ESIG
Large Loads
Task Force

Large Load Modeling for Dynamic Studies

CURRENT PRACTICES AND RECOMMENDATIONS

A Report by the
Energy Systems Integration Group's
Large Loads Task Force

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Large Load Modeling for Dynamic Studies: Current Practices and Recommendations

A Report by the Energy Systems Integration Group's Large Loads Task Force

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Disclaimer

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Preface to ESIG Large Loads Task Force Reports

This report is one of 11 reports by the ESIG Large Loads Task Force, which was formed to assist the power industry in addressing new challenges introduced by the rapid proliferation of large electronic loads such as data centers, as well as other large loads including manufacturing, electric vehicle fleets, and hydrogen production. The titles of the 11 reports are as follows:

- Grid Integration of Large Loads: Introduction to the Large Loads Task Force, Data Needs, and Flexibility Overview
- Forecasting for Large Loads: Current Practices and Recommendations
- Interconnection Processes for Large Loads: Current Practices and Recommendations
- Large Load Performance Requirements: Current Practices and Recommendations
- Large Loads: Behaviors, Capabilities, and Limitations
- Reliability Impacts of Large, Power Electronics–Interfaced Loads
- Large Load Disturbance Events
- Large Load Modeling for Dynamic Studies: Current Practices and Recommendations
- Transmission Planning with Large Loads: Current Practices and Recommendations
- Resource Adequacy with Large Loads: Planning for Flexibility to Accelerate Integration
- Wholesale Market Design and Operations for Systems with Large Loads: Current Practices and Recommendations

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Contents

Abbreviations

EMT	Electromagnetic transient
ENTSO-E	European Network of Transmission System Operators for Electricity
HVDC	High-voltage DC
MQT	Model quality test/testing
NERC	North American Electric Reliability Corporation
PEM	Proton exchange membrane
PSPD	Positive-sequence phasor-domain
RoCoF	Rate of change of frequency
RUG	Releasable user guide
STATCOM	Static synchronous compensator
TSO	Transmission system operator
UDM	User-defined model
UPS	Uninterruptible power supply
WECC	Western Electricity Coordinating Council

Executive Summary

The electric power system is entering a period of rapid transformation driven by the growth of large loads primarily connected at the transmission level, such as data centers, cryptocurrency mining operations, hydrogen production plants, and advanced manufacturing. These large loads are fundamentally different from the aggregated residential, commercial, and industrial demand that historically dominated electricity systems. These types of large load facilities are often concentrated geographically, comparable in size to large generating plants, and composed of tightly controlled power electronic equipment that can respond to grid disturbances on much faster time scales than traditional motor-dominated loads. As a result, their dynamic behavior can materially influence local power quality, bulk power system stability, and reliability.

This report provides a comprehensive overview and recommendations for modeling of large loads in power system dynamic studies. These studies focus on transient and short-term dynamic behavior—from the initiation of a disturbance through approximately 30 seconds afterward—the time horizon relevant to stability, voltage recovery, and frequency response assessments used in transmission planning and interconnection processes. The guidance is intended primarily for engineers responsible for transmission planning studies, interconnection assessments, and development or application of dynamic models in positive-sequence phasor-domain (PSPD) and electromagnetic transient (EMT) simulation tools.

Why Large Load Modeling Needs to Change

Historically, load modeling received less attention than generator and transmission equipment modeling. Loads were relatively smaller and geographically dispersed, as compared to generators, making aggregated and approximate representations sufficient for most power system studies. Initially, constant impedance (Z), constant current (I), constant power (P)—the so-called ZIP—models were used. Over time, a more sophisticated approach, the composite load model, was developed to better capture motor behavior, particularly in response to major disturbance events that revealed the importance of load dynamics for voltage recovery and oscillatory stability.

New large loads further challenge these established approaches. These facilities are dominated by power electronic converters, uninterruptible power supplies, variable-speed drives, and tightly coordinated control systems. These components introduce fast, control-driven dynamics, sensitivity to voltage and frequency excursions, and the potential for interactions with inverter-based resources (i.e., wind, solar, battery energy, storage), as well as other power electronic loads. Recent grid events have demonstrated that large converter-based loads can disconnect or rapidly change operating state during normally cleared transmission faults, leading to over-frequency or over-voltage conditions and, in some cases, cascading disconnections of generation and load. Existing composite load models, designed primarily to study induction motors, are not sufficient to capture these behaviors.

At the same time, planners face practical constraints. Standardized library models for power electronic loads are limited in most commercial simulation tools, and detailed information about facility-specific equipment, control, and protection settings is often unavailable. All together, these challenges create uncertainty in transmission interconnection and planning studies at a time when confidence in modeling results is more important than ever.

Modeling Frameworks and Study Objectives

This report distinguishes between two broad categories of dynamic assessments, having different modeling requirements:

- **Bulk system dynamic studies** focus on system-wide phenomena such as transient stability, voltage recovery, frequency response, and inter-area oscillations. These studies typically examine dynamics below approximately 10 Hz and rely on PSPD simulators to model large interconnected systems efficiently. For these applications, load models must capture relevant low-frequency dynamics, ride-through behavior, and control responses while remaining computationally feasible.
- **Local specialized dynamic studies** address higher-frequency and localized phenomena—such as subsynchronous interactions, controller instabilities, voltage flicker, and switching transients—that can arise at the point of connection of a large load facility. These studies require EMT simulators with detailed, three-

Two broad categories of dynamic assessments have different modeling requirements: bulk system dynamic studies focus on low-frequency, system-wide phenomena, while local specialized dynamic studies address higher-frequency localized phenomena.

phase representations of equipment, controls, and protection systems, often at microsecond time steps. While computationally intensive, EMT studies are essential when fast dynamics or unbalanced conditions are material to power system risk.

Recognizing these distinct use cases is critical. Not every study requires full device-level EMT modeling, but planners need guidance in understanding when simplified PSPD representations are sufficient and when higher-fidelity EMT modeling and analyses are necessary to reveal potential reliability concerns.

Essential Modeling Components for Large Loads

To realistically represent emerging large loads, dynamic models must move beyond static (i.e., ZIP model) or purely motor-based (i.e., composite model) assumptions and incorporate key new large load facility behaviors, including:

- **Active power and frequency response**, where loads may modulate consumption, shift to on-site generation resources, or disconnect in response to frequency excursions.
- **Reactive power and voltage control**, including power-factor control, Q–V droop behavior, and interactions with reactive support devices such as capacitor banks, reactors, static synchronous compensators (STATCOMs), or synchronous condensers.
- **Voltage and frequency ride-through characteristics**, reflecting actual protection and control logic rather than theoretical assumptions.
- **Ramp-rate limits and reconnection behavior**, which influence a large load facility's response following a disturbance and during restoration.
- **Mechanical load dynamics** for large load facilities that still have large motor-driven processes (in addition to power electronic–based components), where motor inertia and torque characteristics affect voltage recovery and stability.
- **Operational load profiles**, particularly for facilities with rapidly varying demand, such as artificial intelligence–driven data centers.
- **On-site generation and storage**, which must be modeled explicitly if intended to operate in parallel with the grid.
- **Appropriate level of aggregation**, which depends on the study objective. Aggregated representations may be suitable for bulk system studies, while detailed component-level modeling is often necessary for local EMT assessments.

Generic Versus Site-Specific User-Defined Models

There are trade-offs between generic library models and site/vendor-specific user-defined models. Generic models offer transparency, standardization, and computational efficiency, making them valuable for early-stage planning and regional studies. Site-specific models, while more complex and often proprietary, are necessary when facility-specific controls or protection behaviors materially affect system performance. Selecting the right approach requires balancing study objectives, data availability, and the need for accuracy.

A central theme of this report is the need for fidelity to actual plant behavior. Models that do not reflect real equipment settings, controls, and protections can lead to misleading conclusions and inappropriate mitigation strategies.

Model Fidelity, Verification, and Validation

A central theme of this report is the need for fidelity to actual plant behavior. Models that do not reflect real equipment settings, controls, and protections can lead to misleading conclusions and inappropriate mitigation strategies. To address this risk, the report outlines clear expectations for:

- **Parameter verification**, ensuring that model parameters correspond directly to installed equipment settings of the large load facility.

- **Model validation**, using field measurements, staged tests, or disturbance recordings to confirm that simulated responses match observed behavior.
- **Model quality testing**, including flat run tests, ride-through evaluations, phase-angle jump tests, and controlled changes in operating point to assess the numerical stability and robustness of a large load model. Model quality testing may also be used to assess a load model's capability to conform with applicable grid code requirements.

While such practices are well established for synchronous generators and inverter-based resources, they are not yet consistently applied to large loads. Extending these practices to large loads is essential as their system impact grows. This report concludes with guidance and recommendations in this regard.

Key Challenges and a Path Forward

Two challenges dominate current large load modeling efforts: the limited availability of standardized library models for power electronic loads, and insufficient access to detailed facility data for model development and parameterization. Addressing these challenges will require coordinated action among transmission planners, load owners, equipment manufacturers, and standards organizations.

This report provides initial recommendations for harmonized practices for large load modeling. By clarifying modeling objectives, defining essential model components, and outlining expectations for verification and validation, the report provides a foundation for improving the quality and consistency of dynamic modeling of data centers, cryptocurrency mining operations, hydrogen production plants, and advanced manufacturing. As large loads become an increasingly significant part of the power system, continued collaboration and refinement of these practices will be essential to maintaining system reliability and enabling efficient integration of new demand.

Two challenges dominate current large load modeling efforts: the limited availability of standardized library models for power electronic loads, and insufficient access to detailed facility data for model development and parameterization. Addressing these challenges will require coordinated action among transmission planners, load owners, equipment manufacturers, and standards organizations.

Introduction

Maintaining reliable operation of a power system requires simulating its behavior during the planning phase to identify risks associated with both expected and unexpected events. These simulations help determine whether the system can withstand disturbances and continue operating reliably. Simulation results guide the development of remedies, including infrastructure investments and operational measures to ensure reliability under a wide range of conditions. Simulating system operations and identifying reliability risks and mitigations are a key part of system reliability assessments. The need for high-fidelity simulations is becoming even more critical with proliferation of large loads, such as data centers, cryptocurrency mining operations, hydrogen production plants, and advanced manufacturing,[1] introducing faster, more complex, and less predictable dynamic responses than traditional loads.

> **Simulating system operations and identifying reliability risks and mitigations are a key part of system reliability assessments.**

Stability Phenomena Assessed in Simulation Studies

Simulation studies are performed across different time horizons to address distinct reliability needs. Power system dynamic assessments are a category of simulation studies that are used to assess the response of a power system following disturbances such as:

- Faults on transmission, generation, and distribution equipment
- Switching of devices like breakers and other grid support equipment
- Sudden loss of generators and loads

Depending on the issue analyzed, assessments simulate system operations with microsecond to millisecond time resolution and focus on the immediate aftermath of disturbances. These studies focus on the system's behavior for tens of seconds following an event to confirm that stability is maintained and transient voltage variations are within acceptable limits without any sustained or underdamped oscillations.[2] Power system stability can be broadly categorized as:

- **Rotor angle stability:** the ability of synchronous machines in an interconnected power system to remain in synchronism and to restore synchronism after small or large disturbances. Instability appears as either large non-oscillatory angle divergence or growing oscillatory rotor swings.
- **Voltage stability**: the ability of the system to maintain acceptable steady voltages at all buses after a disturbance. Instability typically results in declining voltages, loss of load, or cascading disconnections. Voltage stability is further classified as short and long term. Short-term stability refers to voltage stability involving fast-acting components such as induction motors, electronically controlled loads, and high-voltage DC (HVDC) converters, with dynamics occurring over a

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[1] These are new large load types that many systems are experiencing in addition to traditional large loads like petrochemicals, mineral mining operations, and large steel and aluminum manufacturing plants.

[2] Other assessments that simulate chronological system operations are production cost modeling and resource adequacy simulations. These studies focus on much slower system dynamics like intra-hour and hourly load variability and simulate the system with an hourly or sub-hourly time resolution to evaluate feasibility of system dispatch and assess whether sufficient resources exist to meet system demand under normal and extreme conditions, including outages of generation or transmission equipment. See https://www.esig.energy/reports-briefs/large-loads-resource-adequacy.

time scale of seconds. Long-term stability refers to voltage stability associated with slower equipment such as tap changing transformers and generator current limiters, evolving over minutes and usually involving progressive voltage decline.

- **Frequency stability:** the ability of the system to maintain steady frequency following a severe imbalance between generation and load. It involves inertial response, primary control, and secondary control.
- **Resonance stability:** a class of stability phenomena where oscillations grow due to insufficient damping in resonant electrical or electromechanical interactions. Resonance stability encompasses subsynchronous oscillations and related resonance phenomena. It can be further classified into electrical resonances and torsional resonances that are related to the turbine shaft.
- **Converter-driven stability:** instabilities caused by interactions involving the fast control dynamics of power electronic converters (such as phase-locked loops (PLLs) and current controllers) with the grid, covering both low-frequency and high-frequency phenomena.

A more thorough description of power system stability can be found in the 2021 IEEE paper "Definition and Classification of Power System Stability—Revisited and Extended"[3] and the recent CIGRE publication "Suitable Classification of Power System Stability Phenomena."[4]

Background on Dynamic Assessments

Dynamic assessments are essential because they allow engineers to evaluate whether the system can maintain stability following disturbances. Unstable voltage and frequency conditions can either damage critical equipment or, worse, potentially lead to cascading failures of multiple devices across the system. By analyzing voltage and angular stability, voltage control, frequency stability, and frequency control, operators can identify vulnerabilities and implement corrective actions. These actions may include control strategies such as inertia support, fast frequency response, and voltage support or investments in assets such as transmission lines, synchronous condensers, static VAR compensators, and active filters.

