Draft

Data Center Load Modeling Technical Reference

Document Subtitle

Month Day, Year

RELIABILITY | RESILIENCE | SECURITY

POWERING TODAY. PROTECTING TOMORROW.

Table of Contents

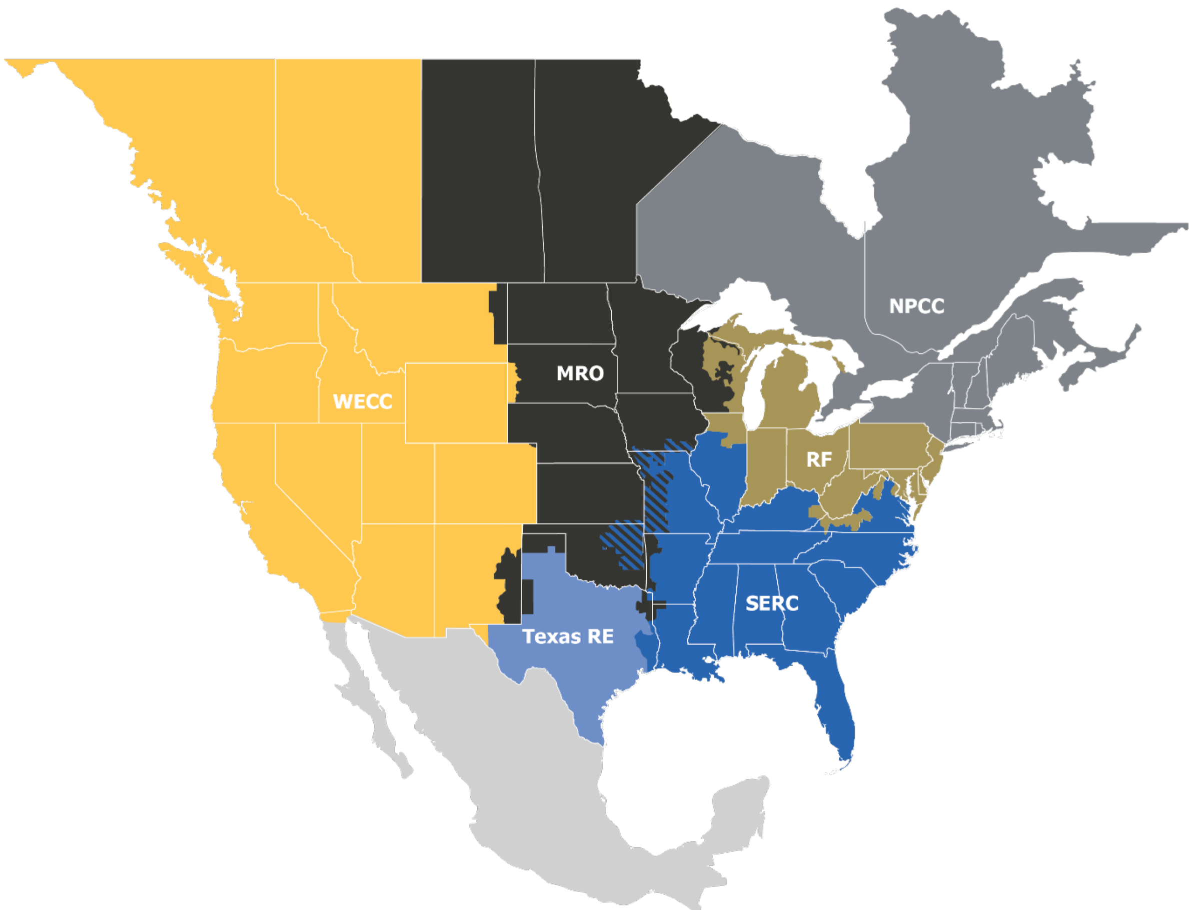
Preface

Electricity powers our modern life and is the bedrock of our economic wellbeing. The Electric Reliability Organization (ERO) Enterprise—comprised of NERC and the six Regional Entities—is firmly committed to assuring a highly reliable, resilient, and secure bulk power system (BPS) in North America. The ERO Enterprise enables collaborative engagement with industry, regulators, and stakeholders, embracing innovation and supporting the needs of nearly 400 million people.

RELIABILITY | RESILIENCE | SECURITY

POWERING TODAY. PROTECTING TOMORROW.

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



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

Preamble

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

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

Executive Summary

Modern data centers represent some of the fastest-growing and most power-intensive loads on in the power system. The study of data centers can be significantly complex due to their complex behavior. This technical reference provides a comprehensive framework to model data center loads for power system stability studies.

High-fidelity simulation and validation are important for understanding system responses under normal and contingency conditions, including ride-through events, and rapid demand ramps and cycling. Realistic modeling supports transmission planning, operational decision-making, and facility design, ensuring that grid stability, reliability, and efficiency are maintained as the data center loads expand their presence and impact across the bulk power systems in North America.

This technical reference provides detailed information on data center load modeling considerations as well as the Power Electronic Reconnection and Ceasing (PERC) Model and acts as a technical reference for Transmission Planners, Planning Coordinators, Reliability Coordinators, manufacturers, consultants, software vendors, and other industry experts who require robust, accurate, and practical modeling approaches for system planning and operational studies. This technical reference delves into the following topics:

- Motivation for realistic data center load modeling
- Nature of the data center loads
- Data Center typical topologies, designs and their steady state and dynamic behavior
- Considerations for steady state modeling
- Considerations for dynamic modeling
- Considerations for electromagnetic transient modeling
- Application of different models for system planning studies

Chapter 1: Introduction and Background

Changing Nature of Large Electrical Loads

The composition, scale, and electrical behavior of large loads on the North American bulk power system (BPS) are undergoing rapid and unprecedented transformation. Historically, the largest contributors to system demand consisted primarily of mechanically-driven industrial processes—pumps, fans, compressors, and induction-motor-dominated manufacturing facilities—as well as conventional commercial loads with relatively predictable electromechanical characteristics. The dynamic behavior of these loads was well understood and their response during system disturbances could be modeled using established frameworks for induction motors, static loads, and composite load aggregates.

Today, however, a new class of large power electronic loads is emerging. These loads are characterized by the pervasive use of converter-interfaced equipment, fast and sometimes discontinuous ramping, high sensitivity to voltage disturbances, and a much greater dependency on internal control systems compared to traditional loads. Key drivers of this shift include:

- **Explosive growth in data centers**, particularly facilities supporting cloud services, artificial intelligence (AI) training and inference workloads, and content delivery networks. Many such facilities now exceed 100–500 MW per site, with hyperscale and AI-training platforms proposing individual campuses ≥ 1–2 GW.
- **Cryptocurrency mining and high-performance compute farms**, whose computational hardware behaves as a concentrated block of rectifier-fed electronic load with rapid, sometimes erratic, power consumption patterns. These loads can cycle hundreds of MW within seconds, creating system balancing and frequency stability challenges.
- **Industrial electrification and hydrogen production**, where electrolysis plants rely on multi-MW modular power-electronic conversion blocks with minimal mechanical inertia and highly coupled control interactions. These facilities may reach multi-gigawatt scale with 80–90% of load consisting of power electronic converters.

Unlike conventional motor-driven loads, the performance of power electronic interfaced loads is governed by **firmware, digital controls, internal protection logic, uninterruptible power supplies (UPS) units, and proprietary power-management architectures**. As a result, their behavior during BPS events such as fault-induced voltage disturbances, frequency excursions, oscillatory conditions, or system separations, may differ substantially from traditional expectations for load response. Recent events in both the Eastern Interconnection and ERCOT involving **simultaneous loss or rapid reduction of voltage-sensitive power electronic loads** have underscored the urgency of understanding and modeling these behaviors.

These shifts mirror the disruptive evolution of smaller-scale end-use loads noted in the Dynamic Load Modeling Technical Reference Document[1], where the introduction of variable-speed drives, electronically commutated motors, and consumer electronics introduced a growing fraction of electronically coupled load into the aggregate composition. However, the new class of loads differ in magnitude, speed of response, and grid impact by orders of magnitude, making the development of new modeling approaches essential for system planning and real-time operational studies.

[1] NERC Load Modeling Technical Reference

Need for Advanced Dynamic Modeling

As power-electronic-dominated loads grow in scale and diversity, the limitations of traditional load modeling—static ZIP models, aggregate induction motor models, or simplified electronic-load representations—become increasingly evident. The NERC Electric Vehicle Technical Reference Report[2] highlighted this need for newly emerging, converter-interfaced load classes whose performance is governed by internal control loops rather than electromechanical inertia.

Similarly, the NERC Large Loads Working Group (LLWG) *Characteristics and Risks of Emerging Large Loads* white paper[3] identifies numerous reliability risks driven directly by inadequate modeling of the large loads, including:

- Voltage and frequency ride-through uncertainty caused by internal protection or transfer-to-backup mechanisms.
- Fast real-power ramping, sometimes exceeding 1–2 pu/second during AI training transitions.
- Voltage-sensitive load reductions or trip-outs due to internal thresholds not coordinated with BPS protection practices.
- Converter-driven stability interactions with nearby inverter-based resources or series-compensated lines.
- Forced oscillations arising from periodic computational cycles or control interactions.
- Reactive power behavior that deviates from classical static ZIP assumptions, especially when large UPS systems, harmonic filters, or power factor correction stages are present.

Recent events demonstrate that large power electronic loads can behave similarly to distributed inverter-based resources with respect to:

- sensitivity to momentary voltage dips,
- sharp discontinuities in real and reactive demand,
- low short-circuit contribution,
- strong dependence on internal phase locked loop-type synchronization schemes, and
- the potential for group behavior leading to MW-scale coincident response.

Given these characteristics, modeling approaches for EV chargers, rooftop PV inverters, and electronically coupled end-use devices, such as positive-sequence dynamic models with block-based logic, provide a conceptual foundation but must be extended and adapted to reflect the vastly larger scale, operational patterns, and protection behaviors of computational loads.

Purpose and Scope of This Technical Reference Document

The purpose of this document is to serve as a technical foundation for developing, parameterizing, and validating a new dynamic load model for large power electronic loads. The following sections will provide more information on the below topics:

[2] https://www.nerc.com/globalassets/who-we-are/standing-committees/rstc/lmwg/ev_modeling_technical_reference_report.pdf
[3] https://www.nerc.com/globalassets/who-we-are/standing-committees/rstc/whitepaper-characteristics-and-risks-of-emerging-large-loads.pdf

- Develops an in-depth understanding of the characteristics of different load components in a data center and their different characteristics with material impact on the power system response to a disturbance
- Provides guidance on developing steady state models
- Provides guidance on parameterizing the PERC1 model
- Provides information on the considerations for EMT modeling
- Provides guidance on using data center models for standard, advanced and special reliability assessments

This document is intended for Transmission Planners, Planning Coordinators, Reliability Coordinators, manufacturers, consultants, software vendors, and other industry experts who require robust, accurate, and practical modeling approaches for system planning and operational studies.

Chapter 2: Data Center Design and Operation

To properly model data centers, an understanding of their design and operation is critical. This chapter covers overall data center design with a focus on the elements that impact power system models such as the power distribution system, backup power systems, cooling systems, and operational characteristics. This includes components like utility interfaces, transformers, Information Technology (IT) loads, UPS units, cooling loads, Battery Energy Storage Systems (BESS), generators, protection systems, and higher-level control systems.

In today's digital age, data centers are the backbone for much of the world's computational infrastructure. These are facilities that provide computing and storage capabilities to end-users, which could be the facility owner or leased to other clients. More traditional data centers such as enterprise, multi-tenant/colocation, cloud, or modular facilities provide compute to traditional business and cloud services. Meanwhile newer hyperscale and AI data centers such as shown in **Figure 2.1** are purpose built facilities that run vast amounts of internet infrastructure and provide compute for high-performance applications and AI training.

Figure 2.1: An image of a hyperscale data center[4]

Classification of Data centers

While there are many ways to differentiate the types of data centers, it is important to classify the data centers based on the operating model and based on the nature of use since that will help differentiate the key elements for modeling and studies.

Classification Based on Operating Model

Classification based on operating model[5] is shown in **Figure 2.2**. The first operating model type is where the end load owner also owns the data center. This type consists of two types, Enterprise and Hyperscale.

[4] https://datacenters.google/discover-more/photo-gallery/

[5] Bitterlin, Ian. Data Center Power Systems: A Practical Design Handbook (2025): 1-10.

- Enterprise data center- An enterprise data center is a physical facility designed specifically for a single organization to store, process, and manage its data and IT operations.
- Hyperscale data center- A hyperscale data centers are massive facilities owned by some of the largest technology companies in the world and designed to efficiently process and store enormous amounts of data, supporting cloud computing, AI, and large-scale digital applications.

The other type of data center is multi-tenant[6] data centers. These data centers typically serve more than one customer and could take multiple forms.

- Hosting data center - The facility owns all the infrastructure including the servers, and the customers lease computing capacity, storage and managed services. Managed services refer to support services provided by the facility owner to support the customer (software upgrades, hardware monitoring, and providing internet security).
- Wholesale data center- The customer has full ownership of the servers. This consists of three different types of ownership:
    - where the facility owns all the infrastructure including the UPS. The racks and every other downstream component are owned by the customer
    - where UPS is also owned by the customer
    - where some UPS will be owned by the facility owner and some will be owned by the customer (hybrid). In this hybrid type the customer owned UPSs could mostly be rack mounted UPS topology (Open Compute distributed design).

In these cases, the space, cooling and the power for the customers are provided by the facility and the end load owner maintains full operational control over all their equipment. The data center owner and operator are responsible for maintenance and facility management, but they are not privy of the details of what computational tasks are being run.

Classification based on Computation Type

The second classification for data centers is based on the type of end application supported by the data center. The classification of data centers based on this criterion is shown in **Figure 2.3.** Note that while there could be dedicated data centers to conduct each of these applications, but they could also be conducted in any of the operating models shown in **Figure 2.2**.

- **Cryptocurrency Mining:** These data centers are used for cryptocurrency mining applications.
- **AI Data Centers:** AI data centers are used to train large AI models such as large language models and run trained models for various applications. They are comprised of the same infrastructure as other data centers but typically have a much higher percentage of GPU or other advanced accelerator technologies for AI training. They could be used for AI training as well as AI inferencing applications.
- **Cloud Computing:** These data center provide physical and virtual infrastructure required for cloud computing.

  Enterprise Computing - Enterprise computing data centers are specialized facilities designed to support the IT operations of a single enterprise.

[6] Crosby, Chris, and Chris Curtis. "Hosting or Colocation Data Centers." *Data Center Handbook: Plan, Design, Build, and Operations of a Smart Data Center* (2021): 65-75.

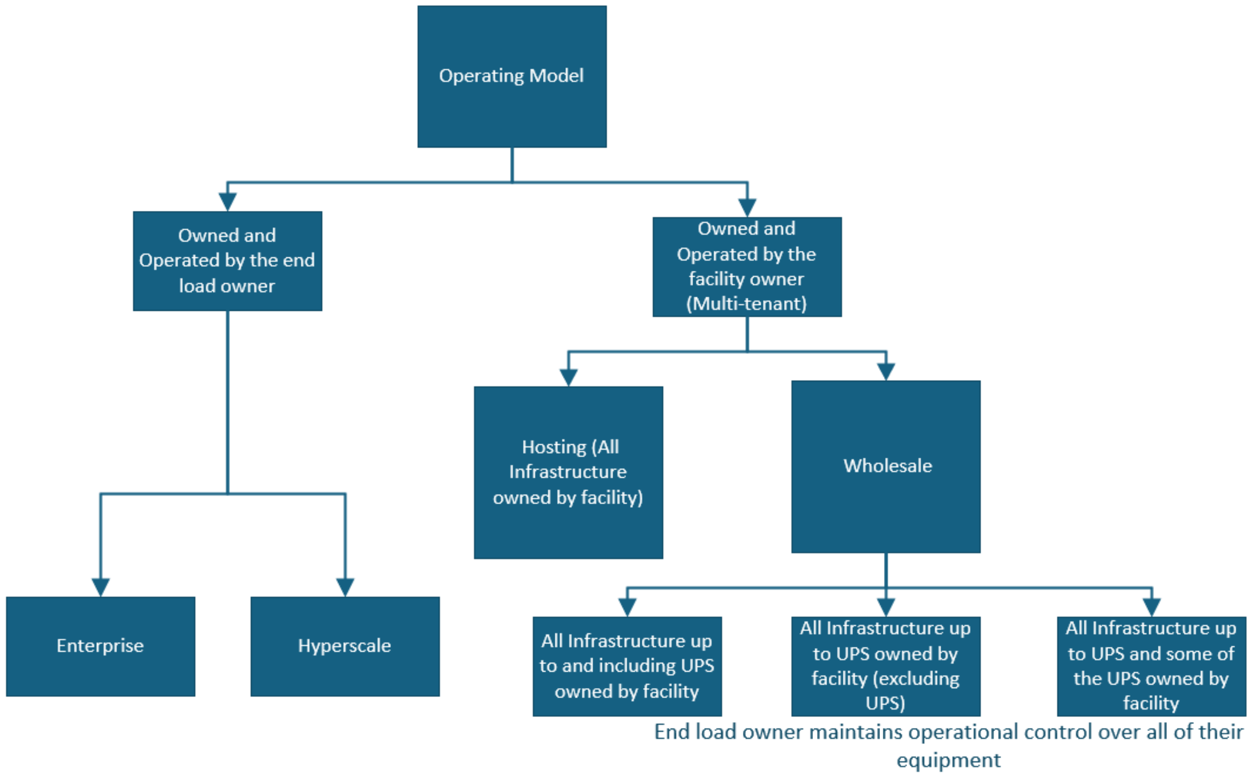


Figure 2.2: Classification based on the operating model

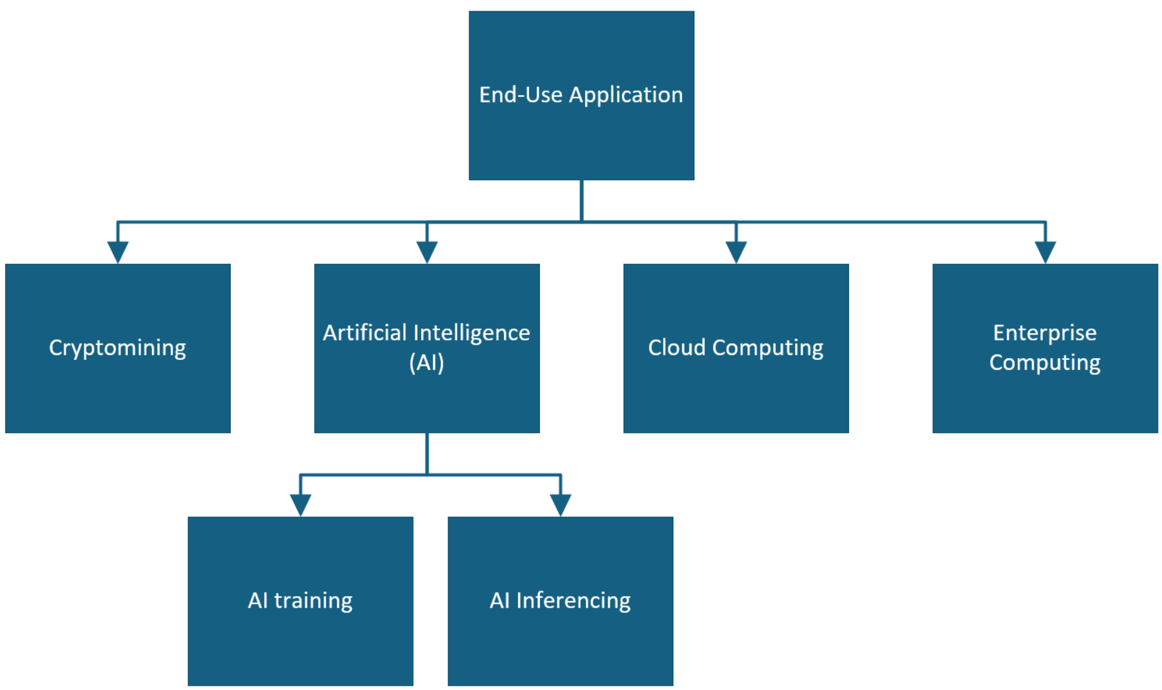


Figure 2.3: Classification based on the end-use application

Data Center Power System Architecture

A data center's design and subsystems are based on its end-use purpose and uptime requirements. Most data centers will have a similar set of subsystems, but their specific designs will vary. Most current data center designs are focused entirely on providing a high up time for computing and have no consideration for demand flexibility and grid resilience. A typical data center uptime requirement can range anywhere from 99% to 99.999% downtime means significant losses for businesses. Across this uptime spectrum emerges the concept of data center tiers of availability. However, some data centers such as those focusing on artificial intelligence (AI) training or high-performance computing may not have such high uptime requirements and have no redundant backup power capabilities to cover significant portion of the load.

System Overview

The general form of a data center electrical system is shown in **Figure 2.4**. In this single line diagram, the data center connects to the utility High Voltage Transmission System (>100 kV). Next the high voltage is converted to medium voltage (13.8 - 34.5 kV) by using a main power transformer. This voltage is finally converted to Low Voltage (< 415 V) through distribution transformers. Long-term backup power sources such as diesel generators are typically available in many Data centers. These sources power the data center if the grid supply is lost for a longer time duration. The switch between the long-term energy storage and grid supply is controlled by an Automatic Transfer Switch (ATS). The ATS does not typically allow long-term energy storage to operate synchronized to the grid.

The critical loads are supplied through UPS. If there are any short interruptions to the grid voltage, the UPS can fully serve the critical Load without interruption. If the power interruption duration goes beyond a certain limit, the load is transferred from the UPS to the Long-term energy storage. The data center also has other loads that are non-critical and these loads would lose the ability to function if main utility power supply is lost. However, the data center is designed to be able to operate safely without these non-critical loads for a certain period.

The design of the data center could involve including multiple redundancies at different levels to meet the power availability needs of the data center[7]. Availability of the data center can be enhanced by adding redundancies (e.g.- 2N+1, N+1, 2N) in the design by including one or many of the elements below and interconnecting them with multiple power flow paths. This redundancy can include redundant grid interconnection points and main power transformers, redundant distribution transformers, and redundant UPS units.

However, for the scope of this technical reference it is sufficient to be able to model the components that have an interplay with the grid in the period of interest (0-40 seconds). Not all components in this diagram, including redundance components and power flow paths, have a material impact on the grid response.

[7] Uptime Institute Tier Classification System - Uptime Institute

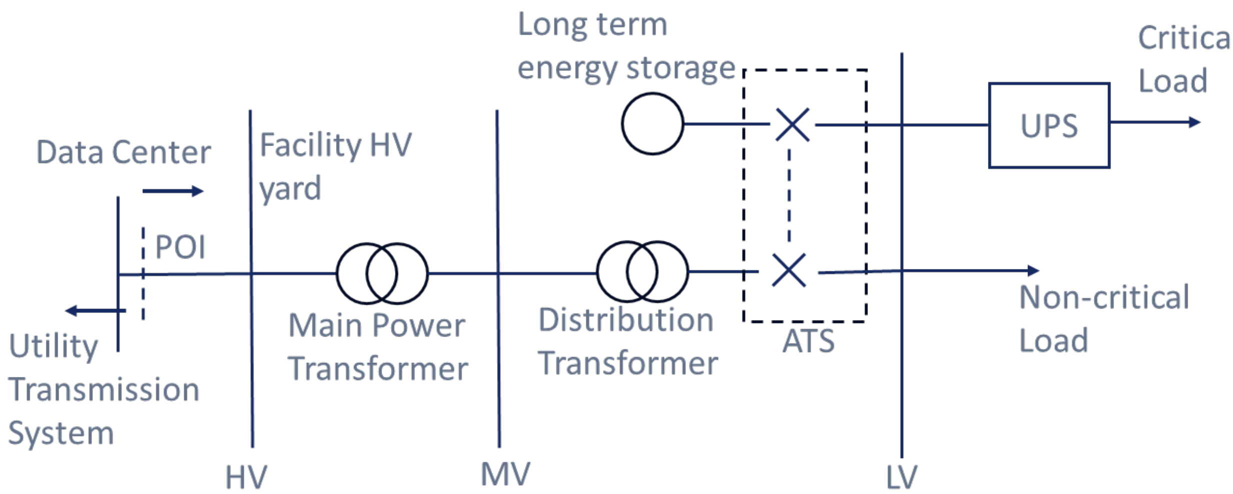


Figure 2.4: General electrical overview of a data center

Data Center Subsystems

The two main types of data center subsystems that collectively encompass all aspects of a data center's load. These are computational and auxiliary subsystems.

Computational Subsystems

Computational related subsystems or IT (Information Technology) load in a data center contains the equipment providing compute, storage, and networking functionalities.

- **Compute**: Compute infrastructure is the equipment that processes data and is generally comprised of equipment like Central Processing Units (CPUs), Graphic Processing Units (GPUs), and specialized accelerators such as Tensor Processing Units (TPUs).
- **Storage:** Storage infrastructure provides equipment for data storage such as hard drives.
- **Networking**: Networking infrastructure is equipment that connects servers within the data center and to the outside world.

The IT hardware that comprises computational subsystems inside a data center is voltage sensitive and is typically designed to meet the requirements provided in the Information Technology Industry Council (ITIC) curve. The ITIC curve as shown in **Figure 2.5.** The ITIC curve provides an AC voltage boundary that most IT hardware is designed to tolerate without experiencing unexpected shutdowns or malfunctions. The ITIC curve specifies that input an AC voltage below 0.7 pu is considered a dropout event where the system should survive for 20 ms and an over voltage event of 1.2 pu should survive for at least 3 ms. Typical IT equipment operates at ~400 V, so appropriate transformation of the MV supply from the substation needs to be incorporated into the design.

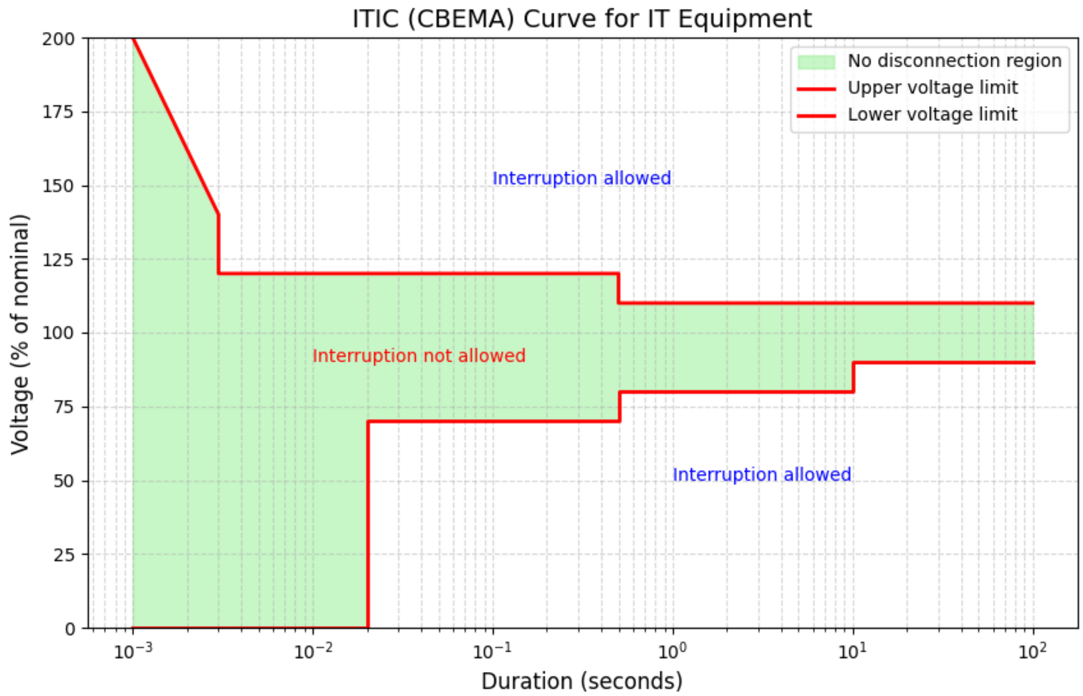


Figure 2.5 ITIC Curve[8]

Auxiliary Subsystems

Auxiliary subsystems or non-IT load in the data center handles power distribution, cooling and environmental controls, and other infrastructure like lighting and office power.

- **Power Distribution**: Infrastructure that handles power distribution and backup power needs within the data center.
- **Cooling and Environmental Controls**: Cooling and environmental infrastructure manages temperature and humidity to cool the IT load.
- **Other Infrastructure:** This equipment includes lighting, office equipment, and other necessary infrastructure to operate a data center etc. Based on the design of the data center a portion of these loads will be considered non-critical, and the rest of the loads will be considered critical.

Transfer Switches

An Automatic Transfer Switch (ATS) is an electromechanical device designed to provide an automatic transfer from one primary electrical source to secondary source as shown in **Figure 2.6**. This is typically a transfer from utility (primary) to generator (secondary) to provide emergency power to critical loads downstream of the ATS. This occurs when the primary source of power is lost and backup power is required and when the preferred source power is restored, the ATS will automatically transfer back.

Typical data center design requires maximum uptime, redundancy, and operational reliability such that multiple power sources are available to minimize or eliminate single points of failure in the electrical distribution system. Depending on uptime requirements, appropriate redundancies are implemented in the

[8] Graphic based on http://www.itic.org/resources/Oct2000Curve-UPDATED.doc

power distribution system feeding the IT and cooling loads. These redundancies facilitate concurrent maintainability and automatic fail over to alternate power feed to meet uptime requirements. The presence of redundancy is managed through ATS or static transfer switches (STS). More information on the ATS is provided in **Appendix B.**

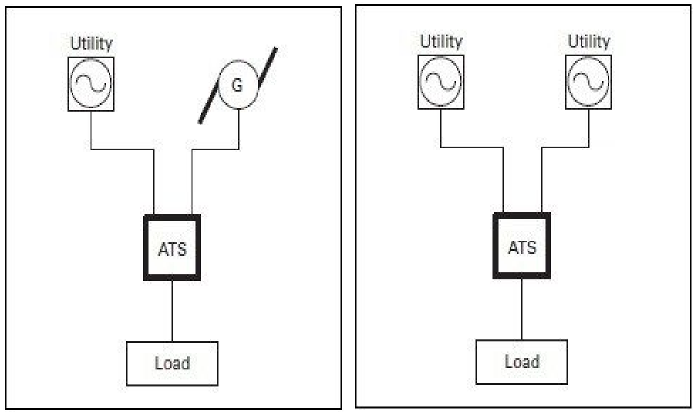


Figure 2.6: Common ATS Configurations

Backup Power Supply

The ATS will switch the power source between the grid and the long term back up power supply. One example of long-term storage is diesel generators. These are slow devices and require some start up time (>5 s). After startup, the load transfer must be done in a controlled and gradual manner to minimize impact on the lifetime of the generator. Additionally, once a generator starts, it is required to run it beyond a certain loading level above a minimum time duration to ensure the generator's lifetime is not negatively affected by phenomena such as wet stacking[9].

