin equivalent representation enable targeted testing under controlled grid strengths such as those below (however, metrics should be system specific):

- Strong Grid: High Short Circuit Ratio, typically >5
- Moderately Weak Grid: SCR ~3-5
- Weak Grid: Low SCR, typically <3

This setup isolates the IBR's control and protection system behavior without interference from external network dynamics. To examine the dynamic performance of a **generation facility** or dynamic transmission element, all site-specific dynamic models needed to represent the facility shall be included in the test. The following model guidelines apply:

- The facility model is connected to a controllable infinite bus behind an equivalent impedance whose voltage and frequency can be adjusted for testing.
- For generation **resources**, the generator is dispatched at full real power output, and the POI bus voltage is initialized to nominal 1.0 per-unit unless the test requires otherwise. Facilities that include energy storage systems should also be tested at full real power withdrawal. The initial reactive power exchange at the POI should be near zero unless the test requires otherwise.
- Behind the POI, the generator(s) and step-up transformer(s) shall be represented along with any additional planned or installed static and dynamic reactive equipment.
- Station transformer taps and static switched shunts should be initialized to a nominal position appropriate for the initial POI voltage and real power dispatch.
- Any switching controls that are expected to provide a response within 20 seconds (e.g. automatic switched shunts or on-load transformer tap changers) should be reflected in the dynamic model for the resource.
- Aggregate generation **resources**, such as wind and solar, should be represented by a single equivalent aggregate model per registered Resource (i.e. allowed aggregation) and include a representation for the collector impedance and pad-mount transformer. All dynamic control systems should be modeled (generator, exciter, governor, power system stabilizer, automatic voltage regulator, power plant controller, voltage, and frequency protection, etc. as applicable).
- Simulations should be run for a minimum of 20 seconds and show that the facility response has stabilized.

Ride-Through and Dynamic Performance Tests

The following section outlines a suite of EMT validation tests used to evaluate the accuracy, control behavior, and grid-support capabilities of IBRs. These tests are recommended to ensure that EMT models submitted by developers are capable of replicating real-world behavior across a range of operating conditions and grid strengths.

These simulations are typically conducted by the system operator or a designated third party to ensure conformance with grid codes and industry standards. They assess model performance under steady-state, dynamic, and disturbed system conditions.

Each entity may have its own specific ride-through requirements (that meets NERC Reliability Standard PRC-029 at minimum) or may follow an industry standard such as IEEE 2800. IEEE 2800 includes expected performance under abnormal system conditions — primarily related to voltage and frequency excursions, fault events, and phase angle dynamics. This section uses IEEE 2800 as an example to demonstrate details of different ride-through or dynamic performance assessments. As of the time of writing, ride-through and dynamic performance tests are guided by IEEE 2800 for grid following IBRs. These performance tests will need to be adjusted to meet grid forming requirements if grid forming is more widely implemented.

Flat Start Test: Perform a no-disturbance test of the prepared simulation case for a minimum of 20 seconds. Flat responses of voltage, MW, MVAR, and frequency are expected to remain very close to the initial system condition.

Voltage Disturbance Performance Tests: These refer to large disturbances (e.g., fault-type events) and small disturbances (e.g., normal switching-type events, changes in generation and load) performance characteristics for inverter-based resources. These types of responses are differentiated by the following:

- Small Disturbance: Voltage stays within the continuous operating range of the plant
- Large Disturbance: Voltage falls outside the continuous operating range of the plant (i.e., "ride-through mode")

The transition between large and small disturbance behavior is coordinated between the plant-level controller and the individual inverter controls. This is typically based on the boundary of the continuous operating range, which is typically ± 10 percent around nominal operating voltage. When voltage remains within the continuous operating range, the plant-level controls drive the overall plant response. Faster local inverter controls take over when voltage falls outside this range during severe transient events that result in large variations in voltage at the POM and at the inverters. The voltage disturbance performance is typically assessed in the NERC Reliability Guideline BPS-Connected Inverter-Based Resource Performance-2018, Chapter 3 and IEEE 2800, Chapter 5.