Dynamic studies are integral to:

- Reliability assessments that ensure secure and stable future grid operations
- Interconnection assessments that ensure that any new equipment (generator or transmission device) or load does not compromise system stability and security

Grid codes worldwide mandate these assessments as a part of transmission planning[5] and generator interconnection processes.[6]

Dynamic assessments rely on specialized simulation tools—power system dynamic simulators—which fall into two categories based on the bandwidth of system dynamics being modeled.[7] These two types of simulators are positive-sequence phasor-domain (PSPD) and electromagnetic transient (EMT):

- PSPD simulators model slower balanced three-phase dynamics (generally less than 10 Hz) of the system with the network and equipment modeled in a positive-sequence framework.[8]
- EMT simulators model faster balanced and unbalanced system dynamics (generally higher than 10 Hz) with the network and equipment modeled in full three-phase details.[9]

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[3] https://ieeexplore.ieee.org/document/9286772

[4] German system operators recently revisited the concepts of "resonance stability" and "converter-driven stability" introduced in the IEEE paper "Definition and Classification of Power System Stability Phenomena" and proposed a classification scheme better suited for model simplification and stability phenomena simulations of converter-dominated power systems. See https://cse.cigre.org/cse-n037/suitable-classification-of-power-system-stability-phenomena.html.

[5] The North American Electric Reliability Corporation (NERC) through its TPL-001 standard mandates utilities to perform power system dynamic assessments as a part of their long-, medium-, and shorter-horizon transmission planning studies.

[6] The Federal Energy Regulatory Commission (FERC) requires public utilities to use a Large Generator Interconnection Procedure (LGIP) for interconnecting large generating facilities (over 20 MW) to the transmission system, including dynamic assessments as a core component of the study process.

[7] Bandwidth of system dynamics refers to the frequency range of the phenomenon being studied. For example, inter-area oscillations in a power system are typically in the 0.1 Hz to 1 Hz range. Subsynchronous oscillations are faster—typically in the 5 Hz to 55 Hz range.

[8] Examples of PSPD simulators are Siemens PTI PSS®E, GE PSLF™, DSATools, DigSILENT PowerFactory, PowerWorld Simulator.

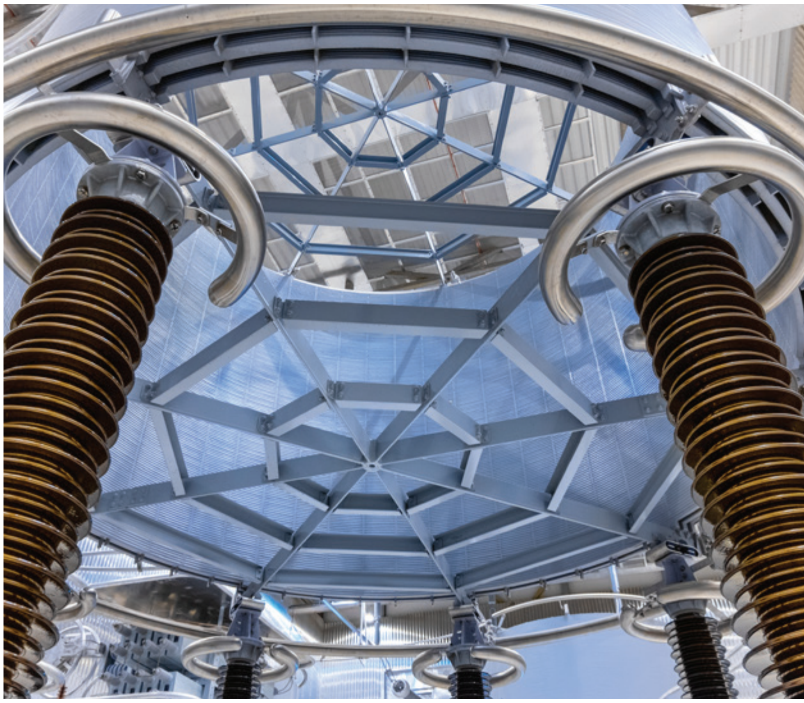
[9] Examples of EMT simulators are EMTDC/PSCAD and EMTP.

These simulation platforms require separate models (also known as dynamic models), which are described in further detail in this report in the section "Dynamic Model Development Guidelines and Requirements."

Accurate models of power system components are critical for these tools to produce reliable results. Grid codes worldwide mandate submission of these models for generation and transmission equipment as well as various levels of model validation during the interconnection process and the equipment lifetime. For example, the North American Electric Reliability Corporation's (NERC's) MOD-26 standard mandates that owners of both synchronous generators and inverter-based resources periodically validate the performance of voltage and frequency control models. Furthermore, modeling of generation and transmission equipment (e.g., static VAR systems, HVDC links) is a fundamental area of education for power systems engineers, ensuring that they possess a sufficient level of understanding of these types of equipment and their behaviors during powersystem disturbances.

Although the importance of load modeling for grid reliability is widely recognized now, historically it was treated with less rigor than generators and other transmission equipment. Loads were generally much smaller than individual generators and widely distributed across the power system, so an approximate aggregated representation of their dynamic behavior was considered sufficient given modeling needs and computational limitations. In addition, unlike generators, load interconnection is not regulated at the federal level,[10] meaning stringent national requirements for modeling and validation did not apply.

Researchers have continued to introduce more sophisticated load models. In the 1980s, EPRI developed component-based approaches leading to the algebraic ZIP model, which represents a load as a combination of constant impedance (Z), constant current (I), and constant power (P) components. The model was kept simple to ensure that the computational framework available at the time could execute the simulation runs in reasonable time.



The WECC Composite Load Model

Following major system events such as the 1996 outages in the Western Electricity Coordinating Council (WECC) region, IEEE adopted dynamic load models. The WECC events specifically highlighted that modeling of three-phase and single-phase motors were needed to capture the contribution of loads to system oscillations and voltage recovery. That led to the development of the WECC composite load model (also referred to as CMLD) (Figure 1, p. 4), consisting of integrated sub-models for better representation of loads.[11] The sub-models are described as follows:

- A distribution substation and feeder equivalent to model the voltage regulation from the substation to the load terminals
- Motor A: Three-phase induction motor driving a relatively low inertia, constant torque–type load like positive displacement compressors and pumps
- Motor B: Three-phase induction motor driving a relatively high inertia, variable torque–type load like blower fans and large centrifugal compressors

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[10] In North America, loads are not NERC- or FERC-registered entities.

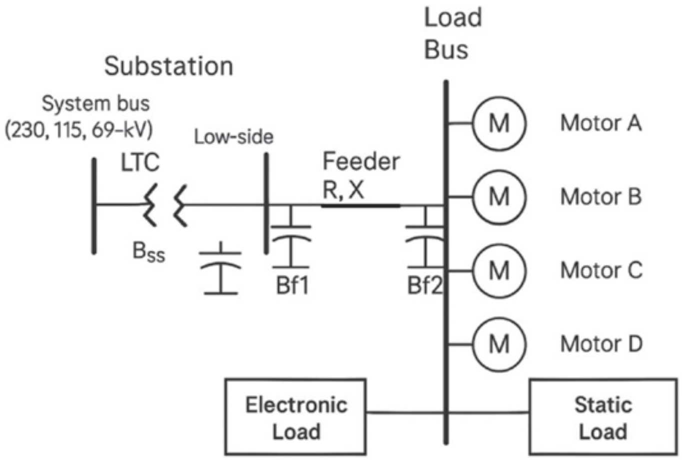
[11] The sub-models can be accessed and used as individual models in all simulation platforms.

- Motor C: Three-phase induction motor driving a relatively low inertia, variable torque–type load like small centrifugal pumps
- Motor D: A performance-based algebraic model of a single-phase residential heat ventilation and air-conditioning system
- Static load: The conventional constant impedance, constant current, and constant power (ZIP) model
- Electronic load components to model consumer electronics like laptops and televisions

Motor A, B, and C sub-models use differential equation-based representations of induction motors.[12] The motor D, static load, and electronic load sub-models use algebraic representations. The WECC composite load model also allows users to model the effect of end-use load disconnection. End-use load disconnection refers to the action of protective devices like relays and undervoltage disconnect contactors that trip the load when voltage at load terminals falls below or goes above operating ranges.

FIGURE 1

The WECC Composite Load Model



Source: Energy Systems Integration Group.

These protection systems are put in place to ensure that loads (e.g., motors, variable-speed drives,[13] and power electronic converters) are not operated at abnormal voltages, damaging the device.

This model is widely used today, including by utilities across North America, and implemented in major simulation platforms to represent residential, commercial, and industrial loads.[14] This modeling approach has proven effective for system studies because it provides a detailed representation of both three-phase and single-phase induction motor loads, which constitute the predominant share of system demand during peak operating periods.

Moving Beyond the Composite Load Model for Large Loads in North America

Recent grid events have highlighted that the existing composite load model may not be sufficient for new modeling challenges for large loads. NERC defines a large load as "any commercial or industrial individual load facility or aggregation of load facilities at a single site behind one or more point(s) of interconnection that can pose reliability risks to the bulk power system due to its demand, operational characteristics, or other factors. Examples include, but are not limited to, data centers, cryptocurrency mining facilities, hydrogen electrolyzers, manufacturing facilities, and arc furnaces."[15] Large load facilities like data centers, cryptomining facilities, and green hydrogen production rely heavily on power electronic converters, which behave differently from traditional motor-driven loads. Recent events have shown that large converter-based loads can disconnect (switch over to their back-up supply) unexpectedly during power system disturbances, causing over-voltage and over-frequency conditions on the grid. Existing composite load models, designed primarily for motor representation, do not adequately capture these behaviors. To address this gap, accurate dynamic models of these new large loads are needed to ensure their behaviors and impacts on

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[12] Differential equation–based models are better at capturing transient behavior of the underlying equipment. Algebraic equation–based models, for example, ZIP, are sometimes employed as an approximate alternative; however, these models do not capture the transients with the same fidelity.

[13] A variable-speed drive is a power electronic device that controls an electric motor's speed and torque by adjusting the frequency and voltage of the power supplied to the motor.

[14] The composite load model is available as a library model in PSPD simulators. In addition, many researchers and engineers have implemented this model in EMT simulators using library models of the sub-components.

[15] NERC Large Loads Task Force White Paper, "Characteristics and Risks of Emerging Large Loads," July 2025, https://www.nerc.com/globalassets/who-we-are/standing-committees/rstc/whitepaper-characteristics-and-risks-of-emerging-large-loads.pdf.

TABLE 1

Examples of Industrial Loads and Grid Impacts

Industry	Components	Example Local Impacts[a]	Example Bulk System Impacts[b]
Paper manufacturing	Motors	Voltage flicker, harmonics, subsynchronous oscillations, ferroresonance, switching transients, and others	High reactive power demand from motors resulting in delayed recovery of voltage after faults
Petrochemical refining	Motors, line-commutated converter-based drives		
Steel manufacturing	Motors, arc furnaces		
Aluminum smelter	Arc furnaces		—
Semiconductor manufacturing	Variable-speed drive–connected processes		Unexpected disconnection from the grid due to the voltage-sensitive nature of the load resulting in over-frequency and over-voltages on the grid side
Data centers	Uninterruptible power supplies for data center server racks		

a Local impacts are those that are limited to a few buses from the interconnected device.

b Bulk system impacts are those experienced across a broader portion of the connected power system. The bulk power system is the portion of the electricity system consisting of any transmission components connected at 100 kV and above, along with associated generating resources, as defined by NERC.

Source: Energy Systems Integration Group.

Accurate dynamic models of new large loads are needed to ensure their behaviors and impacts on the power system are appropriately captured in the interconnection and planning studies.

the power system are appropriately captured in the interconnection and planning studies. Table 1 lists examples of industrial loads and their impacts on the system.

In North America, load modeling practices are primarily guided by NERC standards for transmission planning. Specifically, the TPL-001 standard mandates that transmission planners use dynamic models capable of representing the transient response of loads within the system.[16] Unlike generators and transmission-connected devices such as HVDC systems and static synchronous compensators (STATCOMs), where equipment owners are responsible for submitting parameterized models, the responsibility for developing load models lies with the transmission system provider. These models are typically developed using information obtained from load facility owners or in coordination with distribution system providers.

Transmission planners generally approach load modeling by categorizing efforts into two areas: (a) modeling residential and commercial loads, and (b) modeling industrial loads. The composite load model is the most-used model for representing these load types, although some planners continue to use the older complex load model (CLOD) or develop custom models using available library components (e.g., CIM5/6 models in PSS®E). Specifically for industrial loads, the load modeling working groups (e.g., the NERC Load Modeling Working Group (LMWG) or regional working groups, such as the WECC Model Validation Subcommittee) have developed template models for different industry types, and these templates are used for bulk system studies.

While transmission planners or transmission service

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[16] https://www.nerc.com/standards/reliability-standards/tpl/tpl-001-5.1

providers may request load models during the interconnection process under NERC FAC-001 and FAC-002,[17] formal validation and verification of these models is not required at that stage. Generally, such models are requested only if a stability or power quality issue that affects the local system is identified that needs further assessments using a dynamic simulation tool. These models are generally, but not necessarily, EMT models and are site-specific.

Model validation is typically conducted under the NERC MOD-033 standard, which involves system-wide event analysis.[18] Additionally, transmission planners are required to submit load models to their planning coordinators in accordance with MOD-032 requirements.[19]

Large Load Modeling Guidelines in Europe

The use of the composite load model is not as prevalent in Europe as in the U.S., partly due to the relatively lower residential air-conditioner usage in Europe, which is the primary reason for using the composite load model.