Due to these issues, the decision to start the generator is only taken after facing a utility power interruption that goes beyond the timeline of interest for power system stability studies (disturbance response) and does not need to be typically considered for stability studies.

Uninterruptible Power Supply (UPS)

The UPS unit serves the critical load of the data center and plays a key role in defining the response to grid disturbances. A UPS also includes short-term storage, that is sized to typically continue to serve the full load for multiple minutes. The minimum battery size will be constrained by the long-term storage startup and loading time, as well as the IT process emergency shutdown time. There are two main types of UPS units in use at present.

- **Double conversion UPS:** Centralized large UPS supporting a large portion of the facility. Provides AC output to PSE
- **DC UPS:** Decentralized rack-based UPS with DC output to PSUs

Double Conversion UPS

A double conversion, voltage and frequency independent (VFI) UPS takes the form shown in **Figure 2.7**. The double conversion UPS consists of a rectifier, battery converter, inverter, monitoring/operation control panel, digital logic, and communications. While the battery is added separately to the UPS, for the purpose of this technical reference it is assumed that the battery is an integral part of the UPS. These components collectively operate to provide continuous power the load on the output of the system. If the utility or

[9] Jabeck, Brian. "The impact of generator set underloading." *Caterpillar* (2014).

generator power is unavailable, the UPS will operate on its battery backup supply for a specified period. Should there be a fault condition on the output of the UPS or an internal failure, the UPS has an emergency bypass consisting of a static switch that can protect the load from an outage by transferring it to utility or generator power. Additionally, there will also be a manual bypass (Bypass switch) when the static transfer switch is unavailable.

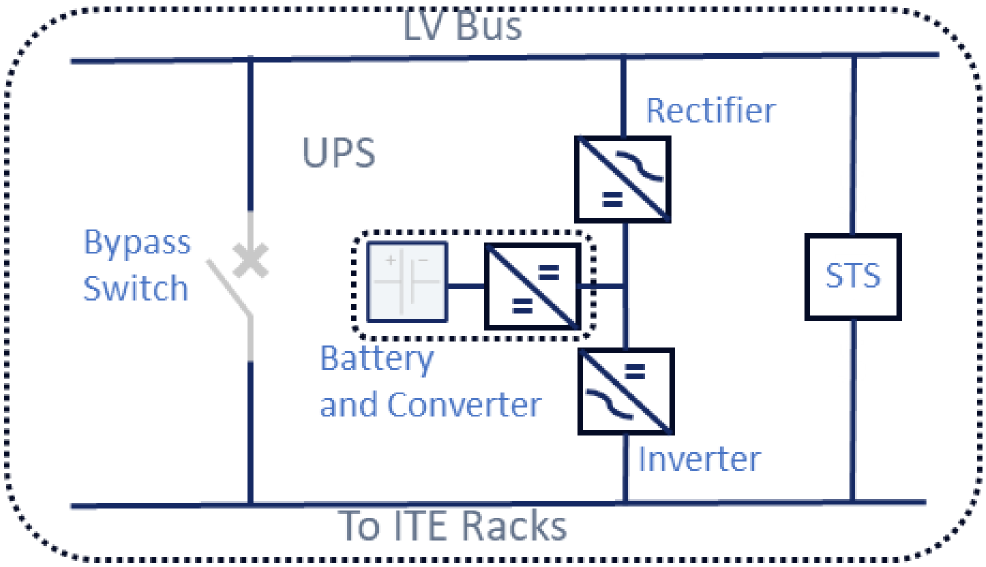


Figure 2.7: Functional overview of a double conversion UPS

Standard Modes of Operation

1. **Normal mode:** As shown in **Figure 2.8**, the main power flow path is LVAC -> Rectifier->Inverter-> End Load; power for the system is from the incoming utility to the rectifier circuit. The rectifier takes the incoming three phase AC power and converts it to DC using switching devices to produce a regulated DC voltage to the inverter. While operating on incoming AC the battery will be charged, if necessary, from the regulated rectifier output and through a DC-to-DC converter that matches the battery string voltage. The battery is always connected to the UPS and available to supply power for the inverter. Using the regulated DC output of the rectifier, the inverter will produce a three-phase AC output. The inverter uses high-speed switching to produce the regulated and filtered AC output to support the customer's load.

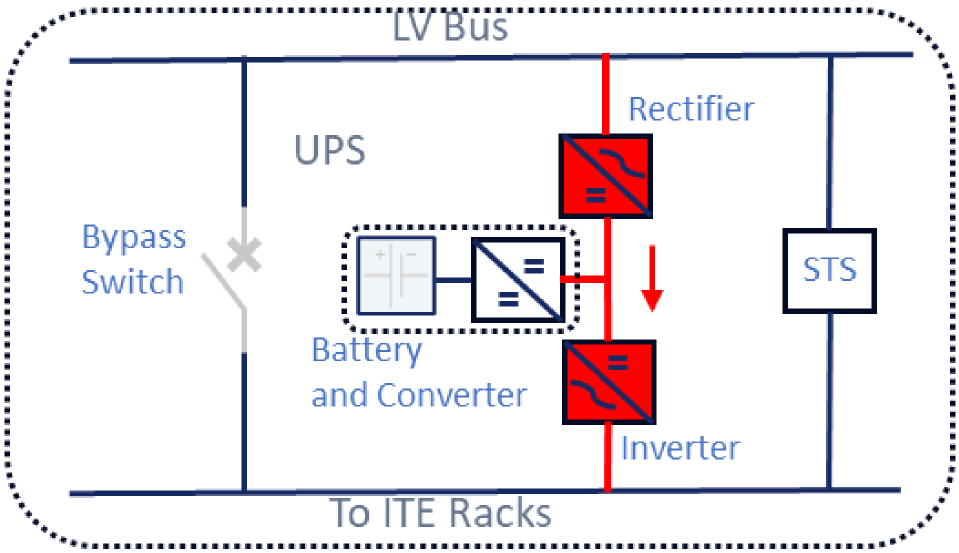


Figure 2.8: Power flow path in the normal mode

2. **Battery mode:** As shown in **Figure 2.9**, the main power flow path Battery->Inverter-> End Load; If the incoming utility power is interrupted or out of the input tolerance window the UPS will automatically switch to Battery mode operation. In the battery mode, the battery provides emergency DC power to the inverter to maintain UPS output voltage. If the input power does not return or is not within acceptable levels, the battery will continue to discharge in support of the inverter. Unless input power returns to within the specified levels the UPS will alarm that it will shut down as the battery levels continue to get lower. If the bypass source is available the system will transfer to bypass, otherwise it will shut down when the battery reaches a DC undervoltage condition.

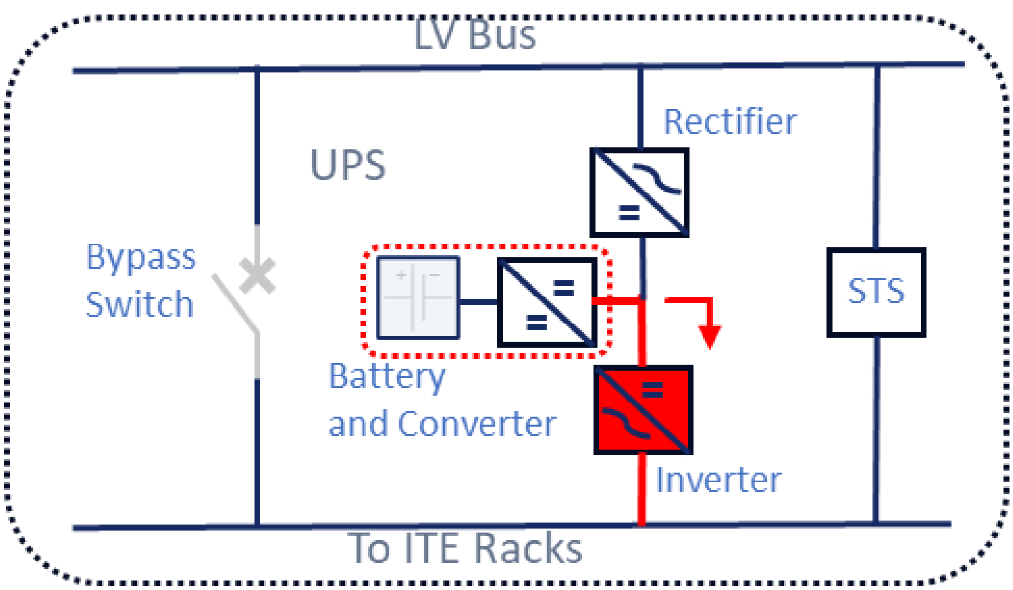


Figure 2.9: Power flow path in the battery mode

3. Eco-mode: As shown in **Figure 2.10**, the main power flow path LVAC -> STS-> End Load; This refers to the mode of operation where the power flow path is routed with the Static Transfer Switch. The main reason to do so is to increase power distribution efficiency by eliminating associated with the normal mode. If a degradation of the utility power quality is detected the eco-mode is programmed to change to double conversion mode, or battery mode as shown in Figure 10. Some OEMs continue to keep the Rectifier synced to the grid in the eco-mode to allow for fast transition to normal mode if there is a disturbance to the input power quality.[10,11]
4. Bypass – This refers to when the IT Load is directly supplied by the utility supply by closing a bypass switch. Typically used for UPS maintenance, or when there is a UPS failure.

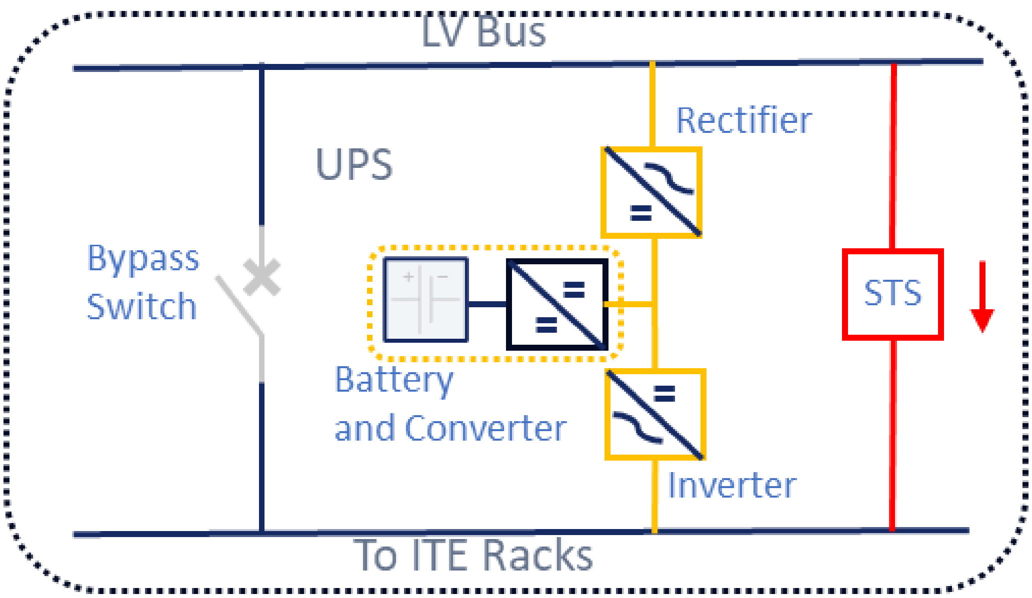


Figure 2.10: Power flow path in the Eco-mode

Interlink between UPS Pre-disturbance Operational Mode and disturbance response

The UPS operation mode at the point of the disturbance will determine the model parameters that need to be used for the simulation. The model or the corresponding parameters could change significantly based on whether the UPS will be in normal mode, bypass mode or eco-mode. The state transition diagram pertaining to system states associated with disturbance response is show in **Figure 2.11**.

- Normal mode: The grid sees a load supplied by a UPS. Typical performance for a grid fault is defined by the UPS characteristics and selected parameters.
- Battery mode- The grid does not see a load since the load is fully isolated from the grid. While not shown here the same applies when supplied using long term storage.
    - Normal mode to Battery mode- When there is a significant grid disturbance at which point the rectifier is unable to operate safely, then the system transitions to the battery mode. A UPS in eco-mode will transition to normal mode if the utility power quality decreases beyond a pre-set

[10] Paananen, Janne. *White Paper: Eaton Energy Saver System: Facts and Principles*
[11] Schneider Electric. White Paper: *eConversion*

limit. These limits are selected to minimize the impact of the adverse power quality on the sensitive end load and therefore the bandwidth for the mode will be much tighter than the normal mode.

- Eco-mode: When a UPS is on eco-mode the response to a grid fault could vary since the eco-mode has separate voltage band of operation. Anytime the voltage is beyond this lower limit, the UPS will transition to Normal or Battery mode. The transition is very fast and could occur in less than 2 ms.
    - Slight voltage dip - If a voltage disturbance starts with the voltage dipping to 0.91. Assuming an eco-mode band of 0.95-1.05 pu, then in most cases the UPS will transition to the normal (double conversion mode). The grid will see a transient in a time less than 2 ms – and therefore the power as seen from the grid will stay constant.
    - Significant voltage dip – If the voltage dip is higher (say 0.7 pu), then the UPS could go to normal mode first and then go to the battery mode, or the UPS could directly go to the battery mode. It is important to note that since the bandwidth of the voltage in eco-mode is much less than in normal mode, a UPS in eco-mode could have faster load rejection. The parameters for reconnection and ceasing could also be different from normal mode.
- Bypass mode – The grid sees a load supplied by a SMPS. Typically, performance for a grid fault is defined by the ITIC curve.

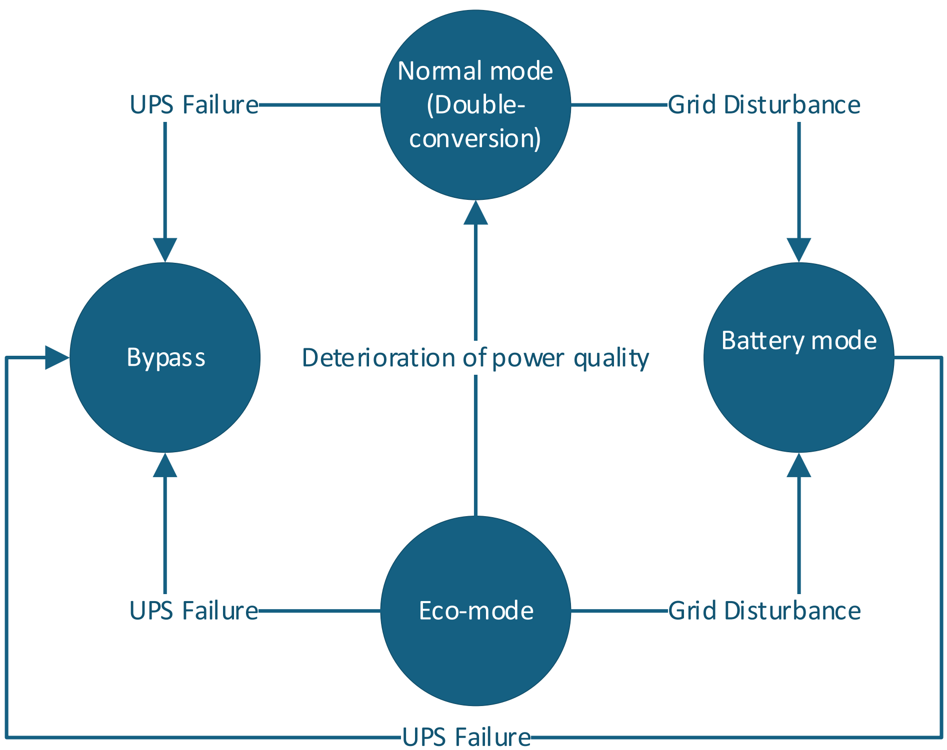


Figure 2.11: UPS state transition diagram

Single Conversion DC UPS

The other main static UPS architecture currently in use was introduced by facebook Inc.[12], used by many hyperscalers, and standardized through a data center association called the Open Compute Project.[13] This architecture features a distributed single conversion UPS topology mostly geared towards serving the unique needs of the hyperscalers. The typical structure of the DC UPS is shown in **Figure 2.12**.

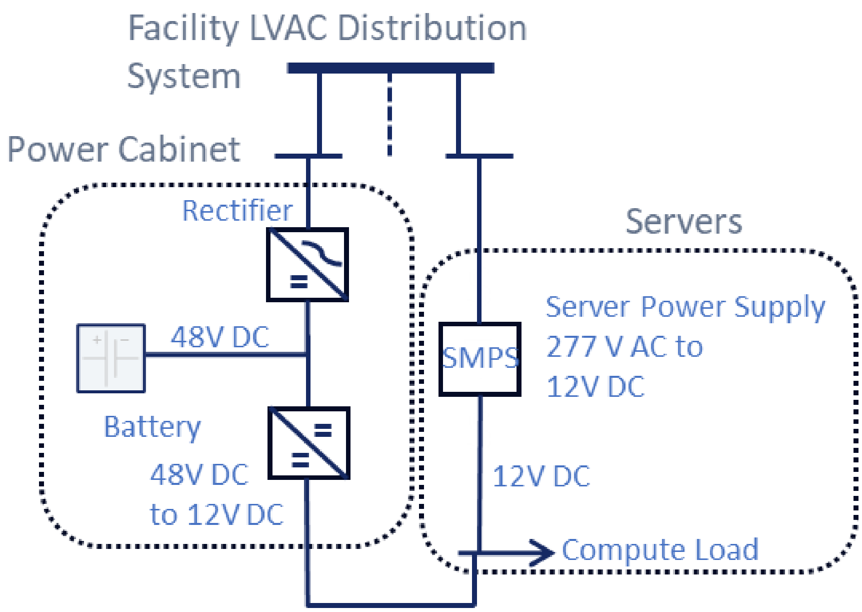


Figure 2.12: Structure of the DC UPS

Operation Modes

- In the normal mode power is directly supplied through the path shown in **Figure 2.13**. The power is routed directly to the Servers and the Servers' SMPS converts to power to 12V DC for the consumption of the server loads.

[12] Megdiche, Malik, Jay Park, and Sarah Hanna. "Data Center Electrical Design." *Data Center Handbook: Plan, Design, Build, and Operations of a Smart Data Center* (2021): 441-481.
[13] Opencompute Website - https://www.opencompute.org/

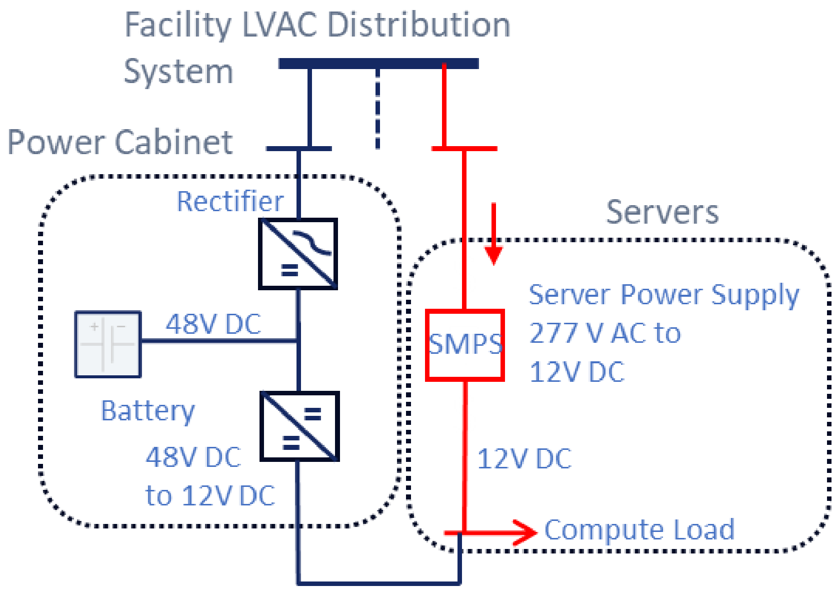


Figure 2.13: Power flow path for normal operation

- In battery mode power is supplied from the battery with the 48V DC converted to 12V DC level through a buck converter as shown in **Figure 2.14**.

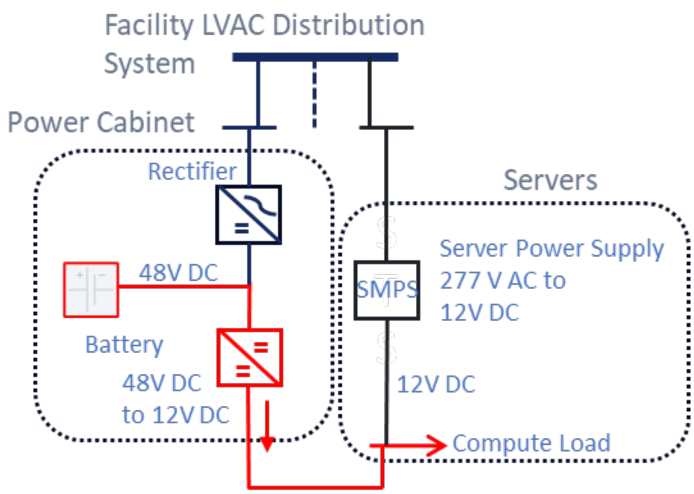


Figure 2.14: Power flow path for the battery mode

Note that the UPS will have other power flow paths, such as when the batteries are charging after a backup event. There could be a post-disturbance because of this. For example, if a significant amount of battery energy that is consumed at the time of disturbance could cause an increase in power consumption in a transient response timeline as seen from the grid. However, this should only affect the post fault power flow levels in a time that is longer than the one of interest for power system stability studies. Notwithstanding, there might be a study that could require accurate capture of these types of responses.

Cooling Systems

The cooling system in data centers comprises pumps, chillers, air handling units, coolant distribution units, which are LV loads (~400-480V). Many of these have variable frequency drives. In most data centers the IT and cooling loads are on separate power distribution systems. Appropriate backup power systems are put in place for critical cooling loads to meet the uptime requirements of the data center. Some of the cooling loads might be non-critical and therefore served with direct utility supply. In recent times, cooling systems in data centers are being considered for load flexibility.[14] More information on modeling flexibility is provided in **Appendix D**.

Cooling subsystems can be categorized into several types, each with distinct electrical and thermal characteristics:

- Air-Based Cooling: Traditional systems like Computer Room Air Conditioning (CRAC) units and Computer Room Air Handling (CRAH) units use fans and compressors to circulate cold air through raised floors
- or hot/cold aisle containment setups. These are common in legacy data centers and consume power primarily through fan motors and refrigeration cycles. Electrical characteristics include compressor starting currents and Variable Frequency Drive (VFD)-driven fans, which can introduce 5th and 7th order harmonics.[15]
- Liquid-Based Cooling: Emerging for high-density AI racks, including direct-to-chip cooling, immersion cooling (single-phase or two-phase), and rear-door heat exchangers. These systems use pumps to circulate coolants (e.g., water, dielectric fluids) and offer higher efficiency (lower PUE) but introduce risks like leaks, necessitating redundant pumps and sensors. Liquid cooling can reduce energy use by up to 40% compared to air systems [16]. At rack power densities approaching 1 MW, servers are expected to transition predominantly to liquid cooling to manage thermal loads effectively.[17]
- Hybrid and Free Cooling: Combines air and liquid methods with economizers that leverage ambient air or evaporative cooling during favorable weather, reducing mechanical cooling needs. Control logic switches modes based on temperature/humidity thresholds, as per ASHRAE thermal guidelines recommending inlet air temperatures up to 27°C (80.6°F) for energy savings.[18]

From a power system perspective, cooling loads are typically low-voltage (400-480V) and can exhibit nonlinear behavior due to VFDs, leading to total harmonic distortion (THD) levels that may exceed IEEE 519 limits if unmitigated. Harmonics from VFDs can cause overheating in transformers and neutral conductors, necessitating filters or harmonic mitigating transformers. In grid interaction studies, cooling systems offer flexibility potential: for instance, temporarily raising setpoints or curtailing non-critical cooling can provide 10-20% load reduction during peak demand, supporting grid stability without impacting on IT uptime.[19] More information on typical cooling loads is included in the NERC Load Modeling Technical Reference.[20]

Protection and Control Systems

Protection and control systems in data centers are critical for safeguarding electrical infrastructure, ensuring uninterrupted operation, and mitigating risks from internal faults or grid disturbances. These systems detect anomalies, isolate faults, and coordinate responses to maintain power quality and reliability. As data centers

[14] Program 170: Grid-Edge Customer Technologies | Product Abstract
[15] https://www.transcoil.com/wp-content/uploads/2017/12/Harmonic-Distortion-in-Data-Centers.pdf
[16] https://newsletter.semianalysis.com/p/datacenter-anatomy-part-2-cooling-systems
[17] https://cloud.google.com/blog/topics/systems/enabling-1-mw-it-racks-and-liquid-cooling-at-ocp-emea-summit
[18] https://dallas-ashrae.org/images/meeting/041625/the_ashrae_thermal_guidelines_for_data_centers_____past__present_and_future.pdf
[19] https://www.aceee.org/sites/default/files/pdfs/opportunities_to_use_energy_efficiency_and_demand_flexibility_to_reduce_data_center_energy_use_and_peak_demand.pdf
[20] See NERC Dynamic Load Modeling Technical Reference

grow in scale and integrate with inverter-based resources, these systems must address increasing complexities in stability and cybersecurity.

Protection and control subsystems can be categorized into several types, each with distinct functions and characteristics:

- Relay-Based Protection Systems: These employ digital relays for real-time monitoring and rapid response to electrical anomalies. Common implementations include over/under-voltage (UV/OV), over/under-frequency (UF/OF), and rate-of-change-of-frequency (ROCOF) relays that trip circuits to prevent equipment damage during events like voltage sags or frequency excursions. Differential relays protect transformers and buses by comparing current inflows and outflows, while directional overcurrent relays ensure selective fault clearing in radial or meshed distributions. In 2025 practices, multifunction relays like those from SEL or Siemens integrate arc-flash detection, reducing clearing times to under 50 ms for safety. Surge arresters and transient voltage surge suppressors (TVSS) at the service entrance and PDUs handle lightning or switching transients, rated up to 400 kA per phase.
- Redundancy and Transfer Systems: To achieve high uptime (e.g., Tier IV's 99.995%), automatic transfer switches (ATS) and static transfer switches (STS) provide seamless source switching between utility feeds, generators, UPS, or BESS. ATS uses mechanical contactors for transfers in 10-30 cycles, while STS employs silicon-controlled rectifiers (SCRs) for sub-cycle (under 4 ms) shifts, minimizing IT disruptions. Modern designs incorporate sync-check relays to verify phase alignment before closing, preventing out-of-phase transfers that could damage loads. In large-scale facilities, these integrate with breaker-based schemes for N+1 or 2N redundancy, allowing maintenance without downtime.
- Cyber-Physical Security Integration: With increasing digitization, protection systems incorporate cybersecurity features to counter threats like unauthorized access or malware.

Higher-level control systems, including supervisory control and data acquisition (SCADA), energy management systems (EMS), and building automation systems (BAS), provide oversight for optimized operations. SCADA aggregates data from relays and sensors for real-time visualization and alarming, using protocols like DNP3 or Modbus for remote control of breakers and DERs. EMS coordinate power flows, dispatching generators or BESS for load balancing and demand response, often with predictive algorithms to anticipate peaks.

From a power system perspective, protection operates across low-voltage (480V) distributions for IT loads and medium-voltage (13.8-34.5 kV) utility interfaces, ensuring compliance with ITIC curves for voltage tolerance. While most of these systems will not have an impact on defining the response of the data center to a grid disturbance, past events have shown that there could be some instances where the Control and Protection systems could play a key role[21].

[21] Incident Review: Considering Simultaneous Voltage-Sensitive Load Reductions

Chapter 3: Modeling Data Centers for Power System Studies

This chapter shares information on data center load models that can be used for different types of studies while the next chapter provides a methodology to select the appropriate studies and corresponding models to comprehensively assess the impact of Data Centers.

As shown in **Figure 2.1**, the applied model should be carefully selected to meet the needs of the study of interest. The practitioners can select from steady state, dynamic, electromagnetic transient and short circuit studies. Once the study type is selected, next the practitioner needs to select an appropriate model to use for the study of interest. Each section of this chapter will include the methods that can be employed to model the data centers for the study of interest. Note that for a given use case there might be a requirement to conduct studies in a certain logical order. A method to identify the order of the studies is detailed in Chapter 4.