Voltage Ride-Through Performance Assessment

The voltage ride-through (VRT) study scenario aims to evaluate the ability of the inverter-based resource plant to remain connected and provide appropriate current support during and after voltage disturbances. IEEE 2800 includes minimum capability requirements for IBR plants in response to abnormal events occurring on the transmission system and is a good reference for analyzing performance in EMT dynamic performance studies. The ride-through performance is typically assessed in the following terms and in the following order according to Chapter 4 of [8]:

- **Self-Protection**: Devices must remain connected during voltage/frequency disturbances that stay within the defined ride-through envelopes. Tripping or self-protection in this range is considered non-compliant. See PRC-029-01, and Chapter 7 of [8]

- **Return to Service**: After fault clearance, active power output should settle close to pre-disturbance levels, indicating a stable return to operation. See Chapter 7 of [8].
- **Current Injection**: During the fault, devices should inject appropriate levels of positive-sequence real and reactive current (typically prioritizing reactive), along with negative-sequence current in unbalanced conditions. The response must be fast and stable. See Chapter 7 of [8].

- **Post-Event Grid Support**: After the disturbance, the devices should continue to provide voltage and frequency control with sufficient responsiveness and stability to support the power system. See Chapters 5 and 6 of [8].

Frequency Ride-Through Performance Assessment

This study scenario evaluates the inverter-based resource plant's ability to remain connected and provide necessary grid support during and after frequency disturbances within the mandatory operation region as defined in regional entity standards, NERC Reliability Standard PRC-029, or IEEE 2800. Both low frequency and high frequency events must be simulated to assess compliance with ride-through capability and performance requirements. The following aspects (cited from IEEE 2800) should be assessed as part of EMT dynamic performance testing for frequency disturbance ride-through:

- **Self-Protection Behavior**: Assess whether the IBR plant maintains synchronism and does not trip or self-protect when system frequency remains within the mandatory operation region ($f4 \leq f < f3$ for low frequency; $f2 < f \leq f1$ for high frequency), and within the plant's volts-per-hertz limits. Protection functions must not be activated under these conditions.

- **Active Power Response**: Evaluate whether the plant maintains or modulates active power appropriately. For energy constrained **resources**, if operating below available power, the plant must increase output to support system frequency recovery. The active power response must reflect the underfrequency or overfrequency control strategy as specified by the Transmission Owner applicable standard.

- **Reactive Power Output**: Confirm that the IBR plant maintains reactive power injections during the frequency disturbance period in accordance with its capability and does not disengage voltage support functionalities.

- **Current Exchange and Dynamic Behavior**: Verify that the plant continues to exchange current with the TS, with acceptable active and reactive current oscillations that are positively damped. The dynamic current response must be stable and not initiate unwanted protection or cause instability.

- **Return to Service**: Post-disturbance, the IBR plant should return to its pre-disturbance power output or a level required by the TS owner, demonstrating fast and stable recovery of both active and reactive power levels.

This study ensures the IBR plant can ride-through both temporary low frequency and high frequency disturbances without disconnecting.

Rate of Change of Frequency (ROCOF) Ride-Through

The ROCOF disturbance ride-through performance requirements should apply when the IBR plant operates within the mandatory operation region and continuous operation region, where the frequency rate of change magnitude is less than or equal to 5.0 Hz/s.

Example ROCOF Ride-Through Requirements (IEEE 2800):

- **Mandatory Operation Region:** The IBR plant shall remain connected and operational during frequency excursions that have an absolute ROCOF magnitude ≤ 5.0 Hz/s, provided the frequency remains within the specified operating region and the duration is within the allowable limits. The ROCOF shall be calculated as the average rate of change of frequency over an averaging window of at least 0.1 second.

- **Mutual Agreement for Higher ROCOF Levels:** Upon mutual agreement between the transmission system operator and the IBR plant operator, the IBR plant may be required to ride-through and not trip for higher ROCOF levels. This can be an operational requirement for more rapid frequency changes.

- **Response Verification:** The IBR plant shall not trip for frequency disturbances with ROCOF ≤ 5.0 Hz/s, ensuring continuous operation even during rapid changes in frequency.

EMT studies are used to verify the plant's ability to stay synchronized with the transmission system and maintain operational integrity under ROCOF conditions. This study ensures that the IBR plant can provide continuous support and maintain stability during frequency disturbances with rapid ROCOF, avoiding unwanted trips or protective actions during such events.

Voltage Phase Angle Changes Ride-Through

The voltage phase angle change ride-through performance requirements should apply when the IBR plant operates within the applicable phase angle change limits, following faults or grid disturbances.