The requirements of modeling and model submissions in the European regions are guided by the European Network of Transmission System Operators for Electricity (ENTSO-E)—the association that coordinates Europe's electricity transmission system operators—that has developed and put into force the Demand Connection Code (DCC). Article 21 of the ENTSO-E DCC allows each transmission system operator (TSO) to request simulation

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[17] https://www.nerc.com/pa/Stand/Reliability%20Standards/FAC-001-4.pdf and https://www.nerc.com/pa/Stand/Reliability%20Standards/FAC-002-4.pdf

[18] https://www.nerc.com/pa/Stand/Reliability%20Standards/MOD-033-2.pdf

[19] https://www.nerc.com/pa/stand/reliability%20standards/mod-032-1.pdf

models or equivalent data that illustrate how transmission-connected demand facilities or distribution systems behave under both steady-state and dynamic conditions. TSOs are responsible for defining the required content and format of these models, which should include steady-state and dynamic behavior modeling (i.e., PSPD and EMT) and structural and block diagram representations. The article also states that TSOs should establish data recording requirements for these facilities. This is to enable comparison between model outputs and actual system recordings, which supports model validation. Not all TSOs enforce this requirement. However, some include load model submission requirements as part of their interconnection process. In practice, utilities typically rely on either models provided by the load facility or those developed by the TSO to ensure system reliability.

Challenges Hindering the Development of Accurate Models for Dynamic Assessments for Large Loads

Two primary challenges hinder the development of accurate models for dynamic assessments for large loads. First is a lack of standardized library models that can be readily implemented in PSPD or EMT simulation tools. Second is a need for detailed information about the power conversion equipment used in these large load facilities—such as converters and variable-speed drives—and their operational characteristics, including control strategies and power consumption profiles. This detailed information is often unavailable, which significantly limits the ability to create models accurately representing the behavior of these loads.

To tackle these issues, the Energy Systems Integration Group's (ESIG's) Large Loads Task Force established the Load Modeling Project Team to recommend harmonized practices and provide guidance for dynamic model development and validation for large loads. This report represents an initial step toward documenting modeling needs and approaches aimed at improving the fidelity of transmission interconnection and planning studies and ensure continued grid reliability as large load facilities become a significant part of the power system.

The next section covers the need for dynamic load models for new large loads, followed by a section discussing essential components for dynamic models of new large loads. The report then discusses key modeling requirements for power system dynamic assessments and dynamic model development guidelines and requirements. The subsequent section covers model parameter verification, validation, and quality test guidelines. The report then discusses reliability impacts of inadequate or improper load modeling and concludes with a set of recommendations for modeling large loads.

Dynamic Load Models for New Large Loads

Traditional industrial loads have typically been represented in bulk system studies using composite load models in PSPD tools (EPRI, 2020), with EMT studies reserved for specialized local phenomena such as fast transients, flicker (Grasso et al., 2016), or control interactions (Song-Manguelle, Sihler, and Schramm, 2011). These approaches have generally been sufficient for motor-dominated facilities (MHI, 2023). However, many emerging large loads—such as data centers, crypto mining operations, and electrolysis plants—are dominated by power electronic interfaces with fast controls, ride-through logic, and complex internal power distribution systems. These characteristics introduce dynamic behaviors that are not well captured by existing load models or consistently supported by current PSPD and EMT libraries. As a result, there is a need for new modeling approaches, clearer guidance on the appropriate use of PSPD versus EMT simulations, and improved data for model development and validation to reliably assess both bulk system and local area impacts of these facilities.

Modeling Large Loads Involving Power Electronics

A detailed description of the large load facilities can be found in the ESIG Large Loads Task Force report *Large Loads: Behaviors, Capabilities, and Limitations.*[20] Readers are highly encouraged to review that report to gain a better understanding of these load facilities and their components that drive the need for new modeling efforts. But there is still much to learn about how power electronics–dominant large loads interact with the grid.

Power electronic converters introduce fast control-driven dynamics to the grid, which are on much shorter time scales than those of traditional synchronous machines and include rapid active and reactive power modulation, voltage sensitivity, and potential control interactions with other power electronic loads or inverter-based resources (such as wind, solar, and battery storage). These faster dynamics can influence system stability, fault response, and interactions between devices, especially in low-inertia or weak-grid conditions.

The modeling of power electronic converters for dynamic studies has gained momentum in the past decade, primarily driven by the rise of inverter-based resources. However, while modeling of inverter-based resources is better understood, modeling of converter-based loads is still in its early stages, and most commercial power system dynamic simulation tools lack standardized library models to accurately represent these devices.

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[20] https://www.esig.energy/reports-briefs/large-load-interconnection-performance-requirements

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PSPD and EMT Load Models Currently in Use

Traditionally, load modeling for power system dynamic assessments has been conducted in the PSPD simulation tools, with the primary objective of evaluating the impact of loads on bulk system angular, frequency, and voltage stability. This approach emphasizes the representation of slower load dynamics (occurring at less than 10 Hz), which can affect a larger portion of the power system.

Motor Loads

Among the available models, the composite load model represents the most advanced framework implemented in PSPD simulation platforms (EPRI, 2020).[22] Although this report does not delve into the composite load model in detail, it is important to note that its development has largely focused on the accurate dynamic modeling of motor loads. A key advancement over the past decade has been the refinement of the single-phase induction motor model, which has proven critical in analyzing the fault-induced delayed voltage recovery (FIDVR) phenomenon. This issue has been particularly prominent in regions such as the southern United States, where residential air conditioning loads are significant during summer months.

Power Electronic Loads

Most recently, EPRI, in collaboration with NERC, Lawrence Berkeley National Laboratory, and ISO New England, has developed a model that can be used to represent the behavior of large power electronic loads, especially the ride-through behavior (EPRI, 2022).[23] While this model is still being improved, it is available as a library model in the GE PSLF™ and as a dynamic linked library model in PSS®E. At the time of writing, efforts are being made to make this available as a library model in most major positive-sequence simulation platforms.

In contrast, EMT modeling of loads has not been commonly employed for bulk system dynamic assessments. This is primarily due to the scale of the loads and the traditional focus of EMT modeling on resolving power quality issues or high-frequency interactions that affect the local system. But EMT simulation platforms offer flexible building blocks that allow modelers to construct detailed device-level models. Depending on the specific study requirements, modeling engineers can either develop custom EMT models or adapt existing library models to achieve high-fidelity system representations. Examples of detailed facility-level models for large load installations can be found in numerous reports (Dattaray et al., 2017). The generic EMT model for a data center is another example of a facility-level model development in an EMT simulator (Ross and Follum, 2025).

Need for New Models to Represent Power Electronic–Interfaced Loads

Large load facilities like data centers, crypto mining operations, and green hydrogen production plants primarily rely on power electronic–interfaced loads, which are highly controllable and exhibit significantly different transient responses compared to motors during grid disturbances. Recent events have shown that large power electronic-interfaced facilities like data centers can unexpectedly disconnect from the grid (or switch over to their back-up power supply) during normally cleared grid faults, leading to over-voltage and over-frequency conditions on the grid and potentially cascading disconnection of additional generation and loads (NERC, 2025b, 2026). These incidents have sparked industry-wide discussions about the need for simulation models

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[21] Note that power electronic-connected generation is typically called inverter-based generation or an inverter-based resource since the main purpose of the power electronic device is to unidirectionally invert the DC power at the source to AC power supplied to the grid. For loads, the power electronic device can operate as a bi-directional device; hence, the general term converter, which encompasses inverter and rectifier, is used.

[22] Examples of PSPD simulation platforms include PSS®E, PSLF™, DSATools™, PowerWorld, and DIgSILENT PowerFactory.

[23] Although the initial model was developed for electric vehicle chargers, EPRI has shown through lab demonstrations as well as through simulation demonstrations that this model can be used to represent all types of large electronic loads. A detailed explanation of the model is also available in "Load Characteristic Model: PERC1," at https://www.powerworld.com/WebHelp/Default.htm#TransientModels_HTML/Load%20Characteristic%20PERC1.htm.

As very large power electronics-interfaced loads become more prevalent, especially when located near both conventional and inverter-based generation sources, EMT assessments will be needed for every large load interconnection analysis to assess grid risks associated with both individual and clusters of these new loads.

that can realistically capture this behavior in power system dynamic studies. The existing composite load model, which primarily focuses on better representation of motors, includes only a simplistic representation of power electronic components, making it unsuitable for modeling these behaviors of large load facilities.

The widespread use of power electronic equipment and the high-frequency load variability for some loads (e.g., AI training runs) have raised concerns about higher-frequency interactions with other grid equipment (Sun et al., 2022; Dimitrov et al., 2025). Studying such interactions requires EMT assessments. While such assessments are sometimes conducted by grid planners for facilities like arc furnaces and liquefied natural gas compression stations (Badrzadeh et al., 2008), they are not a common practice. As very large power electronics-interfaced loads become more prevalent, especially when located near both conventional and inverter-based generation sources, EMT assessments will be needed for every large load interconnection analysis to assess grid risks associated with both individual and clusters of new large loads such as data centers. As a result, discussions around load modeling for PSPD analyses that focus on examining lower-frequency dynamic phenomena are now expanding to include EMT modeling.

Modeling will continue to play an important role in enabling grid planners to identify previously unknown reliability risks associated with such large loads proactively. Therefore, it is essential to gain a better understanding of these loads and develop high-fidelity dynamic models to assess these reliability risks.

Important Considerations for Modeling of Load Facilities

A summary of the key considerations for large load facility modeling is presented here, and this topic is discussed in more detail in the section "Essential Components of Large Load Models."

- **Component-level load contribution:** Large load facilities consist of various components such as motors, uninterruptible power supplies (UPSs), and power supplies, each supporting different processes within the facility. Each of these devices will have a different

dynamic behavior and hence will need a separate component model. It is important to understand the contribution of each component to the overall load of the facility in order to model the facility accurately.

- **Internal power distribution:** For some specialized assessments—typically investigating faster dynamics affecting the local system—modeling the internal power distribution within the facility may be critical as the cable and transformer impedances can have an impact on the assessment results. It is necessary to have a clear understanding and appropriate representation of the facility's power distribution network for accurate modeling in these cases.
- **Dynamic behavior of equipment:** Components within the load facility that are relevant to the specific study must be modeled appropriately. Equipment, protective functions, or control loops that participate in faster dynamics typically influence localized system impacts, whereas those involved in slower dynamics affect system-wide behavior.
- **Ride-through characteristics:** Large loads may exhibit varying disturbance ride-through behaviors. Proper modeling of these characteristics is essential, as the ability or inability of equipment to ride through disturbances can significantly influence the outcomes of dynamic analyses.
- **Operational profiles and power consumption:** Load facilities may not have constant power consumption, and some facilities can have significant demand variability. It is important to ensure that their power consumption levels are accurately represented in power flow cases, as power flow cases are the starting point of dynamic simulation studies. If the power consumption changes are fast enough, such as in AI training activities where the load can change every few seconds, these need to be accounted for in the dynamic load model itself.
- **Validation and verification of the developed load model:** A developed model can be relied upon only if it has been verified and validated against the actual response of the load. Therefore, a model validation exercise is crucial for ensuring high-fidelity models. This topic is discussed in the section, "Model Parameter Verification, Validation, and Quality Testing Guidelines."

Additionally, it is important to consider where detailed modeling in an EMT simulator is desired and where a simplified model in a PSPD simulator is sufficient. While detailed modeling sounds appealing, simulation time must be considered, as well as the benefits gained by adding details. For power system dynamic studies, this can broadly be divided into two use cases:

- **Bulk system dynamic studies**: These assessments focus on analyzing the risks to system-wide stability and require modeling the entire interconnected power systems (e.g., Eastern Interconnection, WECC, Continental European Grid), and all phenomena of interest are at a frequency of less than 10 Hz. PSPD models and simulators are best suited for these studies. Simplified modeling allows for faster simulation times, while the models have sufficient detail to reflect the <10 Hz dynamics.
- **Local specialized dynamic studies:** These assessments focus on analyzing higher-frequency phenomena (greater than 10 Hz) whose impact is limited to a local area in the power system. These studies generally require detailed full three-phase modeling (as opposed to positive-sequence modeling) of the local system (with meaningful equivalencing of the rest of the interconnection), and the relevant equipment including all fast and slow control systems. EMT models and simulators are best suited for these studies. Furthermore, since high-frequency disturbances remain local (due to the inductive nature of the power system), modeling the local system only is sufficient to capture the impacts of such disturbances. Hence EMT simulations, even with detailed modeling, can be done in reasonable time.

The needs for bulk system and local specialized assessments are described further in the following subsections.

Load Modeling Needs for Bulk System Dynamic Studies

The following should be considered while developing large load facility models for bulk system dynamic studies:

- **Phenomena of interest in bulk system dynamic studies:** Bulk system dynamic studies typically focus on several critical dynamic phenomena, including

transient stability, voltage recovery, frequency response, inter-area and local oscillation damping, and mitigation. These phenomena affect large portions of the bulk connected power systems.

- **Bandwidth of response and modeling details for bulk system dynamic studies:** Bulk system dynamic studies typically focus on system dynamics that are less than 10 Hz. PSPD models used in these studies must therefore capture fast transitions (e.g., sub-second motor stalling or recovery, ride-through behavior), responses of slower control loops (bandwidth of less than 10 Hz), medium-term dynamics (e.g., response to voltage changes over 1 to 30 seconds), and longer-term dynamics (e.g., frequency response over tens of seconds). The load models must be capable of representing these time-domain behaviors to ensure accurate system-level insights.
- **Suitable level of aggregation:** Given the scale of bulk system studies, it is often necessary to aggregate load models to reduce computational complexity while preserving essential dynamic characteristics. The level of aggregation should reflect the dominant load types and their dynamic behavior, preserve the diversity of load responses where relevant, and be consistent with the spatial resolution of the study (e.g., substation-level versus regional-level aggregation). Appropriate aggregation enables efficient simulation without compromising the fidelity of results. The paper “A New Composite Load Model Structure for Industrial Facilities” provides an example for developing an aggregated model structure for a general industrial facility (Liang, 2016). A similar approach can be used to develop an aggregated model structure for the emerging large loads for PSPD simulation platforms.

