NERC

NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

Reliability Guideline

Electromagnetic Transient Modeling for BPS-Connected Inverter-Based Resources—Recommended Model Requirements and Verification Practices

March 2023

RELIABILITY | RESILIENCE | SECURITY




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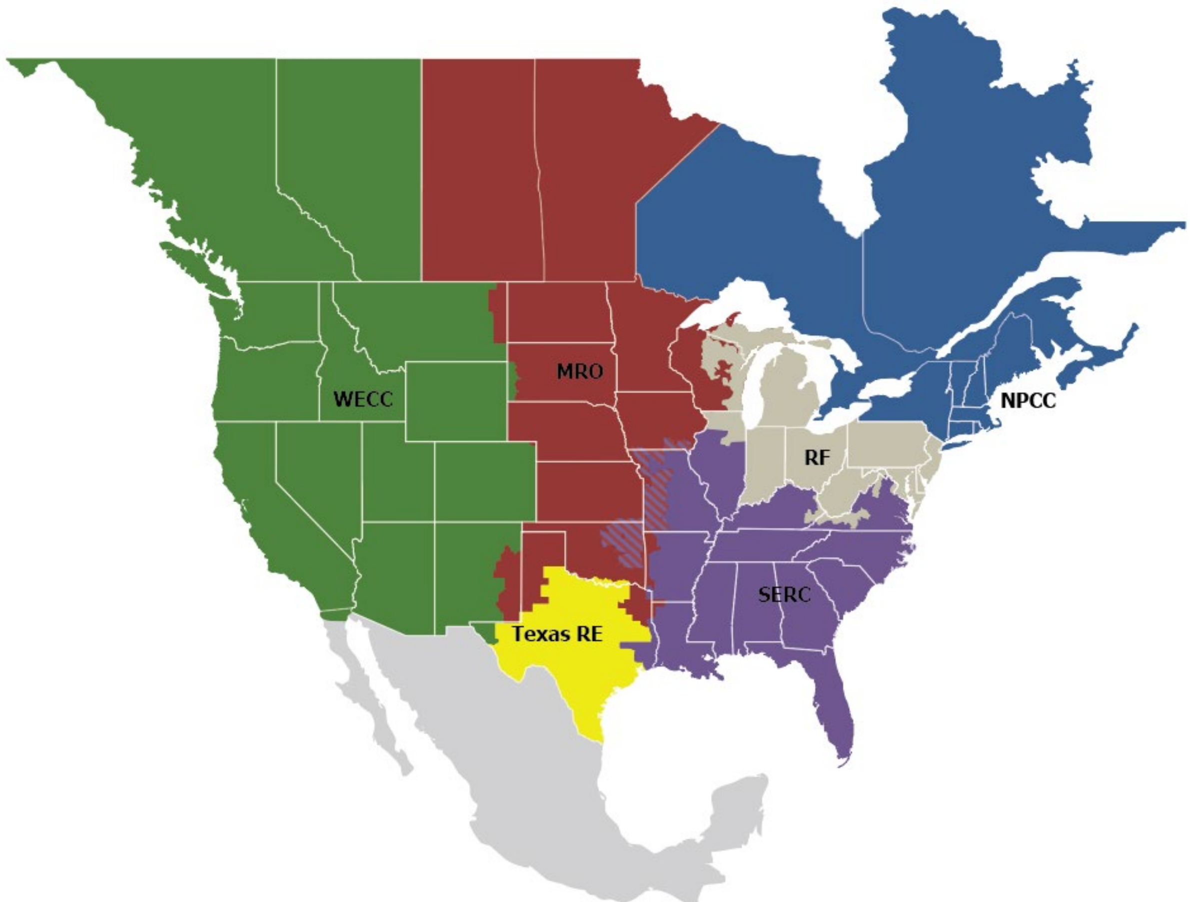
Preface

Electricity is a key component of the fabric of modern society and the Electric Reliability Organization (ERO) Enterprise serves to strengthen that fabric. The vision for the ERO Enterprise, which is comprised of the NERC and the six Regional Entities, is a highly reliable, resilient, and secure North American bulk power system (BPS). Our mission is to assure the effective and efficient reduction of risks to the reliability and security of the grid.

Reliability | Resilience | Security
Because nearly 400 million citizens in North America are counting on us

The North American BPS is made up of six Regional Entity boundaries as shown in the map and corresponding table below. The multicolored area denotes overlap as some load-serving entities participate in one Regional Entity while associated Transmission Owners /Operators participate in another.



MRO	Midwest Reliability Organization
NPCC	Northeast Power Coordinating Council
RF	ReliabilityFirst
SERC	SERC Reliability Corporation
Texas RE	Texas Reliability Entity
WECC	WECC

Preamble

The NERC Reliability and Security Technical Committee (RSTC), through its subcommittees and working groups, develops and triennially reviews reliability guidelines in accordance with the procedures set forth in the RSTC Charter. Reliability guidelines include the collective experience, expertise, and judgment of the industry on matters that impact BPS operations, planning, and security. Reliability guidelines provide key practices, guidance, and information on specific issues critical to promote and maintain a highly reliable and secure BPS.

Each entity registered in the NERC compliance registry is responsible and accountable for maintaining reliability and compliance with applicable mandatory Reliability Standards. Reliability guidelines are not binding norms or parameters nor are they Reliability Standards; however, NERC encourages entities to review, validate, adjust, and/or develop a program with the practices set forth in this guideline. Entities should review this guideline in detail and in conjunction with evaluations of their internal processes and procedures; these reviews could highlight that appropriate changes are needed, and these changes should be done with consideration of system design, configuration, and business practices.

Executive Summary

Transmission Planners (TPs) and Planning Coordinators (PCs) across North America face interconnection queues filled with requests to connect rapidly growing levels of inverter-based resources (IBR) to the BPS. As the penetrations of inverter technology continue to rise in many TP and PC footprints, these entities will need to ensure reliable operation of the BPS by executing studies to identify and mitigate any possible reliability issues. Conventional fundamental-frequency, positive-sequence dynamic simulation tools used by TPs and PCs for many years are inadequate for effectively identifying reliability risks of inverter-based resources in some ways. Electromagnetic transient (EMT) simulations are necessary to adequately identify and mitigate BPS reliability risks moving forward.

Today, NERC strongly recommends that Transmission Owners (TOs), TPs, and PCs enhance their interconnection requirements as established per the NERC FAC-001 and FAC-002 Reliability Standards. NERC *Reliability Guideline: Improvements to Interconnection Requirements for BPS-Connected Inverter-Based Resources*[1] recommends that all TOs "specify requirements for inverter-based resources to provide EMT models in situations where an EMT-type study may be needed now or in the foreseeable future." The guideline also mentions that the need for EMT models will increase to identify and study complex reliability issues and evaluate suitable solutions to those issues as the resource mix changes. However, many TPs and PCs are currently unfamiliar with using these models to understand and require high-quality EMT models, to perform EMT simulations, and to make decisions about BPS reliability. NERC further recommends that EMT models be required for all newly connecting BPS-connected inverter-based resources and provides guidance on establishing model requirements and model verification[2] practices.

This two-part reliability guideline is intended to address modeling gaps identified in recent disturbance reports,[3] such as models not matching actual facilities and these model's inability to reproduce poor disturbance ride-through performance. This guideline will also serve as a useful reference for TPs and PCs during the interconnection study process or during planning assessments as they begin requiring high-quality EMT models and performing or coordinating EMT studies. This guideline is Part I in the series and provides recommendations regarding the development of EMT models as well as the definition and verification of EMT model quality.[4] Part II will focus on the use of EMT models, modeling practices, and study techniques applicable to system impact studies and other BPS reliability studies. NERC encourages TPs and PCs to adopt the practices outlined in this reliability guideline, particularly related to understanding and ensuring high-quality EMT models and performing EMT simulations. GOs and inverter-based resource developers are also encouraged to implement the practices and techniques provided in this reliability guideline, particularly collecting and verifying EMT models provided by equipment manufacturers, combining models to accurately represent the overall facility, and providing those models and supporting materials to the TP and PC.

Recommendations

This guideline provides recommendations for TPs, PCs, GOs, equipment manufacturers, and consultants conducting EMT modeling and studies for inverter-based resources; NERC strongly encourages these entities to adopt all of the recommendations contained throughout this guideline. **Table ES.1** outlines the high-level recommendations contained in this paper.

[1] https://www.nerc.com/comm/RSTC_Reliability_Guidelines/Reliability_Guideline_IBR_Interconnection_Requirements_Improvements.pdf

[2] The term "verification" used throughout the guideline refers to processes that verify that models meet the performance and quality requirements. The term "validation" refers to processes that ensure models represent actual equipment as closely as possible.

[3] https://www.nerc.com/pa/rrm/ea/Pages/Major-Event-Reports.aspx

[4] This reliability guideline focuses specifically on site-specific, user-defined EMT models that represent actual or planned facilities.