Example Phase Angle Change Ride-Through Requirements (IEEE 2800):

- **Positive-Sequence Phase Angle Change:** The IBR plant shall ride-through positive-sequence phase angle changes within a sub-cycle-to-cycle timeframe, ensuring the angle change does not exceed 25 electrical degrees.

- **Handling Unbalanced Faults:** The IBR plant shall remain operational during phase angle changes caused by unbalanced faults (e.g., single-phase faults), provided the positive-sequence angle change does not exceed the 25-degree limit.

- **Post-Disturbance Behavior:** After the disturbance, the IBR plant may experience active and reactive current oscillations, which should be positively damped to ensure system stability. Current blocking during the post-disturbance period is not permitted.

- **Synchronization with transmission system:** The IBR plant shall continue exchanging current with the transmission system and not initiate protective actions. The system must be able to respond to and manage phase angle changes without disconnecting.

This study ensures that the IBR plant can continue to operate and contribute to grid stability during voltage disturbances that cause significant phase angle changes, while ensuring that the system remains synchronized and stable.

6. EMT Analysis Considerations

Broad System-level Evaluations

This section outlines the study methodologies relevant to common types of EMT studies performed as part of system-level evaluations for generator interconnections and transmission planning.

Dynamic system impact assessments and SSO studies are typically performed during the generator interconnection process as part of the broader system impact assessment. These studies go beyond a Thevenin equivalent representation by including a wider, relevant portion of the power system, and are essential for evaluating the dynamic response of IBR plants under a range of disturbance conditions, including faults, switching events, and abnormal system configurations. Such studies help ensure that IBRs can maintain stability, contribute to voltage and frequency control, and ride-through disturbances without adverse interactions with the bulk system. In addition, these studies may evaluate the dynamic performance of a group of IBR plants, typically using aggregate or partially aggregated plant models. In addition to assessing IBR plant performance against applicable criteria, the broader power system included in the EMT model should also be evaluated to the fullest extent possible.

Prior to conducting EMT dynamic studies, steady-state power flow and phasor-domain transient analyses should be performed when feasible. The system model used for EMT simulations must incorporate all upgrades or mitigation measures identified as necessary in those preliminary studies. Given that EMT dynamic performance studies generally require significantly longer simulation times compared to steady-state or PDTS studies, it is often practical to conduct preliminary modeling and analysis activities in parallel with steady-state and transient stability work to maintain project timelines.

Analyzing EMT study results is generally more complex than interpreting phasor-domain studies due to the detailed nature of device models, which often include proprietary "blackbox" controls and real control code. Additionally, EMT simulations operate on instantaneous phase quantities rather than RMS values and require very small time steps to capture fast transient events, including zero and negative sequence components. A strong grasp of the EMT simulation environment, IBR control dynamics, and fundamental power system principles is essential before conducting EMT dynamic performance studies. While many performance aspects such as balanced fault ride-through, oscillation damping, and voltage recovery can be initially evaluated using phasor-domain transient stability analysis, EMT studies provide the deeper insight necessary for comprehensive assessment.

Selecting Study Scenarios

The selection of appropriate study scenarios is a critical step in the planning and execution of EMT simulations. Given the computational intensity and detailed nature of EMT models, it is essential to prioritize the most impactful and representative cases to ensure efficiency while maintaining technical rigor.

Scenario selection shall consider the following guiding principles:

- **Risk-Based Prioritization**: Focus on events that are expected to impose the most significant stress on the IBR facility or the surrounding power system.
- **System Strength Sensitivity**: Evaluate performance under conditions of low SCR, as IBR behavior is particularly sensitive in weak grid environments.
- **Complementary RMS Screening**: Use results from phasor-domain (RMS) studies to identify system conditions or contingencies that may warrant detailed EMT analysis.
- **Worst-Case Configuration**: Apply combinations of minimum fault levels, generation dispatch that results in low inertia, maximum IBR output, high interface transfers, and high reactive demand to evaluate edge-case performance limits.
- **Consider Planning and Operational Limits:** Studies should be conducted considering the existing system limits. During stressed system conditions, such as close to voltage collapse operation, considering detailed IBR performance might further reduce the system limits.

The study plan should include a representative selection of the following types of scenarios listed in Table 3.