Selecting the granularity of the model

- Use engineering judgement on what model fidelity is appropriate for the application of interest

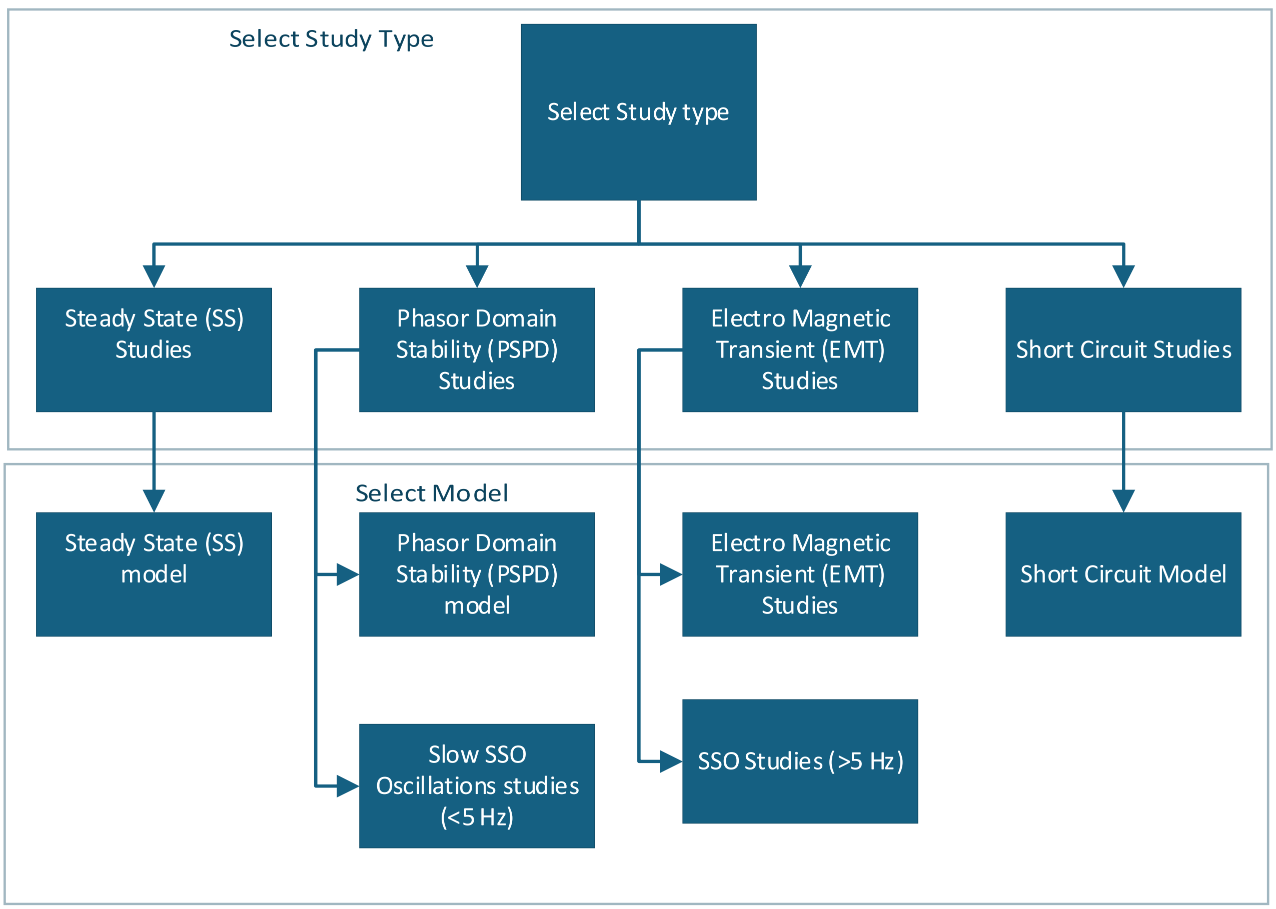


Figure 3.1: Selection of model based on study of interest

Steady State Studies

Modeling the steady state behavior in power flow studies is the typical starting point for any analysis. The below section shares more information on building a power flow model, while a typical application is provided in the **Appendix F**. Engineering judgment must be exercised to decide how the data center load is represented in the power flow studies.

Detailed Power flow Modeling

Detailed Power Flow Modeling is important to evaluate the impact of data center load on the grid. The modeling will include the power system components and their controls down to the MV level, as well as an aggregate representation of the Power Distribution and the Data Center End Load. A detailed model for the data center could take the form of **Figure 3.2**.

If there is material impact from the transmission lines from the circuit connecting the rest of the system to the MV bus, those must also be represented in the model. In addition, if there is significant compensation installed at the MV bus – that should be also included in the model. The aggregate representation of the distribution feeder is next included in the model. If a modular distribution software representation is used, the rest of the models including the distribution feeder can be organized as different components under one load module.

In the provided example, it is assumed that there are two markedly different dynamic responses from the materially significant computation loads, and therefore the computation load is split into two loads. This example includes significant noncomputational loads, those are also represented in the model. The VFD driven cooling load and the chiller motor load are therefore separately represented in the model. The portion of loads outside the computational and cooling is assumed to be negligible for the study of interest. The distribution representation requires model aggregation and a standard method[22] can be used for this purpose. It is recommended to refer to the NERC Load modeling technical reference for more details on representing noncomputational loads such as cooling, lighting and small power.

Modeling the Cooling Load

Power usage effectiveness (PUE) is a ratio that describes how efficiently a data center uses energy: it represents how much total energy is consumed by a data center relative to the energy consumed by computing equipment. Many conventional data centers use evaporative cooling, and achieve PUE below 1.1, which means that the cooling load is less than 10% of the total load. PUE is dependent on climate where data center is located and ambient conditions, a data center in dry climate in the middle of the winter will have much lower PUE than a data center in humid area in the middle of the summer. Newer Artificial Intelligence (AI) and High-Performance Computing (HPC) data centers require liquid cooling because of high density computing. Environmental sustainability considerations also drive the need for liquid cooling to reduce water consumption by evaporative cooling. Data centers with closed cycle liquid cooling can have PUE above 1.3, which means that the cooling load can be as high 25 to 30% of the total load.

If explicit information for the cooling load is unavailable It is possible to use the data center power usage effectiveness (PUE) to approximate the total amount of cooling load since. PUE is defined as:

$$\text{PUE} = 1 + (\text{Non IT Load})/(\text{IT Load})$$

If the PUE is 1.3, that would mean that $(\text{Non IT Load})/(\text{IT Load})$ ratio is 0.3. For example, if the IT Load is 1000 MW, the total cooling load will then be 300 MW. However, this approach needs to be used judiciously

[22] Muljadi, E., et al. "Equivalencing the collector system of a large wind power plant." 2006 IEEE Power Engineering Society General Meeting. IEEE, 2006.

noting that cooling load is based on average energy usage, highly dependent on internal (facility design) and external (weather) factors.

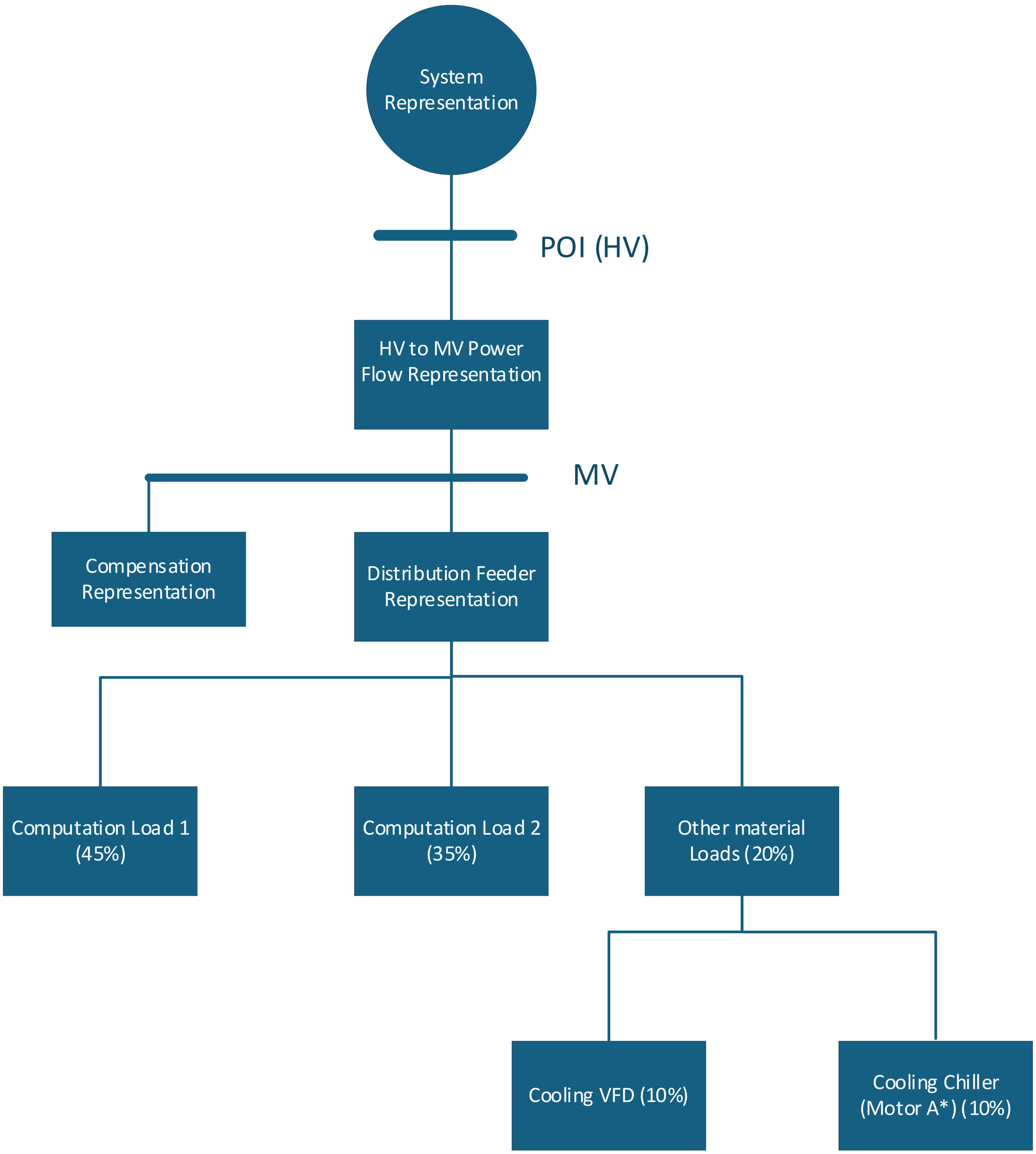


Figure 3.2: Data Center Detailed Load Representation

A Use case For Detailed Load Modeling

For detailed power flow modeling NERC LMWG recommends the following practice for representing large data center loads in power flow base cases, as illustrated **in Figure 3.3**:

- Represent HV to MV transformers explicitly in power flow base cases

    - Transformer model to Include tap changer controls if applicable
    - Individual transformer modeling is preferred rather than aggregation
- Model data center loads at MV load buses
    - Default power factor of 0.99 to 1.0 (Q=0), unless a customer specifies a different power factor and provides technical justification
    - Represent shunt reactive devices at high and medium voltage if applicable
    - If the facility consists of data center loads that are significantly different in their dynamic characteristics, it is important to model different types of data centers separately so that these different dynamic characteristics can be reflected in the corresponding positive sequence dynamic models (e.g. multi-tenant data centers with different physical UPS vendors and technologies)
    - If there are other commercial loads (such as cooling load) connected to MV bus, represent them as separate loads where appropriate (use engineering judgement to decide on the required extent of separation)
    - Use appropriate load type identifiers with data center records to link with modular CMLD model definitions (see dynamic model section)

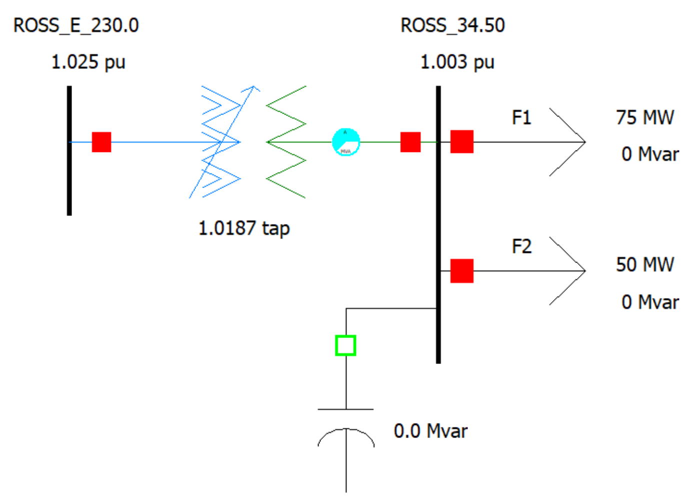


Figure 3.3: Illustration of recommended detailed power flow modeling approach for large data center loads

Modeling Considerations

- A transmission system connected to data centers typically has a dedicated high voltage substation. For example, an interconnecting utility could own and operate the high to medium voltage transformer (e.g. 230/34.5-kV or 115/13.8-kV), and data center customers will interconnect at medium voltage (typically 13.8-V or 34.5-kV). In urban developments, several data center customers can interconnect at the same medium voltage substation. In some cases, other types of customers can connect at a medium voltage substation, such as a distribution center or commercial office park. The recommended modeling approach is aligned with ownership demarcation between an interconnecting utility and data centers.

- As discussed earlier, large data centers usually deploy modular approaches featuring fully integrated power, cooling, and IT infrastructure. IT (computing and networking) and cooling are the largest end-uses in a data center. A power transformer steps voltage from medium voltage (34.5-kV, 13.8-kV) down to low voltage (e.g. 480V) where electrical end-uses are connected. These transformers have typical 6% impedance; therefore, reactive power losses are very small.
- Computing and networking equipment is usually connected via power electronic interface which has high power factor, close to unity. Most of the cooling equipment components (chillers, fans, pumps) are also connected via VFDs with active front end rectifiers. Therefore, typical power factor for a data center, as seen at medium voltage bus, is expected to be 0.99 or higher.
- Data center load may be involved in interconnecting utility's UFLS, UVLS, or RAS programs. Contingency analysis tools should have capabilities to represent RAS actions, including disconnecting entire load or scaling down the load. In this regard a detailed steady state load representation will provide more flexibility to simulate realistic scenarios.

Phasor Domain Stability Studies

Typically, after ensuring adequate performance for power flow studies, the next step is to study transient stability of the system when operating with the data center loads. This has two portions to it, the typical Positive-sequence phasor-domain (PSPD) studies and the new use case specific to AI training when there is a need to model impact of slow forced oscillations emanating from AI training.

Positive Sequence Phasor Domain Modeling of Data Centers

The growing concentration of large, converter-dominated data centers has created a renewed need to understand how such facilities influence bulk power system stability. Modern data-center electrical architectures rely heavily on uninterruptible power supplies, rectifier systems, and electronically controlled cooling equipment, all of which behave differently from traditional induction-motor-based loads when subjected to system disturbances. As these facilities continue to expand in size and number, their collective response to voltage and frequency events has become a significant factor in system-level planning.

A reasonable positive-sequence representation captures the essential balanced behavior of the load and provides a practical means of evaluating how significant new load types interact with generators, transmission networks, and protection systems. The Power Electronic Reconnection and Ceasing (PERC) model[23] was developed to represent the aggregate behavior of power-electronic data-center loads, including their voltage-dependent real and reactive power characteristics, current-limiting behavior, as well as their ride-through, ceasing, and reconnection actions.

For emerging large loads such as data centers, the purpose of PSPD modeling is to represent the aspects of load behavior that materially influence system stability—including active- and reactive-power control responses, ride-through and disconnection behavior, and restoration or reconnection dynamics—while maintaining computational feasibility for large interconnected system studies.

Parameterizing the PERC1[24] model requires careful consideration of the facility's electrical design, protection settings, and operational characteristics. This document identifies the data needed to populate these parameters—including total load composition, UPS and cooling configurations, transformer and

[23] J. Weber, "Power Electronic Reconnecting and Ceasing Load Model", NERC Load Modeling Task Force Webinar November 18, 2025, [online] https://www.powerworld.com/files/Power-Electronic-Reconnecting-and-Ceasing-PERC1-Load-Model.pdf

[24] PowerWorld, "Power Electronic Reconnecting and Ceasing Load Model", https://powerworld.com/WebHelp/#TransientModels_HTML/Load%20Characteristic%20PERC1.htm

collector-system characteristics, reactive-device settings, and voltage and frequency thresholds for transfer or disconnection. It also emphasizes the use of site-specific ride-through settings, timing delays, reconnection requirements, and measured disturbance data to ensure that the model reflects the facility's actual behavior. Collectively, these parameters determine how the modeled load interacts with system and impacts the bulk power system stability

Applicability of PSPD in Transmission Planning

Positive-sequence phasor domain modeling is advised when transmission planning studies focus on bulk system dynamics that occur below approximately 10 Hz. These studies examine slower, balanced three-phase phenomena such as transient stability, voltage recovery, frequency response, and oscillations that affect large portions of the interconnected system.[25]

PSPD tools are designed for these applications because they efficiently represent wide-area dynamics while maintaining manageable computational requirements.[26] Within this frequency range, phasor models can capture the outer-loop control behavior of power-electronic-driven loads, including active-power control, frequency droop, power-factor or voltage control, and ride-through logic, making them suitable for representing the system-level impacts of large loads such as data centers. These models are also effective in studying load disconnection and reconnection behavior, which can influence voltage and frequency stability following disturbances. Phenomena involving fast converter controls, sub synchronous oscillations, harmonic interactions, or switching transients fall outside the phasor domain and instead require electromagnetic transient (EMT) simulation.

Practical Use Cases of Phasor-Domain Modeling for Utilities

Utilities use phasor-domain models to perform bulk-system transient and short-term dynamic assessments, particularly for system-wide evaluations such as those required under NERC TPL-001. These studies allow planners to:

- Represent large, aggregated loads—including data centers—in a manner suitable for interconnection-wide simulations, where detailed device-level modeling would be impractical.
- Assess disturbance behavior, including the effects of voltage dips, frequency deviations, and the resulting ride-through, ceasing, and reconnection actions (e.g., as captured by the PERC1 model). These studies help evaluate risks related to over-voltage, over-frequency, and transient stability.
- Examine voltage-recovery performance, especially in areas prone to slow recovery due to constant-power load characteristics or regions where rapid reconnection of large loads may influence post-disturbance voltage behavior.
- Evaluate stability margins, such as damping of local and inter-area oscillations, overall voltage-recovery capability, and the system response to both load shedding and load restoration.
- Develop and test ride-through criteria for large converter-dominated loads. When utilities need to establish appropriate voltage- or frequency-ride-through requirements, dedicated phasor-domain studies can be commissioned to identify criteria that best support bulk-system stability

Requirements of a PSPD Model

- Represent the facility in a positive-sequence framework appropriate for balanced bulk-system studies.

[25] L.Sundaresh, P.Mitra, "Impact of Large Load Disconnection on System Stability". CIGRE Grid of the future conference, 2024
[26] P. Mitra, D. Ramasubramanian and A. Gaikwad, "Impact of Load Modeling on Power System Oscillations," *2022 IEEE Power & Energy Society General Meeting (PESGM)*, Denver, CO, USA, 2022, pp. 1-5, doi: 10.1109/PESGM48719.2022.9917087

- **Justification:** Bulk-system dynamic studies typically use positive-sequence phasor-domain (PSPD) simulators, which assume balanced three-phase conditions and focus on system behavior below approximately 10 Hz. These tools are designed to capture slow electromechanical dynamics relevant to transmission-level analyses.

- Be able to represent the facility-wide aggregate response of by aggregation of internal components into an equivalent representation suited to the study objective.
    - **Justification:** Aggregating devices reduces computational complexity while preserving the facility's dominant dynamic characteristics. The appropriate level of aggregation depends on the mix of internal components, their interactions, and the granularity required by the study.
- Initialize at the correct operating point consistent with the power-flow case and return to a physically realistic steady state following disturbances.
    - **Justification:** Accurate initialization and proper tuning ensure that the model begins simulations from valid operating conditions and settles to a stable post-disturbance equilibrium, which is essential for meaningful dynamic-study results.
- Limit the modeled dynamic bandwidth to phenomena below roughly 10 Hz, omitting high-frequency switching and harmonic behavior.
    - **Justification:** PSPD simulators intentionally exclude fast electromagnetic and switching dynamics because they are designed for slower electromechanical behavior. Higher-frequency effects require electromagnetic transient (EMT) modeling.
- Explicitly represent control loops with bandwidths between approximately 0.05 Hz and 10 Hz, including:
    - active-power control
    - frequency droop
    - reactive-power, power-factor, or voltage-control modes
    - ride-through and other logical control actions
    - **Justification:** Controls operating in this bandwidth influence bulk-system frequency, voltage recovery, and stability. PSPD models should include these outer-loop controls and logic, while much faster inner loops are generally simplified or omitted.
- Include voltage-ride-through (VRT), frequency-ride-through (FRT), and disconnection logic that reflects actual protection and control behavior.
    - **Justification:** Large converter-based facilities may trip, block, or change operating mode during normally cleared faults. Incorporating realistic ride-through and protection logic improves the fidelity of simulations under disturbed conditions.
- Represent ramp-rate limits and reconnection behavior relevant to restoration and post-disturbance recovery.
    - **Justification:** Ramp-rate constraints and reconnection sequences affect how a facility contributes to system recovery. These behaviors should be explicitly implemented, including limits on active-power reference changes when applicable.
- Ensure numerical stability and robustness, including appropriate time-step selection and avoidance of ideal step changes.

   - **Justification:** Numerical stability is improved by choosing a simulation time step small relative to the smallest model time constant, verifying stable flat-run behavior, and using filtered or gradual transitions instead of instantaneous changes.

- Document assumptions, limitations, parameter ranges, and configuration guidance in a releasable user guide.

   - **Justification:** Clear documentation—including parameter descriptions, valid ranges, modeling assumptions, and configuration guidance—supports correct parameterization, reproducibility, and appropriate use of the model.

Selecting the Appropriate PSPD Model and Corresponding Parameters

Based on Chapter 2, the response of a data center could vary not just based on the hardware and topology but also based on operational mode. The ideal case is using a perfectly parameterized white box model of the data center. The next best option is to use a perfectly parameterized black box model (User Defined Model (UDM)). The next best option is to use an approximately parameterized generic model. This could be an option to study future scenarios- where the nature of the data center instead of its exact parameters are known.

Assuming a UDM is unavailable, a framework for selecting the appropriate model or parameters to represent the Data Center computational load is shown in **Figure 3.4**. If the computational load is directly connected to the grid, then the parameters selected should correspond to the ITIC Curve. Theoretically, even if the facility has a UPS, a computational load could be directly connected to the grid, even though the probability of this occurring is negligible.

If the computational load is supplied by a UPS, then the model parameters for the generic model will have to be selected for each relevant setup shown in Figure 18. It is important to note that a significant portion of data centers operate on what is known as the eco-mode (ESS) and the effective parameters for this mode could be significantly different from the parameters when it operates on the double conversion mode. Additionally, some AI and crypto mining data centers have operated directed connected to the grid and without UPS, and those data centers can still be modeled using a generic model assuming an appropriate set of parameters are selected in the model.

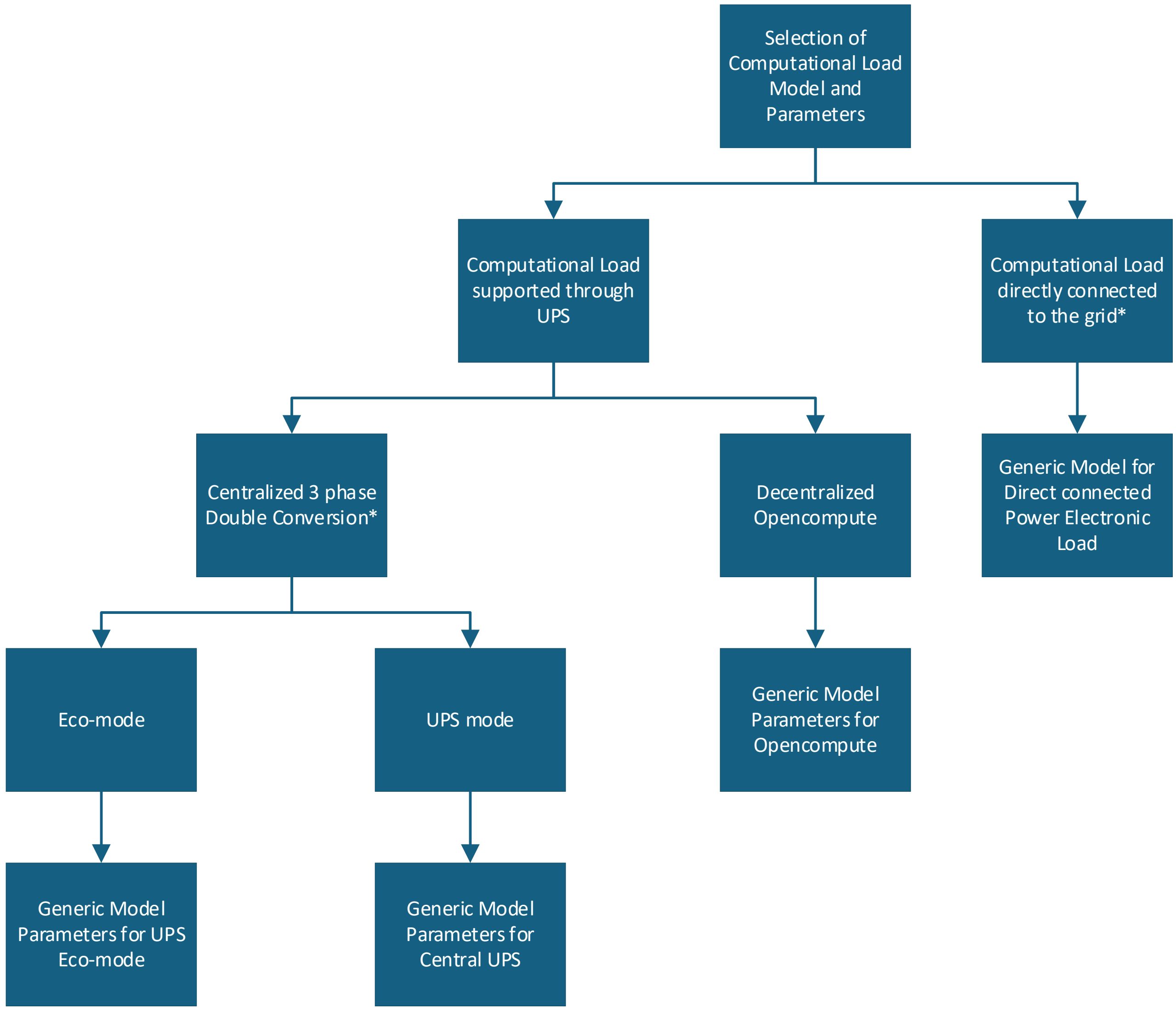


Figure 3.4: Selection of PSPD Model Parameters

State of the Art Generic Model to Represent Computational Loads

A PSPD model for a data center in bulk system studies is typically an aggregated representation that captures the facility level active and reactive power response, relevant outer loop controls, and ride through, ceasing, and reconnection behavior of dominant converter interfaced components such as uninterruptible power supplies and other power electronic equipment. PSPD modeling focuses on the impact of the load on the AC transmission system rather than reproducing all internal equipment details[27].

Overview of the Power Electronic Reconnection and Ceasing (PERC) Model

[27] PowerWorld, “Power Electronic Reconnecting and Ceasing Load Model”, https://powerworld.com/WebHelp/#TransientModels_HTML/Load%20Characteristic%20PERC1.htm

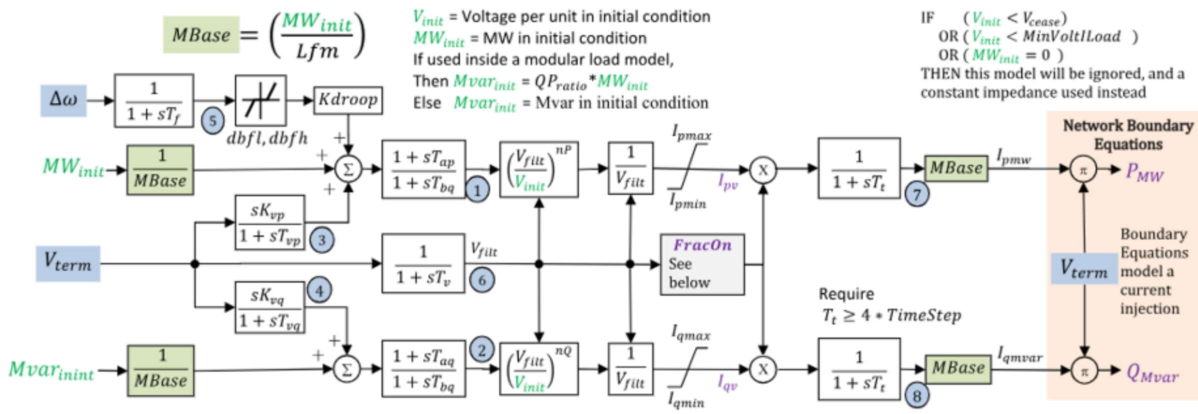


Figure 3.5 Power Electronic Reconnecting and Ceasing Load Model (PERC1) model[28]

Within the PERC1 model, steady state real and reactive power are represented as algebraic functions of terminal voltage with exponent parameters ***nP*** and ***nQ*** that span constant impedance, constant current, and constant power behaviors depending on exponent values.

- The model converts computed power to current by dividing by voltage and then applies current limits using I_{pmax} and I_{pmin} for real current and I_{qmax} and I_{qmin} for reactive current.
- The model may include derivative response where MW and Mvar vary with the derivative of terminal voltage, enabled or disabled through K_{vp} and K_{vq}.
- Real power may include a frequency droop with deadband characteristic, controlled by K_{droop}, although typical input data may set K_{droop} to zero.
- Lead lag blocks T_{ap}, T_{bp}, T_{aq} and T_{bq} can be used to represent dynamic response, though typical input data may set T_{ap}, T_{bp}, T_{aq} and T_{bq} to zero.
- Short delay blocks can be placed on model outputs for numerical stability and are required to be set larger than four times the simulation time step.