Table ES.1: Recommendations and Applicability	
Recommendations	**Applicability**
Resourcing: TPs and PCs should prepare for the growing need for EMT modeling and studies related to the reliable interconnection of inverter-based resources in the near future. As the penetration of inverter-based resources grows, the need for conducting EMT studies to adequately ensure reliable operation of the BPS increases more rapidly. This may require upskilling existing staff as well as acquiring new talent and resources in this area. Computational capabilities and process improvements are likely needed to enable effective and efficient execution of EMT studies.	TPs and PCs
EMT Model Requirements and Model Quality Verification: GOs should prepare for the need to provide high-quality, validated, and facility-specific EMT models along with documentation to the TP and PC while working closely with equipment manufacturers and consultants (where needed). This may include enhancing contractual terms and conditions with equipment manufacturers and any consultants (where applicable) to ensure that models are accurate and modeling support is available in the future. GOs should request from TPs and PCs network information (e.g. short-circuit strength) pertinent to configuring the site-specific EMT model early in the process.	GOs
EMT Model Requirements and Model Quality Verification: TPs and PCs should establish EMT model requirement for all newly connecting BPS-connected inverter-based resources. These model requirements should be developed to provide clear and consistent detail, model types, model accuracy, performance and usability, and interoperability. TPs and PCs are encouraged to develop EMT modeling checklists that could be provided to GOs to help registered entities develop a clear understanding of the model requirements. These model requirements could also be used by TOs in the development of revised interconnection agreements to enhance and improve the interconnection study and long-term planning processes. TP and PC should assess the quality of all submitted EMT models to ensure that the models meet the specific requirements. The model used to conduct interconnection studies should be fully verified prior to commercial operation of the inverter-based resource. No resource should be allowed to interconnect until the model has been fully verified to match the as-built settings installed in the field. Any differences between the model used for study and the actual installed settings in the field should be deemed a qualified change per FAC-002-4 and be reviewed by the TP and PC prior to commercial operation to determine whether the existing studies are still valid.	TPs, PCs, and GOs
Cross-Platform Model Benchmarking: TPs and PCs should establish model requirements to ensure that submitted EMT models and positive sequence dynamic models are benchmarked against each other by GOs such that all models sufficiently match each other (given modeling and simulation platform limitations) and reflect the as-built equipment installed in the field.	TPs and PCs
EMT Study Screening: TPs and PCs should establish repeatable and quantifiable screening approaches to determine when EMT studies are necessary in the interconnection study process and long-term planning horizon. These screening processes should be documented and enforced to ensure that sufficiently detailed studies are conducted to accurately identify possible BPS reliability risks. Screening techniques and executing EMT studies will be discussed in detail in Part II of this guideline.	TPs and PCs

Introduction

EMT modeling and simulations date back to the late 1960s and were commercialized in the 1970s and 1980s. EMT studies have historically been focused on unbalanced conditions, high frequency transients, lightning protection, ferro-resonance, harmonics, black start studies, and other phenomena.[5] However, as the penetration of inverter-based resources (and distributed energy resources) continues to grow, EMT modeling and studies have become increasingly necessary to help ensure reliable operation of the BPS. The following is a list of the most notable drivers for performing EMT studies to study BPS-connected inverter-based resources (IBR):[6]

- Integration of inverter-based resources into low system strength networks
- Sub-synchronous control interactions (plant-to-grid)
- Inverter-based resource controls interactions (plant-to-plant and within the plant)
- Inverter-based resource controls stability (large and small disturbance)
- Benchmarking and verifying RMS positive sequence dynamic models
- Inverter-based resource frequency and voltage ride-through capability and performance
    - Poor ride-through performance identified in recent disturbance reports due to instantaneous inverter ac overcurrent and overvoltage protection, inverter dc-bus unbalance protection, unbalance current protection
- Inverter-based resource short-circuit current analysis
- Majority of grid faults are unbalanced faults
- Potential misoperation of protection system
- Power quality studies (e.g., harmonics, rapid voltage change)[7]
- Plant startup studies
- Black start and system restoration studies
- Verification of IEEE 2800-2022[8] performance requirements

Industry experience thus far has shown that developing EMT models and executing EMT studies is not an easy task. The purpose of this reliability guideline is to provide industry with recommendations for actions to take to prepare for current and future study needs. The need for EMT studies to assess BPS reliability is expected to grow exponentially in the coming years based on planned projects in the interconnection queues.[9] Industry will need to act quickly to develop the skills, processes, tools, infrastructure, and capabilities to perform these studies effectively and efficiently.

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[5] https://resourcecenter.ieee-pes.org/publications/technical-reports/PESTR7.html
[6] https://www.nerc.com/comm/RSTC_Reliability_Guidelines/Item_4a._Integrating%20_Inverter-Based_Resources_into_Low_Short_Circuit_Strength_Systems_-_2017-11-08-FINAL.pdf
[7] Some equipment manufacturers can do harmonics analysis using their EMT models while others cannot because component-level hardware irregularities cannot be captured in the model. TPs and PCs should work with GOs and the equipment manufacturers to ensure that appropriate models are used for each type of study.
[8] https://standards.ieee.org/ieee/2800/10453/
[9] https://emp.lbl.gov/queues

Scope of Guideline

This reliability guideline provides recommendations for the development of EMT model requirements, model quality checks, and verification practices specifically for EMT models used to represent BPS-connected inverter-based resources in reliability studies conducted by TPs and PCs. The guidance presented here is intended specifically to help ensure that EMT models provided by GOs are representative of the expected behavior of the actual or planned facility to the greatest extent possible. This guideline also provides insights on screening considerations to determine when EMT studies are needed, when and how to assess ride-through performance, and the resourcing to prepare for increased workload. This guideline focuses specifically on plant models (i.e., a combination of system components and unit-level models provided by inverter and plant-level controller manufacturers to represent the expected behavior of equipment).[10]

This guideline is intended to support critical NERC Reliability Standards enhancements focused on incorporating EMT modeling and studies into the interconnection study process and long-term planning assessments.[11] These enhancements are intended to establish minimum requirements in the applicable standards; however, this guideline complements and supplements that effort with additional details that TPs and PCs will need to develop and/or enhance their detailed EMT modeling and studies requirements and processes. All TPs and PCs are strongly encouraged to adopt all recommendations contained in this guideline to enhance their modeling and study processes and bring consistency to EMT modeling efforts moving forward.

Typical Makeup of an IBR Plant Aggregate Model

Equipment-level EMT models are supplied by equipment manufacturers and then combined by the GO (or a consultant). The GO configures the individual equipment models by changing parameters and control modes based on the facility's electrical and control requirements (e.g., power and voltage rating), grid support functions (e.g., primary frequency response), and associated control parameters (e.g., gains and deadbands). For most BPS reliability studies, the EMT model provided by the GO to the TP and PC should be an aggregate or partially-equivalent representation of the inverter-based resource.[12] In an aggregate model, multiple inverters are represented as one larger unit with the collector system represented as an equivalent line or cable model. A single inverter controller controls the equivalent inverter model and is connected to a plant controller. A reasonable assumption is that all inverters are of the same type (make, model, and firmware) and respond to the plant controller in a consistent manner and at the same time.[13] **Figure I.1** illustrates a typical aggregate plant EMT model.

[10] This guideline is not intended for academic, exploratory, or other research-related studies where generalized assumptions or generic representations may be acceptable. For planning-related exploratory studies, TP/PC should collaborate with GOs to obtain appropriate models that are configurable to allow parametric studies.

[11] https://www.nerc.com/pa/Stand/Pages/Project2022-04EMTModeling.aspx

[12] GOs may need a detailed plant model to assess intra-plant issues and their impact on ride-through performance. See **Appendix A** for more information on aggregate plant model and detailed plant model. GOs should work with equipment manufacturers to develop appropriate aggregation of IBR plants with multiple inverter equipment manufacturers and hybrid IBR plants, such as PV + battery.

[13] If the plant contains inverters of different type, it may be necessary to model the plant as two or more separate aggregate units, each representing inverters of the same type to more accurately model plant performance.

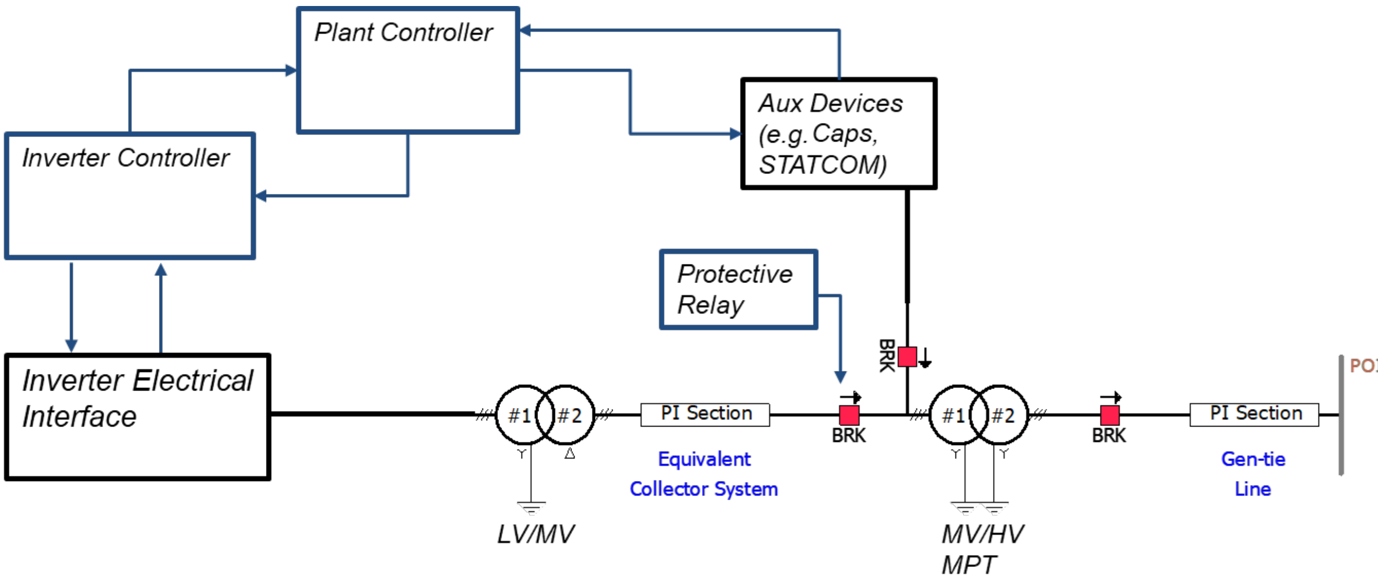

Figure I.1: Typical Components of an Aggregate[14] Plant EMT Model

Outline of Two-Part Guideline

This guideline provides specific recommendations in multiple areas of EMT model development and submittal, model verification, and study use cases. Part II of this two-part guideline will cover executing studies and analyzing results as well as other relevant areas of focus. Figure I.2 provides a high-level process flowchart of EMT modeling and studies to illustrate the concepts covered in both the guidelines.