Table 3: EMT Study Scenarios

Types of Scenarios	
Scenario Type	Purpose
Close-in Faults at POI	To assess voltage ride-through (VRT) and current injection capability
Remote Faults or System-wide Events	To evaluate voltage support and frequency control following grid disturbances
Contingency Events	To examine IBR response to generation trip, load rejection, or system separation
Oscillation-Prone Conditions	To screen for SSCI or SSO risks
Weak Grid Conditions	To test IBR stability and controller behavior under low SCR
High IBR Penetration Cases	To evaluate potential inter-plant interactions and control coordination

Study Area Selection

Selecting the study area and the details that need to be included in that area depends on the study objective. For instance, a study to determine the performance of IBR under weak grid conditions would require having the entire weak grid modeled. Likewise, for a study to determine the control interaction with another device it would be necessary to model, at minimum, the two devices and the network in-between.

While the decision on study area selection could be subjective, it is recommended to preferably have a documented quantifiable criterion to ensure consistency among different studies with similar objectives. Some of the methods that can be used for selecting the study area are described below.

Number of buses away. A fixed number of buses (e.g. 5) away from the project POI can be used to determine the EMT boundary area. The advantage is its simplicity and can be done quickly. The disadvantage is that it can have different outcomes in different portions of the system such as weak vs strong grids. If there are few tap points on a single line, then the methodology can quickly reach the maximum number of buses away and not capture what would be necessary for the study objective.

Electrical proximity. The idea here is to include anything that is electrically close to the project. This should capture all relevant network elements that could be impacted by the interconnection of IBRs. To find the electrically close buses, a 3-phase fault can be applied at the IBR point of interconnection and all the buses with voltage below a certain threshold (e.g. 0.3 pu) would be included in the study area. A 3-phase fault generally reaches further out in the system and hence will be more conservative as it will result in including more buses in the network boundary.

The advantage of this method is that it adapts to different grid conditions at the interconnection points. For example, unlike the fixed number of buses away, this method will not stop too close to the project if there are multiple tap buses on the nearby lines. The disadvantage is that a threshold for proximity is arbitrary and could result in an unnecessarily big area, or worse, a small area missing some events of interest. Additionally, an IBR that has an output consumed in a local area would have less of an impact on the grid, but this method does not differentiate that.

Predetermined study areas. For large, interconnected regions, smaller portions of the system bounded by strong buses may be practical for study of small DER. The advantage is that it reduces the study's setup work, particularly for small studies, as it may not be required to create a new EMT network representation. The disadvantage is that it is ineffective for studying large facilities with significant system impact. In addition, it may not be appropriate for facilities close to boundary buses.

Normally, the study area is limited by available computational power and the effort for collection of modeling details. Computational burden is heavily impacted by the number of fast switching inverters, and a larger study area can be selected if fewer of these models can be included in the area (e.g. by aggregating inverters at the same bus).

Selection of Critical Contingencies

Comprehensive contingency analysis forms a critical component of power system EMT studies, enabling identification of system vulnerabilities and assessment of IBR performance under stressed conditions. This section outlines considerations for conducting thorough contingency analysis in EMT simulations.

The selection process for contingencies must focus on events that represent the most severe stresses on system stability and IBR performance. Critical contingencies typically include:

- Transmission corridor tripping events that alter power flow patterns significantly across the network. These events may expose weak grid conditions that challenge IBR operation.
- Large load rejection scenarios that create sudden changes in system voltage profiles and frequency excursions requiring rapid response from IBRs.
- Generation plant trips that test the system's ability to maintain stability through redistribution of power flows and frequency regulation.
- Various fault scenarios across the network that stress voltage ride-through capabilities and transient stability of connected **resources**.
- Information from system operators regarding known oscillatory behaviors under specific network topologies should be incorporated into the contingency selection process.
- Results from phasor domain transient stability studies provide valuable guidance in identifying critical contingencies requiring detailed EMT analysis.

Quantities to Monitor in Simulation

To effectively assess the dynamic behavior of IBRs and overall system performance, the following quantities should be monitored during EMT simulations:

Device and POI Electrical Quantities: Monitor instantaneous voltages and currents, RMS voltages, and active/reactive power (P/Q) at device terminals and at the POI. Sequence components and real/reactive current components may also be derived and analyzed to assess fault ride-through and post-disturbance behavior. Close inspection of transient events (ex: fault initiation, clearing, etc.) may require time windows shorter than 1-2 seconds.

Control Signal Exchanges: Monitor P/Q commands between plant-level and inverter-level controllers. These signals help identify the source of control actions, especially in unexpected scenarios (e.g. power drops or plant tripping). Additional exchanged signals may include power availability, terminal conditions, and voltage/frequency setpoints.