Load Modeling Requirements for Local Specialized Dynamic Studies

The following should be considered while developing large load facility models for local specialized dynamic studies:

- **Phenomena of interest in local specialized dynamic studies**: Local specialized dynamic studies account for higher-frequency phenomena (greater than 10 Hz) that can arise from large loads and affecting the power system locally to the large load’s point of interconnection (POI). These include (but are not limited to) subsynchronous oscillations, unstable controller interactions, and voltage flicker, which are caused by load controls or high-frequency periodic load variation. Phenomena like ferroresonances and transient over-voltages that are caused by passive network elements within the load facility (e.g., transformers and cables) are also assessed as a part of local specialized dynamic studies.

- **Bandwidth of response and modeling details for local specialized dynamic studies:** Local specialized assessments focus on dynamics that are beyond the 10 Hz range. As such EMT models used for these studies need to include suitable modeling of all slow and fast control loops of the load equipment. Some studies may require modeling of switching details of power electronic equipment (which are in the kHz range), whereas for other studies, average modeling may be desired. These need to be accounted for when creating the models. Some studies may also require detailed representation of any active or passive filters, cabling systems, transformer saturation, and circuit breakers. These should also be considered when developing models for local specialized dynamic assessments.
- **Suitable level of aggregation:** While local assessments require detailed modeling, some level of aggregation may still be suitable depending on the assessment being undertaken. As an example, for nearby inverter-based resources, many EMT local assessments use aggregated representation of the individual solar or wind inverters and the collector system, without jeopardizing the study results. Opportunities for such aggregation should be fully considered and leveraged to reduce modeling and simulation time.

Table 2 describes the features and applications of PSPD and EMT simulators as they apply to bulk system and local specialized dynamic assessments.

TABLE 2

Features and Applications of Positive-Sequence Phasor-Domain (PSPD) and Electromagnetic Transient (EMT) Models and Simulators

Feature	PSPD Models and Simulators	EMT Models and Simulators
Typical studies	Bulk system dynamic studies like transient stability assessments, inter-area and local oscillations, voltage recovery, frequency response, etc.	Local interactions like subsynchronous oscillations, torsional interactions, fast control interactions, low short-circuit ratio (SCR)-driven fast oscillations, phase-locked loop instability, ferroresonance, switching transients, active filter design, etc.
Example simulation tools	Siemens PTI PSS®E, GE PSLF™, DSATools, Powerworld Simulator, DigSILENT Powerfactory	EMTP, PSCAD/EMTDC
Time scale and simulation resolution	Longer periods (10–30 seconds), steady-state operation (snapshot) Time step used: 1 to 4 milliseconds	Very short time scales, fast transient phenomena (10–15 seconds) Time step used: microseconds
Modeling detail	Simplified, lumped parameters, average values	Detailed, instantaneous values, switching dynamics captured
Control system modeling	Typically models outer control loops	Capable of including fast inner-loop controls
Simplifications	Uses simplifying assumptions due to time step and positive-sequence nature	Avoids classical simplifications, captures more detailed dynamics
Computational burden	Computationally efficient, suitable for large-scale studies	Computationally intensive, typically limited to smaller systems or specific parts of the network

Source: Energy Systems Integration Group.

Challenges Related to Modeling of Large Loads

The challenges associated with modeling large loads can be broadly categorized in two primary areas:

- Limited availability of library models in power system dynamic simulators (both PSPD and EMT)
- Insufficient information for model development and parameterization

Limited Availability of Library Models

The lack of available library models is a key limitation for PSPD simulation platforms. While the composite load model includes components capable of representing motor behavior, it is inadequate for capturing the dynamic responses of large power electronic drives and UPSs commonly found in large load facilities. This poses a significant challenge for transmission planners conducting bulk system dynamic studies. In contrast, EMT studies typically rely on custom-built models tailored to specific facilities or equipment, reflecting their actual physical and control characteristics. EMT platforms generally offer the necessary components to construct these models, and the absence of building blocks is rarely a limiting factor.

Insufficient Information for Model Development and Parameterization

There is also a lack of information about the individual load components and control methods employed within the load facility, which presents a more pervasive challenge across both EMT and PSPD tools. For PSPD tools, which are less detailed, information on load composition and ride-through capabilities is essential for proper parameterization.[24] EMT modeling requires even more granular data, including control algorithms, protection schemes, power conditioning controls, and the nature of the load (e.g., fluctuating patterns as seen in AI training workloads). The current scarcity of such information significantly hinders the development and effective use of both EMT and PSPD models.

The following sections present a short summary of the currently available load models and modeling practices in North America and Europe.

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[24] Parameterization refers to appropriately tuning the parameters of a device model (essentially a set of mathematical equations representing the device's physics) such that the model can replicate the responses of the actual device it is meant to represent.

Essential Components of Large Load Models

To accurately simulate system dynamics, models of large loads must incorporate their key control loops, internal (to the load facility) protective functions, and other relevant factors.

Active Power/Frequency Control

Some large loads may be able to modulate their real power consumption in response to grid frequency conditions. In these circumstances, the model needs to be represented as a droop or governor-like control on load: if frequency (f) falls, the load reduces active power consumption (P) (under-frequency response) or shifts to stored energy (in case of on-site battery storage being present). This loop is important because it can affect the system frequency nadir and rate of change of frequency (RoCoF)during grid disturbances. In PSPD models, one typically implements a P–f droop block (sometimes with a deadband) or a fixed power setpoint logic that can be controlled by an external signal. Without it, simulations assume loads remain fixed in a frequency disturbance, which can hide the effect of a load facility's frequency response on system frequency.

Reactive Power and Voltage Control

Large loads can draw or supply reactive power (Q) through power electronic converters, motor components, or associated filters and are required to comply with strict power factor limits.[25] Utilities may require facilities to support voltage (V) by adjusting reactive power consumption if possible or by installing compensation devices such as switched reactors/capacitor banks or STATCOMs. Many facilities also employ slower voltage regulation devices, such as on-load tap changers, to maintain voltage at the supply point at a specified setpoint. These functions can be modeled in PSPD simulators as a reactive power–voltage (Q–V) control loop, power factor control loop, or a bus-level voltage regulator that adjusts reactive power injection at the POI. Appropriate representations of these controls are essential because they directly influence voltage at the POI, and omitting them can lead to an incorrect assessment of post-disturbance voltage recovery. If supplementary support devices like STATCOMs or other static VAR compensation devices are present, these devices and their associated controls need to be modeled separately.

Ride-Through Behavior

Faults and large power swings can lead to voltage dips or frequency excursions across the power system. Unlike small loads, many large electronic loads—such as AI data centers with internal generation—are sensitive to such events. These loads may disconnect from the grid (or switch over its internal supply) during even small disturbances, potentially causing significant system-wide impacts, such as subsequent cascading generation and load outages and potentially a system-wide blackout.

Currently, there is no comprehensive standard for large loads that defines a ride-through requirement equivalent to IEEE 2800-2022 (Clause 7) or NERC PRC-024/029 applicable to inverter-based resources. Nevertheless, even in the absence of formal voltage and frequency ride-through requirements, load models must still accurately reflect the real-world behavior of these loads. This means dynamic load models should be able to incorporate voltage and frequency ride-through logic or protection mechanisms.

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[25] Filters have both inductive and capacitive components and can be a passive source of reactive power injection or consumption.

Ramp-Rate Limiting

Large loads (especially data centers) may have controllers that limit how fast power consumption can change, to avoid flicker or stress equipment. For instance, a data center might specify "no more than X% load change per minute" during reconnection after an outage. Similarly, grid operators might ask for ramp-rate limits on new large loads, to ensure smooth restoration.

This type of limitation needs to be implemented in the model. This can be implemented by a rate-limiter block on the load facility's active power reference, which is widely available in commercial simulation tools. The rate limit caps the derivative of P, preventing instantaneous full load pickup or drop. This is important for scenarios like system restart, load curtailment, or load restoration after a fault event. A load modeled without a ramp limiter could change too fast, exaggerating oscillations or flicker. Enforcing ramp limits on large loads helps to prevent spurious oscillations or flicker during restoration studies.

Each of the above control loops reflects physical or contractual controls in the large load facility (UPS transition, power flow controllers, ride-through specifi-cations, dispatch agreements, etc.). Collectively, they ensure that a large load is not a static "black box" but rather a responsive element.

Mechanical Load Modeling for Motor-Driven Loads

Many large load facilities, even ones dominated by power electronics, still have large motor-driven loads that are used to run fans, pumps, or compressors for a variety of applications. Examples of such loads are cooling systems in data centers and hydrogen compression in electrolysis facilities. These motors can be direct-connected (in older facilities) or connected through adjustable-speed drives.[26] For these types of loads, particularly the direct-connected motors, it is important to model the variation in mechanical load (pumping process, compression process, etc.) as the rotor speed changes during grid disturbances. The documentation on the composite load model describes this at great length. Even when these motors are connected to the supply via variable-speed drives, the nature of the mechanical load has an impact on the ride-through of these drives (EPRI, 2009). Failure of a

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[26] Adjustable-speed drives is the overarching term that includes variable-frequency drives.

critical motor-driven process to ride through an event can result in the entire facility shutting down. An example of such critical processes is cooling systems in large data centers. Ensuring that these effects are understood and modeled properly is important for simulation studies.

Load Profile

Some loads, such as AI data centers, exhibit highly variable load behavior. Their power consumption can change rapidly, potentially contributing to voltage fluctuations, power quality issues, and interactions with other system controllers that may lead to forced oscillations. Therefore, the load profile of large loads must be accurately modeled and evaluated under various operating scenarios to ensure they do not adversely impact system stability or performance.

Considerations for Blackstart Modeling

EMT models and simulations are necessary for assessing the plant and system performance in the case of a blackstart scenario. The major auxiliary loads within a large load facility, including fans and pumps exceeding 1 MW each, should be detailed with information regarding their size and the number of motors. Additionally, their inertia, operational reactance, and time constants should be specified, along with whether they are directly connected to the system or interfaced through a variable-speed drive. Details concerning the transformers supplying the auxiliary loads should also be included:

- During blackstart, automatic load-shedding schemes may be used to prevent large loads from coming online abruptly.
- Blackstart simulations help determine safe load pickup sequences and generation ramp-up strategies.

Unbalanced Voltage Operation

Models provided for harmonic studies are sufficient for conducting voltage unbalance studies, but the network elements that adequately represent voltage unbalance must be included, such as the fact that negative-sequence impedances for loads must be modeled.

On-site Generation

Many large load facilities maintain on-site generation, either for back-up power or as a bridge resource. Back-up generators are typically isolated from the grid, with protection schemes such as automatic transfer switches ensuring they operate only when the facility is disconnected from the grid. In contrast, bridge generators often run in parallel with the grid. Any generator operating in parallel should be modeled explicitly using established generator modeling practices rather than being netted out from the load. When modeling such generators, all relevant control systems, ride-through capabilities, and protection mechanisms must be included to accurately capture interactions between the generator and the load.

Key Modeling Requirements for Power System Dynamic Assessments

Large load facilities exhibit complex and highly controllable behaviors that can significantly affect grid dynamics. To ensure system stability and reliable operation, it is essential to establish modeling requirements that reflect their actual performance. This section outlines the key modeling considerations that must be incorporated into both PSPD and EMT models of large loads to accurately capture their impacts on a power system.

To ensure reliable operations and prevent system instability or cascading outages, it is essential for transmission planners and operators to use appropriate models in order to assess the impacts of large loads connecting to the bulk power system. This section elaborates on the principles of model development, which are instrumental in establishing the requirements for these models.

Fidelity to Actual Plant Behavior

Model fidelity in dynamic studies refers to how accurately a model represents the real-world behavior and response of electrical equipment. For large load dynamic models, high fidelity is essential to correctly capture how frequency- and voltage-sensitive loads behave under different system conditions. Accurate representation of these dynamics is critical for predicting how loads influence bulk power system stability during disturbances and for ensuring reliable system planning and operations. Insufficient fidelity can lead to misleading conclusions, such as incorrect assessments of risk of voltage collapse when motor load dynamics are not properly modeled. High-fidelity models are also vital for forensic analysis, enabling planners and operators to replicate past disturbance events, identify root causes, and develop strategies that enhance system reliability and efficiency.

There are several considerations when selecting appropriate model fidelity. First, capturing the dynamic response of every individual load within a bulk power system may not be necessary depending on the study's objectives or feasible in terms of computational burden. Simplifications in modeling can be beneficial. For example, wind power plants can be represented with a single-generator equivalent model for bulk system studies, which provides an average response of all the wind turbine generators in the plant. Likewise, representing individual components of a large load facility as an aggregate model that captures the facility's average response may be sufficient for bulk power system studies. Second, computational constraints need to be acknowledged: while computationally less burdensome, PSPD models used in dynamic simulations may not fully capture the complexity of actual asset behavior (such as a large load or inverter-based resource), compared to EMT; however, this limitation is generally acceptable for many system studies, particularly those focused on slower dynamics, such as the characteristics of dynamic recovery, rather than the detailed conditions during the transient events.

Guidelines to ensure sufficient model fidelity include:

- **Model verification activities:** Model verification refers to the process of ensuring that the model structure is capable of representing the equipment being modeled and model parameters and settings reflect actual equipment settings in the field—for example, having a representation of ride-through protection that can be tuned to reflect the behavior of the actual facility or equipment.
- **Model validation activities**: Model validation is the process of confirming that the modeled response

reasonably matches the actual plant response under various grid events. This involves comparing simulation results to real-world measurements obtained from the asset.