[14] Representing the entire plant as an aggregate, as shown here, has been a common practice, but it may have limitations that should be considered and documented. Use of an aggregate model is generally recommended to balance computational burden and model fidelity.

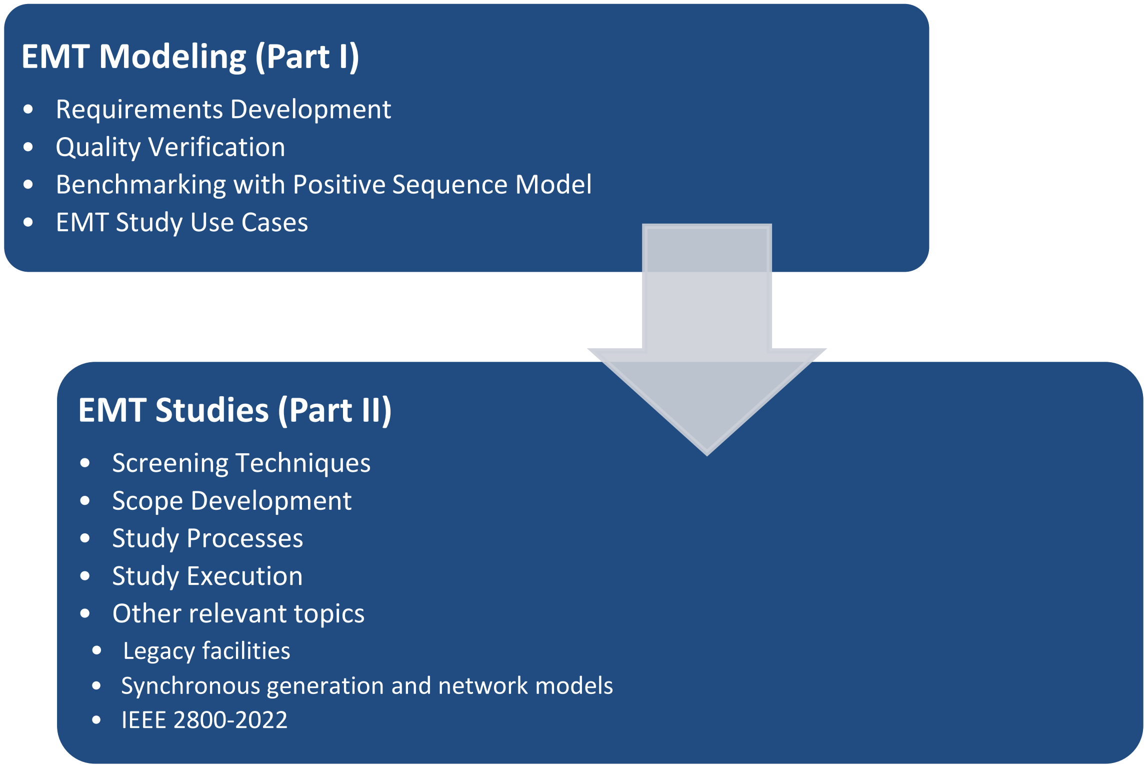

Figure I.2: Reliability Guidelines on EMT Modeling and Studies

Chapter 1: Recommended EMT Model Requirements

As the industry continues to expand its EMT modeling and study capabilities, some TPs and PCs have established detailed EMT model requirements for newly interconnecting inverter-based resources (see **Appendix B**). NERC strongly recommends that all TPs and PCs establish clear model requirements to ensure high-quality EMT models are collected at the time of interconnection for newly interconnecting inverter-based resources. [15]

The following are recommendations pertaining to TPs and PCs establishing EMT model requirements:

- TPs and PCs are strongly encouraged to establish EMT modeling requirements as part of the interconnection study process per FAC-002 for all newly interconnecting BPS-connected inverter-based resources.[16] The model requirements should cover the following at a minimum:
  - Plant and model documentation
  - Model verification and validation documentation
  - Model components and level of detail
  - Model construction, accuracy, usability, and efficiency
- TPs and PCs should create a "checklist" of EMT model requirements that can be provided to the GO and then to the equipment manufacturers. An example is provided in **Table 1.1**. TPs and PCs may include additional model requirements; GOs may consider adding these model requirements as well as model support through the life cycle of the facility as part of their agreements with the equipment manufacturers and entities involved in the creation of the plant EMT model.
- Even if EMT studies are not commonplace for any one TP or PC today, all TPs and PCs should require high-quality EMT models as a prerequisite of interconnection to ensure the models are available for future use, if and when needed.[17]
- The EMT model provided by the GO should be an accurate representation of the inverter-based resource, representing all pertinent controls,[18] and protections (both software and hardware) that could affect the electrical output of the facility for the types of studies in which it is intended to be used. More details on attestations and their impact on model quality are provided in **Chapter 2**.
- TPs and PCs should require that all submitted EMT models include attestations by the equipment manufacturers (i.e., inverter manufacturer and plant-level controller manufacturer) that the model represents the site-specific controller tuning and implementation of their equipment.
- TPs and PCs should also require attestations from the GO (or third-party consultant) that the aggregate model representation of the entire plant includes site-specific models, settings, protections, and controls to ensure the whole plant model is accurate, notwithstanding the limitations of aggregation.
- TPs and PCs should include change management requirements and protocols regarding how any changes that affect the facility should be reflected in EMT models provided by the GO. TPs and PCs should clearly document the specifications in interconnection requirements and in transmission planning processes for when and how these model updates should occur when changes are made at the interconnecting facilities.

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[15] https://www.nerc.com/comm/PC_Reliability_Guidelines_DL/Reliability_Guideline_IBR_Interconnection_Requirements_Improvements.pdf

[16] References for existing detailed EMT model requirements are provided in **Appendix B**.

[17] This may require TPs and PCs to collaborate with applicable TOs to establish interconnection requirements that would obligate GOs to provide EMT models for each interconnecting project.

[18] This may include representation of measurement techniques for quantities—such as voltage, current, frequency, and rate-of-change-of-frequency—since the way these quantities are measured and calculated may affect inverter performance.

- TPs should clearly define the purview and duration of EMT simulations to support project developers, GOs, and equipment manufacturers develop an EMT model with sufficient fidelity and accuracy.
- TPs and PCs should establish and specify the software platform for which GOs should provide the EMT models as there are multiple options available and they are generally not cross compatible.
- TPs and PCs should specify which software features the models should be compatible with, such as parallel computing or automation.

Table 1.1: Example Checklist of EMT Model Requirements

Status	Model Requirement
Usability	
	Pertinent control functions and associated parameters are accessible.
	Model works across a range of time steps and does not require a specific time step.
	Maximum simulation time step to retain model accuracy is specified.
	It is easy to identify product variants or specific configuration intended for the facility.
	Model can be easily dispatched various commands, such as power commands and voltage control set point.
	Model comes with a comprehensive documentation, such as user guide covering software dependencies and model limitations
	Model package simulation includes all required files (Dynamic Link Library (DLL) and other libraries) to run a quick test simulation to verify.
	Easy to scale the plant model to represent smaller or larger plant capacity.[19]
	Multiple instances of the model can coexist in a single simulation.
Efficiency	
	Maximum simulation time step required by the model is not too small.
	Model can initialize itself to a dispatched level and can reach steady state quickly.
	Model is compatible with the software features required by TPs and PCs such as parallel computing and automation.
	If the software chosen by the TP and PC requires specific compilers or other software frameworks, the model is compatible with the versions that TP and PC specify.
	Model does not cause unusual or unreasonable computational burden.
Accuracy	
	Plant collector system and inverter GSU equivalencing techniques are documented and ratings are visible to the end-user

[19] This may not be applicable to HVDC/FACTS models as they may be tailored made for a particular size.

Table 1.1: Example Checklist of EMT Model Requirements	
Status	**Model Requirement**
	Aggregation and scaling techniques used to develop the aggregate inverter model and their limitations are clear to the end-user and documented
	Main power transformer, substation components, and gen-tie lines are modeled explicitly and visible to the end-user for verification purposes
	Transformer nameplate values matches transformer test report and winding configurations match site design
	Transformer models should include saturation characteristics to the extent that they are known.
	Detailed fast control loops of the power electronics are implemented as installed in the actual equipment in the field.
	DC side and any current, power or energy limitations are represented in the model[20]
	All pertinent control features and operating modes of the actual installed equipment (both inverter and plant-level) are included in the model.
	Control settings are agreed upon and "certified" by the equipment manufacturers as being configured appropriately in the field.
	All protection functions relevant to the performance of the facility are included. (Actual firmware code is recommended to be implemented in the model for these features.)
	Inverter-level protections (software and hardware), including all hardware limitations and protections
	Plant level protection which could result in the plant tripping such as current, voltage and frequency elements, with as detailed vendor-specific protective functions as possible.
	Each equipment installed in the field is traceable back to a specific inverter make, model, and software version.
	Model quality attestations (see **Chapter 2**)
	Equipment manufacturer certification that the EMT model matches the equipment that is (or will be) installed in the field.
	Communications delays between devices and sampling delays—inverters, plant-level controllers, automation controllers, metering, and protective relaying
Site-specific Plant and Model Documentation	
	Type of facility (e.g., solar PV, wind, battery energy storage system, hybrid)
	List of all equipment manufacturers (particularly for the inverter, plant-level controller, and any other significant controls within the facility) installed at the site

[20] Modeling dc side with an ideal voltage source is not acceptable if such a representation prevents the possibility of protection operation during external system events.