Device Trip and Ride-Through Flags: Monitor trip indicators and ride-through mode flags (e.g., LVRT, HVRT) to explain device responses, particularly when internal control logic is not transparent in blackbox models.

Internal Control Signals: If available, observe internal signals like PLL frequency and tracking error, measured RMS voltage, and real/reactive current. These aid in diagnosing performance issues during faults (though access to these signals may be limited by OEM restrictions).

System-Wide Electrical Quantities: Track system-level instantaneous voltages, RMS voltages, and P/Q flows at key buses and branches to evaluate broader system response and compliance with performance criteria.

Mechanical System Quantities (if synchronous machines are nearby): When synchronous generators are electrically close to an IBR, shaft torque, rotor speed, and torsional oscillation states should be captured. These signals are critical for identifying SSTI, as torsional resonance often couples with IBR control loops under weak-grid or high-impedance conditions.

High-Speed Electrical Waveform Sampling: High-resolution instantaneous voltages and currents at the inverter terminals and POI should be recorded to capture subsynchronous components often missed by RMS-based quantities.

Mitigation Options for IBR Control Instability

Mitigations related to the IBRs' control instability include, but are not limited to:

System reinforcement: New transmission circuits can reduce the system impedance, but it may not be a viable option due to its expensive cost and long lead implementation time. Series capacitors can also be considered to reduce the impedance. However, the subsynchronous instability concerns, which are described in the following section, should be considered. Synchronous condensers are presently the primary solution to improve the system strength because of multifaceted benefits including large capability to supply fault current, inertia, and voltage support capability. However, synchronous machine stability should be considered when recommending synchronous condensers.

Controller changes: PLL, inner loop current control, and plant-level voltage control are three key controllers in the IBRs that can cause control instability in a low system strength grid. Any control tuning should be performed by the OEM or with direct permission or instruction from the OEM as other parties are not aware of the full implications of individual parameter changes and should not take responsibility for these changes. Control tuning done outside of the purview of the OEM should be considered investigative only. In some cases, changes to the PLL, inner loop current control, and plant-level voltage controllers may alleviate the issues related to low system strength. Changes to the plant-level voltage control generally include time constants and gains. They are typically adjusted to have slower response for a low system strength application. Voltage droop can also be deployed to reduce inter-plant control interaction. Changes to the PLL and inner loop current control loop may require complex engineering efforts. Control instability issues cannot always be fully addressed with controller changes. Controller changes are often system specific and should be determined in close coordination between the transmission planners, generation owners, and manufacturers. IBR controller tuning may also need to be reviewed if significant changes are made to the **bulk power system** or connected **resources**, and changes to these controls may necessitate changes to other system controllers, or requirements for new system controllers.

FACTS devices: Static Var Compensators (SVCs) and STATCOMs can help provide dynamic reactive support to control the voltage fluctuations as well as help with transient ride-through capability. However, these devices themselves have fast control loops and care should be taken as these devices may also be subject to low system strength control instability.

Reduction in plant capacity or output: System strength can be improved by either reducing the plant capacity or limiting plant output. Although this option may not be a desired option, it is often the only viable short-term solution if control instability is encountered in real-time or near real-time until a longer-term solution can be implemented.

Post-Disturbance Event Analysis

The typical post-event EMT analysis should reflect the actual system disturbance that occurred, and use EMT simulations to explain, replicate, determine root cause of abnormal system behavior during that event, and suggest mitigation and corrective actions if any. This type of EMT analysis also corrects potential errors in existing EMT models and is an important validation function introduced between reality and simulation study. This section outlines the essential steps for conducting post-event EMT analysis.

Study Area Selection

When a system event occurs, operational and event logs help summarize the observed phenomena. The process for selecting the study area follows the principles outlined in the previous subsection on Study Area Selection. In addition to those guidelines, it is essential that engineers apply sound engineering judgment when defining the boundaries for post-event EMT analysis.