- **Data collection and parameter selection**: Model parameters are selected based on test results and data collected from the plant, such as equipment drawings, nameplate ratings, and control and protection settings. It is crucial to consult with equipment manufacturers and load/asset operators to obtain proper parameters and to ensure that the relevant control and protection schemes have been modeled in sufficient detail and with accurate settings.
- **Baseline model validation**: Initial simulations are performed to validate that the model accurately represents the individual equipment or the facility response—whichever is being modeled, depending on the assessment at hand—based on baseline test data.
- **Event-based model validation**: Event monitoring is done by using high-sampling-rate devices like digital fault recorders which can automatically record voltage and current and which are suitable for validating faster dynamics from large load facilities. The measurements can be used for large load model validation and are also suitable for post-event analyses to better understand load behavior as well as to ensure that loads are complying with any disturbance performance requirements.
- **Continuous operation–based model validation**: Model validity can be monitored continuously by comparing modeled responses to actual responses during continuous operation. Continuous monitoring at a higher sampling rate can be achieved by using devices like phasor measurement units (PMUs) and which are helping with model validation of some of the slower dynamic responses from large loads.
- **Using existing models and developing improved models**: Significant improvements in modeling fidelity can be achieved by using existing generic dynamic load models and by developing new and improved models where needed.

Some considerations when selecting appropriate model fidelity are:

- **Aggregate load behavior**: Depending on the study, capturing the dynamic response of every individual load within a bulk power system may not be necessary or feasible.

- **Simplifications in modeling**: In some cases, modeling simplifications are necessary to achieve practical development and simulation times. For example, just as wind power plants are often represented by a single-generator equivalent model in bulk system studies, a data center might be modeled as aggregated servers with an equivalent distribution system.
- **Computational constraints**: It is important to acknowledge that PSPD models used in dynamic simulations may not fully capture the complexity of actual asset behavior, particularly during transient conditions. However, this limitation is generally acceptable for most studies. Ultimately, the level of necessary modeling complexity needs to be chosen based on the study objectives and the available computational resources.

Generic Versus User-Defined Large Load Models

When modeling power system equipment (e.g., large loads or generators), it is critical to select between generic models and site/vendor-specific, user-defined models (UDMs) to achieve desired assessment outcomes. Both types of models, whether generic or site-specific, can be implemented as either EMT or PSPD models, depending on the specific phenomena being studied.

Generic models provide a broad representation of typical system components and behaviors and are useful for initial assessments and general planning purposes, offering a simplified view that can be applied across various power system conditions without the need for detailed customization. On the other hand, site-specific/vendor-specific UDMs are tailored to the unique characteristics and requirements of a particular facility or technology provider. They incorporate detailed data and specifications, offering a more precise representation of the system's behavior. This consideration is relevant mainly for PSPD studies focusing on bulk system impacts. For EMT studies, site-specific/vendor-specific UDMs are typically preferred by the transmission planners, to ensure detailed modeling of the varied control, protection and switching schemes.

For PSPD studies, the choice between using generic models or UDMs can be a critical one. This decision impacts the accuracy of the study results, the complexity and time required for the modeling process, and the overall feasibility of the analysis.

Here we discuss some key considerations when deciding whether to use a generic model or develop a customized one.

Generic Models (Standard Library Models)

The advantages of generic models are:

- **Ease of use**: Generic models are standard library models provided by simulation software, representing the typical behavior of an electrical component.
- **"White box" nature**: Generic models tend to be available in power system dynamic simulation libraries with proper documentation that provides detailed guidance to users.
- **Standardization**: These models promote uniformity and standardization in modeling across different studies and platforms, which is beneficial for regional planning studies.
- **Computational efficiency**: Reduced-order generic models can be computationally efficient, making them suitable for studies involving many components.
- **Version portability**: Whenever power system dynamic simulators update versions, generic models are automatically available in the future versions.
- **General nature**: Since the models are generic in nature and do not reflect a single technology, these models are very well suited for longer-horizon planning studies where the specific manufacturers of devices have not been finalized yet.

Disadvantages of generic models are:

- **Their limited representation of the actual device/facility**: Generic models may not accurately capture the specific characteristics and dynamic responses of unique or complex equipment. These features are important to model for some studies where a unique response from a load (or generation) facility can result in a grid risk that needs to be resolved. These risks are often identified after or near to the commissioning phase, and UDMs may be available by then.

- **They may not capture specific details**: Generic models may not be suitable for assessing compliance with specific ride-through requirements like voltage and frequency tolerance, as these are often engineered as part of the plant design and require more detailed modeling.

Site- or Device-Specific User-Defined Models

Advantages of UDMs are:

- **Higher fidelity**: UDMs are custom-made by equipment manufacturers to represent the specific characteristics of a particular component, generally providing a more accurate representation of its behavior. (However, this highly depends on how the UDM was created; all UDMs are not guaranteed to have high fidelity.)
- **Ability to model complex equipment**: UDMs are useful for modeling complex or specialized controls that are unique to a particular manufacturer, and they are often necessary to accurately capture the unique factors and challenges involved in integrating specific equipment into the grid.
- **Flexibility**: UDMs offer flexibility to build, customize, and refine models based on site-specific needs.

Disadvantages of UDMs are:

- **Proprietary details**: UDMs are often proprietary; therefore, the underlying details may not be accessible to a user, making them "black box models." When issues arise, identification of root causes and mitigation presents a major challenge, especially if the appropriate states and variables of the model are not accessible in the model during the simulation.
- **Maintenance requirements**: UDMs require continual maintenance and updates to remain compatible with evolving software versions, which may be a significant challenge.

In summary, while generic models offer a convenient starting point for large load interconnection, site-specific/vendor-specific UDMs are essential for achieving accuracy and compliance in complex facilities. The choice between these modeling approaches will be guided by the specific needs and characteristics of the project and study's scope. It is worth noting that the load consumption of some data centers that run AI training compute cycles can be extremely site- and technology-specific.

> **While generic models offer a convenient starting point for large load interconnection, site-specific/vendor-specific UDMs are essential for achieving accuracy and compliance in complex facilities. The choice will be guided by the specific needs and characteristics of the project and study's scope.**

Aggregated Versus Component-Level Modeling

The question of aggregated versus component-level modeling is a key consideration for power system studies, since the level of detail incorporated into component models significantly impacts the accuracy, computational requirements, and outcome of the study. The choice between aggregate or detailed modeling is heavily influenced by the type of study.

Some key features and limitations of aggregate models are the:

- **Focus on system-level behavior**: Aggregate models are well suited for studies that focus on the overall

power system behavior and stability over longer periods, assuming quasi-steady-state operation.

- **Computational efficiency**: Aggregate models are computationally efficient due to their simplified nature and use of larger time steps, making them suitable for large-scale studies involving many power system components.
- **Potential limitations regarding the characteristics they capture**: Aggregate models may not accurately capture the specific characteristics of individual components or fast transient phenomena. They are generally not suitable for studies requiring detailed analysis of instantaneous voltage and current values.

Some key features and considerations when using detailed component-level models are that they:

- **Provide detailed representation**: These models represent the intricate details of individual components within a generation or large load facility, including their internal dynamics, controls, and nonlinear characteristics.
- **Capture fast transients**: Detailed component-based models are crucial for analyzing fast transient phenomena such as switching events, fault conditions, and lightning strikes.
- **Are used in EMT simulations**: Detailed models are typically used in EMT simulations, which solve differential equations in the time domain to capture instantaneous values of voltages and currents.
- **Are required for specific studies**: Detailed models are necessary for assessing compliance with specific requirements, such as harmonic injection analysis, subsynchronous resonance evaluations, transient over-voltage analysis, and others.
- **Are computationally intensive**: Simulations with detailed models are computationally intensive due to the small time steps required to accurately capture fast transients, making them less suitable for large-scale studies. In addition, if multiple instances of such detailed models are used, it further increases the computational burden, making the assessment prohibitive.

In summary, the choice between aggregated load and detailed component-based modeling, as well as between PSPD and EMT models, depends on the specific requirements of the study. High-level planning studies may benefit from aggregated and PSPD models, while studies focusing on the assessment of specific device control–related phenomena (e.g., subsynchronous oscillations, fast dynamics, and power quality) may require detailed EMT models to accurately identify the problem as well as the corresponding mitigation measures.

Numerical Stability and Robustness

For power system dynamic studies, ensuring that a load model demonstrates numerical stability and robustness is paramount for reliable simulations and accurate analysis. Numerical stability refers to the ability of the model's numerical solution method to remain stable and avoid divergence or unrealistic oscillations, particularly when simulating dynamic events. Robustness refers to the model's ability to provide consistent and realistic results even when subjected to various operating conditions, disturbances, and parameter variations.

For power system dynamic studies, ensuring that a load model demonstrates numerical stability and robustness is paramount for reliable simulations and accurate analysis.

Achieving numerical stability and robustness in load modeling is critical because load models are often incorporated into large, complex power system simulations. These simulations involve solving systems of differential and algebraic equations that represent the interrelated behavior of various components. Numerical instability or lack of robustness can lead to unreliable simulation results and potentially causes misleading conclusions about system performance during critical events. This can be especially challenging with the increasing levels of inverter-based resources and new types of loads, which introduce complex, nonlinear dynamics that can impact numerical stability of dynamic simulations. Thus, it is essential to carefully select numerical integration techniques, appropriate model parameterization, and thorough model validation to ensure that load models contribute to stable and reliable power system simulations, enabling effective system planning and operation.

Dynamic Model Development Guidelines and Requirements

PSPD-Specific Modeling Requirements

Positive-sequence phasor-domain simulations are the backbone of transient stability evaluations of bulk power systems. PSPD simulations are suited for understanding the lower-frequency (less than 10 Hz) dynamic interactions between different components in a power system. For large loads, PSPD domain models aim to capture the lower-frequency dynamic responses from the power electronic devices and the impact of sudden load disconnections or sudden load ramps on the power system dynamics.

Recommended guidelines from the project team for developing PSPD models to be used in PSPD simulations include:

- **Site-specific dynamic load models**: Stability studies require the use of detailed PSPD load models that reflect the actual load composition (power electronic blocks, motors, static loads, etc.). Generic library models may lack the controls and protection features that are present in large load systems. When standard models prove inadequate (e.g., failing to reproduce voltage ride-through behavior), it becomes necessary to implement user-defined dynamic models keyed to the site's equipment and control logic.
- **Relevant control loops**: For PSPD studies, it becomes necessary to explicitly represent any control loops whose bandwidth falls in the 0.05–10 Hz range. This means modeling outer-loop functions such as active-power control, frequency-droop or power-factor controls, and ride-through/logical actions. The Australian Energy Market Operator's guidelines, for example, emphasize that dynamic models for generators "include detailed representation of all inner and outer control loops" for converter-connected plants (AEMO, 2023). In practice, one typically implements simplified equivalents of converter voltage/current regulators if they significantly affect system stability in the phasor-domain frequency bandwidth. Very fast inner loops (e.g., pulse-width modulated (PWM) current regulators at hundreds of Hz) are usually approximated or omitted in PSPD models since their effects fall above the intended bandwidth.
- **Correct initialization and tuning**: It needs to be ensured the PSPD model is initialized at the correct operating point (matching the power flow case) and can settle to the proper steady-state after disturbances. Parameters (gain settings, time constants) should be set or tuned based on the load facility data so that the model's low-frequency response (gain and phase within 0.05–10 Hz) matches expected behavior. In short, the model must both start from and return to realistic load conditions in dynamic studies.

Here we discuss the PSPD modeling requirements for large load facilities, outline key modeling challenges, and propose approaches for developing accurate, representative load models. This is intended as a foundational guide for engineers, analysts, and planners tasked with integrating large loads into modern power systems.

Limitations of PSPD Simulation Models and Platforms

While we outline limitations of PSPD simulations here, it is important to note that the goal of these simulations is to identify bulk system dynamic issues which may require broader grid investments or specific mitigation actions by system operators in real time. Such investments or operator actions are usually determined by system-wide stability issues, which generally fall into the category of slow and balanced dynamics. Hence, even with limitations, PSPD

modeling and simulations are a cornerstone of system reliability assessments.

Limitations include the following:

- **High-frequency dynamics omitted**: By design, PSPD models filter out fast dynamics. Any load behavior or control action above approximately 10 Hz will not be captured, including, for example, the impact of harmonic currents, fast inner control loops, frequency-tracking controls, sub-cycle converter switching effects, or rapid gating actions. If the study involves fast transients, harmonic interactions, or control loops beyond the phasor-domain bandwidth, a full EMT model is required.
- **No unbalanced effects**: PSPD simulators assume balanced voltages and frequency not deviating significantly from nominal (i.e., 60 Hz/50 Hz). The effect of unbalanced system events and their impact on controller actions cannot be simulated using PSPD models.
- **Subsynchronous oscillations:** Inverter–converter interactions or load oscillations can lead to subsynchronous control interactions (SSCI) or subsynchronous torsional interactions (SSTI) with nearby generators (synchronous machines or inverter-based resources), typically occurring in the 5 Hz to 55 Hz range, which is outside the PSPD simulation domain. Analyzing these phenomena requires detailed modeling of synchronous machines (including multi-mass turbine shaft representations) and inverter-based resources (including control systems and drive trains for Type 3 wind) and detailed modeling of load controls along with the load variation pattern, as applicable, at a site. Because these interactions involve fast dynamics and complex electromechanical behavior, capturing them reliably necessitates high-fidelity EMT models.
- **Sensitive event responses**: Certain large load behaviors observed in real systems (such as partial or full trip on shallow voltage dips) may not be reproducible by simple PSPD models. In some cases, exploratory assessments need to be performed using detailed EMT models to identify the possibility of such conditions and then represent these in PSPD models to study their impact on the bulk power system.

In summary, whenever the load's dynamic response extends into frequencies above approximately 10 Hz or involves unbalanced conditions or fast nonlinear interactions, phasor-domain PSPD modeling is not recommended, and more advanced modeling (EMT or hybrid methods) is required.