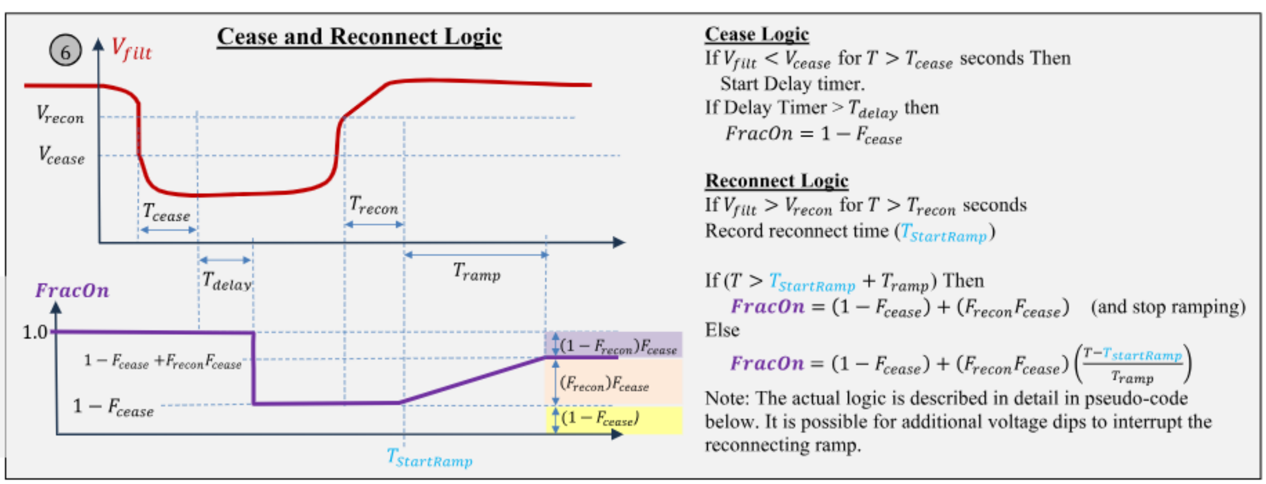


Figure 3.6 PERC1 model internal logic

[28] PowerWorld, "Power Electronic Reconnecting and Ceasing Load Model", https://powerworld.com/WebHelp/#TransientModels_HTML/Load%20Characteristic%20PERC1.htm

- Ceasing and reconnecting are represented by a multiplier FracOn that scales the load, with FracOn defined as the fraction of the load that remains connected after the.
- A voltage ceasing timer triggers when filtered voltage remains below V_{cease} for T_{cease} seconds, followed by a short delay T_{delay} after which FracOn drops to one minus F_{cease}, where F_{cease} is the fraction that ceases.
- Reconnection occurs when filtered voltage recovers above V_{recon} for T_{recon} seconds and then FracOn ramps up over Tramp toward one minus F_{cease} plus F_{recon} times F_{cease}, where F_{recon} is the fraction of the ceased portion that reconnects. Under a minor disturbance with recovery of frequency and voltage and no permanent fractional tripping, the model brings MW and Mvar back to the initial condition.

Data Requirements for Parameterizing the PERC1 Model

1. Load composition and component ratings
    a. Description: MVA size and number of major components such as uninterruptible power supply units, cooling systems, servers or miners.
    b. Format or unit: MVA and count
    c. Source of data: Facility drawings and equipment nameplates
    d. Quality checks: Provide for parameterization and aggregation of facility level model.
2. Collector system and internal electrical network characteristics
    a. Description: Impedance parameters of cables and overhead lines used to connect facility components and collector system equivalents.
    b. Format or unit: Ohms or per unit as used in study base
    c. Source of data: Engineering design data and impedance calculations
    d. Quality checks: Use consistent base quantities and verify plausibility against design values.
3. Substation transformer parameters
    a. Description: Leakage reactance and MVA base, winding ratio, X over R ratio, winding connections, fixed tap position, and saturation curve characteristics when needed.
    b. Format or unit: Per unit on transformer base and nameplate units
    c. Source of data: Transformer test reports and nameplate data
    d. Quality checks: Cross check parameters against commissioning data and documentation.
4. Reactive devices and compensation equipment:
    a. Description: Shunt capacitors, reactors, filters, capacitor banks, and dynamic reactive devices such as SVC STATCOM or synchronous condenser including nameplate ratings.
    b. Format or unit: Mvar ratings and equipment settings
    c. Source of data: Substation design and equipment specifications
    d. Quality checks: Ensure consistency with power flow representation and dynamic model settings.
5. Control and protection settings:
    a. Description: Voltage and frequency ride through characteristics and protection settings including fast protections considered in appropriate modeling domain.
    b. Format or unit: Per unit thresholds, Hz thresholds, seconds delays

   c. Source of data: OEM settings, HMI extracts, protection and control tuning reports
   d. Quality checks Prioritize parameters with one to one correspondence and verify against field settings.
6. Measurements for validation:
   a. Description: High resolution measurements at the point of interconnection from PMU or DFR for event triggered or continuous recording to support model validation.
   b. Format or unit: Voltage current power frequency time stamped
   c. Source of data: PMU and DFR data retention systems
   d. Quality checks: Use defined tolerance bands such as plus or minus five percent for power and plus or minus five milliseconds for timing when provided.
7. Simulation configuration data
   a. Description: Selected PSPD simulation time step and any required output delays that must exceed four times the time step for numerical stability in the PERC1 model.
   b. Format or unit: seconds
   c. Source of data: Study setup settings in the simulator
   d. Quality checks Apply recommended time step selection guidelines and output delay requirement.

Parameterizing the PERC1 Model Using the NERC Data Center Questionnaire

The NERC Data Center Information questionnaire was developed to gather non-intrusive information that enables data centers to be modeled accurately in transmission-level studies[29]. It collects details on total facility load, the composition of server and cooling demand, the presence of UPS and backup generation, and the specific voltage and frequency conditions under which components disconnect, transfer, or reconnect. This information is intended to support representation of large center loads in stability studies where their behavior during voltage or frequency disturbances can meaningfully affect system performance. The **Table 3.1** summarizes how typical responses inform specific parameters; example response wording is illustrative of common data-center practices.

Table 3.1: Mapping questionnaire responses the PERC1 parameters

Questionnaire Item	Example Response	Mapped PERC1 Parameters	Modeling Note
Total MW and power factor; composition of server vs. cooling vs. auxiliaries	Reported facility MW; percentages for server and cooling loads	P0, Q0; nP, nQ	P0/Q0 set at nominal; exponents chosen based on dominant behavior (UPS ≈ constant-P; motors/VFDs may trend toward constant-Z/I).
Voltage sag threshold and minimum duration for server/UPS transfer	Specific pu level and duration (e.g., per site policy)	Vcease, Tcease	Defines onset of ceasing logic.

[29] NERC, "Data Center Information Collection", [online], https://www.nerc.com/globalassets/who-we-are/standing-committees/rstc/lmwg/data-center-information-collection-questionnaire.pdf

Fraction of load that transfers or disconnects under sag	Portion of servers or cooling that cease	Fcease	Applied to FracOn to reduce connected fraction after Tdelay.
Delay from detection to transfer	Small delay inherent to controls	Tdelay	Applied after cease condition is detected.
Reconnection criteria and timing	Utility voltage ≥ 0.95 pu for 10 minutes before transfer	Vrecon, Trecon	Defines reconnection initiation.
Reconnection profile (step vs. ramp) and magnitude	All-at-once via ATS; or gradual ramp	Tramp; Frecon	Ramp time and fraction of ceased portion that returns.
Frequency thresholds for transfer or support behavior	±0.5 Hz window noted by facility	Dbdl, Dbdh; Kdroop (optional)	Frequency droop is commonly inactive in planning inputs; thresholds may be documented even if not modeled.
Cooling drive types and control (VFDs vs. across-the-line)	VFD-driven fans/pumps vs. fixed-speed motors	Kvp/Kvq (optional)	Derivative paths may be enabled for VFD-like behavior if warranted.
Current capability/limits of front-end converters and auxiliaries	UPS and drive current limits	Ipmax/Ipmin, Iqmax/Iqmin	Applied after conversion of P/Q to currents.
ATS/Backup generation sequencing and restoration steps	Minimum grid-stability window before ATS return; staged restoration	Trecon; Tramp; Frecon	Used to shape restoration behavior in bulk studies.

Example of Creating a Data Center Model Record Using the Model

Step 1: Select a PSPD load model form for the aggregated data center that can represent ceasing and reconnecting behavior with explicit timing, noting that PERC1 was developed for generic power electronic loads and is described as useful for modeling uninterruptible power supply behavior for computing loads including data centers[30].

Step 2: Define the voltage dependent steady state behavior by selecting exponent parameters nP and nQ consistent with the intended constant impedance, constant current, or constant power characteristics.

Step 3: Configure current limit parameters I_{pmax} I_{pmin} I_{qmax} I_{qmin} to bound the derived current after converting power to current by dividing by voltage

Step 4: If needed, configure derivative response using Kvp and Kvq to represent temporary MW and Mvar modulation at fault inception and clearing.

Step 5: If needed, configure real power frequency droop with deadband using K_{droop}, noting typical input data may set this to zero.

Step 6: If needed, configure lead lag dynamics using T_{ap} and T_{bp}, noting typical input data may set these to zero. [2]

Step 7: Configure ceasing logic using V_{cease}, T_{cease} and T_{delay} along with F_{cease} to represent when and how much of the load ceases and remains disconnected.

[30] PowerWorld, "Power Electronic Reconnecting and Ceasing Load Model", https://powerworld.com/WebHelp/#TransientModels_HTML/Load%20Characteristic%20PERC1.htm

Step 8: Configure reconnection logic using V_{recon} ,T_{recon} , T_{ramp} and Frecon to represent when and how much of the ceased portion reconnects and the ramp back behavior.

Step 9: Configure output delay blocks to support numerical stability and set the delay larger than four times the simulation time step.

Step 10: Store the model record in the simulator load model data structure as a parameter set associated with the data center bus, ensuring the model initializes to the operating point and can return to realistic steady state after disturbances.)

Implementation Notes and Limitations

Implementation guidance for PSPD models emphasizes correct initialization to the power flow operating point, selecting parameters and time constants so that low frequency response matches expected behavior, and ensuring the model can settle back to realistic conditions after disturbances [1,2]. For numerical stability, guidance includes using a sufficiently small simulation time step relative to the smallest model time constant, validating no disturbance stability through flat run tests, and avoiding ideal step changes by using gradual transitions and filtering.

- Within the PERC1 model, output delay blocks are added to help numerical stability and must be set larger than four times the simulation time step.
- The PERC1 model description notes that typical input data may not use frequency droop and lead lag dynamic response features at present by setting K_{droop} to zero and Tap and Tbp to zero.
- The PERC1 discussion notes that timing logic is useful for modeling uninterruptible power supply behavior in computing loads and that the model aims to represent the impact on the AC transmission system rather than all load details.
- PSPD platform limitations include omission of higher frequency dynamics above about ten Hz, inability to represent unbalanced effects, and potential inability of simple models to reproduce sensitive behaviors observed in practice; in such cases EMT modeling or hybrid approaches may be required.
- Some studies show that certain grid strengths and fast DC-bus control can cause oscillations below 10 Hz. This suggests future models should include the DC-bus control loop. Since the current model cannot represent it, this remains an important limitation.

PERC1 Model Parameter Descriptions

The parameters used in the PERC1 model are described in **Table 3.2**.

Table 3.2: PERC1 parameter descriptions

Parameter	Description
Lfm	Loading factor used to calculate MVAbase of model as MWinit/Lfm. Select Lfm to ensure correct facility MVA is selected for the calculations. If Lfm < 0.001 then software will use a value of 0.80
QPratio	Q/P ratio for Q0 computation from P0 when used as a component of a CompLoad.
	When used as a stand-alone load model, Q0 = Qinit always.
Dbdl	Deadband on frequency response low (<=0) [pu]
Dbdh	Deadband on frequency response high (>=0) [pu]
Kdroop	Frequency droop [per unit]

Kvp	Proportional constant for active power washout
Tvp	Time constant for active power washout [seconds]
Kvq	Proportional constant for reactive power washout
Tvq	Time constant for reactive power washout [seconds]
Tap	Lead time constant for real power path [seconds]
Tbp	Lag time constant for real power path [seconds]
Taq	Lead time constant for reactive power path [seconds]
Tbq	Lag time constant for reactive power path [seconds]
nP	Active Power Exponential
nQ	Reactive Power Exponential
Ipmax	Maximum Ip [per unit]
Ipmin	Minimum Ip [per unit]
Iqmax	Maximum Iq [per unit]
Iqmin	Minimum Iq [per unit]
Fcease	Fraction that will cease (between 0 and 1)
Vcease	Voltage threshold for cease logic [per unit]
Tcease	Time delay for cease logic to be initiated for (>= 0) [seconds]
Tdelay	Time delay to cease after detection for (>= 0) [seconds]
Vrecon	Voltage threshold to initiate power ramp reconnection logic (Vrecon >= Vcease) [per unit]
Trecon	Time delay for ramp up logic to be initiated (>= 0) [seconds]
Tramp	Ramp up time (>= 0) [seconds]
Frecon	Of the Fraction that ceases, this is the fraction that then reconnects (between 0 and 1)t]
Tt	Time delay for outputs [seconds] (If < 4*TimeStep will be treated as 4*TimeStep)
Tv	Voltage measurement time constant [s]
Tf	Frequency measurement time constant [s]

Modeling Slow Forced Oscillations using Positive Sequence Phasor Domain System Models

The practitioner has the option to model and study impact of slow forced oscillations emanating from AI training work in data centers by using a simple power flow model without needing the PERC model as shown in **Figure 3.7**. This workflow has two main steps and is shared below.

- Step 1- Extract the shape of AI training load profile from the data center. Alternatively, the practitioner can develop a set of waveforms that covers the spectrum of expected forced oscillations
- Step 2- Develop these curves into data files where the power values are changed with time to reflect the power oscillation that is being injected. The system response to the simulated AI training can be found by playing back these files into steady state load models that can be used to control the load active power. In the bridge UDM developed by ISO-NE this can be done by using PERC1 and changing the active power setpoint. However, the ability to do so will change from software platform to software platform. It might be easier to do this study directly without using PERC1 (since PERC1 characteristics are not used for this non-disturbance simulation). Note that this can only be applied when the only disturbance in the simulation period is the variation in the power usage of the data center load.

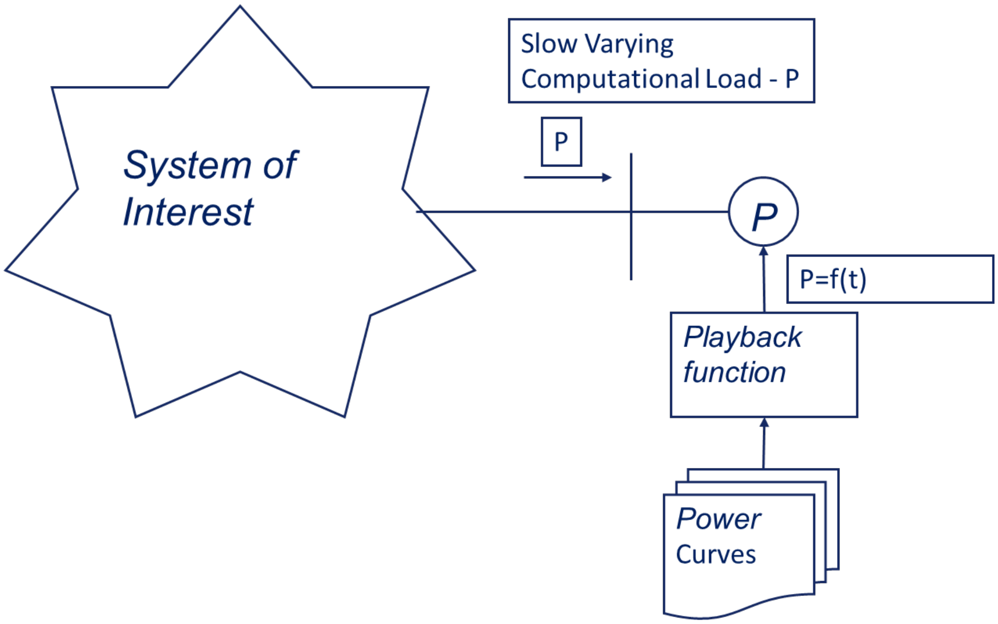


Figure 3.7: Approach to model slow sub synchronous load flow changes in data centers emanating from AI training

Note that the PSPD simulation does not model internal torsional modes of the generators or faster dynamic in the system. Therefore, this approach is useful to understand the impact of slow forced oscillations (typically less than 5Hz) and how they propagate across the system. Alternatively, a small signal stability study would be able to evaluate the impact on the system without needing explicit simulation of the forced oscillation.

Dynamic Modeling of a Data Center – EMT Modeling

Introduction

Electromagnetic Transient (EMT) modeling provides high-fidelity, time-domain simulation of electrical systems that captures sub-cycle dynamics, nonlinear switching phenomena, control interactions, and detailed device behavior. EMT studies are typically required when phenomena of interest occur in the order of microseconds to milliseconds and/or involve nonlinearities (e.g., magnetic saturation or surge arrestor conduction) which cannot be adequately represented in PSPD simulation tools.

The guidance on when EMT modeling is warranted for data center studies including how to select or develop an appropriate level of model details consistent with study purpose and available data is provided in Chapter 4 EMT studies are most applicable when dynamic interactions involving power electronics, fast control actions, or detailed device-level responses are under examination. This section does not cover traditional EMT applications (e.g., switching overvoltage studies, ferro resonance studies, validation of advanced protection systems) for which industry approaches are mature. These may be necessary as part of the data center design or interconnection process, but do not necessarily require a change in established practices simply because the site is a data center, rather than some other end use.

Types of EMT Model Representations

In general, EMT models used for data center studies can be broadly classified into two types: vendor or Original Equipment Manufacturer (OEM)–provided models and generic EMT models. Vendor-provided EMT models are typically delivered as black-box implementations, where internal details of the control logic and measurement algorithms are not fully disclosed to the user. These models may include detailed representations of power electronic devices, control systems, and measurement logic, often reflecting the actual methods implemented in the hardware. Vendor models may be integrated into EMT simulation tools through compiled libraries (e.g., DLL-based implementations) or provided as high-level representations with embedded control behavior.

From a modeling perspective, vendor-provided EMT models may be represented using different levels of detail, including:

- **DLL-based models** that incorporate proprietary device internals, control logic, and protection functions.
- **Detailed switching models** that explicitly represent power electronic switching behavior and device-level dynamics.
- **Average EMT models** that neglect explicit switching behavior through idealized representations to improve calculation efficiency while retaining dominant control dynamics.

Generic EMT models, by contrast, are not black-boxed and provide full transparency of component implementation, control logic, and measurement methods. In the context of power system planning, generic models are particularly useful when OEM models are unavailable, such as during early planning stages or preliminary screening studies. However, generic models may not fully reproduce the exact behavior of a specific data center under all operating conditions, due to the absence of proprietary vendor details. Key limitations may include simplified measurement methodologies, neglecting filtering or communication delays, and generalized control logic that may differ from actual equipment implementations.

Outside of a planning context, generic EMT models can also be valuable for evaluating performance expectations and study objectives among stakeholders such as utilities, research institutions, consultants, and OEMs. Because results derived from vendor-specific models are often subject to non-disclosure agreements, their broader applicability is limited when building consensus, comparing modeling practices, or addressing issues beyond a site-specific scope.

As a best practice, model selection should prioritize the use of available OEM-provided EMT models when detailed performance assessment of a specific site is required. Generic EMT models may be used when OEM models are unavailable, if assumptions and limitations are clearly documented and aligned with study objectives.

In addition to model availability, the following considerations are fundamental in determining the appropriate scope and application of EMT modeling:

- **Model fidelity versus computational cost:** High-fidelity EMT models with detailed switching elements and control systems offer the most accurate representation of transient behavior but impose significant computational demands. Average model or reduced-order representations may be acceptable when justified by study objectives and supported by appropriate validation. For example, in transmission-level stability studies, the incremental accuracy gained from explicitly modeling high-frequency switching is typically limited; therefore, average-value models may be used to represent converter switching behavior, provided that the associated control loops are modeled with sufficient accuracy.
- **Simulation time step and study duration:** EMT simulations typically require very small-time steps (on the order of microseconds) to resolve fast switching events and control-loop dynamics. Simulation durations should be selected to capture the full transient behavior of interest, including post-disturbance recovery.

Applicability of EMT in Transmission Planning

EMT modeling is a specialized but increasingly essential tool in transmission planning, particularly as power systems integrate complex, fast-responding loads and converter-based technologies such as data centers with UPS and static transfer equipment. EMT studies complement PSPD analyses by resolving dynamics that occur at time scales and levels of detail beyond the capability of positive-sequence tools.

Oscillatory Interaction

Data centers may be involved in oscillatory interactions within the power system; therefore, their EMT models should be developed appropriately for such studies. Oscillatory interactions associated with data centers can be broadly divided into two categories:

- ***Forced Oscillations***: Rapid changes in data center load profiles may introduce forced oscillations into the power system. This is generally a concern for large data centers performing large-scale parallel computing tasks, such as training or inference of large AI models. **Figure 3.8** illustrates a representative data center load profile during AI training, shown over a two-minute interval and, in more detail, over a five-second window. For forced-oscillation studies, EMT tools may implement playback sources or variable load representations to simulate time-varying injections consistent with measured or hypothesized disturbance signatures.
- ***Natural Oscillations and Interactions***: Natural oscillations may arise due to resonances between network impedances, controllers of other dynamic devices, and control loops within data center equipment, particularly because power electronics constitute a significant portion of the load. These phenomena may only become apparent in EMT simulations and generally require detailed, component-level models.

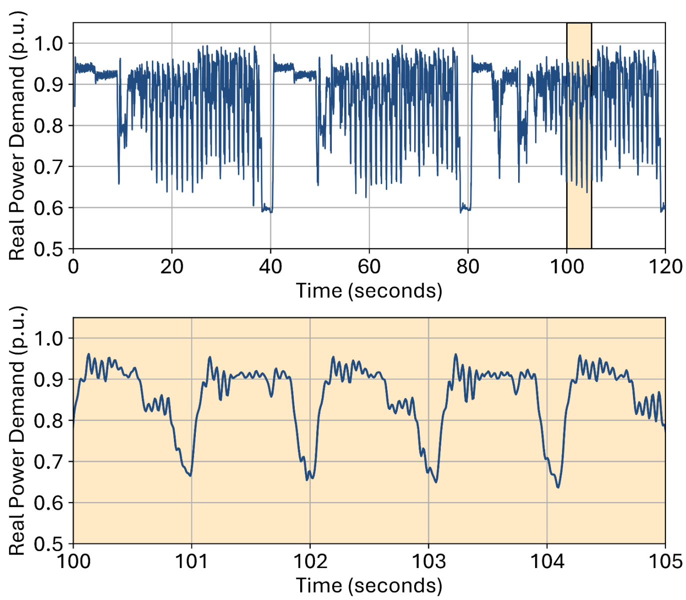


Figure 3.8. Example AI data center load profile during training over two minutes (top) and over a five-second interval (bottom) [31].

Ride-Through and Fault Recovery

To assess in detail how protection and control systems, particularly UPS systems and variable-frequency drives (VFDs) associated with large motors—interact with grid disturbances, EMT studies may be used. EMT models can capture the impact of control-loop implementation details, measurement algorithms (e.g.,

[31] Ref: NERC, Large Loads Task Force White Pape on "Characteristics and Risks of Emerging Large Loads", July 2025

phase-based versus sequence-based logic, filtering, and delays), and protection logic on ride-through performance and fault recovery. For these studies, detailed EMT representations of measurement and control systems are essential, as they influence the sequence of actions during faults and post-fault recovery. The detailed EMT model can be used to validate and understand the consequences of assumptions made in PSPD model.
In addition, even if a power converter has voltage protections set in accordance with voltage ride through requirements, there are many other protection functions which may still cause the device to trip in response to transients which are not represented in PSPD tools (e.g., DC link overvoltage). However, while EMT modeling is required to capture these phenomena, modeling these phenomena will only be of interest in very specific conditions.

Power Quality and Harmonic Studies

When power-quality concerns such as voltage distortion, harmonic propagation, or interactions among multiple power-electronic interfaces are of interest, EMT studies can be used to model the effects on the bulk system. In these circumstances, average models of data center power electronics are generally insufficient. Models with detailed switching and control representations, such as dLL-based implementations, are more appropriate.

Most data centers use high efficiency power electronics devices that produce low levels of current distortion (e.g., less than 2%) and have a harmonic spectrum that, in contrast with simpler devices such as diode rectifiers, is very difficult to predict accurately through modeling. This is because it is primarily determined by nuances in converter topology and switching strategy. For these reasons, it is often more practical to obtain current characteristics from OEMs and derived experimentally. While this data can be played into an EMT model, there are also a variety of phasor-based power quality tools which can be more convenient to use for variety of power quality studies.

Wide-Area EMT Simulation

With increasing penetration of inverter-based resources (IBRs) and reduced system strength, there is a growing concern that wide-area EMT simulation is needed to properly model grid stability. In wide-area EMT studies, a large portion of the grid is represented in the EMT domain, while the remainder is modeled using network equivalents or hybrid PSPD–EMT simulation approaches. In such simulations, all dynamic devices within the EMT portion of the system must be represented using EMT models. Therefore, if a large data center is located within the EMT-modeled area, it should be represented using an EMT model with an appropriate level of accuracy.

EMT-Specific Modeling Requirements

Large loads require detailed EMT models to accurately capture their complex dynamic behavior. EMT models are not only essential for detailed transient studies; a validated EMT model may also serve as a benchmark for verifying PSPD across a broader range of scenarios. This subsection outlines key best-practice considerations related to model accuracy, control representation, and simulation efficiency. Detail in all these respects is by no means required for every EMT study. It is often a matter of practical necessity to tailor model details to the specific studies at hand.

Model Accuracy Features

- ***Component coverage:*** The model should represent all significant subcomponents of the large load—such as power-electronic devices, UPS systems, inverters/rectifiers, motor drives, cooling systems, PDUs, and any backup generation or BESS—either as distinct components or aggregated equivalents. These elements strongly influence the facility’s dynamic response and stability.

- ***Control & protection fidelity:*** The model should include detailed representations of all relevant control and protection systems. Where available, actual converter firmware implementations should be used; otherwise, model validation against test data should be documented. Asset-level controllers (e.g., voltage regulators, PLLs, ride-through logic) and protection devices (AC/DC relays, breakers) should be clearly identified and described.
- ***Reactive & transformer dynamics***: The model should represent switched capacitors or reactors, and it is recommended to include transformer magnetizing characteristics, such as saturation curves. Accurate modeling of these elements is important for representing voltage behavior and fault response, particularly under unbalanced conditions.
- ***Site-specific parameters***: Tunable parameters (e.g., controller gains, protection settings) should reflect site-specific, field-commissioned values rather than generic defaults. Use of actual settings improves model fidelity.
- ***Time-step & stability:*** EMT simulations should be executed using sufficiently small time steps (typically on the order of 10–50 µs) to capture fast transients. Numerical stability should be verified, particularly under weak-grid conditions. Any time-step limitations or solver constraints should be documented.
- ***Test cases & validation:*** Appropriate test scenarios should be defined to reflect the facility configuration, such as balanced and unbalanced faults and step changes in voltage, reactive power, frequency, or active power. Where possible, model performance should be benchmarked against field or laboratory measurements using measured load profiles and monitoring data.
- ***Power quality impacts:*** The model should account for power-quality effects from nonlinear loads, including switched-mode power supplies, VFD-driven motors, and UPS rectifiers. Harmonic and flicker impacts should be represented or specified, along with any filtering or mitigation measures required to meet applicable standards.

Model Usability Features

- ***Initialization & scalability***: The model should self-initialize to a steady-state operating point without external intervention and support operation across a range of loading conditions. Load consumption levels should be dispatchable where applicable.
- ***Computational efficiency***: Simplify repetitive subsystems to improve run-time while preserving accuracy. For example, aggregate identical load units or parallel branches where possible.
- ***External reference inputs***: The model should accept external reference variables, such as real and reactive power setpoints or voltage reference signals, for initialization and dynamic modification during simulation.
- ***Time-Step capability***: The model should be capable of running at time steps in the range of approximately 5–10 µs. The need for significantly smaller time steps may indicate limitations in control implementation, interpolation usage, or network interfacing.

Model Efficiency Features

- ***Software and Compiler Compatibility***: The model should be compatible with current software versions and, where applicable, recent compiler versions (e.g., PSCAD version 5.0.2 or later). Also, the model should be supplied with both 32 bit and 64 bit compiled versions.
- ***Self-initialization:*** The model should support automated self-initialization to a valid steady-state operating point.

- ***Multiple Instance and Multiple-run Support***: The model should support multiple instances of the same definition within a single simulation case. Also, the model should support repeated simulations without manual reconfiguration.
- ***Timed Snapshot Support***: The model should support timed snapshot functionality, enabling continuation of simulations from saved states.

Key Components of Data Center EMT Modeling

Developing a facility-level EMT model typically involves integrating multiple subsystem models—each with its own controls, protection logic, and operating assumptions—into a coherent representation of the overall data center electrical architecture. This process requires consistent treatment of interfaces between components, coordinated control and protection settings, and appropriate aggregation where applicable, to ensure that the combined model accurately reflects the dynamic behavior of the facility under disturbance conditions. Careful integration is essential to avoid unintended interactions when independently developed component models are combined into a single EMT simulation framework.

In EMT studies, the following components require careful representation because they commonly influence transient responses and interactions with the grid:

- ***UPS Systems***: Model common topologies (e.g., double-conversion, line-interactive) with sufficient detail to represent control loops, energy storage elements, switching behavior, and short-term dynamics. UPS models should include logic for bypass operation, transfer sequences, and interactions under voltage sags or interruptions.
- **Grid-connected power supplies**: Large concentrations of AC/DC power supplies for IT load should be represented if they are not isolated from the grid by double-conversion UPS. These may have their own storage systems downstream of the AC system, which can significantly affect ride-through performance.
- ***Static Transfer Switches (STS)***: STS behavior during disturbances, including transfer timing, coordination with UPS controls, and control logic, influence voltage support and ride-through outcomes.
- ***Cooling and Auxiliary Systems***: The dynamic characteristics of large motor, either they are connected directly or through power electronic devices, may impact voltage behavior and should be represented.
- ***On-Site Generation and Storage***: If present, diesel generators, battery energy storage systems (BESS), or PV resources should be modeled with coordinated controls to capture their influence on system dynamics during disturbances and recovery. Interactions among multiple converters and storage devices can create complex dynamic behavior.
- ***Distribution and Grounding Configurations***: System grounding (e.g., TN-S, TN-C, isolated) affects fault current behavior, resonance, and EMC considerations; these details may be relevant for EMT studies depending on study objectives.

Examples of Data Center Generic EMT Models

Generic EMT models can be helpful, particularly in early planning stages or where OEM models are unavailable—but they cannot replace accurate vendor-provided models for detailed site-specific assessments. Many critical behaviors, such as control logic sequencing, measurement filtering, or ride-through logic thresholds, are proprietary and must be captured in OEM models to achieve credible results.

In this section, two open-source resources for generic EMT models are reviewed. These resources can support improved understanding of data center dynamic behavior and serve as a starting point for developing site-specific models for early-stage planning studies, when vendor-provided OEM models are not yet available and detailed interaction studies are not the primary focus.