Event Data Collection

In addition to the contextual details provided in the event description, the main types of data that need to be collected include system measurements and device-specific recordings. Here are examples:

- Date and time of the event (with time-stamp resolution)
- Location of substation, buses, or lines

- Type of disturbance:
    - o Fault (3-phase, single line-to-ground, double line-to-ground)
    - o Line trip or breaker failure
    - o Load rejection
    - o Generator or inverter trip
- STATCOM or inverter-based resource response misbehavior
    - o Sequence of events sources from:
    - o SCADA/EMS trends
    - o PMU recordings of voltage, current, frequency, angle etc.
    - o Disturbance records of oscillography, relay logs
    - o Event or Sequence of Events log
    - o Breaker and protection trip logs
    - o EMS load flow or fault study data at the time

System Modeling Setup

The EMT modeling setup for the post-event EMT analysis is designed to accurately replicate the electrical network and operating conditions at the time of pre-event. The level of detail includes a full representation of the impacted substation along with an equivalent model of the upstream transmission system. The equivalent model of the upstream is usually represented by short circuit Thevenin equivalent system. This approach ensures that both local dynamics and interactions with the broader grid are effectively captured in the simulation. Key components are modeled with sufficient accuracy to reflect their influence on the system's transient behavior.

- IBR/STATCOM is represented using a detailed EMT model, typically provided by the vendor, to capture its fast-acting control response and protection behavior.
- Transmission lines are modeled using appropriate representations, such as frequency-dependent or multi-section PI models, to account for traveling waves and transient propagation.
- Transformers are modeled with nonlinear saturation characteristics, and residual flux may be considered if relevant to inrush or asymmetry observed in the event.
- Load models may include both static and dynamic components, depending on the sensitivity of the analysis.
- Protection elements, including breaker logic and relay settings, are implemented to replicate actual fault-clearing sequences and operational timing.

Initial operating conditions are established using pre-event recording/monitoring data, including voltage profiles, power flows, and device operating states. This ensures that the simulation begins from a steady-state condition that closely matches the system's status prior to the event, providing a credible foundation for dynamic analysis of event occurrence.

System Event Simulation

To simulate a system event accurately, the EMT model should first be initialized to represent the system's steady-state conditions prior to the disturbance. The fault must then be applied at the correct location with appropriate fault impedance, reflecting real system conditions. Breaker operation, including timing and trip signals, should be modeled in alignment with actual protection settings and system logs. The dynamic response of the IBR or FACTS must also be simulated, including control mode transitions, ride-through behavior, and any protective trip logic. Using actual time stamps from field data ensures proper synchronization and helps validate the simulation against real-world observations. Additionally, critical controller behaviors such as the PLL loss of synchronization or current limiter activation should be replicated to fully capture the IBR or FACTS' role in the system event.

Root Cause Analysis

After completing the EMT simulation, the results should be carefully compared with field measurements, not only the peak values but also the steepness and wave shape, to validate the accuracy of the model and its ability to replicate real system behavior. Key waveform plots—such as voltage and current at the POI, IBR or FACTS active and reactive power (P/Q) output, and internal control signals including current reference Iq-ref , voltage reference V_ref, and the PLL angle—should be overlaid with recorded data from PMUs, relays, or digital fault recorders. Additionally, any trip or blocking signals observed in the field should be matched against the simulated protection and control response. This comparison ensures that the IBR and FACTS controller logic, dynamic response, and system interaction are accurately represented, providing confidence in the model's use for further analysis or tuning.

The root cause analysis focuses on identifying any abnormal behavior observed during the system event and determining whether it aligns with expected performance. A key aspect is evaluating whether the IBR or FACTS responded appropriately based on its control logic and functional specification, for example, providing reactive support during voltage sags and remaining connected during fault ride-through conditions. Any deviation, such as premature tripping or lack of dynamic support, should be examined in detail. Protection schemes must also be assessed to determine whether they operated correctly and within their intended time frames. Instances of misoperation or delayed breaker trips can indicate coordination issues. The analysis should further explore the presence of any unexpected oscillations or resonant conditions that could suggest control interaction problems or weak-grid effects. Signs of control instability, such as hunting in voltage or power output, should be investigated through internal control signal tracking. Finally, the simulation should be reviewed for any equipment limit violations—such as overcurrent, DC bus overvoltage, or thermal stress—that may have triggered protective responses. Identifying these root causes is essential for improving system robustness and preventing recurrence of similar events.

Mitigation Recommendations

Based on the findings of the post-event EMT analysis, several mitigation measures could be recommended to enhance system stability and device performance. For example, tuning of the IBR and FACTS controller should be revisited—particularly gain settings, current limiters, and control response time—to improve dynamic performance under disturbance conditions.