Numerical Stability in PSPD Simulation

Below are a few recommended guidelines to ensure numerical model stability for PSPD simulations:

- **Use a small time step.** The integration interval should be set small enough to capture the fastest dynamics. A common rule is to use a step less than half the smallest model time constant. Most simulation tools recommend that the smallest time constants in a model be four times the smallest simulation time step that is chosen and warn the user if this condition is not met.[27] For large load impact studies, this might mean steps on the order of milliseconds. A sufficiently small step avoids numerical instability and ensures solver convergence, although it increases run time. If the simulator allows variable stepping or multi-rate solvers, they can be used to automatically adapt to fast/slow modes.
- **Employ robust integrators.** Where possible, implicit or A-stable integration methods (e.g., trapezoidal or backward-Euler) should be used for stiff systems. Implicit methods allow larger steps without instability at the cost of solving equations iteratively at each step, most likely increasing run time. Solver tolerances (e.g., tighter convergence criteria) should be configured to improve stability. If the tool supports it, solver features should be enabled that monitor convergence (e.g., DIgSILENT's simulation scan) and the run stopped if too many warnings accumulate.
- **Validate no-disturbance stability.** Per industry guidelines, a PSPD model should remain steady over a long "flat run" (i.e., no disturbance simulation). For example, the Australian Energy Market Operator requires (for generation) that voltages, frequency, and power output remain constant for up to 5 minutes of simulation with no disturbance (AEMO, 2021). Any model drift during such a no-disturbance simulation indicates numerical issues or model inconsistencies, and this should be rectified before carrying out studies.
- **Use gradual transitions and filtering.** Ideal step changes in setpoints or loads should be avoided. Where possible, abrupt commands (i.e., ramp any large changes in load or generation MW over a few milliseconds) should be smoothed so the solver does not encounter an unrealistically large instantaneous change. This can be tackled in part by including realistic controller/deadband dynamics in the model.

EMT-Specific Modeling Requirements

EMT modeling is needed when studying higher-frequency dynamic issues with electrically close devices. Additionally, EMT models and associated simulators can capture the effect of system unbalances as the models are created in full three-phase details. It is important to note that EMT models are not only essential for detailed transient studies, but a validated EMT model can also serve as a benchmark for the slower dynamics represented in PSPD models under a wider range of scenarios.

Guidelines recommended by the project team for developing models to be used in EMT simulations are:

- **Component coverage:** The model must represent all significant subcomponents of the large load (power electronic devices, UPSs, inverters/rectifiers, drive motors, cooling systems, power distribution units (PDUs),[28] back-up generators or battery storage, etc.) as distinct models or aggregated equivalents. These elements strongly influence the facility's dynamic response and stability.
- **Control and protection fidelity:** The model needs to include detailed models of all control systems and protection devices. For example, the actual inverter/converter firmware code should be used if available; otherwise a model validation report against test data should be included. Every asset-level controller (voltage regulator, phase-locked loop, ride-through logic, etc.) and protection (AC/DC relays, breakers) in the model should be documented.

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[27] GE PSLF™ User Manual

[28] Power distribution unit is on-site electrical infrastructure that steps down, conditions, protects, and distributes power from the facility's medium-voltage supply to racks, servers, or other sub-loads.

- **Reactive compensation devices and transformer dynamics**: The model must include any switched capacitor or reactor banks and include transformer magnetizing (saturation) curves. Capturing these reactive elements is essential for accurate voltage and fault response in unbalanced conditions as well as any fast transient resulting from the interaction of these line-connected devices.
- **Site-specific parameters**: The EMT model, if generic or user defined, needs to configure all tunable parameters (controller gains, protection settings, etc.) to match the actual equipment on site, not just generic or default values. Ensuring the model uses field-commissioned settings improves model fidelity.
- **Time-step and stability:** The EMT simulation should be run with a fine time step (on the order of 10–50 μs) to capture fast transients. Numerical stability needs to be verified, especially under weak-grid (low short-circuit ratio) conditions. If any time-step restrictions or solver limitations apply, these should be documented.
- **Test cases and validation**: For EMT models that are site-specific, appropriate test scenarios should be defined matching the facility's configuration (e.g., balanced and unbalanced faults, voltage/reactive-power, and frequency/active-power step changes). The model should be validated against field or lab measurements, with actual measured load profiles incorporated and pre-/post-commissioning monitoring data used to validate performance. This is covered in further detail in the section "Key Modeling Requirements for Power System Dynamic Assessments."
- **Power quality impacts:** Power-quality effects from nonlinear loads (e.g., switched mode power supplies (SMPS), variable frequency drive–driven motors, UPS rectifiers, and saturation effects of power and instrument transformers) need to be accounted for, and any filters or mitigation that are needed to meet the local power quality standards (such as IEEE 519 harmonic limits) should be included. The level of power quality–related details that needs to be modeled also depends on the assessment needs. As an example, for a subsynchronous control interaction study, an average model is suitable even though it does not capture the harmonic injections from power electronic equipment.

Model Usability Features

The model usability features ensure that PSPD and EMT models, whether generic or UDM, can be used effectively for power system dynamic assessments. Some of these usability features are more applicable to a particular model type, and those are highlighted here:

- **Initialization and scalability:** The model must self-initialize to steady state without external inputs and support a range of outputs. If the load can operate at different power levels, the load consumption level should be dispatchable. This allows testing the load at different operating levels. **Applicability:** EMT generic and UDM, PSPD generic and UDM.
- **Computational efficiency**: Repetitive subsystems should be simplified to improve run-time while preserving accuracy. For example, average-value converter models (retaining full control loops and protections) should be used instead of detailed switching models for large inverter banks. Identical load units or parallel branches should be aggregated where possible. **Applicability:** EMT generic and UDM, PSPD generic and UDM.
- **Able to accept external reference variables**: This includes real and reactive power ordered values for Q control modes, or voltage reference values for voltage control modes. Models must accept these reference variables for initialization and be capable of changing these reference variables during the simulation, i.e., dynamic signal references. **Applicability:** EMT generic and UDM, PSPD generic and UDM.
- **Capable of running at a range of time steps**: The model should be capable of running at time steps anywhere in the range of 5 μs to 10 μs. Most of the time, requiring a smaller time step means that the control implementation has not used the interpolation features of EMT software or is using inappropriate interfacing between the model and the larger network. Lack of interpolation support introduces inaccuracies into the model at higher time steps. This is generally not an issue with PSPD models. **Applicability:** EMT generic and UDM.
- **Software and compiler version compatibility**: The model should be compatible with the latest software version and, if it includes precompiled components, with recent compiler versions. For example, it is recommended that PSCAD models support PSCAD version 5.0.2 or later and be compatible with Intel Fortran compiler version 15 or higher as well as Visual Studio 2015 or newer. For PSPD generic models this is not an issue, as the library is updated with every version. PSPD UDMs suffer from this problem; however, the issue lies with the simulator design and cannot be addressed in the model design. **Applicability:** EMT generic and UDM.
- **Multiple instance support**: The model must support multiple instances of its own definition in the same simulation case. This feature is important if multiple facilities want to use the same model in an assessment. This is not an issue for PSPD generic models. **Applicability:** EMT generic and UDM, PSPD UDM.
- **No global variable dependency**: The model must not use or rely upon global variables, and it should support multiple instances within a single simulation case. **Applicability**: EMT generic and UDM, PSPD generic and UDM.
- **Timed snapshot support**: The model must support a “timed snapshot” feature and allow the user to continue to simulate different scenarios from a snapshot, saving computation time. This is not an issue with PSPD generic models and UDM. **Applicability:** EMT generic and UDM.
- **Dual architecture binaries:** The model should be supplied with both 32-bit and 64-bit compiled versions. This is not an issue with PSPD generic models and UDM. **Applicability:** EMT generic and UDM.

Model Documentation

Both EMT and PSPD models require proper documentation so that these models can be applied by end users who were not intimately involved in the model’s development. This section describes the documentation requirements for simulation models.

Releasable User Guide

A releasable user guide (RUG) is a structured, clear, and comprehensive resource that helps end users understand how to configure, parameterize, and effectively use the model. A RUG must be submitted with the model. Separate RUGs should be provided for both PSPD and EMT models.

The RUG should include pertinent information on model development and usability and should be clear and concise, such that any user can conveniently use the model while performing studies.[29]

The RUG is expected to include the following details, as well as any other relevant information as applicable:

- Tools and version compatibility of the EMT and/or the PSPD model
- Completed data sheet including proper description of the parameters
- Information that is required to allow correct parameterization of the facility model, to include, at a minimum, ranges of all configuration parameters, control system settings, and component trip/status codes
- If the model is specific for a certain load facility, the parameters that should not be adjusted in the model
- Guidance on representation in a power flow model, and dynamic simulation set up instructions—special initialization techniques, recommended simulation time steps, etc.
- Any other information relevant to the model's usability

Model Assumptions and Limitations

The model documentation needs to clearly state key assumptions and limitations inherent in the model. The following information should be included:

- A model development report should be included that contains modeling approaches and key assumptions made during the creation of the PSPD or EMT model such as aggregation methods, control structure representations, and any simplifications or exclusions.
- Limitations of the model should be clearly documented (e.g., model is not intended or tested for blackstart studies).
- A comprehensive validation and benchmarking report, following the processes outlined in the section "Model Parameter Verification, Validation, and Quality Testing Guidelines" should be provided. The report must clearly highlight any differences between models and explain the reasons. Additionally, it should include all settings used for both generic and UDM models in PSPD and EMT simulations. If parameter values differ between models, the report should include the appropriate translation or conversion formulas used to align them.

Description of Protection and Control System Setup

The following protection and control threshold requirements should be documented and provided with a model:

- Protection settings and controller tuning reports that could be used to align model responses during abnormal conditions with expected facility behavior
- Information related to protection system settings that are vital to load flow or dynamic simulation studies, including, but not limited to, under- and over-voltage or frequency protection settings

Details on Facility-Specific Settings

If the model is being submitted for a specific facility, all settings and parameters used must be clearly documented, including their base values and any changes that may be needed for different operating conditions.

For UDMs, settings information should identify the office and individuals who provided all of the facility-specific data so that these individuals or their successors can be consulted if the model results or facility behavior require reexamination or recalibration.

It is worth noting that if both PSPD and EMT models are submitted for the same load facility to support bulk system and local dynamic assessments, the model developer will need to document the process used to compare parameters between the two models for all portions of the facility (controllers, components, etc.) represented in both platforms. It is also recommended that if both models are submitted, a benchmarking report comparing the model responses and explaining the differences should also be provided.

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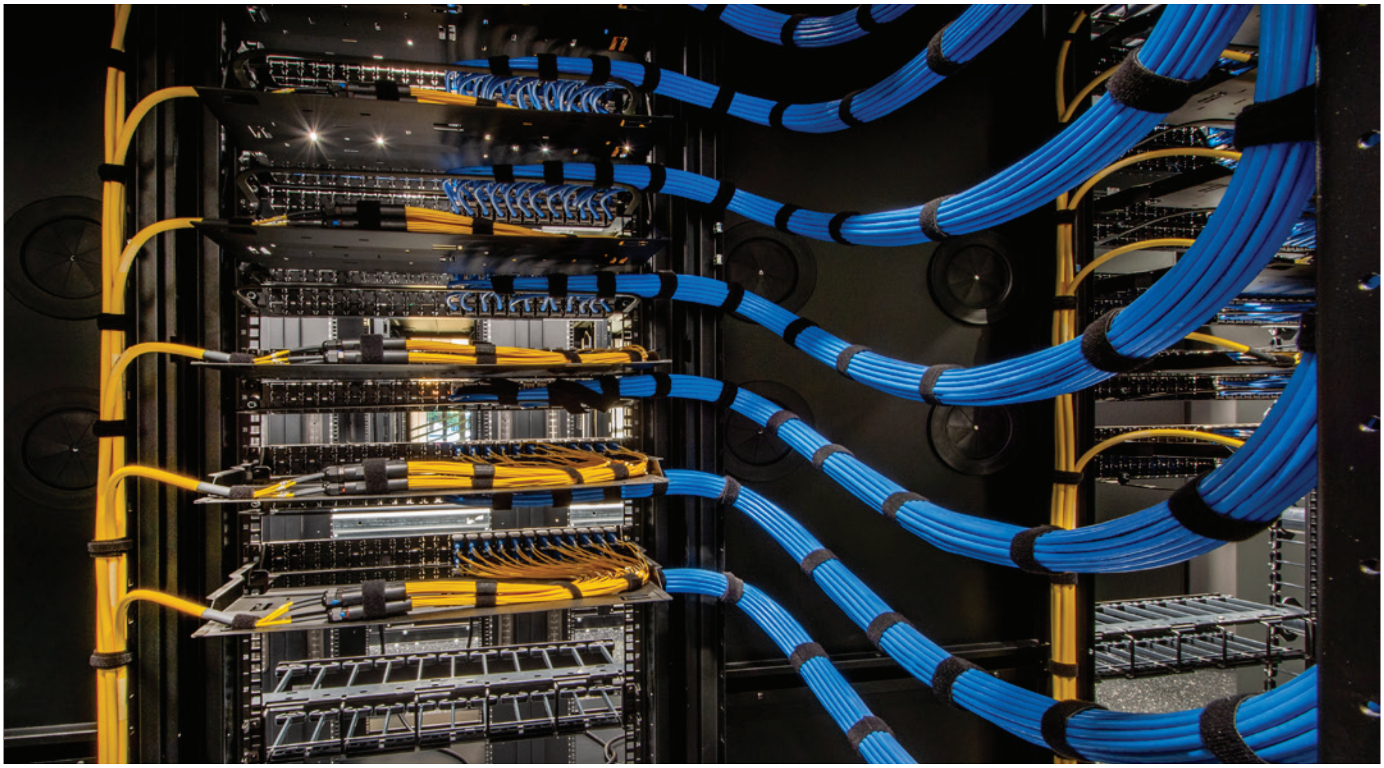
[29] RUGs generally focus more on the usability of the model than describing the theoretical details underpinning the model. However, information that concerns using the model should be included, as a user may need to understand the model representation of a physical phenomenon to be able to parameterize and use the model.

