ESIG
Large Loads
Task Force

ESIG
ENERGY SYSTEMS
INTEGRATION GROUP

Large Load Modeling for Dynamic Studies

Current Practices and Recommendations

EXECUTIVE SUMMARY

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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.

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 documents modeling needs and approaches aimed at improving the fidelity of transmission interconnection and planning studies to ensure continued grid reliability as large load facilities become a significant part of the power system.

The power system dynamic studies covered in the report 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

See the full report—
Modeling for Dynamic Studies: Current Practices and Recommendations

used in transmission planning and interconnection processes. The guidance offered in the report 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.

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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

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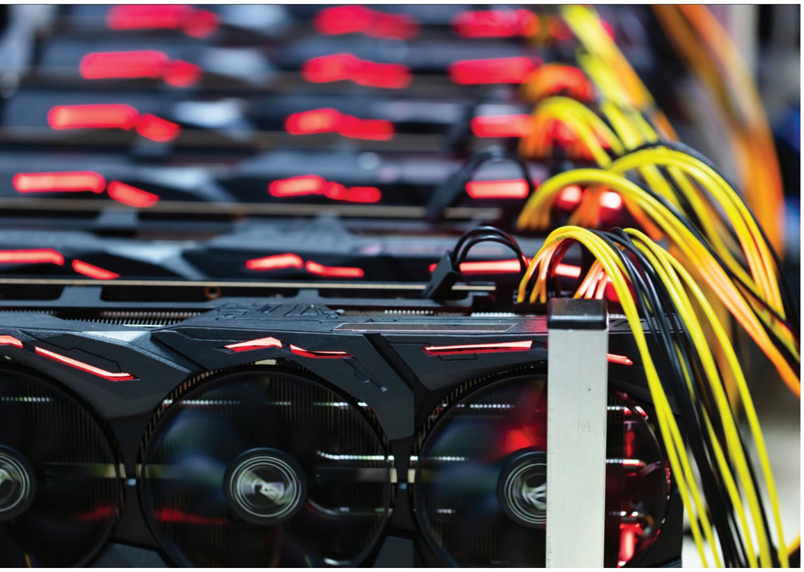
flicker, and switching transients—that can arise at the point of connection of a large load facility. These studies require EMT simulators with detailed, three-phase representations of equipment, controls, and protection systems, often at microsecond time steps. While computationally intensive, EMT studies 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.



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> **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.**

- **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.

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.

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Large Load Modeling for Dynamic Studies: Current Practices and Recommendations, by the Energy Systems Integration Group's Large Loads Task Force, is available at https://www.esig.energy/reports-briefs/large-load-modeling.

To learn more about ESIG's work on large loads, please see https://www.esig.energy/working-groups/large-loads/ or send an email to info@esig.energy.

The Energy Systems Integration Group is a nonprofit organization that marshals the expertise of the electricity industry's technical community to support grid transformation and energy systems integration and operation. https://www.esig.energy.