If issues were observed during fault ride-through (FRT) events, the FRT logic and current limiting mechanisms should be refined to ensure compliance with grid codes while protecting the equipment. In cases where resonance or sustained oscillations were identified, the addition of damping controls or harmonic filters should be considered to mitigate these effects. Protection settings, including relay thresholds and time delays, may also require adjustment to prevent miscoordination or premature tripping during fast-changing conditions. The Protection Validation Studies section will be expanded to include more detailed analysis. After implementing these updates, it is recommended to re-test the system using EMT simulations to validate the effectiveness of the changes and ensure reliable operation under similar scenarios.

Protection Misoperation Considerations

Electromagnetic transient simulations provide a valuable tool for understanding IBR fault responses in detail and validating whether current protection schemes and settings remain effective under evolving grid conditions. In cases where traditional short-circuit analysis is insufficient, EMT studies can offer deeper insight into system behavior and help guide necessary adjustments to protection strategies. The system model developed for the Dynamic System Impact Assessment Study can also serve as the foundation for protection system validation studies. In most cases, an aggregated representation of each IBR plant is sufficient, as the primary focus of these studies is the performance of transmission system protection rather than detailed plant-level dynamics.

A key modeling consideration is the accurate representation of instrument transformers, particularly current transformers (CTs) and voltage transformers (VTs). Protection system behavior is highly sensitive to CT and VT performance, especially under faulted or stressed conditions. CT saturation, for example, can significantly distort measured currents and lead to relay misoperations. Similarly, VTs must be modeled with attention to their response under abnormal voltage conditions, including scenarios involving sub- and super-synchronous harmonics. Ensuring that CT and VT saturation effects are captured in the EMT model is essential for producing realistic relay inputs and for evaluating the robustness of protection schemes under high-IBR system conditions.

Methodology

The methodology for protection validation studies using EMT simulations follows a disturbance-driven approach, similar in concept to dynamic system impact assessments. Engineering judgement should be applied with regards to disturbances being applied at various locations in the system, with the specific set of contingencies determined by the type of protection relays under study. In general, scenarios are chosen to represent conditions where synchronous generator contributions are reduced, since these cases are most likely to challenge relay performance in high-IBR systems. Protection functions most affected by IBR penetration include impedance-based relays such as distance protection, out-of-step protection, and negative-sequence directional elements.

Where available, EMT models of the actual protective devices should be incorporated directly into the simulation, allowing relay operation (whether correct, missed, or misoperated) to be observed within the study environment. However, such detailed vendor-specific relay models are often unavailable. Generic or simplified relay models are not recommended, as relay behavior depends heavily on proprietary elements such as filtering, phasor calculation algorithms, sampling methods, and internal thresholds.

In the absence of detailed EMT relay models, an alternative approach involves recording voltage and current waveforms from the simulation in standard formats (e.g., COMTRADE). These files can then be replayed into physical relays through real-time or hardware-in-the-loop (HIL) testing, providing a practical means of validating relay performance against EMT-derived system conditions.

Quantities to Monitor

To evaluate the dependability and security of protection systems in EMT-based validation studies, a range of simulation quantities should be monitored. These measurements help determine whether protection schemes operate as intended under high-IBR system conditions. Key quantities include:

- Relay operating quantities: The internal variables that relays use for decision-making, such as calculated impedance for distance relays or the output of directional elements.
- Relay settings and characteristics: The thresholds or characteristics against which operating quantities are compared (e.g., blinder and mho circle settings for distance relays).
- Sequence components: Filtered positive-, negative-, and zero-sequence voltages and currents, as these are often used in directional and protection elements.
- Instantaneous waveforms: Raw voltage and current signals, particularly for assessing distortion, harmonics, and CT/VT performance.
- System parameters: Active power, reactive power, and frequency to provide context on system response and stability.
- Relay status signals: Outputs such as trip commands, pickup indications, and timer statuses to directly assess protection operation.

It should be noted that wherever possible, quantities should be taken directly from relay outputs rather than reconstructed externally. For example, if the relay provides its measured impedance as an output, that value should be used instead of calculating impedance separately from generic voltage and current signals. This ensures the analysis reflects the relay's actual decision-making process.