Table 1.1: Example Checklist of EMT Model Requirements	
Status	**Model Requirement**
	Points of contact and contract information for model-related questions for all equipment manufacturers involved in the facility
	List of all makes and models of inverters with version of firmware and plant-controllers within the facility[21]
	Documentation of plant name(s), commercial operation date(s), Energy Information Agency plant name and code, interconnecting TO bus name and nominal voltage, defined POI location
	Equipment specification sheets and user manuals
	Equipment protection settings
	Equipment controls descriptions (e.g., plant-level controls hierarchy, voltage control strategy, theory of operation)
	Inverter or plant-level controller screenshots or settings sheets and mapping of product settings to model settings for all relevant functions
	Facility one-line diagrams
	Communications delays between devices and sampling delays: inverters, plant-level controllers, automation controllers, metering, and protective relaying
	Inverter- and plant-level controller EMT model validation reports (as described in this reliability guideline)
	List of EMT model files provided and their intended purpose
	User manual for EMT model that describes all aspects of the functional use of the model in BPS reliability studies
	Description of inverter- and plant-level settings with units for any applicable settings
	Description of control modes, which may be supplemented by control block diagrams[22]
	Model limitations, including maximum solution time step
	Software requirements, including versions
	Instructions on how to setup and use the model

Equipment-Specific EMT Model Validation Reports

TPs and PCs should specify one or multiple forms of EMT model validation in EMT model requirements. GOs may consider requiring these forms of validation (as specified by the TP and PC) in their agreements with the equipment manufacturers to ensure proper data is provided to the TP and PC to meet the EMT model requirements. Examples of EMT model validation include, but are not limited to, the following:

[21] Any modification to the make and model of inverter or controller, including the software version of the installed equipment that affects the electrical performance of the facility should require an updated EMT model.

[22] Block diagrams for plant-level active and reactive power control loops and any grid support functions should be included.

- EMT model validation to factory test reports of inverter performance to large disturbance fault events
- EMT model validation to hardware-in-the-loop validation testing[23]
- EMT model validation to field measurements of installed equipment following a grid disturbance[24]
- EMT model validation to lab testing of the equipment
- Mapping of inverter or plant-level real code firmware version to EMT model version[25]
- Benchmarking detailed EMT model versus aggregate EMT model to verify that the model performance is consistent

[23] Hardware-in-the-Loop Simulation, Control, and Validation of Battery Inverter Characteristics Through the IBR Control Hardware

[24] This will require DFR-level oscillography data for validation purposes.

[25] The use of a real-code EMT model should not automatically imply that the EMT model is validated. Additional validation is always needed to confirm that the EMT model being used matches the equipment that is (or will be) installed in the field.

Chapter 2: Recommended EMT Model Quality and Verification

Recent disturbance reports[26] have highlighted challenges with relying solely on positive sequence dynamic models. These reports have also highlighted gaps in model verification processes that ensure EMT models are of high quality and accurately reflect the as-built facility. One critical example is the existing EMT models' inability to reproduce poor ride-through performance observed in the events due to the omission of relevant protection and control logic in the model and the lack of modeling requirements that would drive those elements to be included in the model.

TPs and PCs should enhance existing processes to ensure EMT model verification is conducted for each plant. Model quality assessments should take place during the interconnection study process at time of commissioning and on an established periodic basis to ensure that the model matches the plant (control modes, parameterization, and protections). This chapter provides details regarding what constitutes model quality and how to verify the models. Principles of EMT model quality considered in this guideline are summarized in **Figure 2.1**.

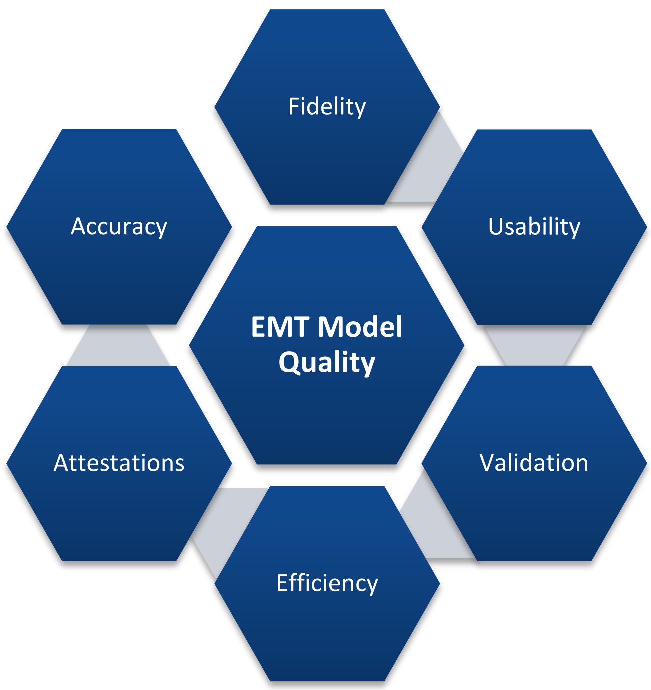

Figure 2.1: Principles of EMT Model Quality[27]

Model Quality Verification and Attestations

A critical component of model verification and model quality checks is ensuring that the GOs and equipment manufacturers have provided sufficient documentation to ensure the model matches the as-built or planned facility. One aspect of documentation used for quality assurance is preparing a model quality attestation, which generally falls into two categories:

- **Model Quality of Individual Models:** TPs should require GOs to provide equipment model quality attestations (E-MQA) for each equipment manufacturer in the facility. This is mainly for inverters and plant-level controllers (and other supplemental dynamic devices in the facility). These models are provided by the equipment manufacturer and are used by the GO to create an aggregate EMT model of the facility. The E-MQA confirms that the user-defined model(s) provided by the equipment manufacturer are site-specific,

[26] https://www.nerc.com/pa/rrm/ea/Pages/Major-Event-Reports.aspx

[27] Model fidelity refers to level of details included in a model.

accurately represent the equipment installed (or planned), and include settings as configured and left on-site (or planned). Key features of the E-MQA that the TP should require as part of the model verification process include the following.

- The E-MQA should attest to meeting the EMT model accuracy, usability, and efficiency requirements.
- The E-MQA should describe exactly how the model is configured: operating mode, settings (including control gains, limits, threshold), and all pertinent forms of protection and controls (enabled and disabled).
- The E-MQA should include the facility name for which the model was provided. This is to ensure that project specific models and parameters have been used.

- **Model Quality of the Entire Facility:** TPs should require GOs to provide plant model quality attestations (P-MQA) that confirm the EMT model of the entire facility accurately represents the equipment installed in the field. TPs should require GOs to work with the equipment manufacturers to ensure that any user-settable parameters are updated to match the equipment in the field. The P-MQA should attest to the following conditions:
  - The EMT model meets all the model requirements set forth by the TP and PC.
  - Each equipment installed in the field is appropriately represented in the EMT model either explicitly or in aggregate. Examples of equipment include, but are not limited to, the following: gen-tie line, main power transformers, collector system, coupling or scaling transformers, inverter models, plant-level controllers, dynamic or static reactive power devices, and any other equipment necessary.
  - The model control modes and settings match the equipment installed in the field. This includes appropriate EMT model parameterization of operating modes, settings, and all forms of protection (enabled and disabled, including protective relays) represented in the model.
  - Equipment manufacturers attest to the parameterization section of the P-MQA submitted to the TP and PC.

Each E-MQA and P-MQA should be unique to a specific facility and include a revision history to track model updates throughout the interconnection process and any modifications after commercial operation.[28] The E-MQA should provide sufficient confidence to the GO, TP, and PC that the user-defined EMT models accurately represent the equipment (make, model, type, version, and parameters) intended for the facility. The P-MQA provides confidence to the TP and PC that the combined EMT models used to represent the overall facility accurately represent the site design and expected performance in the field. This can be confirmed later as part of MOD-26 testing activities, particularly against actual grid disturbances.

Industry has had difficulty ensuring that dynamic models accurately reflect the as-built equipment installed in the field.[29] The recommended processes of EMT model development, collection and model quality verification are illustrated in **Figure 2.2**. They can be broken down to responsibilities and deliverables by the equipment manufacturers, GO (or developer), and TP and PC. Each of these entities plays a key role in ensuring model quality throughout the lifecycle of the facility.

[28] The model update includes changes to model parameters as well as changes to implementation of controls and electrical interfaces. Modifications includes changes to control settings as well as physical equipment. Each model update should be accompanied by a new E-MQA and P-MQA.