Data Center Model Library (DML)

Pacific Northwest National Laboratory has developed a library of data center models for PSCAD/EMTDC[32]. The library contains a range of component-level models for data center modeling but most of the fidelity is dedicated to the UPS and grid-connected power supplies. Other components, such as cooling loads and network protections have relatively simplified representations. Several aggregated data center designs are provided. The models are organized for extensibility, and their input data is documented, but documentation provides relatively little guidance on setting parameters and tuning—proper usage of the models requires a good understanding of EMT modeling of power electronics. Beyond the models themselves, the documentation provided provides an overview of data center power system design, along with a set of EMT modeling guidelines which are a useful supplement to those provided in this technical reference.

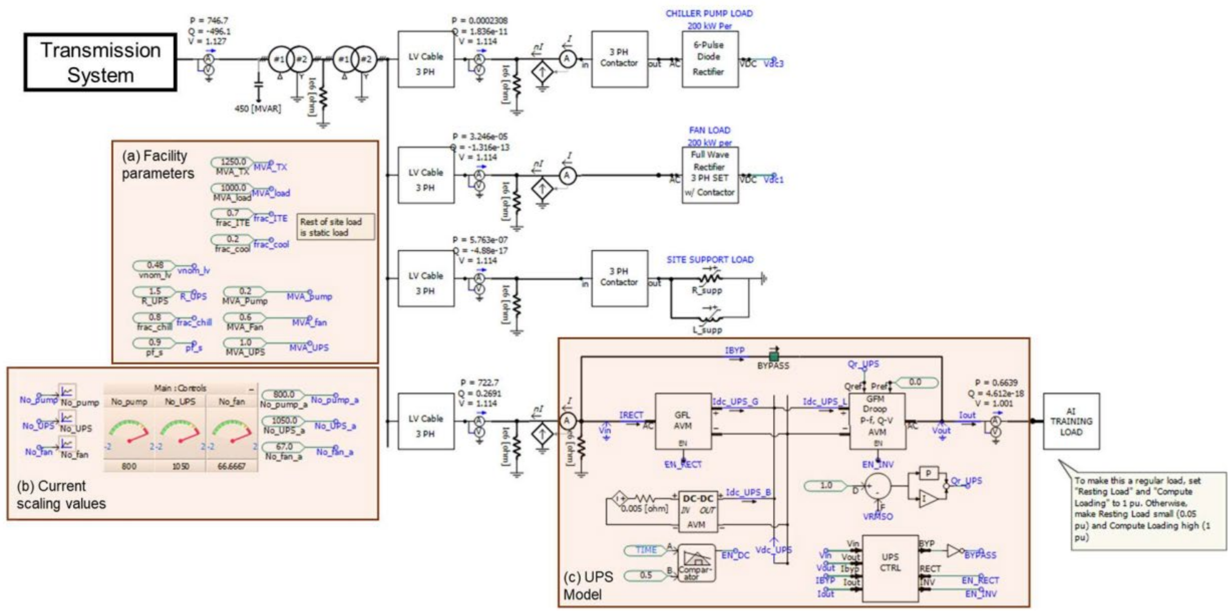


Figure 3.9: Aggregate model for data center with centralized UPS provided as part of the DML[33].

Crypto Miner PSCAD Model

Electric Reliability Council of Texas, Inc. (ERCOT) has partnered with the Texas A&M Engineering Experiment Station (TEES) to develop detailed generic dynamic models of large loads—such as data centers, crypto, and electroliers—and how these loads change their power output during and after a period of grid disturbances (e.g., faults and other power quality events).

The goal of this work is to accelerate the development of generic models for various conceptual studies, gain a better understanding of plant-level characteristics, and benchmark models in the lab as much as possible. The models are developed based on the best available information and are a good first step towards improving data center modeling. At the time of writing this paper, the model developed for cryptocurrency mining facilities is publicly available[34]. More accurately it is a generic model for the AC/DC power converter used in grid-scale cryptocurrency mining facilities and could be used to represent grid-connected power supplies for a data center or cryptocurrency mining facility.

[32] Ross, Brett A., and James D. Follum. *Electromagnetic Transient Modeling of Large Data Centers for Grid-Level Studies*. PNNL-38817. Pacific Northwest National Laboratory (PNNL), Richland, WA (United States), 2026.

[33] OSTI, Electromagnetic Transient Modeling of Large Data Centers for Grid-Level Studies

[34] ERCOT, Grid Research Innovation and Transformation, Large Load Modeling

The model's fault response has been experimentally validated against a commercial power supply—**Figure 3.10** illustrates the measured and simulated responses of the power supply to a voltage sag. The accompanying documentation explains the model's operating principles in detail along with guidance on computing parameters.

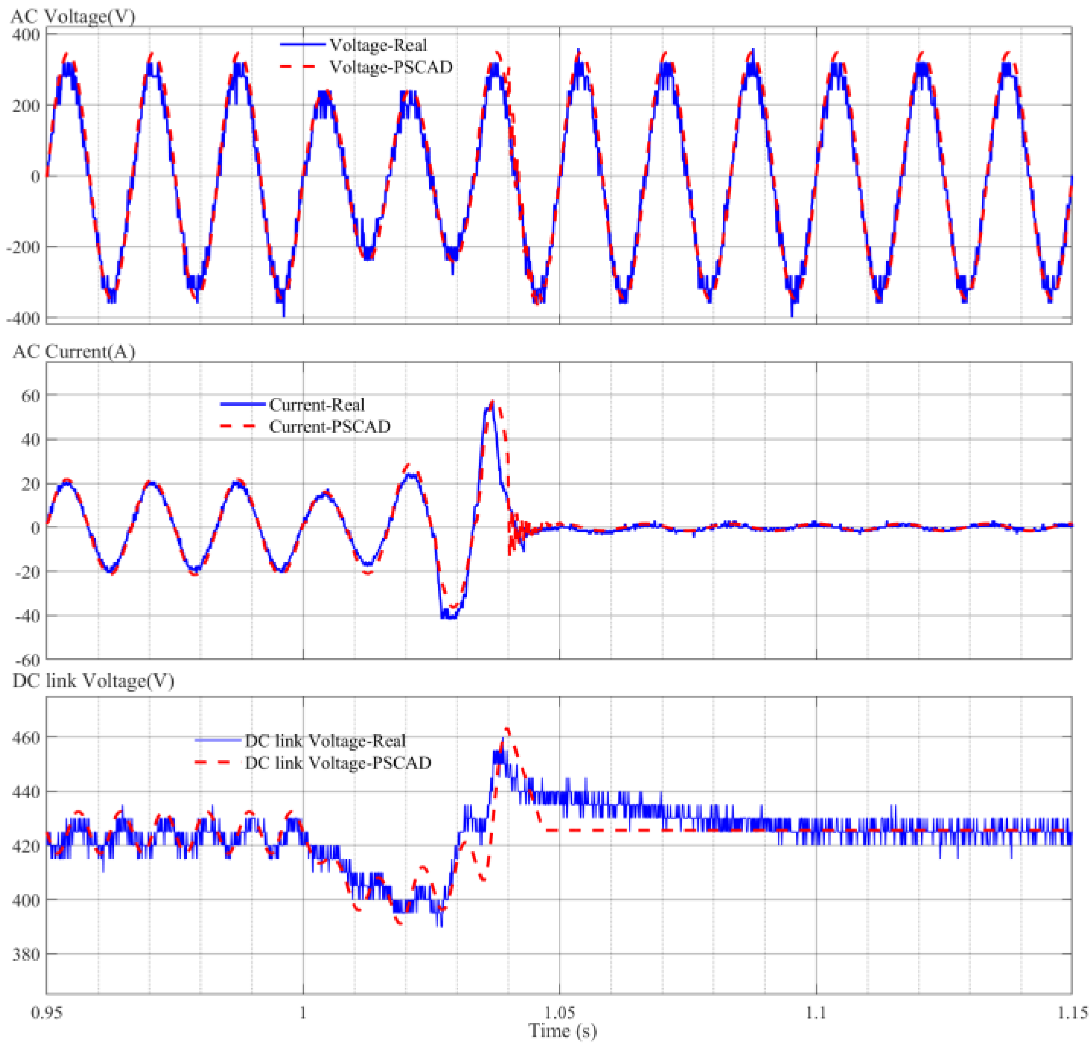


Figure 3.10: Comparison of experimental (red) and simulation (blue) results of crypto miner power supply to voltage sag[35].

Short Circuit Modeling

Data centers short-circuit modeling starts with modeling the electrical system as it functions under normal utility-fed operations since nearly all the equipment responsibilities and protection behaviors are determined by this setup. Data Centers are constructed for high availability and have dedicated utility supply transformers serving the medium-voltage distribution systems supporting UPS systems, mechanical loads, and the downstream IT load infrastructure. With the utility source taking priority over any other form of supply to support this kind of short circuit in this normal state, the short circuit model becomes essentially focused on the utility Thevenin equivalent and the impedances on the transformer, cable, and switchgear

[35] Dynamic Modeling of Crypto-Miner Load in PSCAD

at-location. These components shape the magnitude of symmetrical and asymmetrical fault currents at critical buses throughout the facility.

For data centers, a main principle of modeling is that the IT loads, power distribution units (PDUs), UPS-protected loads, and other downstream equipment do not provide an adequate contribution of short-circuit current. Most of these loads are sinks rather than sources of energy, and the practitioner should ignore these loads for short-circuit analysis, unless there is evidence that it provides short-circuit current. Typical contribution during a fault from a power electronic interfaced load is negligible relative to the stiff utility source for most cases. Even large computer loads or mechanical systems such as chillers and CRAH units behave essentially as impedances whose influence is already captured through network topology, not as current-supplying elements. Because of this, the typical short-circuit model does not include load current contribution; instead, loads are omitted or modeled as passive impedances purely for completeness of connectivity.

While the utility source dominates the system during normal operation, backup generators or inverter-based systems become relevant only under certain circumstances. In many data centers, diesel generators sit on standby and do not parallel with the grid during everyday operation. Under these typical conditions, the generators are simply modeled as out-of-service or ignored, because they do not influence fault current levels. However, data-center operating procedures sometimes could include closed-transition transfers, functional testing, or synchronization sequences that introduce brief intervals of potential parallel operation. It is only under such circumstances, where backup sources can electrically connect to energized buses, that their short-circuit contribution must be represented. In those cases, modeling includes generator sub-transient reactance, grounding behavior, and any individual or aggregated sizing needed to capture their combined effect on the medium-voltage distribution.

If such parallel or transitional states are possible, the model is expanded to examine how additional short-circuit sources alter system behavior. When utility and backup generators momentarily operate in parallel, even for fractions of a second, the combined fault contribution can produce high fault duties seen anywhere in the data center. Conversely, if islanded generator operation is a credible emergency mode for the facility, the model must reflect the generators as the sole sources of fault current, which generally results in lower symmetrical currents but steeper X/R characteristics and different protective device behavior. For inverter-based resources such as battery storage, their contribution is often current-limited, and therefore only influences the SC results modestly; nonetheless, if such resources can energize portions of the facility independently, the model includes them accordingly.

Regardless of each scenario, the goal stays the same: To define true upper- and lower-bound short-circuit duties in a manner consistent with what the data center does, not just installed equipment. Loads continue to play no direct role as sources, but their upstream distribution pathways must be accurately represented to determine how fault current propagates to the various protective devices. By modeling only the conditions that truly reflect operational practice while correctly capturing the behavior of the utility source, backup generation when applicable, and the distribution network impedances, the short-circuit study ensures that all switchgear, transformers, and protective devices in the data center are adequately rated and coordinated for every credible scenario.

Other Modeling Approaches

Simulating the coupling between the electrical system and the cooling system in a data center could be of interest to practitioners modeling phenomena with longer time constants with the intention of evaluating the demand flexibility of the facility. The thermal system in a data center influences data center electrical dynamics on a second to minute time scale and thus does not have a profound impact on the disturbance performance in a transient stability time scale. The thermal modeling of the data center is, however, useful when assessing the load flexibility potential of the data center. Where such modeling is of interest more information is shared in the **Appendix E.**

Model Validation

Validation is an essential step in model development and maintenance for power system simulations studies. During development, to ensure that the model has the fidelity to represent needed characteristics of a grid component type, data from a representative component are collected and used to tune model parameters to match the data. The data must be chosen to display the characteristics of interest. For other components of the same type, parameters may be tuned using additional data or inferred from other information. Models are subsequently re-evaluated to capture changes to behavior over time. Grid codes may require that certain large component models, such as generators and controls, be periodically validated using specific tests or through measured response to grid disturbances.

Models used in grid studies are developed using two different fundamental approaches, or a combination of the two. The first approach involves model derivation using first principles, and common examples include generators, transformers, transmission line models, controls, etc. In these examples, physics and design are known or at least knowable, and the parameters could be derived using geometry and materials, however, more practically a model form is derived and parameters determined using tests and data. The second approach involves the development of a performance-based model with a mathematical representation that need not be derived from first-principal physics. Data is collected and a model is developed to represent the observations. This approach is appealing for generic models in which the underlying components may not be known, and these models will often use generic representations such as polynomials and low-order linear dynamical systems. Some types of load models are common examples. In the context of load models, and in particular classes of load types, a combination of these types of approaches is common. A generic composite load model for transmission system studies will include a representative electric distance for a transmission grid with transformer, and models for various motor types as common loads. A first-principles motor model may represent the aggregate performance of many motors of a particular load class. The model representation will exhibit essential characteristics, such as rotational energy dynamics, and may be tuned to represent observed load performance.

Presently, data centers may be represented as a large power electronic load, which are usually considered constant power loads. The assumption is that the load is controlled to continue through moderate grid disturbances and thus to ride through events (within certain limits) while drawing its needed power. Should an event be severe in magnitude and/or duration the electronic load may trip on protection or transfer to another source. Initial data shown in Chapter 4 shows that a data center load does tend towards a constant power characteristic in response to a nearby voltage event. The effect of controls is evident in the **Figures 4.X1-4.X3** in modest MW load variations during and after the faults. In addition to representing the nearly constant power electronic load characteristic, and the activation of protection or transfer when disturbance limits are exceeded, the evident control dynamics may be represented by a more detail model. The more detailed PERC1 power electronic load model can include dynamics and descriptions for ride-through and protection or transfer. Additional consideration is needed for different types of data centers in which the workload is not constant power and may introduce forced oscillations.

Large loads such as data centers are facilities that could be modeled in arbitrary detail given enough information. For grid planners and operators, a model must capture essential features that describe how the facility will react to grid disturbances, and how the facility's workload may impact the grid. At this relatively early stage of data center modeling during which data center designs are many and continue to evolve with scale, a generic representation may include key components and representative load profiles. As detailed in this report the components include Information Technology load, Power Distribution, Cooling, and Auxiliary Infrastructure. Models for each subsystem may be combined for an overall large load model, or a performance model may be created from data such as a constant power electronic load. For model development and validation, controlled tests are ideal for determining load response to various disturbance. Such tests are impractical in the field. For model development, a common approach is to simulate test disturbances using a very detailed, first-principles model to inform a more practical generic or performance model.

Grid data are used to tune and validate a model. The process involves simulating the model using certain data as input, and others as output, and then assessing the accuracy of the model. Deviations in simulated output from measurements can be used to tune the model. For example, using PMU data, the voltages magnitude and angle measurements are used as inputs to drive the simulated model to produce simulated current magnitudes and angle, and subsequently calculated active and reactive powers, as well as characteristics of ride-through and protection. The current magnitude and angle, active and reactive power and other features are then compared to the PMU measurements to validate the model. The same approach may be applied using other data such as point-on-wave measurements.

The phenomenon of interest dictates the type, rate, and placement or measuring equipment. As with traditional loads, a data center's ride-through and tripping capabilities are important: the response to voltage and frequency disturbances and the actions of local protection. Unlike most traditional loads, some data centers, especially AI training data centers, have workloads that vary significantly over dynamic timescales associated with sub synchronous resonance and intra- and inter-area oscillations.

Data should be aligned with studies. Commonly available PMU devices produce voltage and current phasor information that are typically reported at a rate of 30 or 60 samples/second. While the reporting is on the order of once per cycle or every other cycle, phasor values are not instantaneous as the phasor calculations necessarily involve filtering over 3-6 cycles. These filters are designed to be narrow-band around the nominal fundamental-frequency and strongly attenuate oscillatory components outside the filter passband. The standard IEEE/IEC 60255-118-1-2018 specifies two performance classes for PMUs: the P- and M-Classes, with distinct filtering requirements and bandwidth, tailored to different applications. The standard mandates measurement accuracy only within a limited bandwidth: up to 2 Hz for P-Class PMUs and up to 5 Hz for M-Class PMUs. Outside these ranges, at higher frequencies, the filters' magnitude response attenuates significantly, as illustrated in **Figure 3.11**. For example, a P-Class PMU following the reference designs from the IEEE/IEC standard attenuates measurements by almost -20dB at 30 Hz for 60 Hz reporting rate. With M-Class designs, the attenuation is even sharper. This is demonstrated in **Figure 3.12** using synthetic data containing a 20 Hz oscillation with 0.25 pu peak-to-peak amplitude. An M-Class PMU reporting at 60 Hz, designed per the reference signal processing models in the IEEE/IEC standard, attenuates the oscillation magnitude measurements to approximately 0.05 pu peak-to-peak.

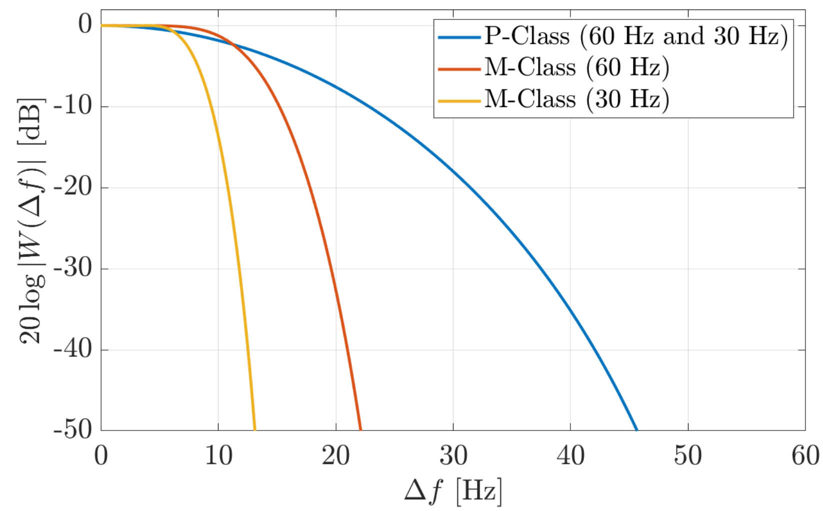


Figure 3.11. Magnitude response of P- and M-Class reference filters from the IEEE Standard, for reporting rates 30 and 60 Hz.

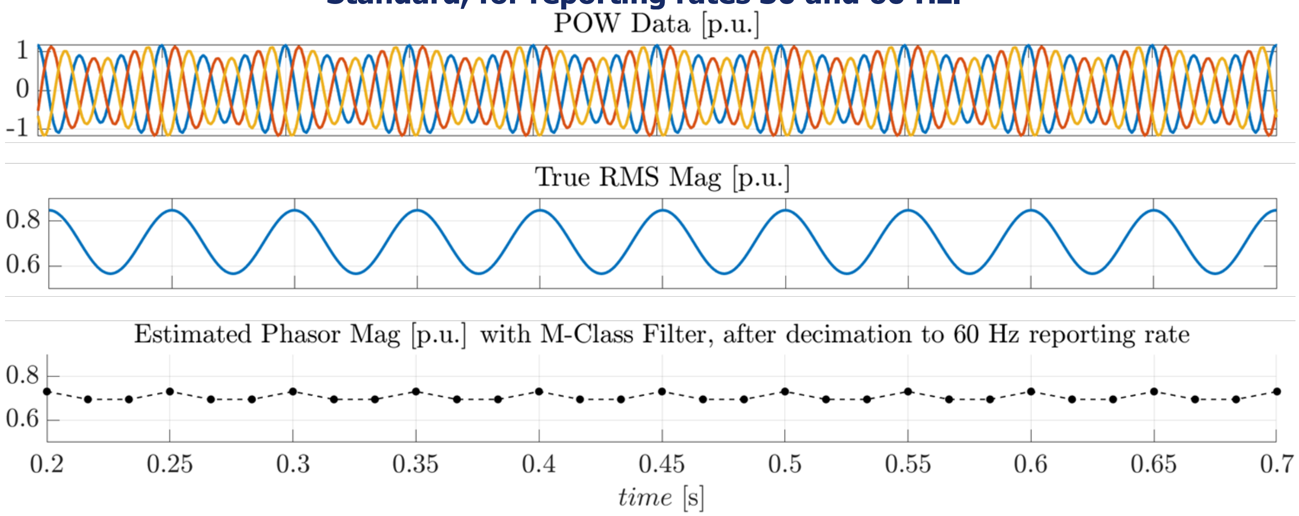


Figure 3.12. Magnitude attenuation of high-frequency oscillations due to phasor estimation. POW refers to waveform or point-on-wave measurements, which is the input to phasor estimation.

PMU data is, therefore, valuable for studying interarea oscillations (frequencies below 1 Hz), but have limited use for the study of sub-synchronous resonances at frequencies greater than 10 Hz, and another faster phenomenon.

Point-on-wave (POW) data, or raw voltage and current measurements, have more flexible use and can be used to tune and validate models for grid-related dynamic phenomenon. The challenge is that the continuous collection of raw measurements accumulates quickly, necessitating significant data storage and management. Alternatively, instead of continuous collection, data may be available from digital fault recorders which provide high fidelity data for short periods of time before, during, and following a large disturbance. Data from events that trigger DFRs are extremely useful for purposes of validation, especially for those that may trigger protection equipment. A limitation of DFR data is that it is tied to triggered events; it may not provide data for load voltage and frequency responses to more distant events or provide information about changing workload conditions of the local load that might impact system resonances.

For purposes of model validation, it is recommended that point-on-wave measurements be collected continuously at the point of interconnection for select data center locations. This data can be used to verify typical workload profiles that can be considered in simulations studies, and should a large local disturbance occur, the data will verify models for ride-through and protection. Over time, these data will display the voltage and frequency responses due to distant and closer grid disturbances as they occur.

Framework for Implementing Model Validation

Effective monitoring and model validation are essential to ensure that high-fidelity data center models accurately represent real operating behavior, especially for fast-ramping AI and GPU-driven workloads. Prior to energization, the facility’s as-planned and as-built modeling data must be validated against equipment specifications, protection settings, load profiles across multiple time scales, and disturbance responses. These validations confirm correct representation of voltage and frequency ride-through behavior, ramp-rate limits, harmonic emissions, oscillatory tendencies, and backup power transitions. While specific requirements vary by transmission provider, many utilities expect large loads to demonstrate compliance with technical performance criteria before initial energization and to update the model whenever equipment or controls materially change.

During the testing and commissioning period, monitored field data may be compared directly to the modeled response. This may include high-speed power traces, harmonic spectra, recordings of voltage and frequency disturbances, transformer energization waveforms, and UPS/BESS dynamic interactions. Monitoring systems such as PMUs, fault recorders, and power-quality meters at the point of common coupling provide independent verification of the model’s fidelity. Any deviation between the modeled and measured behavior must be corrected by updating model parameters, revising control settings, or implementing additional mitigation measures.

Following approval for full operational readiness, ongoing monitoring ensures the model remains aligned with real-world performance. Transmission providers generally require updated as-left models after commissioning and further updates whenever the facility undergoes material changes, such as increases in peak load, modifications to UPS/BESS control schemes, changes in protection logic, or additions of new IT equipment types. Post-commissioning monitoring is used to verify power-quality compliance, ramp-rate adherence, oscillation mitigation, and protection coordination. If operational data reveals behavior inconsistent with the validated model or creates reliability concerns, the utility may require further model updates, re-simulation, or operational mitigation. This closed-loop process ensures long-term reliability and stability as large AI-driven loads continue to grow.

Table 3.3: Pre-Energization Model Validation Requirements

Validation Category	Description	Typical Utility Expectation
Voltage Ride-Through	Validate sag/swell thresholds, delays, and reconnection logic for IT and cooling loads.	Utilities generally review full VRT curves;
Frequency Ride-Through	Validate disconnect thresholds, reconnection settings, and ramp-back behavior.	Must align with utility ride-through curves;
Ramp-Rate Limits	Confirm modeled ramp rates for load increases/decreases meet utility limits.	Many utilities specify maximum MW/min; Southern Co. uses 20 MW/min as an example.
Harmonic Performance	Validate current harmonic injections up to 50th order.	Power-quality limits based on IEEE 519 and utility policy.
Oscillation Mitigation	Ensure models avoid sub synchronous and inter-area frequency injections.	

Transformer Energization	Check inrush/RVC effects and modeled POC voltage dips.	
Protection Coordination	Validate modeled relay timing, ATS/STS transitions, UPS transfers.	required sequence testing.

Table 3.4: Monitoring Infrastructure for Model Validation

Validation Category	Description	Typical Utility Expectation
PMU	Captures sub-second voltage/current phasors and oscillations.	Confirms oscillation damping, ride-through, and transient accuracy.
Fault Recorder (ADFR/DFR)	High-resolution waveform capture during disturbances.	Event replay, protection logic validation.
Power Quality Meter	THD, flicker, harmonics, RVC, imbalance.	Confirms harmonic and flicker models.
Revenue Meter	MW/MVAR accuracy at PCC.	Validates power factor and steady-state load.
SCADA/RTU Telemetry	Operational states, MW/MVAR, UPS/BESS status.	Supports real-time behavioral comparison with model.

Table 3.5: Post Commissioning Monitoring and Validation Triggers

Monitoring Device	Purpose	Use in Validation
PMU	Captures sub-second voltage/current phasors and oscillations.	Confirms oscillation damping, ride-through, and transient accuracy.
Fault Recorder (ADFR/DFR)	High-resolution waveform capture during disturbances.	Event replay, protection logic validation.
Power Quality Meter	THD, flicker, harmonics, RVC, imbalance.	Confirms harmonic and flicker models.
Revenue Meter	MW/MVAR accuracy at PCC.	Validates power factor and steady-state load.
SCADA/RTU Telemetry	Operational states, MW/MVAR, UPS/BESS status.	Supports real-time behavioral comparison with model.

Chapter 4: Application of Data Center Load Models

The focus of this chapter is to provide insights on how to use the models shared in Chapter 3 to conduct power system studies.

Model Acquisition

The first step in any study is to acquire the model. A logical process that can be used to acquire models is shown in **Figure 4.1**. If a validated and quality tested model is unavailable it is required to acquire the model. In situations where a data center entity is unable to provide the model, or data center entities do not exist (e.g. special studies – future scenario), then it is possible to use a suitably parameterized **Standard Library** Model. It is important to use reasonable parameters, and one approach is to use publicly shared sets of parameters such as provided in Appendix E of this technical reference.

If the data center entity can provide the model, then it is ideal to get all reasonable models from the data center, so that the models are available as and when different studies need to be conducted. At the point of accepting the models, it is important to verify and validate the model quality.

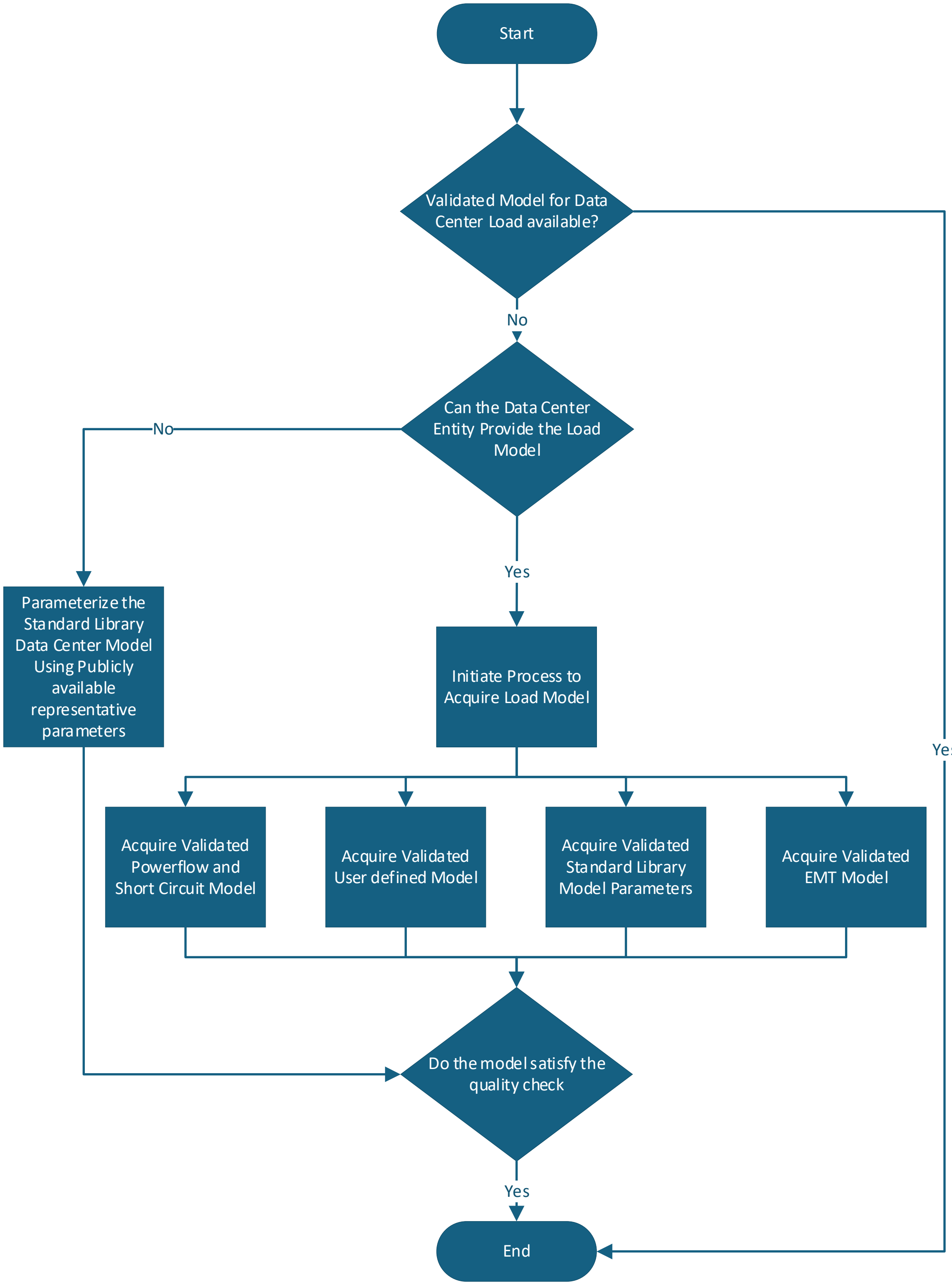


Figure 4.1: Process for model acquisition

Model Selection

Different types of studies could require different types of models, and it is important to select the appropriate model. For example, if the use case is an interconnection study and the study intent is to understand local impact, it might be best to use a User Defined Model which includes information that is specific to the load of interest. On the other hand, if the use case is to study the interconnection-wide response, it might be better to use appropriately parameterized standard library models. More information on model selection is provided in the NERC Dynamic Modeling Recommendations [36].