Model Parameter Verification, Validation, and Quality Testing Guidelines



The usefulness of a model depends heavily on whether it has been parameterized properly and validated to a reasonable extent. A good model would provide misleading results if the parameters and control code used are not reflective of the equipment it represents; therefore, model parameterization, model validation, and model quality testing play an important role. These three activities are defined as follows:

- **Model parameter verification:** This is the process of confirming that all parameters in the dynamic model (e.g., control gains, time constants, and protection settings) accurately reflect the actual equipment settings and configurations in the field. It ensures the model represents the physical device as installed and operating.
- **Model validation:** Model validation involves comparing the model's simulated response to actual measured performance from field tests or disturbance recordings. The goal is to confirm that the model behaves realistically under various operating conditions and disturbances.
- **Model quality testing:** Model quality testing (MQT) is a structured set of tests applied to the dynamic model to verify its stability, robustness, and correct behavior under a range of predefined scenarios such as voltage steps, frequency changes, fault ride-through conditions, and others. These tests check for numerical stability and proper control response and may include elements of compliance assessment with applicable grid code requirements before the model is accepted for planning or operational studies.

These three activities have been defined by many utilities and reliability coordinators for generators as part of the generator interconnection process but are largely undefined for large loads. This section discusses each of these activities in the context of large loads.

Data Collection Requirements for Parameter Verification and Model Validation

The data collection requirements for model verification are documented here.

Electrical Characteristics

The following electrical characteristics of the large load components are required to be provided during the interconnection process and following large load facility hardware upgrades during its lifetime:

- The collector system including cables and overhead lines and their impedance parameters[30]
- Information on the substation transformer, namely:
  - Leakage reactance and MVA base
  - Winding ratio (primary voltage and secondary voltage rating)
  - X/R ratio
  - Winding connections (e.g., Y-ground/Delta)
  - Fixed tap position (typically nominal taps)
  - Saturation curve characteristics (when needed)[31]
- Equipment at the substation such as shunt capacitors, reactors, filters, and/or capacitor banks
- Dynamic reactive devices (static VAR compensators, STATCOMs, or synchronous condensers), if any, and their nameplate ratings
- If the load consists of UPS units, cooling systems, servers, or miners, information on the MVA size and number of each component
- For large loads co-located with generation or storage resources, a classification indicating one of the following configurations:
  - Behind-the-meter
  - Front-of-the-meter
  - Shared POI (Lang, 2024)
  - Non-wire alternatives (Kumar, Zare, and Ghosh, 2017)
  - DC-coupled and AC-coupled configurations (Eurek et al., 2021)

The data mentioned above should be provided such that the submitted model can be parameterized properly.

Control and Protection Settings

The following protection settings are required for the large load components such as power electronics and co-located generators:

- Frequency and voltage ride-through characteristics are needed, which can be provided by the equipment manufacturers.
- Protection settings should not be limited to PSPD-based representations. Instantaneous protections, such as over-voltage, over-current, or DC link protection, must also be considered and implemented within the appropriate modeling domain, particularly in EMT simulations where fast transients are captured accurately.

Parameter Verification Process

Following the submission of a large load model by the facility owners for interconnection request, a formal model parameters verification process must be established to make sure the submitted model accurately represents the parameters used in the real-world facility. This includes verifying that:

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[30] Annex G of IEEE 2800-2022, "IEEE Standard for Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems," provides recommended practices for modeling data for inverter-based resources and can be used as a starting point for large load modeling data requirements.

[31] Transformer saturation characteristics are needed for certain special assessments like ferroresonance. These curves can be hard to obtain and one has to rely on either manufacturer support or estimate the characteristics based on measured inrush voltage and current data as shown in Abdulsalam et al. (2006).

- Model parameters are realistic and site-specific
- Protection logic reflects the actual settings implemented in the field

If possible, component- and facility-level models should be verified by the equipment manufacturers or large load owners to ensure they are properly parameterized. Supporting documentation and attestations should be provided to confirm alignment with actual components- and facility-level settings and protection schemes. These documents should include a model validation study to show that the parameterized model is capable of replicating the actual facility performance.

General Parameter Verification Process

Parameters that have a 1:1 correspondence with equipment settings (e.g., voltage and frequency trip thresholds) should be prioritized.[32] An engineer carrying out the verification process should:

- Match model parameters directly with actual load facility values through human-machine interface (HMI) data
- Use the equipment manufacturer's documentation
- Ensure that a model parameter verification report is produced by the equipment manufacturer that compares the actual equipment performance against those of the EMT and/or PSPD model
- If direct validation is not feasible, prioritize manufacturer attestations or supporting documentation (preferred) or use engineering judgment as an acceptable alternative

Table 3 shows the direct 1:1 parameter matching process.

Special Handling for Approximated Parameters (Not 1:1)

Some parameters such as lookup tables in generic models may not correspond directly to any specific equipment settings. These parameters would be difficult for verification. However, in such situations, qualitative explanations or benchmarking against EMT models can be used as helpful approaches.

Model Validation Process

Model validation is a critical step in the interconnection process to ensure that the models submitted accurately reflect the real-world dynamic behavior of the large load at the component and/or facility level. This involves comparing the parameterized model's simulated response against measured performance data from a large load facility during actual system events or staged tests.

The following steps need to be considered in the validation process:

- A phasor measurement unit or digital fault recorder should be required at the POI between the large load and the grid, collecting continuous or event-triggered high-resolution data on the load's performance and interactions with the bulk power system. A data retention policy should be established for all large loads to capture real-world data during disturbance events and these measurements used to evaluate and validate existing models at the facility level based on actual facility and system behavior.

TABLE 3

Example Direct Parameter Matching (1:1) Process to Document and Verify Parameter Accuracy

Example Model Parameter	Model Value (PSPD or EMT)	Actual Equipment Value (Acquired from the OEM)	Notes/Explanation
Voltage trip threshold	0.88 pu	0.88 pu	Matches original equipment manufacturer (OEM) specification
Delay time	2.00 s	2.00 s	Verified via human-machine interface (HMI)

Source: Energy Systems Integration Group.

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[32] Models with 1:1 mapping between the field controller and model parameters are preferred.

- Simulation results with measurements from component- and/or facility-level staged tests should be compared. An engineer carrying out the model validation process may consider:
  - Defining acceptable thresholds for deviation between simulation and measurements.
  - Applying tolerance bands to assess accuracy (e.g., ±5% for power, ±5 ms for timing deviations).
- Model accuracy should be verified with the manufacturer if significant errors persist, to ensure the model is correctly parameterized.
- Since large loads such as data centers may be changing their operational purposes, patterns, and components regularly, model performance should be reviewed against actual facility data at regular intervals (determined by the local utility) to determine whether the model requires an update followed by a validation assessment. The interconnecting authority should request or require that that the large load customer update the model as per the outcome of the validation exercise.

Model Quality Testing Guidelines

This section outlines the development of MQTs, which are essential to ensure that submitted models at the component and facility level are suitable for use in bulk system dynamic assessments. Ensuring the model quality requires close coordination of the large load facility owner with the manufacturers of the equipment installed in the facility.

A large part of MQT design is influenced by the underlying interconnection requirements, which dictate acceptable model performance for large loads at the component and facility level. And since MQT standards are typically enforced as part of the interconnection process, close coordination with applicable interconnection requirements will be necessary (Schmall, 2022). For more details on interconnection requirements of large loads, see the ESIG report *Large Load Performance Requirements: Current Practices and Recommendations.*[33]

Currently, there are no formal MQT requirements for large load models, and developing appropriate guidelines or standards will require:

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[33] https://www.esig.energy/reports-briefs/large-load-interconnection-performance-requirements/

- Analyzing existing MQT practices for generator and inverter-based resource models
- Reimagining these practices to address the unique characteristics and challenges of large loads
- Extending this requirement to the various components or equipment that comprise the large load as a whole

Therefore, the following tests can be proposed for the large load model quality assessment and can be adapted for the components comprising the large load.

Flat Run Test Requirements

The flat run test evaluates a large load model's initialization, confirms the model's performance under steady-state conditions, and ensures the simulation's numerical stability. This test is recommended to be performed for 20 seconds without applying any disturbances. During this time period, it is anticipated that real power, reactive power, and frequency should remain stable and closely aligned with their initial values.

Voltage and Frequency Ride-Through Tests

Voltage ride-through requirements are essential to ensure that large loads remain connected and support the grid during voltage disturbances.

The large load facility model should be tested under voltage and frequency disturbance conditions that a large load facility is expected to ride through according to applicable ride-through requirements and also under conditions where it is allowed to trip (switch over to its back-up supply). In other words, the large load facility model should be tested to perform as expected per applicable ride-through requirements.

Phase Angle Jump Test

A phase angle jump is a sudden change in the phase of the voltage waveform, typically applied to simulate grid disturbances that cause an abrupt shift in the voltage vector's angle while maintaining nearly the same magnitude and frequency. NERC PRC-029-1, IEEE 2800-2022, and IEC 61400-27-2 specify phase angle jump performance requirements for inverter-based resources (e.g., solar, wind, and battery storage) under grid disturbances. In general, the following are required:

- Ride-through capabilities during voltage phase angle jump events
- No tripping under sudden grid voltage phase disturbances
- The use of robust phase-locked loops or other synchronization methods in the case of power electronics. If a phase angle jump tolerance has been defined by the local utility, the large load facility model should be tested to perform as expected per applicable requirements.

Controlled Change of Load Level or Operating Point

This MQT involves intentionally and suddenly increasing or decreasing the power consumption of a large load model, such as a data center. In real-world operation, sudden load changes are common, especially with servers and information technology equipment that can ramp up or down quickly based on demand. The purpose of this MQT is to evaluate how the transmission system and the load's simulation model respond to rapid changes in power demand for the worst-case scenario during power ramping.

During the MQT, both active power (P) and reactive power (Q) should be measured in the simulation. It is important to observe:

- Any oscillations in active power
- Variations in reactive power

The interaction between P and Q during these transients is critical for understanding voltage behavior and testing the dynamic performance of the load model.

These results support MQT for use in interconnection studies, grid impact assessments, and ride-through capability evaluations.

Reliability Impacts of Inadequate or Improper Modeling

If planners use inadequate or inaccurate load models to assess large load interconnection and bulk power system operation, this could yield incorrect assumptions about grid performance and risks. Potential consequences could include oscillations or voltage and frequency events that harm generators and other equipment on the grid, grid disturbances that cause the large load to trip offline, and potential local or cascading system outages. This section demonstrates the consequences of proper and improper model usage, outlining the importance of using properly parameterized and validated models of large loads for power system dynamic assessments (Sundaresh and Mitra, 2024).

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Case Study 1

Case study 1 (performed by Monash University) highlights the importance of accounting for the physical characteristics and operational constraints of hydrogen electrolysis technologies in power system analysis. This case study concentrates on a specific type of grid connection assessment—namely, the response of an electrolysis plant to frequency disturbances. The case study uses a dynamic model of a hydrogen electrolysis plant, with the external grid represented by a voltage-behind-impedance configuration (Thevenin equivalent), as shown in Figure 2, and illustrates the significance of incorporating partial load limits in electrolysis plant modeling. The partial load limit refers to the minimum active power required to maintain safe and efficient operation of an electrolysis stack, as specified by hydrogen electrolyzer manufacturers.

The case study investigates a contingency involving a 2.5 Hz drop in system frequency from its nominal value (Figure 3, p. 36), with a 5 MW proton exchange membrane (PEM) electrolyzer operating at rated power. In line with safety and operational requirements, the electrolyzer is required to operate above 50% of its rated capacity, setting a partial load limit at 2.5 MW. Below this limit the load would shut down. Table 4 (p.35) shows the typical partial load limits for different commercial electrolysis stacks. Two simulation scenarios are assessed:

FIGURE 2

Test System for Grid Connection Studies of Electrolysis Plant

Single line diagram for the study setup showing an electrolyzer connected radially to a power system.

Source: Monash University.

TABLE 4

Partial Loading Limits on Electrolysis Technologies Developed by Different Electrolysis Stack Manufacturers

Electrolyzer Manufacturer	Type	Partial Loading Limit
Cummins (AEL)	HySTAT	40%
McPhy (AEL)	McLyzer 800	20%
NEL (AEL)	A	15%
ITM Power (PEM)	Neptune II	25%
NEL (PEM)	PSM	10%
Cummins (PEM)	HyLYZER	5%

Notes: AEL = alkaline electrolyzer; PEM = proton exchange membrane.

Source: S. H. Meetiyagoda, B. Bahrani, and M. Ghazavi Dozein, "Distribution-Connected Electrolyzers with Partial Loading Limit and Power Response Characteristics," *2025 IEEE Kiel PowerTech*, Kiel, Germany, 2025, pp. 1-7.

- **Inclusion** of the partial load limit in the electrolysis plant model
- **Exclusion** of the partial load limit in the simulation

The results in Figure 3 (p. 36) demonstrate that when the partial load constraint is ignored, the model overestimates the plant's frequency response capability, allowing the electrolyzer to reduce power by up to 3.5 MW, which is not physically realistic. In contrast, when the partial load limit is incorporated into the model, the simulation more accurately captures the actual operational behavior of the plant, which can only reduce power down to 2.5 MW in response to frequency disturbances.

This case study highlights that omitting stack-level constraints can lead to inaccuracies in dynamic simulations, potentially misrepresenting plant behavior in system connection studies. Accurate modelling of such constraints is therefore essential for realistic assessment of electrolysis plants.