[29] https://www.nerc.com/pa/rrm/ea/Pages/Major-Event-Reports.aspx

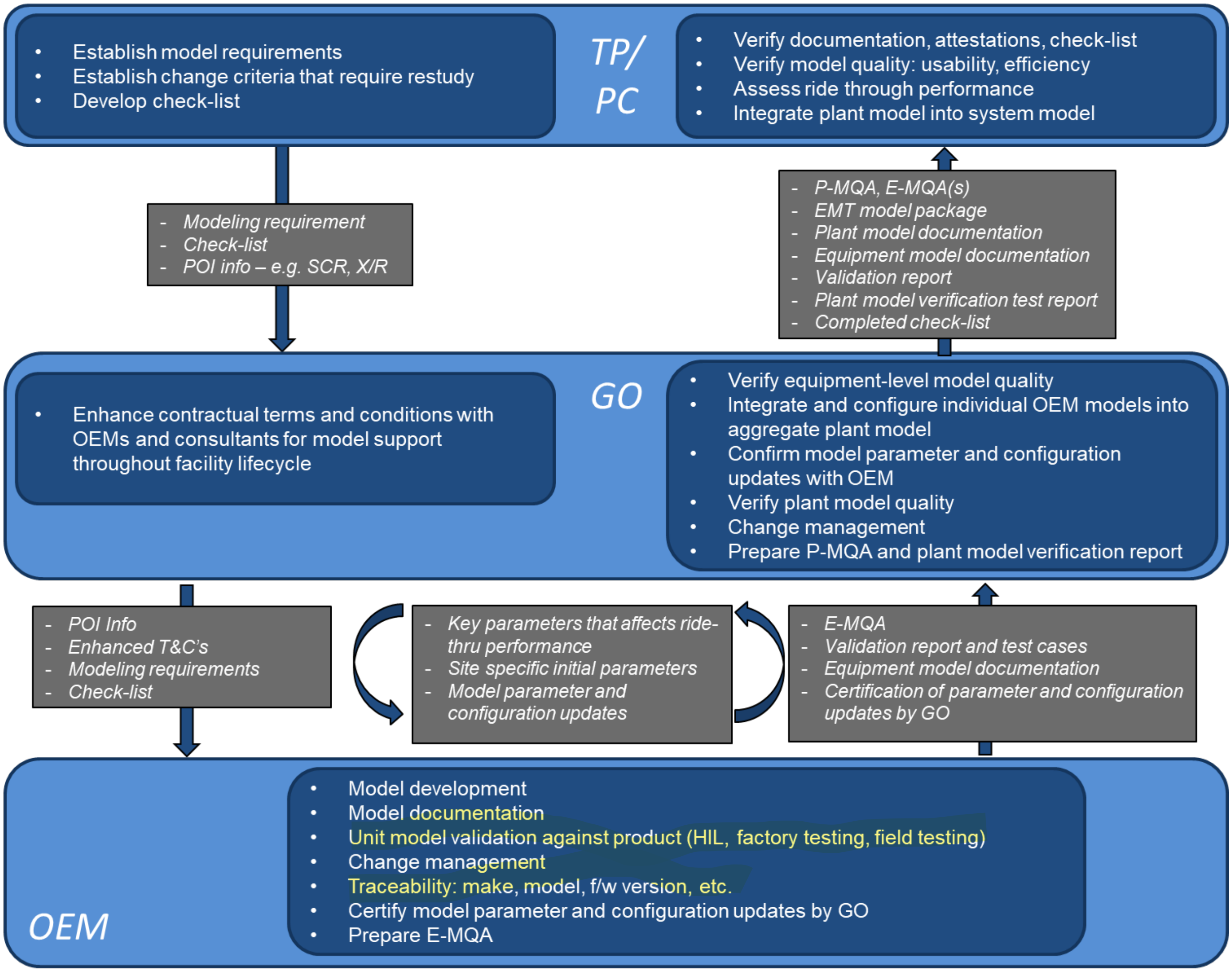

Figure 2.2: Model Quality Verification Processes

The model used to conduct interconnection studies should be fully verified prior to commercial operation of the inverter-based resource. No resource should be allowed to enter commercial operation until the model and the proposed settings have been fully verified to match. Any differences between the model used for study and the actual installed settings in the field should be deemed a qualified change per FAC-002-4 and be reviewed by the TP and PC prior to commercial operation to determine whether the existing studies are still valid. GOs should cooperate with the TP and PC prior to interconnection and during commissioning to ensure a smooth interconnection study process to ensure reliable operation of the BPS.

The following are specific recommendations regarding the roles and deliverables applicable to each entity during EMT model quality verification. Each of these recommendations should be completed prior to the plant entering commercial operation to ensure model accuracy and BPS reliability.

Recommendations for GOs

- GOs, in coordination with the equipment manufacturers, are responsible for verifying the individual component models as well as the overall facility EMT model (comprised of those component models). Individual component models should be provided by the inverter manufacturer, plant controller manufacturer, and manufacturer of any other advanced control systems (e.g., plant coordination controls for hybrid facilities) and FACTS devices installed at the facility (if applicable).

- GOs should consider the following in their model verification process:
  - For individual components mentioned above, each EMT model should be manufacturer-specific as well as site-specific, and accompanied with detailed documentation describing the applicability, functional use, and capabilities of the model.
  - Any parameters made available to the end-user should be clearly defined and documented, including but not limited to, range of acceptable values, units, dependencies on another parameter or mode flag, etc.
  - Parameters related to or affecting ride-through performance and the performance of grid support functions should be clearly highlighted and explained.
  - The range of short-circuit ratios and X/R ratios that the model (and the product) can reliably operate without special or specific settings that may be different from those provided to GO.
  - The overall EMT model should be traceable to specific inverter settings and controls installed in the field.
  - Any equivalent representation that does not match an actual component setting should be described such that the TP and PC understands the aggregation process.
  - The inverter and plant-level controller manufacturers should provide some form of a validation report that demonstrates that the model matches the equipment installed in the field.
  - Ideally, model parameters should match the settings available in the products. If they are different (different unit, scaling, etc.), a parameter mapping table along with an explanation of differences and conversions should be provided along with the models.
- GOs should work with equipment manufacturers to ensure that EMT models provided to TPs and PCs meet all model requirements set forth.
- GOs should ensure that equipment manufacturers provide attestations that their supplied models meet all model requirements.
- GOs should leverage EMT modeling checklists and ensure that the supplier of any EMT model (equipment manufacturer or consultant) review each item in the checklist and confirm that the model meets the requirements of the checklist. Deficiencies should be accompanied by additional data or explanations.
- GOs should ensure that equipment-specific EMT models are provided by equipment manufacturers and are combined to appropriately represent the overall facility up to the point of interconnection.
  - This often involves a third-party consultant or modeling subject matter expert to develop the overall plant model that includes the equivalent inverters, plant controller(s), reactive devices, equivalent and explicit plant components, relevant protection systems that could trip the resource, either partially or as a whole, and other relevant models.
- GOs are responsible for ensuring that the aggregate plant EMT model is configured to meet TP and PC model requirements and is accompanied by documentation demonstrating that the site-specific configuration, impedances, parameters, time delays, etc. represent the overall plant as accurately as possible.
- GOs should confirm with the equipment manufacturers the parameters and configuration changes made to the initial models provided by equipment manufacturers are reasonable, valid and appropriate for the products being considered for the facility. GOs should obtain formal certifications from equipment manufacturer's stating as such.

- GOs should collaborate with equipment manufacturers, consultants and other design and engineering firms to establish clear strategies around operation, control, and protection (e.g., real and reactive power mode, grid support functions and their positions in the control hierarchy, such as inverter-level frequency-watt or site level frequency response function). Throughout the design phase, GOs should consider the following:
  - GOs should review these regularly to ensure alignment with all parties involved in facility design and engineering. Any changes should be reflected in a model update promptly delivered to TPs and PCs per the relevant requirements set in FAC-002.
  - GOs should ensure site design as it evolves (electrical, control, protection, communication) continues to support the established strategies
- GOs should develop a checklist to walk through before and at commissioning to verify and document the following information:
  - Inverter and plant controller control modes and parameters that affect the dynamic performance, including ride-through capability, as compared to the actual product settings being commissioned
  - Inverter-level and plant-level protection functions and settings
  - Plant electrical component parameters in the model matches the actual nameplate values (such as GSU impedance)
- GOs should ensure that ongoing modeling support can be provided for the lifecycle of the plant. GOs should work with equipment manufacturers to establish plans for how model support will be provided in the event that model deficiencies and discrepancies are discovered, the equipment is no longer available, or other issues with future computing infrastructure occurs, such as model compatibility.[30]
- Validation, benchmarking, and model verification should be done prior to TP and PC study work and should be collaboratively carried out by the GO, their consultants, and the equipment manufacturer.

Recommendations for Equipment Manufacturers

- Equipment manufacturers should carefully consider system information provided by GOs and configure the equipment models accordingly to be site specific.
- Equipment manufacturers should not indiscriminately provide models with default parameters to GOs.
- Equipment manufacturers should collaborate with GOs to review and approve any changes to the model parameters and configuration (such as modes of operation, flags, etc.) made by GOs and their consultants.
- Equipment manufacturers should develop change management to ensure traceability of the equipment models to actual product model, variant, firmware version.
- Equipment manufacturers should be prepared to provide unit model validation reports and E-MQAs described above.
- Equipment manufacturers should make clear in model documentation the following:
  - Any built-in, hardcoded, or hardware-based protection that can affect the inverter current output during and post grid disturbances
  - User-settable settings that can affect the inverter current output during and post grid disturbances, such as protection settings, reactive current injection settings (k-factor), filter time constants, voltage and frequency droops (both inverter level and plant level if the same equipment manufacturer supplies both)

[30] Changes resulting from this should be evaluated for model quality impacts.

Recommendations for TPs and PCs

- TPs and PCs should develop a model quality checklist for GO to complete and submit along with the EMT models, attestation and documentations.
- TPs and PCs should establish explicit modeling requirements for GO to provide long-term model support.
- TPs and PCs should coordinate and develop plans to integrate EMT modeling into their interconnection studies process. See **Chapter 4** for resourcing needs. These processes can vary depending on location. Depending on the process and the project life cycle, the model may change (e.g., inverter make/model, available functions, settings) and require re-study.
- TPs and PCs should develop test cases to verify model quality accuracy, usability, and efficiency.[31]
- TPs and PCs should develop test cases to verify disturbance ride through performance of the quality-verified models, including but not limited to, those recommended in **Chapter 3**.
- TPs and PCs should develop clear criteria on what changes to the model or the product requires an evaluation for re-study.[32]
- TPs and PCs should provide GO with system information at POI (e.g., range of SCR and X/R ratios, nearby IBR plants and synchronous machine plants, series compensated lines, or FACTS).
- TPs and PCs should verify that sufficient documentation is provided by the GO for the following:
  - Plant and model documentation outlined in **Chapter 1**
  - P-MQA and E-MQA's
  - Model validation report and test cases
  - A completed checklist (proof of meeting model requirements and model verification tests)
  - That equipment parameter values match a reasonable expectation of the equivalent performance of those applicable components within the facility
  - That explicit models match actual plant component specification sheets, screenshots, or photos of the equipment and their settings
- TPs and PCs should spot check and perform some or all of the model verification tests with the following considerations:
  - Only after the submitted model has been verified as outlined above to meet their model requirements, TPs and PCs should conduct simulations to assess disturbance ride through performance of the plant model.
  - Without thorough model quality control in place, a plant may exhibit acceptable ride through performance in the model but not in the field.[33] Vice versa, a thoroughly vetted plant model that exhibits poor ride through performance may actually be revealing potential issues with the actual plant. If this is the case, TPs and PCs should work with GOs to ascertain the settings and configurations as submitted are appropriate for the conditions at the specific point of interconnection.
  - Any deficiencies identified should be corrected before allowing the resource to continue in the interconnection process.

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[31] These tests should test the rigor, usability, and efficiency of the models. They can be different from testing for performance.