Study Process

The study process for a system with data centers will typically follow the same steps as any power system stability study process and will in fact follow most of the IBR study processes since the mechanisms for instability are similar. The Power flow and Stability Study Process is shown in **Figure 4.2** and **Figure 4.3**.

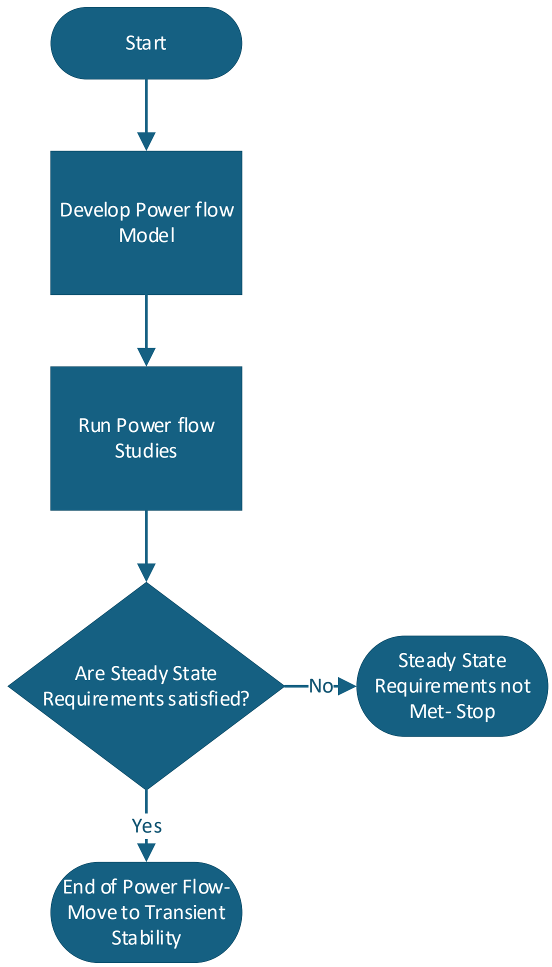


Figure 4.2: Power Flow Study Process

[36] NERC Dynamic Modeling Recommendations

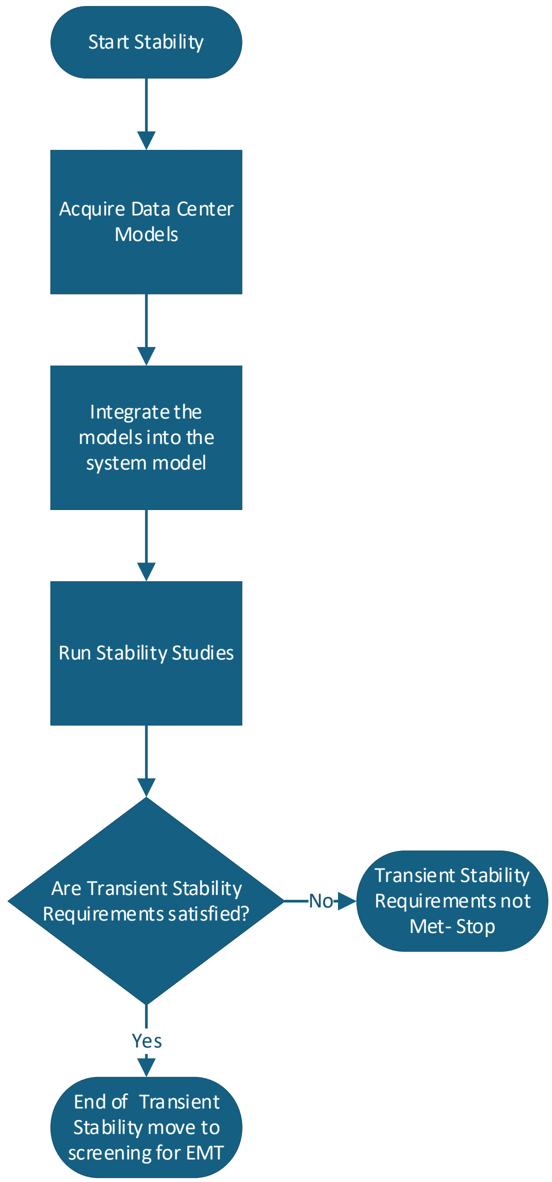


Figure 4.3: Stability Study Process

Need for EMT Studies

The need for conducting EMT studies for data centers is the same as for inverter-based resources. At minimum it is recommended to carry out screening studies to understand the need to carry out further EMT studies. A typical approach that can be used to screen for and conduct EMT studies is shown in

- Before deciding to conduct an EMT study it is possible to screen for possible stability issues due to controller interactions or weak grid conditions to determine whether a more detailed electromagnetic transient (EMT) study is required. Planners may need to transition to EMT only when high-frequency or weak-grid conditions suggest additional risks or based on engineering judgement The basis for the need for EMT Studies is the same as for IBRs and the readers are recommended to refer to the expansive literature available on how to run the screening studies, and how to determine when to conduct EMT Studies. Some example guides are below.

- NERC IRPS White Paper: Electromagnetic Transient Analysis in Operations Planning For BPS-Connected Inverter-Based Resources - June 2025 (Appendix C)[37]
- SSO Screening and Detailed Studies - ERCOT IBRWG Presentation[38]

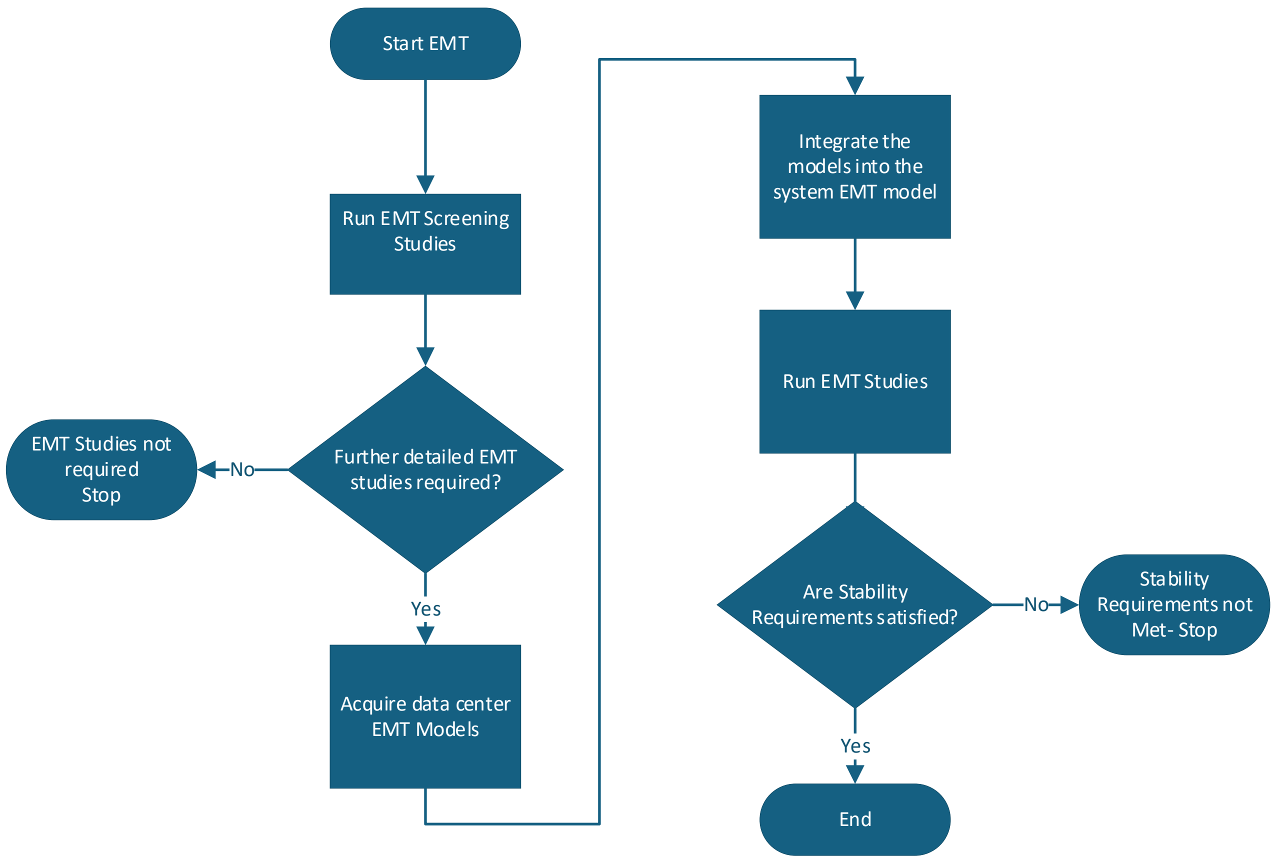


Figure 4.4: Process flow chart for EMT Studies

Data Center Response to Voltage Dips as Seen in Event Records

Experience with many data center event records to date indicates a generally constant power versus voltage characteristic during voltage dip disturbances. **Figure 4.5**, **Figure** 4.6, and **Figure** 4.7 illustrate data center and crypto mine responses to nearby faults typically seen when they ride-through the resulting voltage dip. In both instances, some transient effects are seen but power demand is essentially constant during the voltage dips.

[37] NERC IRPS whitepaper_-emt-analysis-in-operations_v2.0_final.pdf

[38] ERCOT IBRWG Presentation – October 11, 2024 - Anuradha Dissanayaka

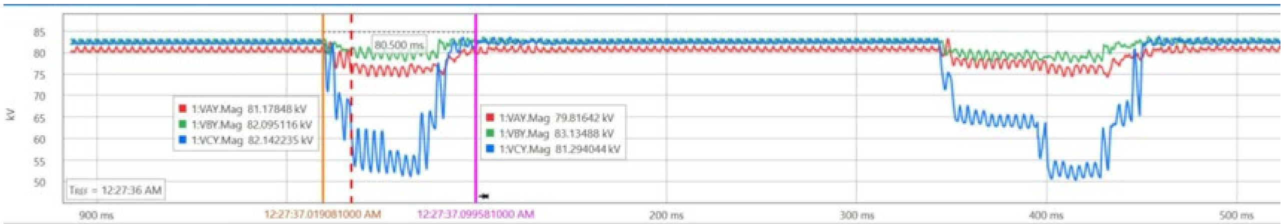


Figure 4.5: A point on wave plot of a data center successfully riding through a voltage disturbance (voltage curves)

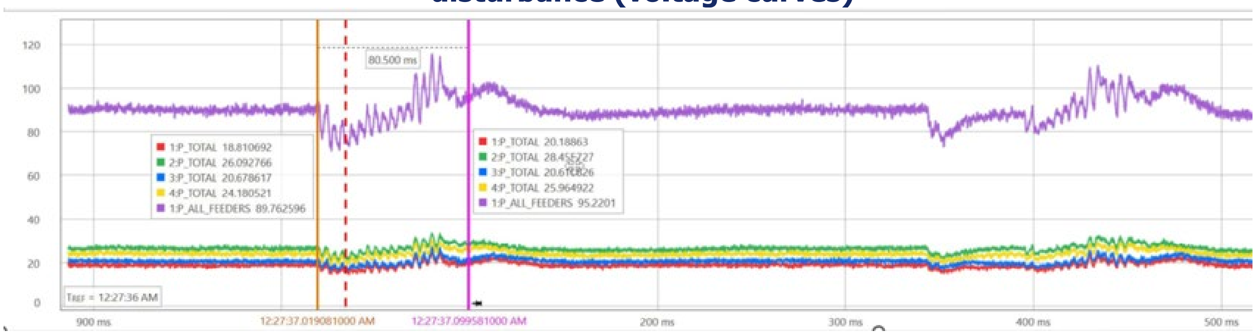


Figure 4.6: Typical data center active power response in MW to voltage dips (initial fault and unsuccessful high-speed reclose attempt) when riding through a nearby phase-to-ground fault.

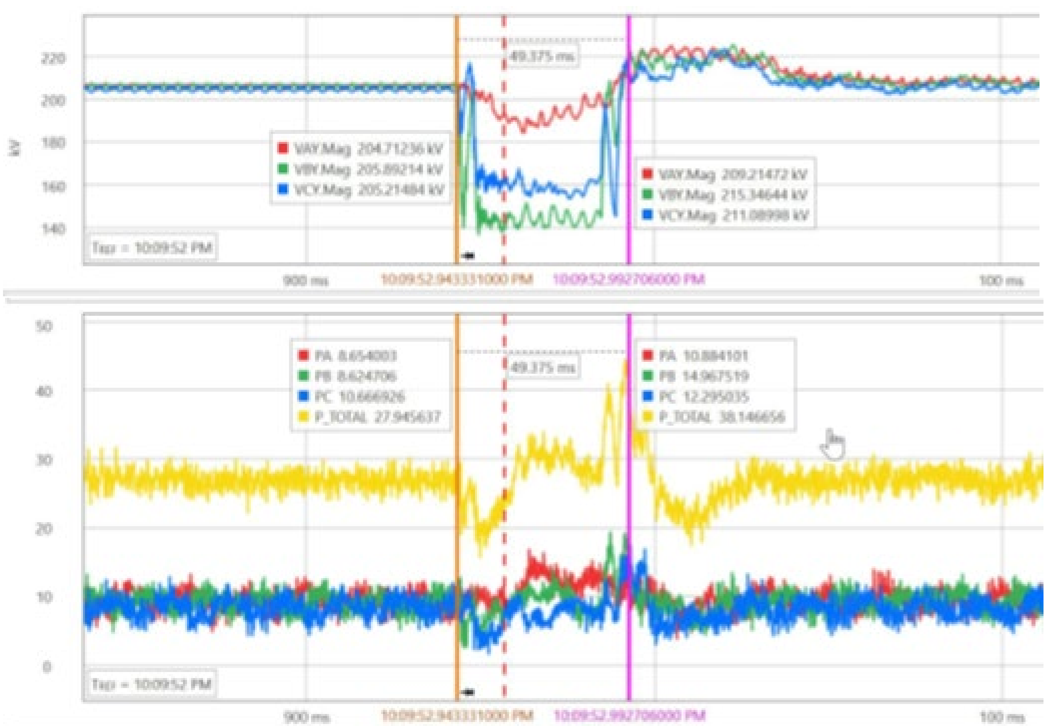


Figure 4.7: Typical crypto mine active power response in MW to a voltage dip when riding through a nearby phase-to-phase fault.

Data centers, as presently designed and built, tend to drop off the system if the voltage dip is deep enough, long enough, or if multiple dips occur frequently enough, and not resume drawing power from the system right away upon fault clearing as most other loads do. **Figure 4.8** illustrates a data center dropout in response to a sequence of preceding voltage dips associated with unsuccessful auto-reclosing after a transmission line fault. The data center rides through the voltage dip event bit then very quickly ramps its power down to zero within about 50 milliseconds.

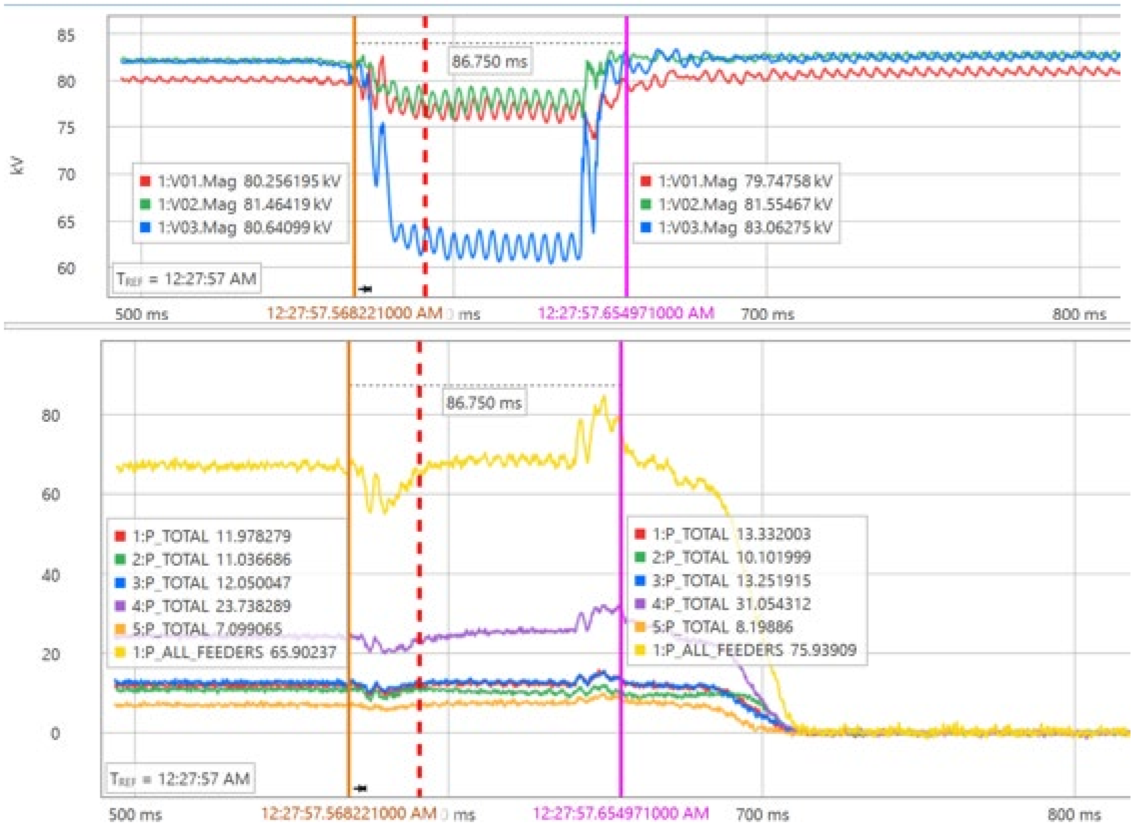


Figure 4.8: Data center with protection logic that counts voltage dips within a pre-set time window response to multiple voltage dips resulting from a nearby phase-to-ground fault and unsuccessful reclose attempts

Event Triggered and Continuous Monitoring Recommendations

The above event records are relay oscillographs which are equivalent to digital fault recorders (DFR). Event recording by DFRs and relays with DFR-type functionality are triggered by events exceeding frequency and voltage thresholds and generally only record for a second or two but not much more. Phasor measurement units (PMR) are also capable of recording faults and the reaction of loads to faults. The advantage of PMUs is that they record continuously and do not depend on frequency or voltage excursions to save event data. However, PMUs are typically set to record 30 or 60 samples per second which is not a sufficiently high rate to accurately discern frequencies toward the higher end of the sub-synchronous frequency range. PMU rates would need to be increased to at least 120 Hz but preferably 240 Hz to cover the sub-synchronous range up to 55 Hz. Alternatively, DFRs or relays with DFR functionality may be triggered manually to record ambient load conditions such as may be the case with AI / ML activity. However, if AI / ML cycling of data center power demand is to be continuously monitored for compliance with restrictions set by Transmission Owners or Regional Transmission Operators, higher resolution point-on-wave devices will be necessary.

Positive Sequence-Phasor Domain (PSPD) Model Parameterization

The PERC1 model described in the previous chapter has been introduced to represent data center electronically interfaced load including all computational load as well as variable frequency drive (VFD) and electronically commutated motor (ECM) driven cooling equipment. If a data center applies specific fault ride-through control logic by means of voltage drop out and restoration thresholds and associated time delays, the PERC1[39] model is essential.

In the case of data center loads for which the UV protection settings are uncertain or the data center operates without any UPS, one might assume any voltage drop below 0.7 pu for 20 ms or longer will cause the load to revert either to UPS battery or UPS battery then backup generation and not return to the utility source for the duration of a simulation. This assumption is derived from the Information Technology Industry Council (ITIC) curve (formerly Computer & Business Equipment Manufacturer's Association or CBEMA) curve shown by **Figure 2.5** and appears generally supported by field observations to this point, though with some variability as to the exact voltage threshold and time delay at any given data center.

As an example of PERC1 use, a recent planning study of a transmission build up plan to accommodate future data center load growth initially applied the CMLD electronic component which resulted in artificially undamped power swings. Because of the abundance of data center constant power load in the study area and the strict constant power boundary condition of the CMLD electronic component, negative damping was introduced. Use of the PERC1 with the washout block enabled softened the constant power boundary condition in the transient time frame enough to suppress the negative damping. See Figures 4.X5a and 4.X5b.

[add these figures]

The electronic load component in the composite load model (CMLD) has been applied to represent data center computational load in planning studies in the past and may still be used. This component consists of the below four parameters:

- Fel - Electronic Load Fraction[40]
- PFel - PF of Electronic Loads
- Vd1 - Voltage at which electrical loads start to drop
- Vd2 - Voltage at which all electrical load have completely disconnected
- Felrst –Fraction of electronic load that can restart

Data center cooling and ventilation load may similarly be represented in a simplistic constant power fashion in the same manner if variable frequency drive (VFD) or electronically commutated motor (ECM) driven. If there are directly connected induction motor loads, the three-phase motor models within CMLD (pump, fan, or compressor) may be applied. However, the electronic component undervoltage (UV) dropout feature in CMLD is limited to a constant power versus voltage characteristic with either a single UV threshold value or a linear drop-off between two UV values and there is no provision for representing time delays associated with either dropout or restoration. CMLD can simulate only immediate dropout and immediate restoration of a preset fraction of the load assigned to the electronic component. **Figure 4.9** illustrates operational logic of the CMLD native electronic component model. **Appendix G** shows a comparison between PERC and the

[39] Power Electronic Reconnecting and Ceasing Model

[40] This is not a parameter that shapes the response of the electronic load – rather provides the amount of electronic load relative to the full load represented by the CMLD model. More information on the CMLD model and its application is available in the NERC Load modeling technical reference.

PE component and highlights the insufficiency of the native Power Electronic Component to capture data center dynamic response. Using it will result in optimistic results that will conceal valid reliability impacts.

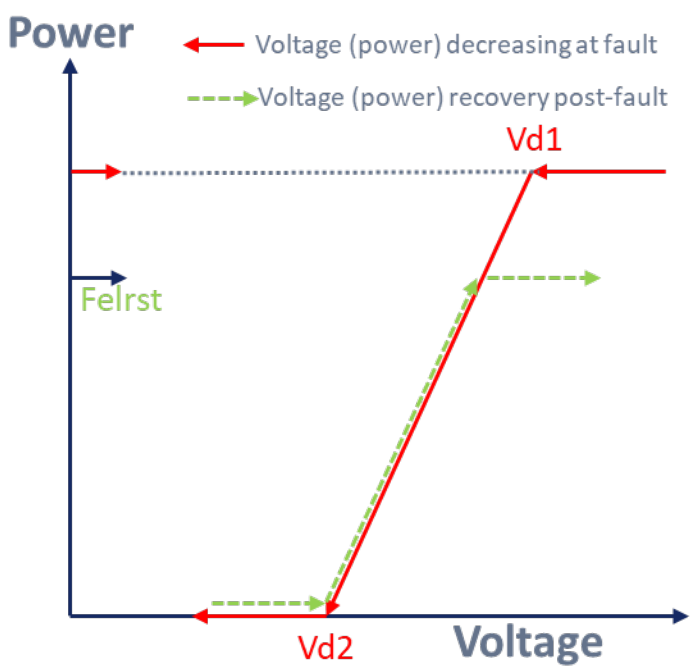


Figure 4.9: The operational logic for the native five parameter electronic component in the Composite Load Model (CMLD)

Positive Sequence-Phasor Domain (PSPD) Studies

Data obtained from data center customers for interconnection studies may be preliminary or of questionable accuracy. In such instances, uncertainty as to data center ride-through performance, that is, whether a system disturbance-caused prolonged transfer to UPS battery or backup generation may occur, is a relevant question. When faced with such uncertainty, a recommended practice in running data center interconnection studies is to assume both 100 percent fault ride through and 100 percent undervoltage dropout as study bookends. First assume 100 percent ride through to test the ability of the system to accommodate the proposed load post-contingency if it should happen to ride through by running all planning event contingencies relevant to the POI. The constant power nature of data center load means these can generally be studied by powerflow analysis alone. Then run selected planning event contingency simulations at and near the studied POI to check for load loss potential assuming the as-given UV protection threshold and time delay. If there is a lack of any specific UV protection data available, a 0.75 per unit instantaneous electronic load dropout level consistent with the ITIC graph as mentioned above and with no restoration in the CMLD data may be assumed.

If a study objective is to assess the potential over-frequency or overvoltage risk caused by multiple data centers dropping out during or following faults, consideration is necessary for determining the extent of the study area wherein multiple data centers may exist. Identifying the study area requires engineering judgment but a check may be run by applying three-phase faults at the proposed data center POI and any other nearby data center POI and noting the buses experiencing significant voltage drop during the fault, say 80 percent or below. This allows one to confirm that all buses experiencing a significant voltage drop are included in the study area. In this fashion, any data center with an undervoltage dropout risk within the area of significant observed voltage drop should be represented in the study. Conceptual examples are shown in **Figure 4.10** (the tan-colored area represents buses experiencing voltage drops) and **Figure 4.11 (**example consisting of a voltage gradient heat map showing how voltage varies with respect to distance from fault location).

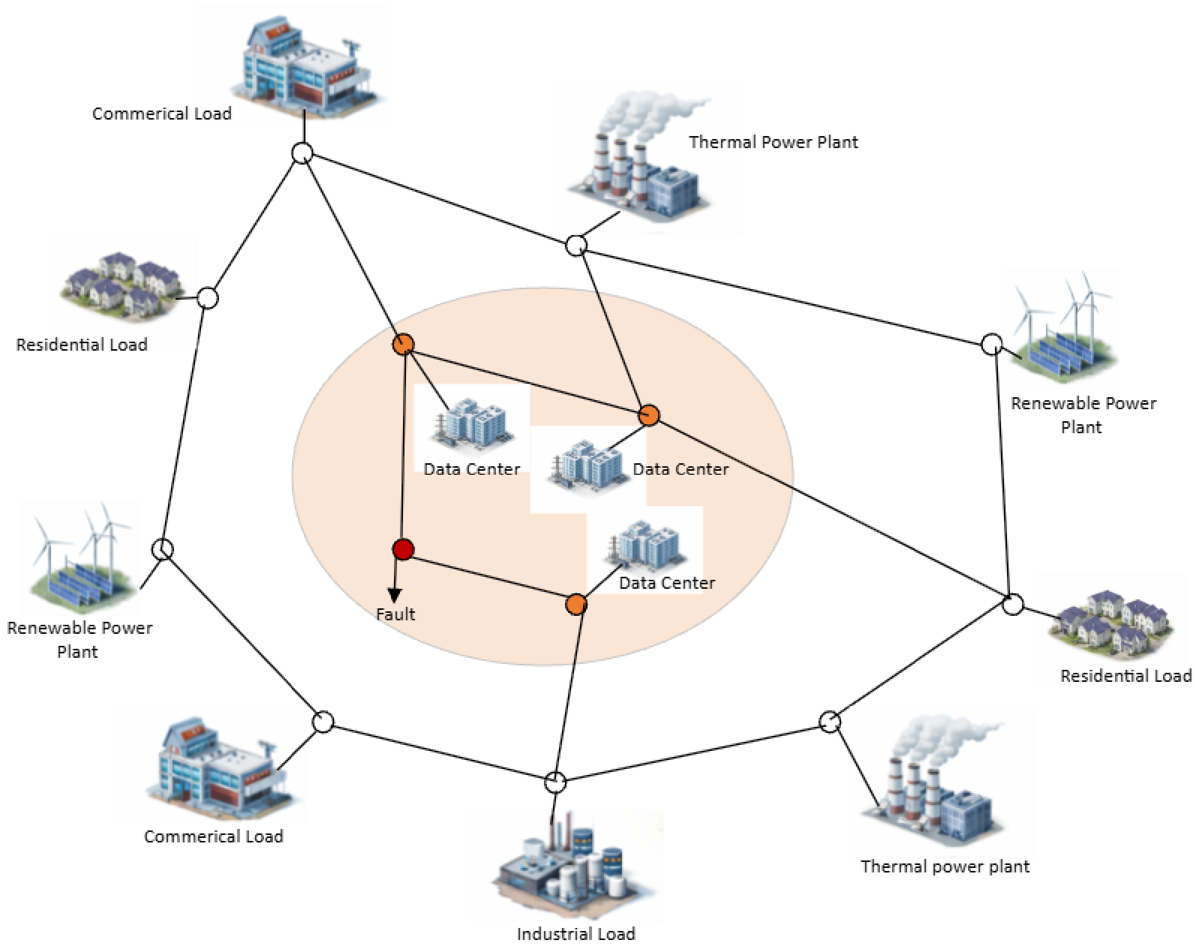


Figure 4.10: A conceptual example of an area voltage drop exceeding an undervoltage dropout threshold

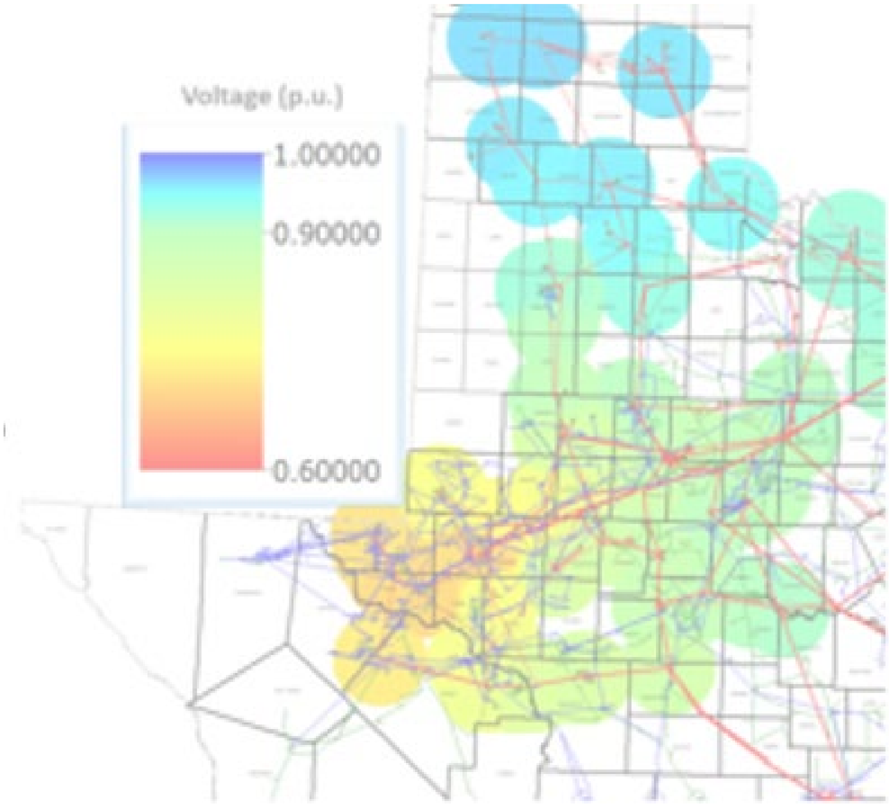


Figure 4.11: conceptual example consisting of a voltage gradient heat map

Another variable that may be analyzed besides uncertain undervoltage ride through thresholds is UPS percent initial loading. This variable will affect how much current draw may be seen during a voltage dip. If the power supply devices are near 100 percent loading pre-dip, since they are current limited, current will not increase during a dip. If the power supply devices are operating at less than 100 percent of their ratings, because they draw constant power, a current increase will be seen during a dip, and depending on the magnitude of the dip, current may increase as high as the rating of the devices.