Analysis of Simulation Results

Simulation outputs can span hundreds of pages, making manual review impractical. To streamline this process, automated post-processing techniques are often employed. These methods apply strict quantitative filters to ensure that only high-performing cases are flagged for further consideration. For instance, in scenarios where no tripping is expected, the absence of both Pick Up and Trip signals is a key indicator of correct behavior. This approach allows engineers to concentrate on identifying and resolving poor performance cases, although all data traces should still be examined with sound engineering judgment.

Mitigation Measures

When a relay exhibits incorrect behavior through misoperation, it is essential to implement corrective strategies to address the issue. Common mitigation techniques include:

- Adjusting the relay configuration or settings
- Refining or updating the protection logic within the relay
- Enhancing or modifying Remedial Action Schemes (RAS) to prevent conditions that lead to relay errors
- Replacing the existing protection system entirely, such as switching from a distance relay to a current differential relay

After selecting a mitigation strategy, it is advisable to re-evaluate the affected scenarios to confirm that the changes have not introduced new issues.

7. Future Revisions

This document provides guidance and suggestions for performing several types of studies through the transient state using EMT software. It is not meant to be binding by creating or changing any **Area** requirements. Revisions to this guideline document are based on growing experience with performing EMT studies, including new and expanded tests for grid forming controls and other capabilities. Periodic revisions are expected to be made as the working group exchanges case studies and increases its collective knowledge of effective IBR integration.

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Appendix I

SCR is defined as the ratio of the short-circuit apparent power (SCMVA) available from a three-phase-to-ground (3LG) fault at a particular point on the system to the nominal power rating (in MW) of the IBR connected at that point:

$$SCR = \frac{SCMVA_{POI}}{MW_{IBR}}$$

where:

- $SCMVA_{POI}$ is the short-circuit MVA level at the POI, excluding the current contribution of the IBR.
- MW_{IBR} is the nominal power rating of the IBR connected at the POI.

Weighted SCR (WSCR) was developed by Electric Reliability COT to address situations involving multiple IBRs by accounting for the combined short circuit contributions from electrically close units. The WSCR formula is

$$WSCR = \frac{\sum_i^N SCMVA_i \cdot P_{RMW_i}}{\left(\sum_i^N P_{RMW_i}\right)^2}$$

where:

- $SCMVA_i$ is the short circuit capacity at bus i without current contribution from non-synchronous generation.
- P_{RMWi} is the MW output of non-synchronous generation to be connected at bus i. N is the number of IBRs interacting with each other, and i is the IBR index.

Composite SCR (CSCR) was proposed by GE for systems with several interacting IBRs. It models all nearby IBRs as if connected to a common equivalent bus, using a combined impedance. Also, it calculates SCR at this equivalent point to assess aggregate system strength. The CSCR formula is

$$CSCR = \frac{CSC_{MVA}}{MW_{VER}}$$

where:

- CSC_{MVA} is the short circuit capacity in MVA at a single bus by excluding the present contribution of IBR
- MW_{VER} is the sum of all considered IBR ratings.

Additional metrics related to system strength and stability are detailed in IEEE 2800™-2022 Annex C.

Glossary

Inverter Based Resource	The working group considers an IBR to be an inverter-connected device, such as generation facilities, HVDC lines, FACTS, and/or SVCs. This reference guideline is developed to describe the recommended practices for testing if an IBR has an impact on the **bulk power system**.
Model Verification	The process of confirming that model structure and parameter values represent the equipment or facility design and settings by reviewing documentation.
Model Validation	The process of comparing measurements with simulation results to assess how closely a model's behavior matches the measured behavior.
System Inertia (df/dP)	The system's ability to resist changes in Frequency, reflecting how much the system can absorb or counteract sudden power imbalances.
Source Impedance Strength (a.k.a., System strength)	This pertains to the magnitude of the impedance seen from a particular point on the grid relative to the size of the connected generator. A system is considered "weak" if the source impedance is high, meaning the grid connection point has limited ability to support stable voltage and current during disturbances.
Phasor-Domain Transient (PDT)	A computational process that simulates electromagnetic transients based on a mix of time-domain and phasor-domain modeling and is typically used for linear circuits or networks.

Version History

Version	Date	Action	Change Tacking (New, Errata or Revisions)
0	XX/XX/2026		New

Northeast Power Coordinating Council, Inc. (NPCC) is a not-for-profit corporation responsible for promoting and enhancing the reliability of the international, interconnected bulk power system in Northeastern North America. NPCC is committed to the collective vision of a highly reliable and secure North American bulk power system.

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