[32] Inverters should be commissioned with the same control settings as those in the model studied. If the actual inverters on-site cannot be set the same way, TPs and PCs should evaluate if the discrepancies make material difference in the plant performance from what was studied and if another study is required

[33] Bad model performance does not necessarily mean bad models. It could be a sign that some control settings or model parameters are not set appropriately for a given interconnection.

Chapter 3: Model Verification Tests

A crucial step in model verification is actually running simulation tests to verify the facility EMT model meets the established model requirements. These simulation tests generally fall into three categories:

- **Model Adequacy Tests**: To verify usability, efficiency and accuracy requirements described in **Chapter 1** and the sample checklist (**Table 1.1**)
- **Functional Tests:** To verify that the EMT model is configured appropriately based on interconnection applications, requirements, and equipment limitations by evaluating the following:
  - The ability to follow power commands, up to the capabilities defined in the application
  - The ability to limit output and output ramp rate, according to the specifications in the interconnection application
  - The ability to represents physical limits
  - The ability to operate with required grid support functions, such as the following:
    - Plant Reactive Power/Voltage control–power factor control, reactive power control, voltage control
    - Plant Active Power/Frequency control–Fast Frequency Response, Primary Frequency Response
    - Dynamic reactive support such as reactive current injection (k-factor)
- **Disturbance Ride-through Performance Tests:** To verify the plant model can ride through common grid disturbances by evaluating the following:
  - The ability to ride through both balanced and unbalanced faults and transients of various severity (fault magnitude and duration)
  - Performance during disturbance within normal operating voltage range at POI meets regional requirements.
  - The ability to ride through high voltage events
  - The ability to ride through severe phase angle changes
  - The ability to ride through expected high rate of change of frequency

The single-machine infinite bus test case, which involves a plant model connected to a Thevenin equivalent voltage source with available short-circuit strength represented as the grid impedance, is sufficient to carry out the tests mentioned above. The tests should be repeated for short-circuit strengths within an expected range as determined by TPs and PCs.

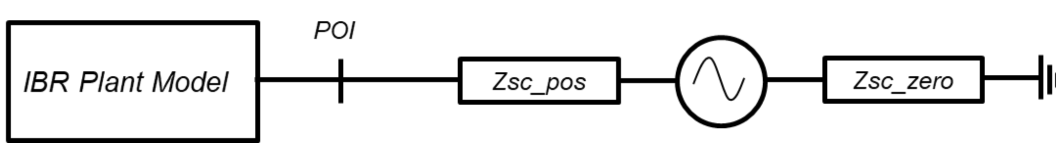

Figure 3.1: Single Machine Infinite Bus Test Case

Chapter 4: EMT Study Use Cases

There are numerous reasons why detailed EMT studies may be needed to ensure reliable operation of the BPS with increasing amounts of inverter-based resources (see **Figure 4.1**). However, with current industry resources (time, expertise, computational ability, etc.), it is often infeasible to conduct detailed EMT studies for every interconnecting plant during the interconnection process or for every reliability issue identified in long-term planning. Therefore, screening tools and techniques are used to identify specific reliability issues where EMT studies are needed.[34] This guideline does not address how to perform actual analysis after EMT study needs are identified.

All TPs and PCs should have clear processes and procedures to determine if and when EMT studies are necessary during the interconnection study process. While EMT studies may not be needed in all situations, an objective and quantifiable screening process should be in place to determine if EMT studies are required. The process should tend to err on the conservative side (i.e., performing EMT studies) so as not to miss potential reliability risks that would otherwise not be identified during positive sequence dynamic simulations.

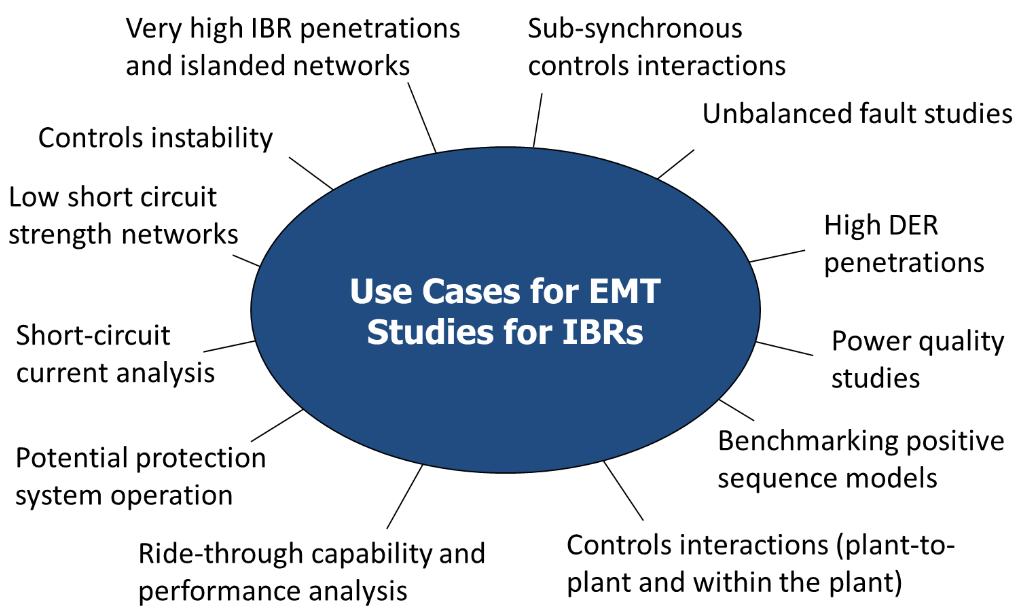

Figure 4.1: Use Cases for Detailed EMT Studies for Inverter-Based Resources

The following are common situations where a detailed EMT study may be needed, and qualitative or quantitative screening techniques may be used to determine when those studies will be conducted:[35, 36, 37]

- **Areas with High Penetrations of Inverter-Based Resources:** This can be assessed qualitatively or quantitatively by considering the number of inverter-based resources within a given area or portion of the larger system. In general, TPs and PCs experiencing high levels of BPS-connected inverter-based resource penetrations may consider adding EMT studies during the interconnection process for all newly interconnecting resources.

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34 One screening approach can be useful for identifying a particular phenomenon that should be further studied using EMT models. No single screening technique should completely rule out EMT study need.

35 The reliability risk issues presented here are not intended to be comprehensive. In all cases, the TP and PC has the requirement to conduct adequate studies to ensure reliable operation of the BPS in their footprint.

36 https://www.esig.energy/download/emt-studies-at-iso-ne-brad-marszalkowski/?wpdmdl=9259&refresh=62f4df6d50fe71660215149

37 https://www.iso-ne.com/static-assets/documents/rules_proceds/isone_plan/pp05_6/pp5_6.pdf

- **Low System-Strength Networks:** Networks with relatively lower system strength, caused by limited to no synchronous generation and/or limited transmission infrastructure (higher effective network impedance) are areas where more detailed EMT studies may be needed. Issues that may arise in these areas include unexpected controller instability issues or controller interactions within or between plants. One common metric used to quantitatively measure system strength is the short-circuit ratio (SCR). There are varieties of SCR-based metrics available, such as the weighted short-circuit ratio (WSCR)[38] or the composite short-circuit ratio (CSCR),[39] to estimate system strength in ideas of high IBR penetrations. Because their application to estimate grid strength is nuanced, TPs and PCs are encouraged to use such metrics judiciously, be conservative in their assessments, and preferentially perform EMT studies.
- **Potential Interactions with Other Transmission Elements**: even at high SCR locations, various grid-related interactions or issues may require detailed EMT analyses. Examples include the following:
  - **Subsynchronous oscillations:** Areas with series-compensated transmission circuits are often analyzed for possible subsynchronous control oscillations. Due to the potential for serious equipment damage, screening approaches will consider many levels of outaged transmission lines to screen for possible risk scenarios. Sub-synchronous oscillations can also occur in parts of a weak system that does not necessarily comprise of series-compensated transmission circuits.[40]
  - **Super-Synchronous Oscillations:** Inverter-based resources generally have control loops for voltage and/or current control characterized by relatively high bandwidths. This leads to potential high-frequency (i.e., super-synchronous) oscillations when there are interactions between inverter-based resources in close proximity and high voltage direct current converters and IBRs.
  - **Power Quality Issues:** TOs, TPs, or PCs may identify power quality issues in a particular area that then could require more detailed EMT studies where applicable. This will require close coordination with equipment manufacturers, particularly in relation to inverter-based technologies.
- **Concerns with Protection System Misoperations:** Areas with high penetrations of inverter-based resources may experience concerns regarding correct operation of transmission protection systems. This has been documented in industry literature and is an increasing concern in many areas.[41] Indeed, traditional protection systems are based on the detection of the high-magnitude short-circuit currents (in the case of over-current relaying) contributed by synchronous generators. The short-circuit contribution of synchronous generators is high enough in magnitude and long enough in duration to be more or less easily detectable. However, inverter-based resources have relatively low-magnitude and short-duration short-circuit current contributions, making rapid detection of fault currents problematic in areas with high concentrations of inverter-based resources. Detailed EMT studies may be needed to explore these impacts in some areas as deemed necessary by TOs, TPs, or PCs.

TPs and PCs can leverage these points to develop their own screening approaches to identify when and where more detailed EMT studies should be conducted. To be on the safe side, TPs and PCs conduct EMT studies any time positive sequence dynamic models are unable to fully explain possible reliability risk issues or where known modeling or simulation tool deficiencies could pose risks to reliable operation of the BPS. Part II of this guideline will provide further recommendations on qualitative screening approaches.