Case Study 2

Case study 2 (performed by Zero-Emission Grid) demonstrates the need for accurate, detailed modeling of large, fast-acting loads, focusing on a data center load interfaced by a UPS operating in an online mode.[34] This configuration is one of the most common for data centers due to its higher reliability during grid events. The study highlights how simplified load representations can fail to

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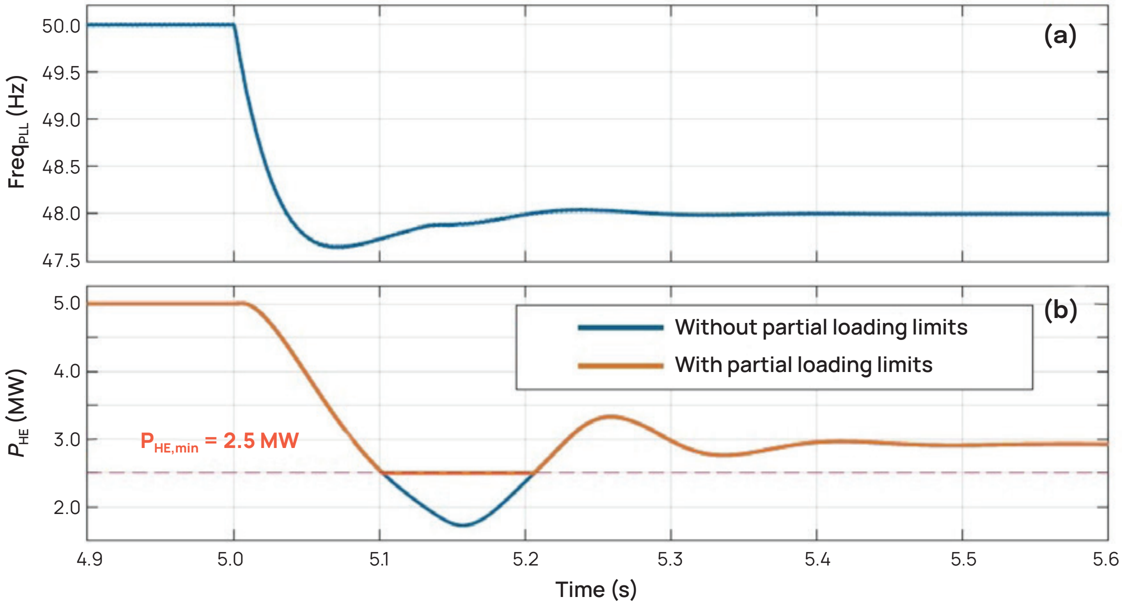
[34] See the ESIG Large Loads Task Force report *Large Loads: Behaviors, Capabilities, Limitations* for detailed description of the facility at https://www.esig.energy/reports-briefs/large-load-interconnection-performance-requirements.

FIGURE 3

System Frequency and Frequency Response from Electrolyzer

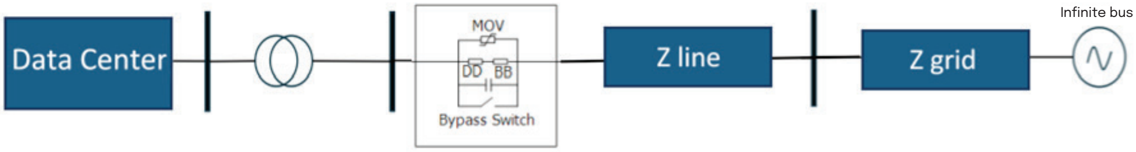


The importance of partial load limit modeling in capturing actual plant behavior when responding to a frequency disturbance: (a) system frequency dynamics at the electrolysis plant terminals, and (b) simulation results representing electrolysis plant behavior with and without partial load limit modeling.

Source: S. H. Meetiyagoda, B. Bahrani, and M. Ghazavi Dozein, "Distribution-Connected Electrolyzers with Partial Loading Limit and Power Response Characteristics," *2025 IEEE Kiel PowerTech*, Kiel, Germany, 2025, pp. 1-7.

FIGURE 4

Test System for Case Study 2



Single line diagram for the study setup showing a data center connected radially to a power system.

Notes: BB = bypass breaker; DD = damping device; MOV = metal oxide varistor.

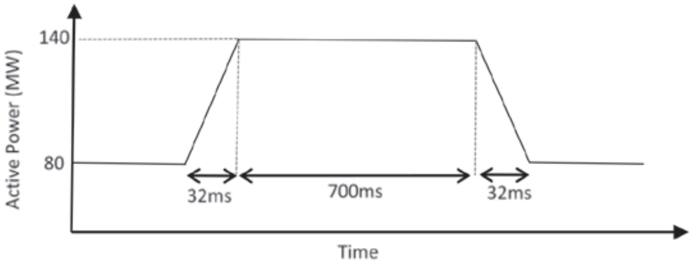
Source: Amin Dadashzade, Zero-Emission Grid.

capture critical dynamic interactions, particularly in networks with series-compensated transmission lines. Figure 4 shows the system under study. The data center is connected to the grid through a series-compensated transmission line with a compensation ratio of 25%. The series capacitor is protected by a metal oxide varistor during over-voltages and is also equipped with a damping device and a bypass breaker to protect the metal oxide varistor.

In this case, the data center's active power consumption fluctuates between 80 MW and 140 MW, as shown in Figure 5 (p. 37). The load initially consumes 80 MW, followed by a sharp step increase to 140 MW over a 32 millisecond period. It then remains at 140 MW for approximately 700 milliseconds before dropping back to 80 MW, repeating this sequence periodically. Such load patterns can occur in practice due to the cycling of high-performance computing equipment in response to changing operational demands.

FIGURE 5

Data Center Load Profile for Case Study 2



The data center's active power consumption fluctuates between 80 MW and 140 MW. The load initially consumes 80 MW, followed by a sharp step increase to 140 MW over a 32 millisecond period. It then remains at 140 MW for approximately 700 milliseconds before dropping back to 80 MW, repeating this sequence periodically. Such load patterns can occur in practice due to the cycling of high-performance computing equipment in response to changing operational demands.

Source: Amin Dadashzade, Zero-Emission Grid.

To assess the impact of using accurate load models to capture dynamic interactions that may occur in practice, two different modeling approaches are compared:

- Simplified load model: A data center load represented in the EMT domain using a variable resistor—an algebraic model that does not incorporate any internal dynamics
- Detailed switching model: A high-fidelity UPS model that includes all relevant controllers and captures the full dynamic behavior of the UPS system

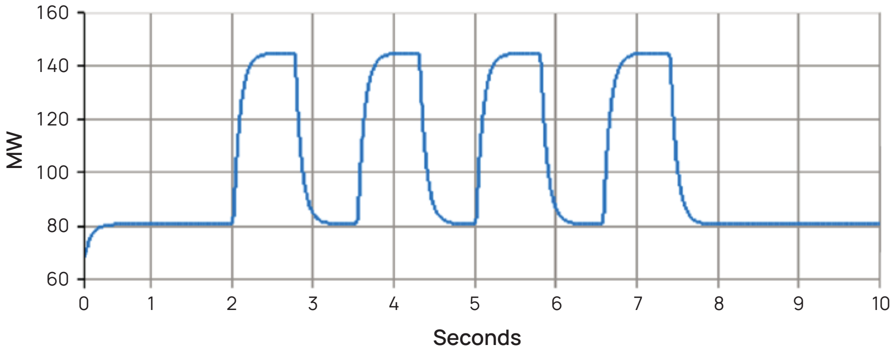
When the load is represented as a variable resistor with a time-varying conductance profile, the system exhibits stable behavior, and no adverse effects are observed on the surrounding transmission network. Figure 6 illustrates the data center load profile modeled using a variable resistor, replicating the target profile shown in Figure 5. However, this simplified model neglects the internal dynamics of the UPS system, including its control loops and power electronic switching behavior.

Figure 7 (p. 38) shows the active power load profile of the data center using a detailed EMT model of the UPS. Unlike the simplified case, the EMT model captures the full dynamic response of the UPS, including voltage regulation, current control, and phase-locked loop behavior. When subjected to the same load profile, the simulation reveals sustained oscillations at the POI. Further analysis indicates that these oscillations are caused by adverse interactions between the UPS control system and the series compensation in the transmission line. Such control interactions cannot be identified when using a simplified load model.

This case study illustrates that relying on overly simplified load representations, such as variable resistors, can obscure important control-driven instabilities. For accurate system impact assessments, particularly in EMT studies involving fast-acting, power electronic–interfaced loads, it is essential to incorporate detailed internal models of devices like UPS systems. Failing to do so may lead to underestimating critical risks, including instability, resonance, or protection malfunction that may affect the power grid.

FIGURE 6

Data Center Load Profile for Case Study 2, Modeled Using a Variable Resistor

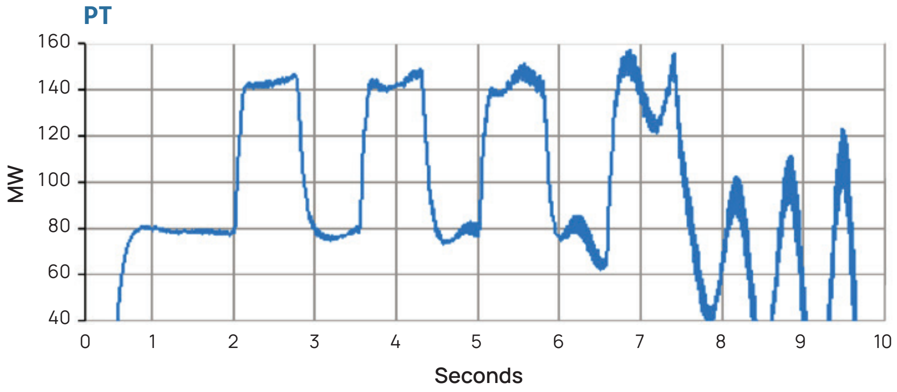


Data center active power profile showing the variable load due to AI training.

Source: Amin Dadashzade, Zero-Emission Grid.

FIGURE 7

Data Center Active Power Load Profile for Case Study 2, Using Detailed EMT Modeling



Data center response showing the instability identified using proper EMT modeling.

Source: Amin Dadashzade, Zero-Emission Grid.

> For accurate system impact assessments, particularly in EMT studies involving fast-acting, power electronic–interfaced loads, it is essential to incorporate detailed internal models of devices like UPS systems. Failing to do so may lead to underestimating critical risks, including instability, resonance, or protection malfunction that may affect the actual power grid.

Recommendations for Accurate Large Load Model Development

The accurate modeling of load facilities is critical to ensure transmission system reliability, particularly as power systems become more dynamic and complex. At the same time, new large loads are becoming more complex, novel, and large in size; these factors make it harder to predict how they will interface with the bulk power system and are why accurate system and load modeling is so essential. However, several challenges persist that hinder effective load representation in both PSPD and EMT simulations. The project team concludes by outlining key actions needed to advance load modeling practices and improve system dynamic assessments.

Key Challenges

Limited Availability of Mature Generic Library Models

PSPD simulation tools lack mature generic library models that can be readily used by planners and load facility owners to represent the dynamic response from a load facility.

Insufficient Data for Model Development and Parameterization

Both EMT and PSPD models require detailed design and operational data, which are frequently unavailable or incomplete. A standardized process does not currently exist for getting this information from load facility owners.

Lack of Standardized Model Submission Requirements

There is no consistent mandate for large load facilities to provide simulation models or modeling information to transmission service providers. This space is, however, evolving, with some utilities asking for this information during facility interconnection processes.

New large loads are becoming more complex, novel, and large in size; these factors make it harder to predict how they will interface with the bulk power system and is why accurate system and load modeling is so essential.

Lack of Verification or Validation Protocols

Models' parameters are rarely verified against actual large load facilities in the field, and models are rarely validated against actual facility performance, leading to potential inaccuracies in system studies and reliability risks.

Next Steps

To address these challenges, this work identifies the following next steps.

Develop Standardized Modeling Requirements

- Clear guidelines can be established for model submission, including minimum data requirements for both EMT and PSPD models.
- These models should be properly documented so that they can be used appropriately.

Develop Generic Library Models Suitable for Bulk System Dynamic Studies

- Load modeling forums and working groups need to work toward creating generic load models for large load facilities, with these models covering the aspects highlighted in this report.

- Use cases can be developed to demonstrate how sensitivity analyses can be performed for forward-looking assessments to get a sense of the reliability risks the grid might be exposed to.

Implement Model Quality Testing, Model Verification, and Validation Frameworks

- Procedures can be developed to test the quality of submitted large load facility models to ensure that the models are usable for the intended study and that the model at a high level reflects the performance as expected per applicable large load performance requirements.
- Procedures can be developed to verify commissioned large load facility settings and parameters with the models that were submitted and used during the interconnection process.
- Facilities can be required to provide commissioning data and disturbance recordings.
- Validation procedures can be developed to compare model outputs with measured responses.

Enhance Industry Collaboration

- Joint efforts can be encouraged between manufacturers, facility owners, and transmission service providers to improve model fidelity.
- Knowledge-sharing can be promoted through technical workshops and working groups.

Integrate Modeling into Interconnection Processes

- Model submission and model quality testing, verification, and validation can be made a formal part of the interconnection approval process for large loads.

The need for robust modeling remains constant as load designs evolve. By addressing the gaps in model availability, data quality, and validation, the industry can significantly improve the accuracy of system reliability assessments taking into account the increased presence of large loads. The guidelines and case studies presented in this report can serve as a foundation for building a more resilient power system going forward.

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Large Load Modeling for Dynamic Studies: Current Practices and Recommendations

A Report by the Energy Systems Integration Group's Large Loads Task Force

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This report is available at https://www.esig.energy/large-loads-task-force/modeling.

To learn more about the ESIG Large Loads Task Force and the recommendations in this report, please visit https://www.esig.energy/working-groups/large-loads/ or send an email to info@esig.energy.

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