Yet another possibly uncertain variable worthy of study is the timing of UPS restoration back to utility source from all or some of the computational load having been supplied by UPS batteries during a voltage disturbance. UPS devices can be programmed to recover quickly or slowly and may be programmed with adjustable delays and ramp rates. How quickly load is restored will affect how much of a high frequency excursion and possibly high voltage excursion will be seen in the utility source.

Data Center Voltage Disturbance Load Loss Risk

In any utility electric grid, generation and load must be always kept in balance to maintain interconnection frequency within a tight bandwidth. Generation-load imbalances cause interconnection-wide frequency to deviate from 60 Hz either up in the case of load loss or down in the case of generation loss. Large frequency deviations in either direction can result in damaging effects on generation and increased risk of generation loss which will aggravate an already existing low frequency condition or cause an over-frequency condition to suddenly become an uncontrollable under-frequency condition. Utilities are accustomed to dealing with sudden generation loss events as forced outages of individual generating plants occur from time to time. These are typically caused by issues that arise within the plants themselves unrelated to disturbances on the electric grid. Utilities are less accustomed to major load loss events. And now with individual voltage sensitive loads that are much larger than what has been present in the past, the risk of major load loss events and consequent high frequency is increasing.

The ability of interconnected systems to correct for high frequency events is at least as great, if not greater, than low frequency events. Many generating plants, including wind and solar farms operate up to their capability and cannot govern to increase their power. This generation can, however, usually govern to decrease power in response to high frequency. On the other hand, because data centers are tending to congregate in certain localities, fault events may not just be seen by one data center but possibly many. Thus, the risk of data center dropout and consequent load loss, especially during fault events affecting multiple data centers, could potentially be of much greater magnitude than any single generation loss event. Further, unlike generation, loads are presently not subject to mandatory voltage ride-through standards and requirements. However, some utilities and ISO/RTOs are beginning to require large load owners to comply with specified voltage ride-through and disturbance performance requirements as a condition of interconnection or service.

As with forced outages of generation, faults (short circuits) on the transmission system occur from time to time subjecting data centers to voltage dips of magnitudes that can affect their ability to continue to draw power from the grid. Any fault will present concentric footprints of certain voltage dip magnitudes somewhat like contour lines on a topological map. A data center near a fault will see a greater voltage dip than a data center further away. Depending on the sensitivity of loads and their locations with respect to a fault location, any fault could well put not just one but possibly many voltage-sensitive loads at risk of dropping out. There is not much that can be done on the utility side to remove or even minimize fault-caused voltage dips except to clear them as quickly as possible. Fault clearing requires detection by relays, operation of circuit breakers, and depending on the protection system, communication between stations. Fault clearing cannot occur in less than 3 cycles with normal clearing typically in the 4-6 cycle range. If protection equipment fails, the fault durations can be extended to 10s of cycles but rarely more.

A second factor affecting voltage sensitive loads is automatic reclosing of faulted transmission lines. Auto-reclosing is a common utility practice and a benefit to overall system reliability when faults are temporary (such as when caused by lightning) allowing lines to be quickly restored. However, when faults are permanent, such as when lines are contacted by an object, there may be multiple voltage dips within a short period of time, typically a minute or so, as reclosing attempts fail and the fault is re-cleared after each attempt. After so many pre-programmed attempts to reclose, typically 3-4 at the EHV 345 kV and above voltage class level, the automatic reclosing operations cease.
Ideally, data center UPS systems would ease the load loss burden on utility sources if they could be designed and programmed to do the following in response to fault-induced voltage dips:

8. During a voltage dip, either maintain the same magnitude of current draw from the utility source as prior to the dip or operate at a higher but restricted level of current draw. Depending on the magnitude of the dip, supplement the utility source with contribution from the UPS battery as necessary to maintain continuity to the load. It is presumed the UPS would immediately flip over to double conversion mode if it had been in eco mode prior to the dip. Maintaining a constant or restricted current draw from the utility source in this manner will lessen the magnitude of any voltage dip.
9. Once a voltage dip is over and the utility source voltage returns to its normal range, revert back to the utility source immediately by discontinuing further contribution to the load by the UPS battery. Immediate restoration of load back to the utility source once voltage returns to normal will avoid

the difficulties of major load amounts dropping from the utility source, even for short durations following faults, and greatly assist the utility in maintaining the generation-load balance.

The potential of data center UPS systems to ease the load loss risk that data centers are beginning to present to utility electric grids is presently a subject of investigation.

Data Center AI / ML Cycling Risk

Data centers that are engaged in AI / ML training can produce a rapid cyclical MW demand and are a risk of forcing oscillations into the system in either the electromechanical inter-generational range of 0.2 to 2.5 Hz or in the sub synchronous range of approximately 10 to 50 Hz. Examples of cyclical demand are shown in**Figure 3.8.**

Electro-mechanical inter-generational swing modes are present in interconnected electric grids at all times but they are all well damped under all conditions except for possibly the most extreme. These swing modes involve exchanges of energy between individual generators and the rest of the system or between two or more groupings of generators in different localities. In any interconnection, there are large numbers of these naturally occurring modes concentrated in the 0.2 to 2.5 Hz frequency range. These modes also tend to change over time with generation levels and dispatch. It's only when there is a continual provocation at the right frequency at a location that a given mode is susceptible to that one would begin to see continuing oscillations in regions of an interconnection. Cyclical injections from any source at any frequency in this range may provoke one of these electromechanical inter-generational modes within an interconnection. It depends on location of the injection, the frequency, and the controllability / observability matrix of a given swing mode. Sustained oscillations may be seen even quite remote from the injection location, especially if the mode is in the lower inter-generational range. These sorts of scenarios are called forced oscillation events and they can be detected by dynamic monitors called phasor measurement units (PMUs). The location of a cause can be difficult to track down but once operators discover that the source is within their footprint, they can disconnect it to resolve the problem. That is what had to be done in a few past forced oscillation events. Acceptable levels of injections at any of these frequencies are not easily determined. Studies are not generally run to figure out what these modes are and their vulnerability to being provoked. The best thing to do is just avoid prolonged injections within these ranges.

The mechanical shaft systems of turbine generators have naturally occurring modes of oscillation between and among the different turbine sections or between turbine sections and the generator itself. The rotor masses can oscillate against each other in different groupings at different frequencies along the shaft system. These sub synchronous modes are designed to be well clear of 60 Hz and are sufficiently damped under normal operation that they are not a problem. If provoked on a continuing basis, however, there is vulnerability to material fatigue and even catastrophic failure. As with the electromechanical inter-generational modes, so it is with sub synchronous torsional modes within the 10 to 50 Hz frequency range. Here again, an acceptable level of cyclical injection is difficult to determine in general and depends on proximity to a generating plant and how closely the frequency of injection aligns with a particular mechanical mode frequency.[41] The mode frequencies are generally unknown for any given generating plant. It is only known that they are present and sufficiently damped as not to be a problem under normal conditions. Fatiguing would be very difficult to detect until there is real damage. There is no monitoring generally installed that can reliably detect when sub synchronous modes are being provoked. Torsional monitors can be installed if a potential for mode provocation is known but it would also have to be rigged

[41] There is a 60 Hz compliment relation between electrical and mechanical frequencies wherein a mechanical frequency will be seen as equal to 60 minus an electrical frequency. For example, a sinusoidal 20 Hz cyclical injection by a data center will be seen as a 40 Hz frequency (60-20=40) on the mechanical shaft system. If cycling is more square wave in nature than sinusoidal, there will be side bar frequencies that will make any analysis of risk more complicated.

to trip either the generator or the data center. Neither action is desirable. Therefore, it is best just to stay entirely clear of any continuing cyclical injections within this range, especially if there are synchronous generating plants nearby.

Forced Oscillation Suppression or Remediation

Data center representatives indicate that the AI / ML cycling is difficult to avoid and even to predict as to frequency content and duration. Preventing or suppressing the effects of this from being seen on the transmission system will require some form of counter-acting or counter balancing of active power. Battery energy storage systems and statcoms equipped with energy storage capability in the form of capacitors can, in theory, smooth out variations by alternately charging and discharging, but may not remove them entirely. If an AI / ML data center is to be co-located with any synchronous generation or if there is synchronous generation nearby, consideration should be given as to what requirements or limits on the effects of cycling to be seen at the POI should be placed upon that interconnection request.

Electro-Magnetic Transient (EMT) Modeling and Studies

Sub synchronous control interaction (SSCI) and sub synchronous ferro resonance (SSFR) interaction between data centers located on or near series compensated transmission lines are two reliability risks that require study in the EMT domain. Either or both may occur when a data center becomes connected radially through a series capacitor during a contingency. Simulation of SSCI phenomena requires accurate data center models, preferably real-code models that integrate the converter firmware within the EMT model. Simulation of SSFR involves only the data center main power transformer(s) which should have an accurate saturation curve represented. The probability of SSFR increases in the case of nearby multi-phase faults causing post-fault voltage transients.

To properly study interactions, it is obvious that the data center under study needs to represent realistic response to a reasonable set of simulated system conditions including faults under different system contingencies. Accurate modeling of protection and control that pertains to disturbance ride-through is desirable, but future large load ride-through requirements may necessitate improved disturbance ride-through that needs to be analyzed.

In view of this need, another use of EMT modeling and studies pertains to individual phase POI to end-use load power supply device voltage-to-voltage transitioning or correlation. Depending on step-down transformer configuration(s), whether delta-wye or wye-delta, and possibly the facility internal secondary distribution configuration, individual phase POI and low voltage bus correlations may be different. The individual phase voltage seen at the POI may not correlate to individual phase voltage at device terminals. As many data center end-use devices are individual phase rather than three-phase, this difference will influence ride-through performance that may only be analyzed on a three-phase basis. A discussion as to other uses of EMT modeling and studies may be found in [1].

Short Circuit Studies

In general, data center loads do not contribute significantly to short-circuit current. The cooling systems are generally direct or ECM or VFD interfaced induction motors. They do not use synchronous motors. However, if there are either existing short circuit concerns, or if a large cluster of data centers are being served in a small electrical area driving the short circuit levels upwards, a study may be required to confirm that fault current levels remain within breaker duty limits.

Co-located Data Center Load Studies

Introduction to the Co-located Load

A co-located load configuration refers to end-use customer load that is physically connected to the facilities of an existing or planned generation facility on the interconnection customer's side of the point of interconnection (POI) with the Transmission System. Co-located load is distinct from and does not include station power load. Although located behind the POI, co-located load remains electrically connected and synchronized to the Transmission System when consuming power, and therefore benefits from the use of the Transmission System and its associated Ancillary Services.

There are both advantages and challenges associated with co-locating data center load. For example, data centers can source power directly from adjacent generator(s), reducing reliance on wholesale market purchases. However, this arrangement can introduce technical complexities if the co-located generator(s) are forced out of service by either system disturbances or internal plant causes.

To increase sourcing flexibility, a large co-located data center load is often connected to a plant with multiple generators. For instance, if two units are available, the load is normally distributed evenly between Unit 1 and Unit 2. If one unit or its associated electrical path is lost, the load will be served from the remaining unit. Typically, co-located data center load is connected to the high side of the generator step-up (GSU) transformer through a T-terminal with step-down transformer(s).

Co-located Data Center Load Modeling and Study

Interconnection reliability studies should be run to evaluate the impact of a large co-located data center load on the existing generation and the local transmission system. These should consist of at least power flow analysis and may need to include dynamics studies, PSPD and possibly EMT depending on the POI location and circumstances.

Power Flow Study

Studies should check for thermal and voltage limit exceedances should existing generator(s) trip offline. The transmission system should be able to serve the load without its associated generation unless the load is explicitly designed to trip with the generator by means of a RAS or a configuration arrangement wherein the load is disconnected along with outage of the generation.

- The co-located load can be modeled as a constant PQ load with an expected or assumed power factor.
- It may be desirable to model step-down transformers down to a distribution level (e.g., 69 kV or 34.5 kV). If transformer details are not available, they may be omitted, but the equivalent load must account for estimated active and reactive losses.

Stability Study

Studies should check for potential instability of the associated generation if that generation is stability constrained and there is a possibility of data center UV dropout. In this case, the associated generation may become destabilized or exceed an established operating limit should there be a significant loss of the co-located load.

- IT server loads should be mapped to the power electronics portion of CMLD. Check CMLD parameterization provided by customers for possible errors in the allocation of fractions for IT server load, cooling load, lighting, and losses.
- The current composite load model (CMLD) may not adequately capture complex fault ride-through behaviors of data center loads though simplifying assumptions may be satisfactory depending on the

objectives of the study. Customer-provided ride-through information and dynamic models should be carefully reviewed, however.

It is recommended to collect as much **detailed technical information** on the data center load as possible. The NERC Data Center Information Collection Questionnaire[42] is recommended as a reference for obtaining and verifying customer-provided models and parameterization. Again, if a data center load uses specific fault ride-through logic for IT servers that CMLD cannot represent, a **user-defined dynamic load model** or the more elaborate PERC1 model as described in the previous chapter may be necessary depending on the needs of the study. To enable the use of different load component models, the single co-located load in the power flow model may need to be split into several pieces, representing IT server load, cooling load, and lighting and losses.

[42] https://www.nerc.com/globalassets/who-we-are/standing-committees/rstc/lmwg/data-center-information-collection-questionnaire.pdf downloaded on November 26, 2025

Chapter 5: Conclusion

Traditional load models are insufficient to capture realistic dynamics of data centers due to the complex characteristics in data centers. Modeling approaches for data center loads has to evolve significantly, moving from static power electronic representation to full representation to be able to capture realistics response and address the realiability risk associated with unprecedented scale, speed, and growth in omplexity of modern electronic loads.

The technical reference provides the practitioners with neccasaary technical information and guidance to create realistic models for data centers, and carry our studies that allow to study different phenomena associated with data centers.

Validated, high-fidelity simulations enable transmission planners, system operators, and facility designers to anticipate system impacts, optimize interconnections, and ensure grid stability under both normal and contingency conditions. As data center capacity and deployment continue to grow, continued collaboration between utilities, regulators, manufacturers, and research institutions is essential to refine load models, integrate operational data for calibration, and maintain resilient, reliable power system operations. Ultimately, robust data center load modeling serves as a critical foundation for informed planning, and reliable integration of data centers

Appendix A: Glossary of Terms

Term	Description
API	Application Programming Interface is a software-based method for communicating between applications and systems.
Computational Loads	Refers to IT Equipment Loads
DCN	Data Center Network interconnects all IT data center resources together.
CRAH	
CRAC	
GPU	Graphics Processing Unit uses parallel processing which is useful when training and running AI models.
Gray Space	Defined as the area of a data center where mechanical systems such as cooling systems, generators, transformers, UPS and switchgear are located. Typically maintained by facilities managers.
HPC	High Performance Computing is often a cluster of powerful computers to solve complex problems.
Meet-Me-Room	MMR dedicated space for connecting the data center to external sources, ISPs or other data centers, cross connects between different tenants or internal systems.
OEM	Original Equipment Manufacturer builds components which are used by another company to make their own finished products.
PSCAD	Power Systems Computer Aided Design is an application for modeling electromagnetic transient simulations.
IT Load	Information Technology Loads – Encompasses Computer, Network and Storage server loads
PUE	Power Usage Effectiveness measures data center efficiency by comparing the total energy used in a data center against the IT equipment load. PUE value is usually less than 1.3 meaning that the non IT load is at 30% of the IT load or less.
Rectifier	A device which converts alternating current (AC) to direct current (DC).
Torsional Vibration	The oscillatory twisting of a rotating component.

UPS	
White Space	Defined as the area where IT equipment is located, racks of servers, network gear, PDUs and CDUs. Typically maintained by an IT team.
WUE	Water Usage Effectiveness measures the ratio between the total water used in a data center against the energy consumption of the IT equipment.

Appendix B: Future Power Distribution Architectures

As server power densities approach 1 MW per rack and the need for more space on the rack for AI gear increases, newer power distribution architectures will be needed to support these higher power densities and space constraints.[43] The data center industry is moving forward with utilizing direct current for power distribution at both 400V and 800V.

To transition to these higher DC voltages, the data center designs are looking to adopt a sidecar power rack that will convert the incoming AC to 400/800V DC. The Open Compute Project has a design as proposed below where incoming power is stepped down to 416/480/600V AC and then converted to 400V DC in the sidecar as shown in **Figure 5.1**. Then 400V DC is distributed to the servers where a dc-dc converter steps the voltage down to 54V DC.

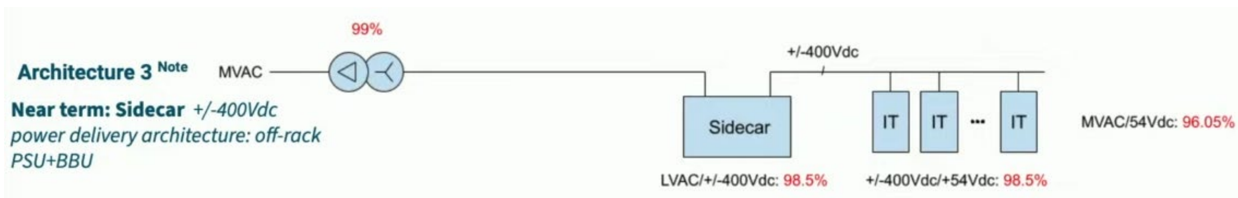


Figure 5.1. Sidecar Based Power Distribution Architecture

With the sidecar system shown in **Figure 5.2Error! Reference source not found.**, the power infrastructure is split from the compute infrastructure as the power infrastructure has its own dedicated rack.[44] This sidecar system addresses the challenges of not having enough room in the traditional rack for battery backup units or supercapacitors for power smoothing.

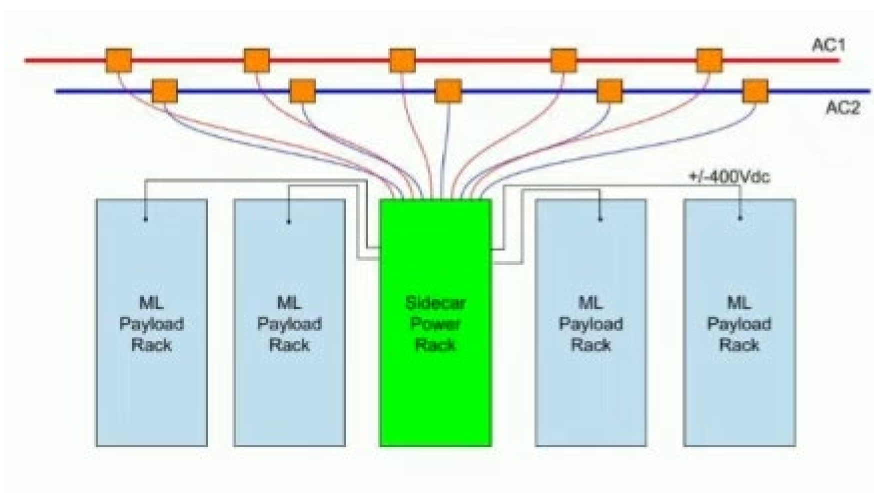


Figure 5.2. Sidecar with Power Infrastructure and Compute Racks[45]

However, the sidecar system is an intermediate design. Eventually data centers want to transition to a site wide DC distribution network at 400/800V DC as shown in **Figure 5.3**. This architecture will utilize a solid-

[43] https://blog.se.com/datacenter/2025/10/16/the-1-mw-ai-it-rack-is-coming-and-it-needs-800-vdc-power/
[44] https://cloud.google.com/blog/topics/systems/enabling-1-mw-it-racks-and-liquid-cooling-at-ocp-emea-summit
[45] https://www.youtube.com/watch?v=l8ChVDv5aoo

state transformer (SST) to convert the medium voltage from the grid interface to 400/800V DC. Then the power is distributed to the servers where a dc-dc converter steps the voltage down to 54V DC.

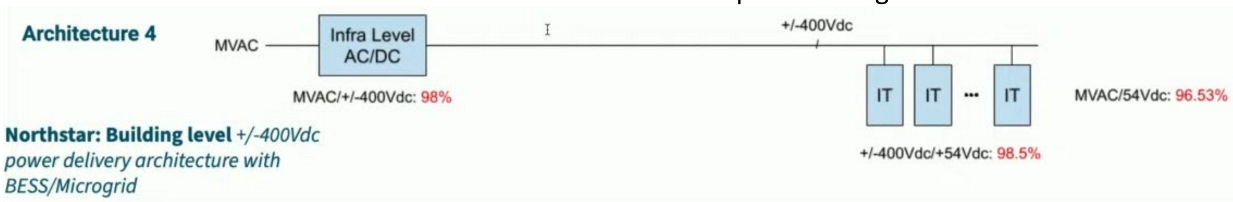


Figure 5.3. Infrastructure Level DC Power Distribution Architecture

Similarly to the 400V DC power distribution system in **Figure 5.4** Nvidia is proposing an architecture based on 800V DC that also utilizes a solid-state transformer as shown in **Figure 5.5.**

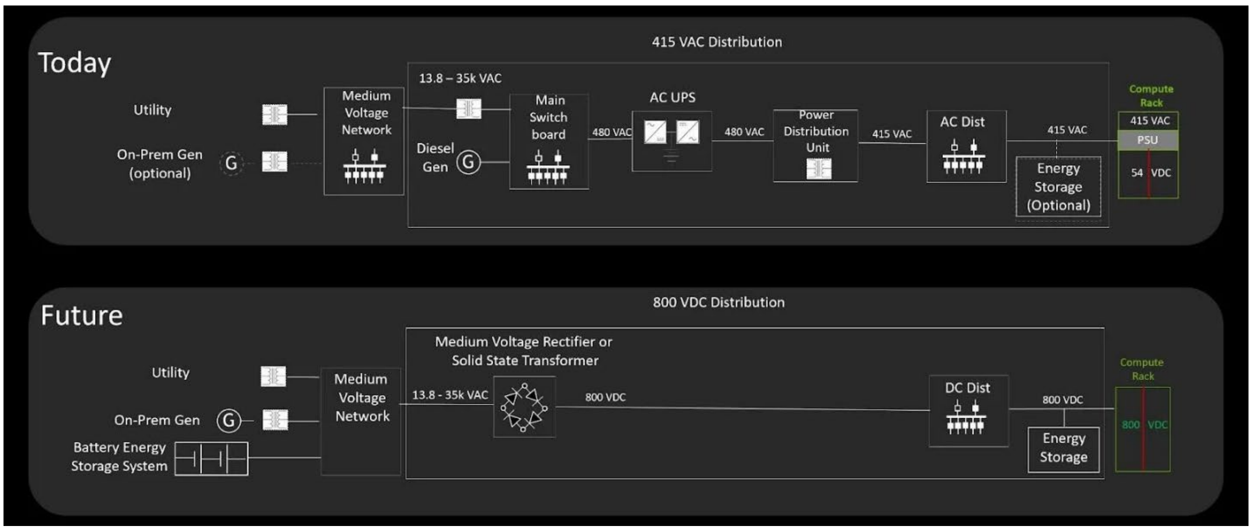


Figure 5.4. Nvidia 800V DC Power Distribution System[46]

In these future designs, the UPS will be phased out for a battery backup unit at the sidecar and then the infrastructure level.

[46] https://developer.nvidia.com/blog/building-the-800-vdc-ecosystem-for-efficient-scalable-ai-factories/

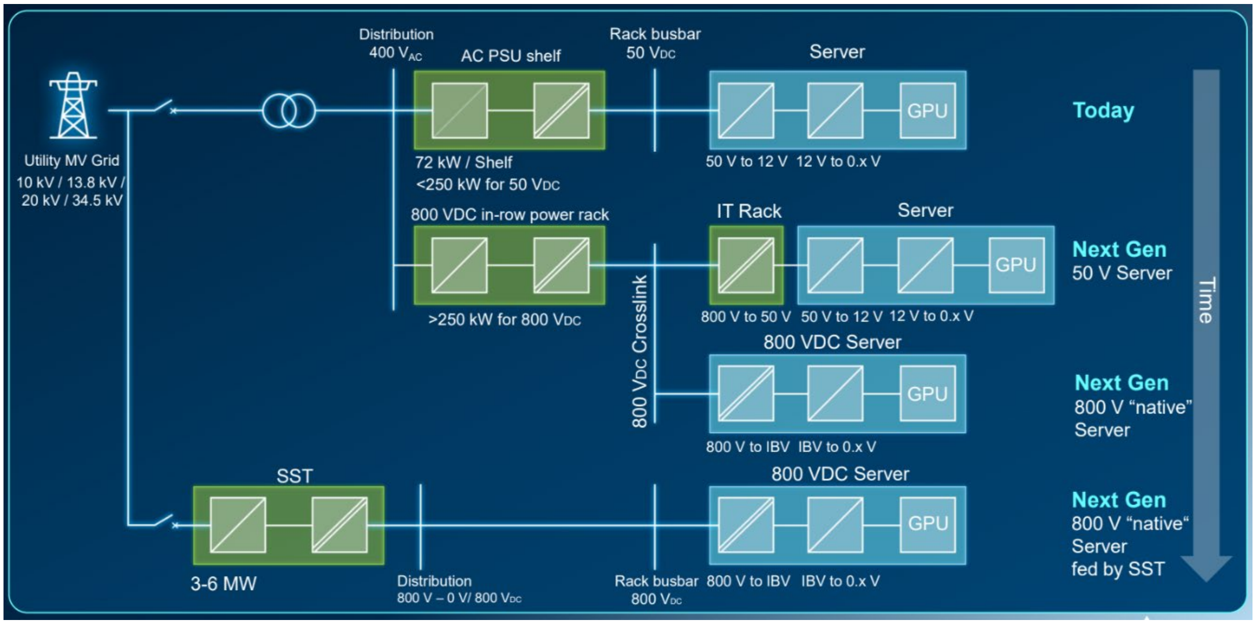


Figure 5.5. Consolidated Diagram of Current and Future Power Distribution Architectures[47]

Operation of the ATS

ATS transition loads between normal and an emergency source with transition options (open/closed). An open transition would be considered a break-before-make transfer which prevents the two sources from connecting during the transfer. A closed transition would be considered a make-before-break transfer that connects the two sources before disconnecting the alternate source. This allows for continuous power provided to the loads during the transfer process.

The switching mechanism for the transfer process would either be a contactor type, molded case circuit breaker, or power circuit breakers up to 5000 amps. The contactor solution is the most cost effective and can be provided by some manufacturers for up to 3000 amps.

Another typical feature of the ATS used in the data center could be the Bypass Isolation ATS that provides improved uptime. This ATS can handle the standard transition from normal to emergency but also offers a bypass switch that serves as a redundant device.

The application or use of an ATS in a critical facility must also consider the withstand current rating (WCR) to ensure the system continues to be reliable when in service. The UL 1008 standard allows for the ATS to be marked with more that one short-circuit and/or short-time WCR as related to the overcurrent protection device type.

[47] https://drive.google.com/file/d/1U9qKtiI-S5xwHPGclfJi3Y_tDGIWxkwE/view

Appendix C: Data Center Load Characteristics

Use cases for computational loads come in many shapes and sizes. As a result, the resultant load profile comes in different shapes and sizes depending on the computational load and end use. This section will describe the primary categories that most computational load shapes fall into.

Traditional Data Centers

Traditional data centers are the oldest (hence the name) and most common type of data center. These data centers most frequently serve websites, applications, and other online products that require data transfer, storage, and computing. IT equipment makes up a majority of the total data center's energy usage. Of all data center types, traditional data centers have the least variable demand profile. In other words, the power demand stays consistent over most time periods. In a report from the Demand Response Research Center, they noted that the daily and yearly load is flat for these types of data centers.