[38] https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=6939043
[39] S. Achilles, N. Miller, E. Larsen, J. MacDowell, GE Energy Consulting, "Stable Renewable Plant Voltage and Reactive Power Control," Presented to NERC ERSTF, June 11-12, 2014
[40] https://ieeexplore.ieee.org/document/9740416
[41] https://resourcecenter.ieee-pes.org/publications/technical-reports/PES_TR_7-18_0068.html

Chapter 5: Other Relevant Topics

Benchmarking Positive Sequence Dynamic Models against the EMT Model

Having accurate and verified models of IBR facilities is fundamental to performing reasonably accurate reliability studies that can be used to make engineering decisions.[42] Ideally, models would be validated against measurement data for large disturbances, but this is often not practical, especially for entire facilities. It is a common practice for different types of models to be benchmarked against each other[43] (e.g., positive sequence RMS model against the EMT model and site measurements) with a higher degree of trust placed in the higher fidelity model. However, EMT models are generally regarded as the highest-fidelity[44] model used in stability studies. Since EMT models can better represent the field-installed equipment, NERC has recommended that positive sequence dynamic models should be benchmarked against verified EMT models to improve their quality. Examples of benchmarking positive sequence models against EMT model for an interconnecting facility are illustrated in **Figure 5.1** and **Figure 5.2**.[45]

TPs and PCs should establish clear and consistent model benchmarking requirements between EMT models and positive sequence dynamic models in their interconnection study process requirements. TPs and PCs should also do this for any modifications to actual plant settings, performance, etc., that would require model updates to either the EMT model or the positive sequence dynamic model.

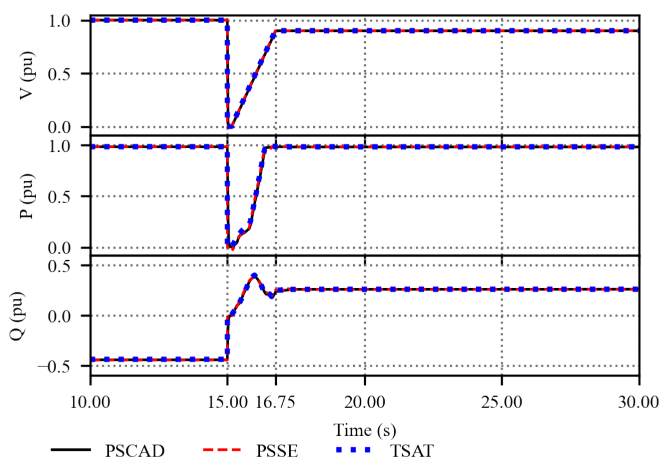

Figure 5.1: Example Model Benchmarking Using Low Voltage Ride-Through Test

42 This is fundamental to all types of power system simulations (e.g., steady-state power flow, positive sequence RMS, EMT, short circuit).
43 Even in situations where the positive sequence RMS dynamic model matches the EMT model fairly closely, TPs and PCs likely will need both models to integrate with larger local, regional, or system-wide studies either in the positive sequence dynamic simulations or EMT simulations.
44 Model fidelity depends on the expansiveness of the actual controls that are represented in the models. EMT platform provides the facility to be able to represent most control logics, especially very fast inner-loop controls.
45 These are exemplary results from benchmarking a real facility-specific user-defined positive sequence model against the corresponding user-defined EMT model. Benchmarking results will vary depending on modeling approaches and platform limitations. Deviations outside of TPs and PCs model requirements should be explained by GOs.

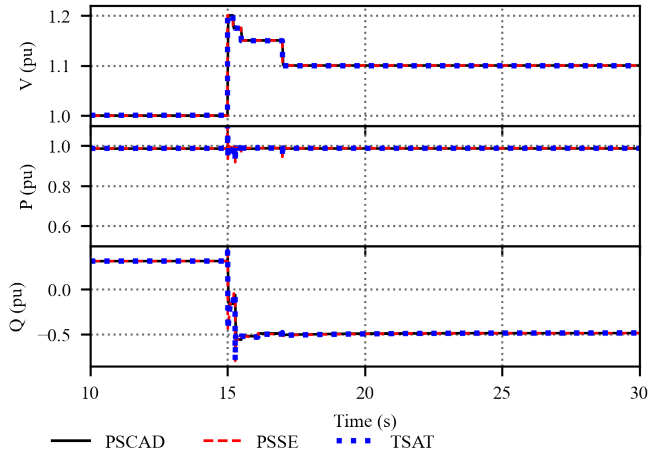

Figure 5.2: Example Model Benchmarking Using High Voltage Ride-Through Test

Resourcing for Future EMT Study Needs

Industry should consider the necessary resources, skills, expertise, computational capabilities, and outside support to successfully prepare for the need for increased reliance on EMT studies in the future:

- All TPs and PCs should develop engineering expertise in the area of EMT modeling and studies as it is expected that these types of studies will become more commonplace in the future. In situations where the TP or PC lacks EMT study expertise, TPs and PCs should establish strong relationships and contracts with subject matter experts, consultants, or other study organizations for situations where EMT modeling and studies are needed.
- Academic institutions with power engineering programs should improve their curricula related to EMT modeling and EMT studies to ensure that all newly graduating power engineers have some understanding and expertise in this area. Advanced degrees (e.g., Masters and Ph.D.'s) should have a requirement to study EMT concepts and graduates should have the capabilities to conduct detailed EMT studies (for respective program concentration areas).
- Research institutes and national laboratories should consider developing educational materials and reference documentation that help industry improve their understanding of EMT models, EMT study approaches, commercial tool capabilities, and other related topics.
- TPs and PCs should coordinate with neighboring TPs and PCs when necessary to ensure any TP/PC boundaries do not hinder the detail of modeling needed to identify reliability issues in EMT studies. This is particularly important for studies conducted near TP or PC planning footprint boundaries. Data sharing agreements should be established with neighboring TPs and PCs to ensure interoperability of EMT models and studies in these cases.

Applicability and Use of IEEE 2800 Guidance

Final approval and publication of IEEE 2800-2022 provides a comprehensive set of modeling requirements that are necessary to be implemented in EMT models by equipment manufacturers based on various ride through performance requirements. Testing and verifications of such features should be possible by using the EMT models of the plant built with models of IBR units, plant controllers from equipment manufacturer and all other components by plant designer. TPs and PCs should leverage the EMT modeling recommendations and future P2800.2[46] testing and verification practices in their interconnection processes.

[46] https://sagroups.ieee.org/2800-2/

There is a certain set of performance requirements specified in IEEE 2800-2022 that can be tested and verified by using a positive sequence stability model. However, there are performance requirements that need to be tested and verified by using only EMT models.

Appendix A: EMT Model Terminology

This appendix provides a description and technical details for terms used throughout this guideline regarding EMT modeling, modeling practices, and studies performed by TPs and PCs.

Generic versus Equipment Specific Models

- **Generic EMT Models:** Generic EMT models are defined here as EMT models that do not represent the proprietary control algorithm of any single equipment manufacturer or specific generating resource. These models are intended to be representative of the general dynamic behavior across a range of equipment manufacturers or plants. However, without the exact control structure of actual equipment (see below), these models are highly unlikely to represent site-specific controller instability scenarios. They should not be used in either BPS interconnection studies or planning assessments to represent specific (planned or installed) BPS resources. In some cases, generic EMT models may be used by the TP or PC to represent aggregate amounts of distributed energy resources if more detailed information is unavailable and if their representation is warranted for the study.
- **Equipment-Specific (Vendor-Specific) EMT Models:** Equipment-specific EMT models represent the actual (planned or installed) equipment installed in the field. These models are developed by the equipment manufacturers and combined to form a plant-level EMT model for the whole facility. These models represent the inner switching logic and detailed control systems of the planned or installed equipment in nearly identical detail. These models may use standard library control blocks[47] or components, dynamic-link library (DLL)-based conversion of actual inverter code,[48] and other means of representing the equipment and controls in detail. These models are parameterized to match actual equipment installed in the field (or planned to be installed in the field). Equipment-specific EMT models should be the only type of EMT models that are used in BPS reliability studies to represent BPS-connected inverter-based resources.

Equipment-Specific Model Types

Regardless of their types, all models should go through model verification process by the TPs, PCs and GOs and certified by equipment manufacturers. Equipment-specific EMT models generally fall into the following three categories:

- **Transparent EMT Models:** Transparent EMT models make the inner controls topology and software code (if applicable) visible to the user. In many cases, these types of models are built by using mostly standard library control blocks (e.g., transfer functions, math functions, logic blocks, classic control blocks) or some openly available custom code to construct the control system. Manufacturer-written compiled code in DLL format is typically not used in these types of models.[49] Electrical elements within the plant are also represented by using standard library electrical component models. These models may not have quite the direct relationship with equipment settings installed in the field unless the model has been verified and validated by the TP, PC, and GO and certified by the equipment manufacturer.
- **"Black Box" EMT Models:** "Black box" models have either all or parts of the EMT model that are not accessible to the end-user. These models are typically built with some portions of the model using DLL-based manufacturer-written code, particularly for the control functions contained within the model. The compiled code is either a direct replica of the controller firmware code or a very close match. An input-output (I/O)

[47] The use of standard library control components that come with EMT software in modeling inverter-level controls (e.g., the PLL) can introduce errors due to differences in implementation details. Thus, such modelling practice is not generally recommended.

[48] In many cases, the manufacturer will develop code in software platforms such as C, C#, MATLAB, or other programming languages, and convert them to useable logic block using DLLs. A *.dll is a Windows feature, which most TPs and PCs use; however, Linux uses a similar *.so.

[49] The act of using a DLL-based model makes the code contained within the DLL not visible to the user unless all documentation regarding the code contained within is provided as well.

interface feeds the model DLL with user-defined inputs where allowable (e.g., time constants, reference quantities) as well as inputs of electrical quantities from the simulation (i.e., voltages, currents) and returns the model DLL outputs (e.g., IGBT gate control signals, voltage references, protection flags). "Black box" models may also use control functions built by using both standard library and custom control components. These models can then be "blackboxed" with specific EMT software features to make them invisible to the user. Electric components of the equipment model may also be blackboxed.

- **"Real Code" EMT Models:** A "Real code" model is a type of black box model[50] that implements the actual control code from the equipment.[51,52] This is accomplished with a DLL as described above. The real-code aspects of the model pertain mainly to the controller-related code in the turbine controls, inverter controls, protection and measurement algorithms, and plant-level controller. The extent to which real code is used in the EMT model varies by equipment manufacturer; however, the inverter and plant controls are often implemented as real code. Real code models can be linked to specific software versions of controls for equipment installed in the field (or being studied during the interconnection process), which can help end-users of the model verify that correct models are being used. Real code EMT models are used by many equipment manufacturers, and are typically recommended for modeling BPS-connected inverter-based resources in BPS reliability studies performed by TPs and PCs.

Detailed and Aggregate EMT Modeling

- **Detailed Representation:** A detailed EMT representation of an inverter-based resource includes minimal to no aggregation of components or controls within the facility. **Figure A.1** shows an example of a detailed representation of a wind plant where each turbine, the collector system, substation, and all controls are modeled. These types of models may be used for any of the following reasons:
  - They are generally not recommended for use in BPS reliability studies due to their complexity and computational burden although they may be required by TPs and PCs for specialized studies. As computational capabilities improve, these models may be used more frequently for complex study purposes as they may be able to provide a greater level of fidelity.
  - They can be used to create or validate the aggregate models for BPS reliability studies (described below) to ensure they match the behavior of the as-built equipment and controls
  - They can be used by GOs to reduce the risk of intra-plant issues, such as temporary overvoltage, individual inverter response to faults internal or external to the facility, and any other interactions issues.
- **Aggregate Representation:** For most BPS reliability studies, the EMT model provided by the GO to the TP and PC should be an aggregate or partially equivalent representation of the inverter-based resource. Multiple equivalence components may be included for resources of different inverter makes and models as well as for hybrid power plants. The equivalent representation of the facility should not compromise the accuracy of the simulation results. This document describes aggregate EMT modeling practices since these models are the preferred type of models used in BPS reliability studies.

[50] Real code models could fundamentally be either transparent or black boxed; however, intellectual property rights typically prohibit real-code from being visible to the end-user and are most likely black-boxed for this reason.
[51] http://www.electranix.com/ieee-pes-tass-realcodewg/
[52] http://www.electranix.com/wp-content/uploads/2019/04/Use-of-Real-Code-in-EMT-Models-for-WECC.pdf

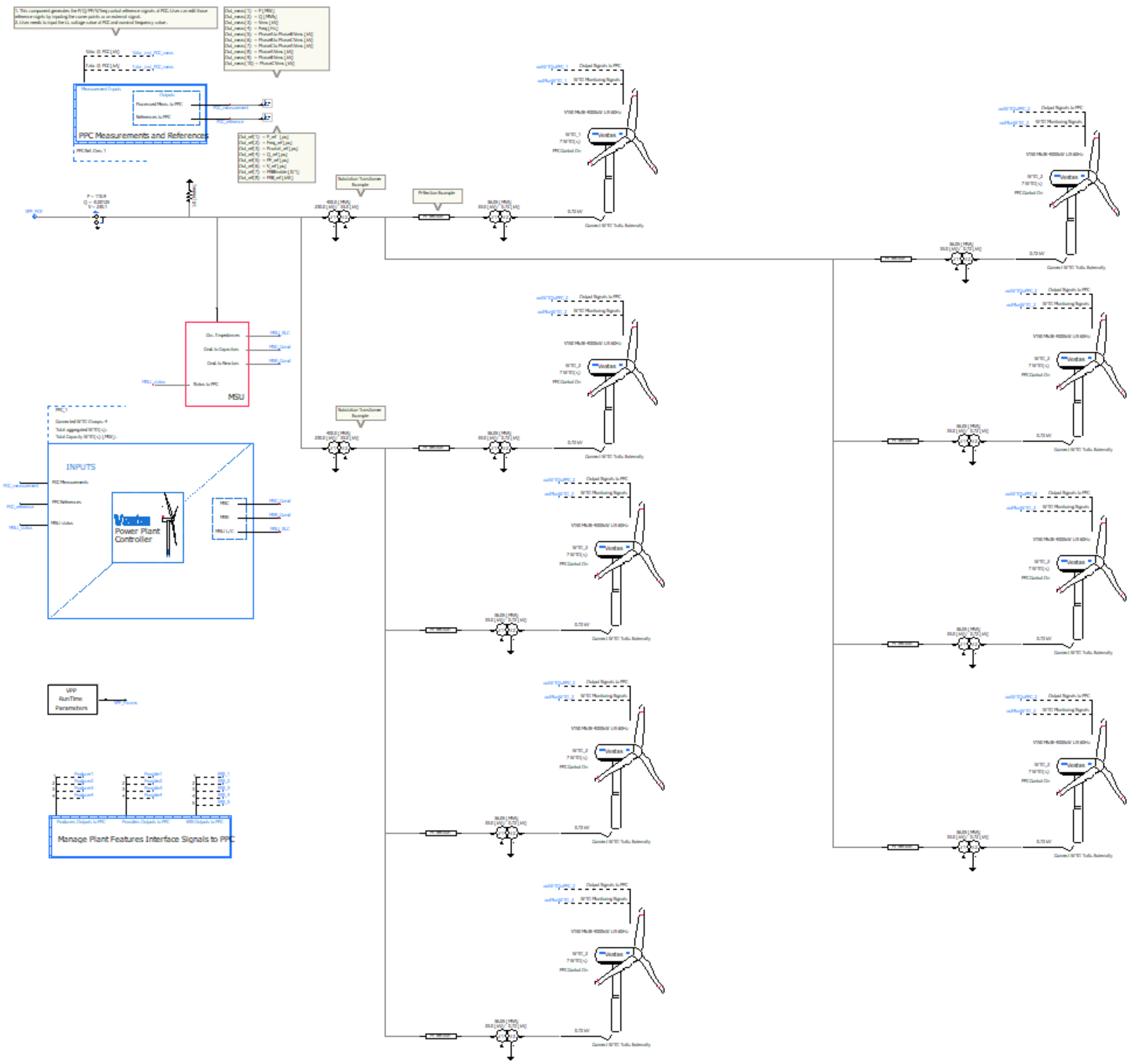

Figure A.1: Example Detailed Wind Power Plant EMT Model

Appendix B: References for EMT Model Requirements

Electranix

- Technical Memo – PSCAD Requirements[53]

ERCOT

- ERCOT Planning Guide revision (PGRR085)[54]
- Planning Guide Section 6.2 Data/Modeling[55]
- Dynamic Working Group Procedure Manual[56]

ISO-NE

- ISO New England Planning Procedure PP5-6, Appendix C – Requirements of PSCAD Models[57]

CAISO

- California ISO Electromagnetic Transient Modeling Requirements[58]

HECO

- Hawaiian Electric Facility Technical Model Requirements and Review Process[59]

MISO

- BPM-015 section 5.2.3.1[60]

Hydro-Quebec

- Technical Requirements for the Connection of Generating Stations to the Hydro-Québec Transmission System[61]

Southwest Power Pool

- SPP Electromagnetic Transient (EMT) Modeling Requirements[62]

[53] https://www.electranix.com/the-electranix-library/
[54] PGRR085
[55] Planning Guide Section 6.2 Data/Modeling
[56] Dynamic Working Group Procedure Manual
[57] ISO New England Planning Procedure PP5-6, Appendix C – Requirements of PSCAD Models
[58] California ISO Electromagnetic Transient Modeling Requirements
[59] Hawaiian Electric Facility Technical Model Requirements and Review Process
[60] BPM-015
[61] Technical Requirements for the Connection of Generating Stations to the Hydro-Québec Transmission System
[62] https://opsportal.spp.org/Studies/Gen

Appendix C: Contributors

NERC gratefully acknowledges the contributions and assistance of the following industry experts in the preparation of this guideline. NERC would like to acknowledge the EMT simulation software vendors and EMT simulation experts for their technical leadership in developing this guideline. NERC also would like to acknowledge all the technical discussions and contributions of the NERC IRPS.

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Jonathan Goldsworthy	ITC Holdings
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Aboutaleb Haddadi	Electric Power Research Institute
Ian Higginson	Power Engineers
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Diwakar Tewari	Leidos
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Jake Walker	Southern Company
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Guideline Information and Revision History

The	
Category/Topic: EMT Modeling	**Reliability Guideline/Security Guideline/Hybrid:** Reliability Guideline:
Identification Number: RG-MOD-0323-1	**Subgroup:** Inverter-Based Resource Performance Subcommittee

Revision History		
Version	**Comments**	**Approval Date**
1		3/22/2023

Metrics

Pursuant to the Commission's Order on January 19, 2021, *North American Electric Reliability Corporation*, 174 FERC ¶ 61,030 (2021), reliability guidelines shall now include metrics to support evaluation during triennial review consistent with the RSTC Charter.

Baseline Metrics

All NERC reliability guidelines include the following baseline metrics:

- BPS performance prior to and after a reliability guideline as reflected in NERC's State of Reliability Report and Long Term Reliability Assessments (e.g., Long Term Reliability Assessment and seasonal assessments)
- Use and effectiveness of a reliability guideline as reported by industry via survey
- Industry assessment of the extent to which a reliability guideline is addressing risk as reported via survey

Specific Metrics

The RSTC or any of its subcommittees can modify and propose metrics specific to the guideline in order to measure and evaluate its effectiveness, listed as follows:

- Number of TPs and PCs that have implemented EMT model requirements as recommended herein
- Number of TPs and PCs performing model quality verifications
- Number of Category 1i events, per NERC Event Analysis Program, involving inverter based resources
- Number of TPs and PCs requiring or performing positive sequence model vs. EMT model benchmarking

Effectiveness Survey

On January 19, 2021, FERC accepted the NERC proposed approach for evaluating Reliability Guidelines. This evaluation process takes place under the leadership of the RSTC and includes:

- industry survey on effectiveness of Reliability Guidelines;
- triennial review with a recommendation to NERC on the effectiveness of a Reliability Guideline and/or whether risks warrant additional measures; and
- NERC's determination whether additional action might be appropriate to address potential risks to reliability in light of the RSTC's recommendation and all other data within NERC's possession pertaining to the relevant issue.

NERC is asking entities who are users of Reliability and Security Guidelines to respond to the short survey provided in the link below.

Guideline Effectiveness Survey