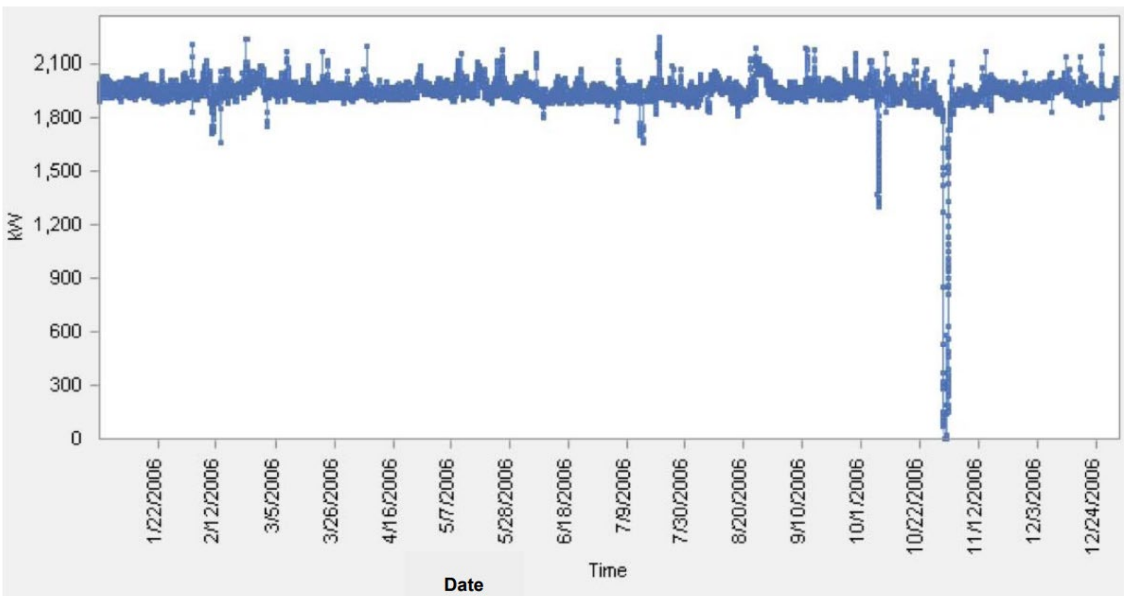


Figure 5.6: Data Center Annual Load Shape for 2006[48]

The report from the Demand Response Research Center also documented a mixed-use office and data center load. They noted that the data center load itself remained relatively constant, similar to the standalone data center load facility. However, the office space load varied primarily with time of day and weather, like a typical conforming load.

Cryptocurrency Mining Facilities

The load shape of cryptocurrency mining facilities is generally described as "flat until it's not". Cryptocurrency mining facilities perform data transfer, storage, and computing, just like traditional data centers. They also aim to maintain as much uptime as possible. The primary difference is that cryptocurrency mining facilities can be responsive to the real-time price of electricity. When price of electricity is less than the profit made mining cryptocurrency, generally the load is at it's maximum. When the price of electricity

[48] G. Ghatikar et al., "Demand Response and Open Automated Demand Response Opportunities for Data Centers," Demand Response Research Center, Jan. 2010. Available: https://www.osti.gov/servlets/purl/981725-mg42YR/

exceeds the profit made mining cryptocurrency for extended periods of time, it is common for the facility to reduce demand to only power minimum "idle" load. Typically this idle load represents 1% or less of the full rated facility demand. In practice, this looks like long periods of time at full demand followed by shorter periods of near-zero demand. An example of this type of operation in the ERCOT region is shown below.

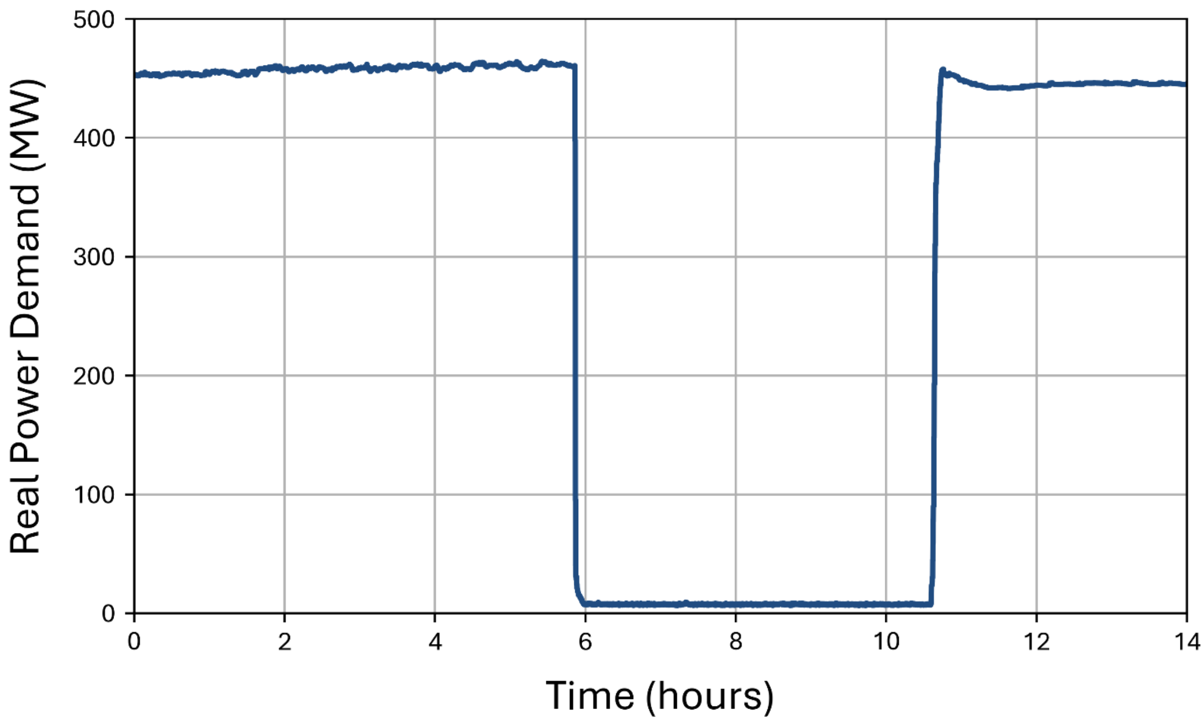


Figure 5.7: Data Center Half-Day Load Shape[49]

Artificial Intelligence Training Data Centers

AI training data centers are similar to other data centers in the physical equipment employed, but very different in how that equipment is operated. The algorithms used to train AI generally demand that all GPU are synchronized, as opposed to working on disparate processes as shown in traditional data centers and cryptocurrency mining facilities. Some literature explains that the typical process relies on forwards and backwards propagation to tune the parameters based on training data. In between the forwards and backwards propagation, power demand can rise and fall dramatically (shown at 40 and 80 seconds in the top plot). Additionally, during the propagation, power may also fluctuate rapidly (as shown in the bottom image). The last thing to note is that the fluctuations in demand are shown to be cyclical in nature, meaning there is an associated frequency with the power demand fluctuations. Some AI training algorithms appear to have cyclical demand frequencies in the range of approximately 1 Hz. Some companies state that this cyclical demand is repeated continuously for days to months[50]. In some ways, these loads are highly consistent and volatile at the same time.

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

[50] Power Stabilization for AI Training Datacenters

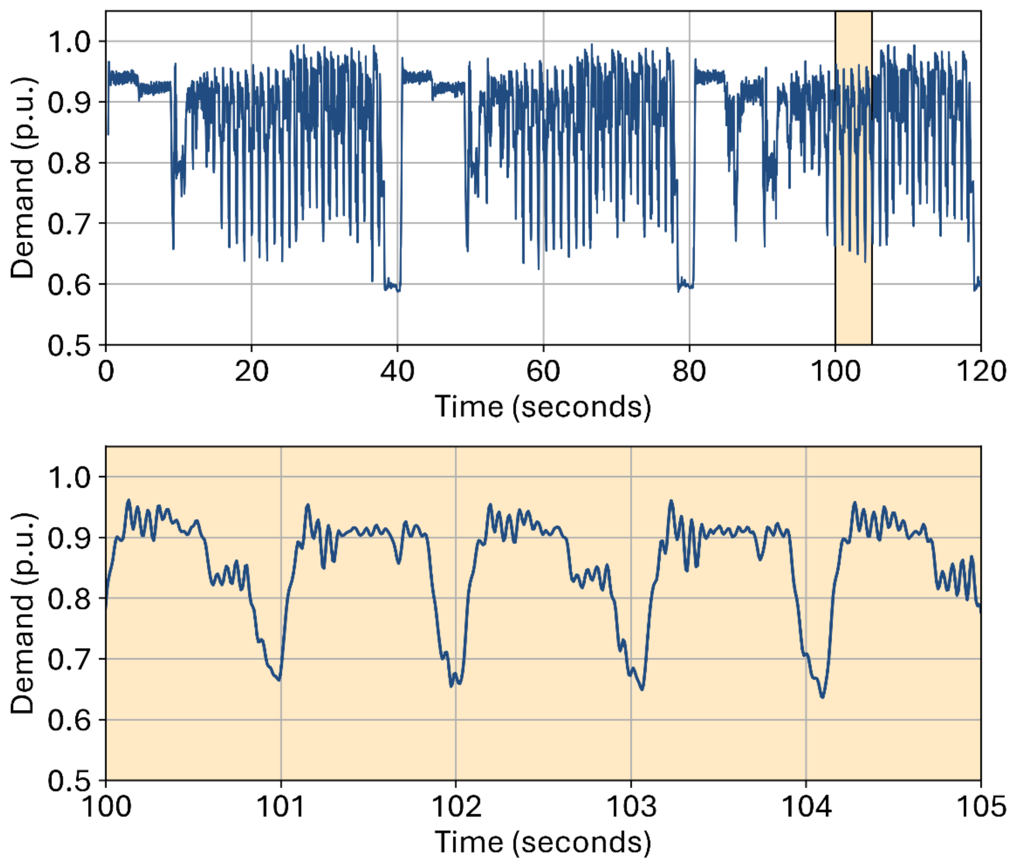


Figure 5.8: Example AI Data Center Load Profile During Training Over Two Minutes (Top) and in a Five-Second Period (Bottom)[51]

In a presentation to the NERC Large Loads Task Force, Microsoft showed that with the latest mitigations the demand volatility can be greatly reduced. See the plot below. This demonstrates that the un-altered load shape can potentially be modified to better suit the needs of the grid and local electrical systems, including systems inside the data center itself.

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

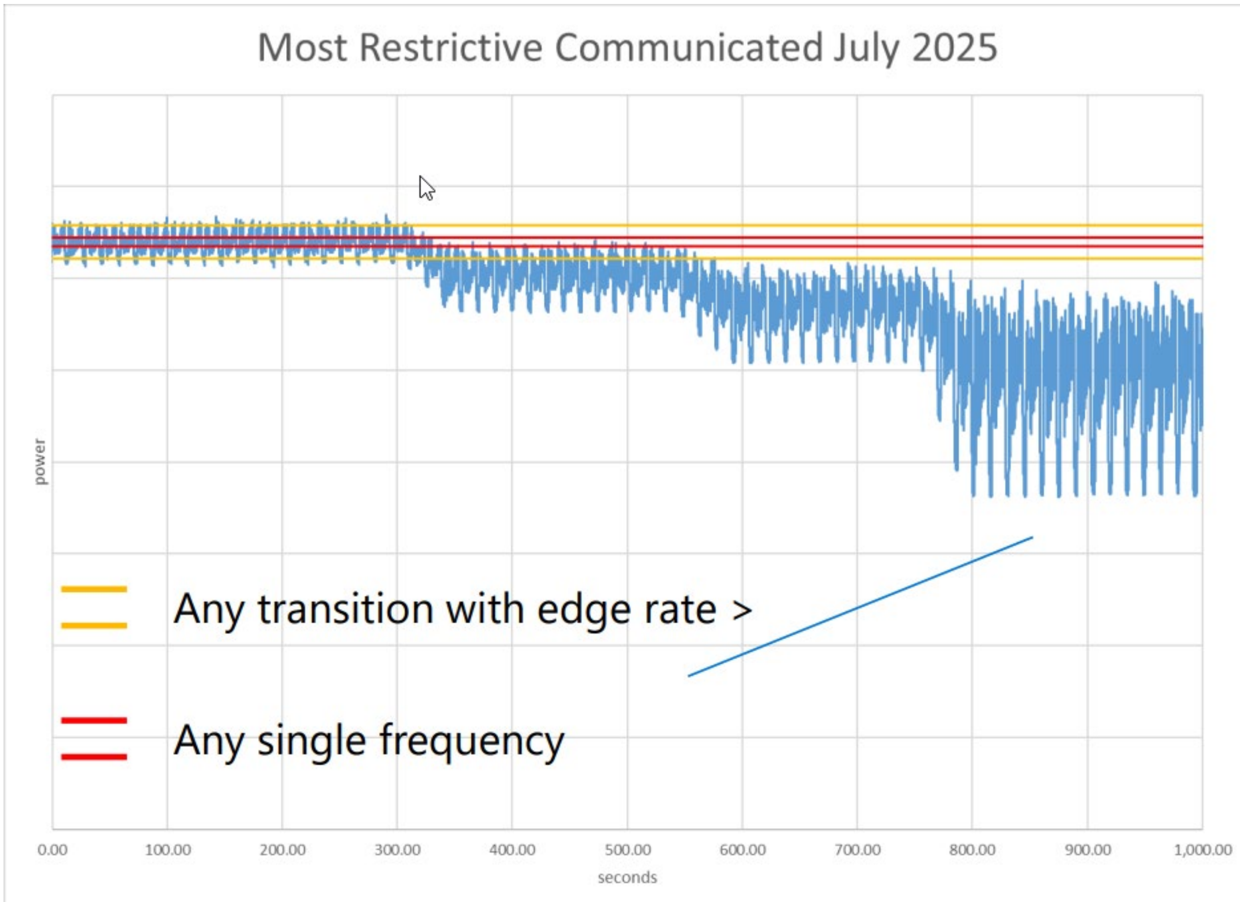


Figure 5.9: Example AI Data Center Load Profile During Training with Smoothing[52]

- Operational modes and logic
- Switching to backup gen and batteries – switching logic, profiles, time delays, etc (within the timescale of the dynamic simulation)

AI training demand profiles could induce forced oscillations in the system as shown in Figure X.

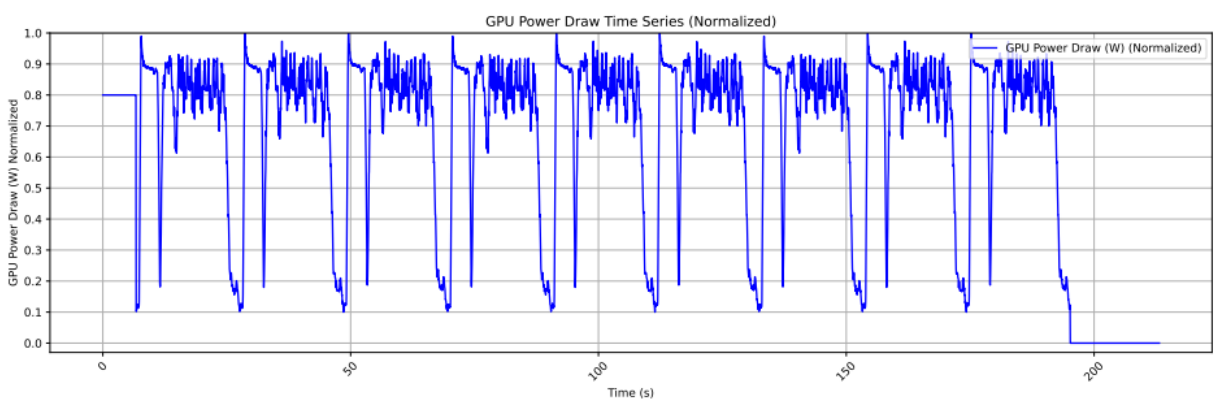


Figure 5.10. AI Training Load Profile from a GPU Rack[53]

[52] S. Heath, Subsynchronous Oscillations and Low-Voltage Ridethrough for the Data Center, presented at the Large Loads Task Force Meeting, Oct. 2025, pp. XX–YY. Available: https://www.nerc.com/comm/RSTC/LLTF/LLTF_Kickoff_Presentations.pdf
[53] https://arxiv.org/pdf/2508.14318v2

Networking

In a typical data center network connectivity can be broken into three areas. The first is connectivity from the data center to the internet and often a corporate network, the second is the complex and often dense network that supports the IT portion of the data center, and the third is the network that supports the mechanical and operational systems of the building.

Connecting a data center to the internet is facilitated by a fiber carrier or ISP. It is often a best practice to select two distinct providers, using different fiber paths entering the building to provide redundancy.

The IT portion of the data center, referred to as white space, is served by a dense mesh of network switches and routers. This network architecture is designed to facilitate high speed communication between servers, GPU-accelerated servers (AI centric), load balancers and other IT equipment. The mechanical and operational part of the data center, referred to as gray space, is often served by a separate network dedicated to monitoring devices that include power systems, cooling systems, generators and environmental sensors.

The primary type of service that a data center provides also introduces the consideration of network latency. A data center that supports real-time financial applications, high speed media services and services that require sub-second response time will need to be in an area with high bandwidth fiber and low-latency access to the internet. A bitcoin mining operation or an AI learning workload may not be as sensitive to latency, thus the distance to a major metropolitan area with dense network connectivity is not as important.

Appendix D: PSPD Modeling Frequently asked questions

1. Can this model be used to model the reduction in damping for slow frequency?
   a. This model can be used to understand certain impacts of loads on the system damping and ensuing oscillations. The impact of electronic loads on damping that can be studied by this model has been discussed in [5]. However, there could be weak grid (high impedance to the controlled grid) oscillatory issues with large electronic loads, which might be challenging to capture with the present implementation. These would be isolated issues, and the modeling would need to include a more detailed representation of the dc bus voltage controller. Improving the model would be a future task for the LMWG.
2. Beyond frequency instability, how are FIDVR and voltage-stability conditions affected? Does constant-power load behavior contribute to these issues?
   a. In the case of FIDVR, it would be ideal for a load to be able to reduce its power consumption and help the system recover. Most constant power loads would still have current limiters and depending on the limit, the load may become a constant current load with its power consumption below the nominal value. These issues can be modeled using the current PERC1 model. The ability to model a particular phenomenon is within the scope of this document.
3. Can this model be used to model slow and periodic changes in AI load that might trigger oscillations?
   a. This model does not include a periodic load change. This could be introduced in the future revision. It is worth noting that any periodic change in the load will trigger periodic changes in power and voltage. If it coincides with the interarea modes, it will trigger oscillations. This will happen and can be studied by using a generator with negative power consumption like we do for forced oscillation assessments. While it does not stop us from including this in the model, we need to evaluate as a group the need for this, when we know the impact it will have.
4. Limitations of this model
   a. Our studies have indicated that in certain cases, the combination of grid scr and speed of control of the dc bus voltage controller can result in oscillations <10 hz. modeling of the dc bus control with explicit representation of the control loop is an improvement to focus on. Not having the ability to account for it is a limitation of the current model.
5. Use of the model for SSO/SSTI assessments
   a. Note that the phasor domain modeling tool itself is not suitable for SSTI studies. This is not a shortcoming of the model or the platform. The platform by design was not intended to study these phenomena. These are localized issues that require a detailed model of the generator and a proper representation of the exciting force (periodic load changes in this case).

Appendix E: PSPD model with Integrated Thermal Dynamics

The root-mean-square (RMS) models (also known as positive sequence transient models) are used in power system studies to assess small-disturbance stability and transient stability. In addition, they can be used for demand response studies and fault-ride-through analysis. A well-designed RMS model can provide accurate predictions of stability, comparable to those of detailed electromagnetic transient (EMT) models.

A data center comprises different components, such as uninterrupted power supplies (UPSs), heating, ventilation, and air-conditioning (HVAC) systems, battery-backup units (BBUs), backup generation, power distribution units (PDUs), power factor correction converters (PFCC), dc-dc converters, and central processing unit (CPU)/ graphics processing unit (GPU) servers[54]. Thus, it is difficult to derive a one single RMS model for the entire data center, and multiple components need to be modelled and integrated to create data center model in RMS domain. Each power electronic (PE) converter can be modelled with an average converter model with detailed controllers to capture the dynamics of the data center at sub-cycle resolution. Since there is a strong correlation between the server workload and the HVAC load, the thermal model should be developed to accurately represent the thermal dynamics of the data center and be integrated with the electrical model[55]. A schematic of the hyper-scale data center model designed with 2N redundancy is shown in **Figure 5.11**.

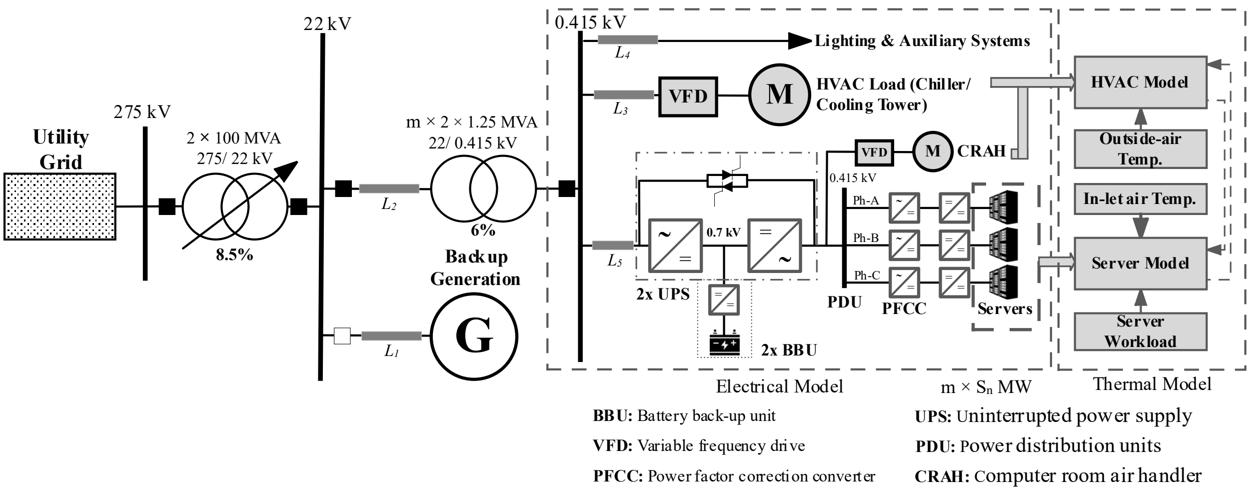


Figure 5.11: Data center model with integrated thermal dynamics

A typical hyper-scale data center is designed in a modular fashion, and each module is known as a data hall. Each data hall has an MV/LV transformer, UPS, BBU, PDU, and PFCCs, data servers (either CPU/ GPU) and computer room air handler (CRAH). Thus, *m* data halls are connected in parallel to the data centre's main substation MV busbar (e.g., the 22 kV busbar in Figure 0.11). Since 2N redundancy is considered, each data hall has two transformers, UPSs and BBUs. In some configurations, each data hall has its own backup generator unit. However, the data center model shown in **Figure 5.11** connects the backup generation to the MV busbar (i.e., 22 kV). In terms of dynamic modelling, all data halls can be lumped together, hence can be represented with a single MV/LV transformer, UPS, BBU, PDU etc. The modelling of each component is described below.

---

[54] 1. Xin Chen and Xiaoyang Wang and Ana Colacelli and Matt Lee and Le Xie, Electricity Demand and Grid Impacts of AI Dat Centers: Challenges and Prospects, 2025. [online]. Available: https://arxiv.org/abs/2509.07218

[55] P. P. Gyang, P. Chakraborty, L. Meegahapola and X. Yu, "Dynamic Modeling of a Data Center for Power System Stability Studies," in IEEE Transactions on Power Systems, doi: 10.1109/TPWRS.2025.3639163

UPS and BBU

All data hall equipment is powered by the UPS, and under normal conditions, the UPS's PE converters are bypassed, with power fed directly to the PDU. However, UPS will be in standby mode during a power outage, with seamless power transfer from the BBU. When the voltage and frequency fall below a certain threshold, the UPS switches to dual-conversion mode, where the AC voltage is first converted to DC and then back to AC. In the event of a total power loss, the BBU will feed power to the UPS DC link to maintain supply continuity. The typical operating modes[56] of the UPS are summarized in Table 1.

Table 1. UPS operating modes and their voltage ranges

Mode	Voltage range
Bypass	0.9 – 1.1 pu
Dual Conversion	0.7 – 0.9
Battery backup	<0.7

Typically, average models can be used to represent power electronic converters in RMS modelling to capture dynamics within a sub-cycle timeframe [5]; hence, all PE converters are modelled as average models. The front-end of the UPS is a three-phase rectifier, which is modelled as a controlled PFC rectifier with the DC voltage regulator[57]. The AC/DC converter is modelled as an average voltage-source inverter with an inner current regulator and an outer power controller[58]. The BBU is modelled as a bidirectional buck-boost converter, and a battery model is modelled with several parallel battery strings. The number of battery cells in each string depends on the DC link voltage and the buck-boost converter specification. Li-Ion battery systems are mostly deployed in BBUs nowadays, and the battery model is built based on[59].

PDU

The PDU delivers power to servers via single-phase links. Based on the data hall rating, several parallel single-phase links feed power to servers. Typically, each phase is connected to an equal number of servers via PFCCs and DC-DC converters to ensure a balanced operation.

PFCC and DC-DC Converter

Since server power supplies draw highly non-linear currents, they are fed through single-phase power-factor correction converters (PFCC). The PFCC can also be represented by an average model with an inner current controller and outer voltage regulator. The PFCC output side is connected to a DC-DC converter, which is typically a single-phase LLC converter. As suggested in[60], detailed modelling of the LLC-isolated DC-DC converter is not necessary for a RMS model, as it behaves like a constant-power source powering the CPUs/GPUs; hence, an average model with detailed controls is not recommended to develop a RMS model of the data centre.

[56] X. Liu, D. Teng, D. Wang, Q. Zhu, and Z. Liu, “Application of eco mode UPS in data center,” in Proc. IEEE Int. Telecommun. Energy Conf., 2017, pp. 30–34.

[57] 4. Miniböck, J., Mauerer, M., Huber, J.E. and Kolar, J.W. (2019), Three-phase buck–boost PFC rectifier with common-mode free output voltage and low semiconductor blocking voltage stress. IET Power Electronics, 12: 2022-2030. https://doi.org/10.1049/iet-pel.2018.5850.

[58] 5. J. Sun, S. Wang, J. Wang and L. M. Tolbert, "Dynamic Model and Converter-Based Emulator of a Data Center Power Distribution System," in IEEE Transactions on Power Electronics, vol. 37, no. 7, pp. 8420-8432, July 2022, doi: 10.1109/TPEL.2022.3146354.

[59] 6. Gu, M., Song, H., Liu, C., Meegahapola, L., Jalili, M., Yu, X. and Dickson, G. (2025), Large-Scale Battery Inverter and Energy Capacity Sizing for Frequency Control Ancillary Services With High Share of Solar-PV Generation: A Data-Driven Approach. IET Energy Syst. Integr, 7: e70003.

[60] 5. J. Sun, S. Wang, J. Wang and L. M. Tolbert, "Dynamic Model and Converter-Based Emulator of a Data Center Power Distribution System," in IEEE Transactions on Power Electronics, vol. 37, no. 7, pp. 8420-8432, July 2022, doi: 10.1109/TPEL.2022.3146354.

Server load modelling

The server load is modelled as a simple, controllable, constant-power DC load. The server workload is modelled as an input parameter, which subsequently changes the DC load power consumption. The same signal is used to estimate the heat dissipation from servers and subsequently used to determine the power consumption of the CRAH and other HVAC systems.

CRAH

In the event of a power failure, the data hall air temperature should remain within the control range. Therefore, CRAH is also powered by the UPS until the backup generator comes online, maintaining data hall temperature within an acceptable range. The CRAH is modelled as a VFD-driven motor load, and power consumption is determined by the server workload and ambient conditions. The modelling of the VFD motor load is delineated under HVAC system modelling.

HVAC system

The HVAC system comprises a number of components, such as a chiller, a heat exchanger, an evaporator, etc. Each of these systems is comprised of fans and pumps driven by VFD. Therefore, from an electrical modelling perspective, all pumps and fans can be represented as an aggregated VFD-driven motor load. The VFD has a controlled rectifier on the front-end and a voltage-source inverter to feed variable frequency power to the induction motor. The VFD front-end rectifier maintains a constant DC link voltage, while the inverter provides variable-frequency power to the three-phase induction motor. Both converters are represented by average converter models and the control loops. The motor is modelled as a third-order induction machine model[61]. VFD motor load power consumption is determined by the thermal model operating alongside the electrical model.

Lighting and Auxiliary Systems

Typically, LED-based lighting systems are used in data centres. The front end of the LED is a PE converter that typically operates over a wide voltage range. Considering the typical behaviour of LEDs, they can be treated as constant-power loads. Also, many auxiliary systems have a front-end PE interface and draw constant power during normal operation. The lighting and auxiliary system load is ~5% of the data center's total load. Considering these facts, the lighting and auxiliary systems can be modelled as constant-power loads.

Thermal Model and Coupling with the Electrical Model

The thermal model is an essential component of the data center model, helping accurately determine the data center's HVAC load, which typically accounts for 30-40% of the data center's total load. The thermal model is developed in[62], considering both ambient conditions (e.g. air temperature and humidity) and the server workload. Also, it depends on the type of cooling system type (e.g., air-cooling or liquid cooling for servers and PE converters) at the data center. In a typical data center, server heat is dissipated into the data hall, and the data hall CRASH should help extract it and transfer it to the main HVAC system. Therefore, the air-cooling heat transfer models presented in[63] can be used to model the thermal load of the data center. Once the thermal load is determined, it is used to calculate the power consumption of VFD-driven motor loads at the CRAH and the main HVAC system. The thermal model influences data centre dynamics on a second time scale and thus does not have a profound impact on the fault ride-through time scale. The

[61] 7. IEEE PES Task Force on MG Dynamic Modeling, "Trends in Microgrid Modeling for Stability Analysis". IEEE PES, Nov. 2022.

[62] 2. P. P. Gyang, P. Chakraborty, L. Meegahapola and X. Yu, "Dynamic Modeling of a Data Center for Power System Stability Studies," in IEEE Transactions on Power Systems, doi: 10.1109/TPWRS.2025.3639163.

[63] 8. G. Zhabelova, M. Vesterlund, S. Eschmann, Y. Berezovskaya, V. Vyatkin and D. Flieller, "A Comprehensive Model of Data Center: From CPU to Cooling Tower," in IEEE Access, vol. 6, pp. 61254-61266, 2018, doi: 10.1109/ACCESS.2018.2875623.

thermal modelling of the data center is useful when assessing the demand response capability and load flexibility potential of the data center.

Appendix F: Data Center Modeling in Power System Simulator

Example of Data Center Modeling in PowerWorld Simulator

This section provides an example of modeling data centers in powerflow and positive sequence dynamics in PowerWorld Simulator.

Figure 5.12 shows powerflow one-line diagram. Two 100 MW data center loads are connected at medium voltage 34.5-kV buses. The loads are assumed to have a high-power factor. The 230/34.5-kV transformers are represented explicitly in the powerflow model. In this example, the 90/120/150 MVA transformers are modeled with 8% impedance at 90 MVA base, and a tap ratio of 1.025 per unit is used on the high voltage side.

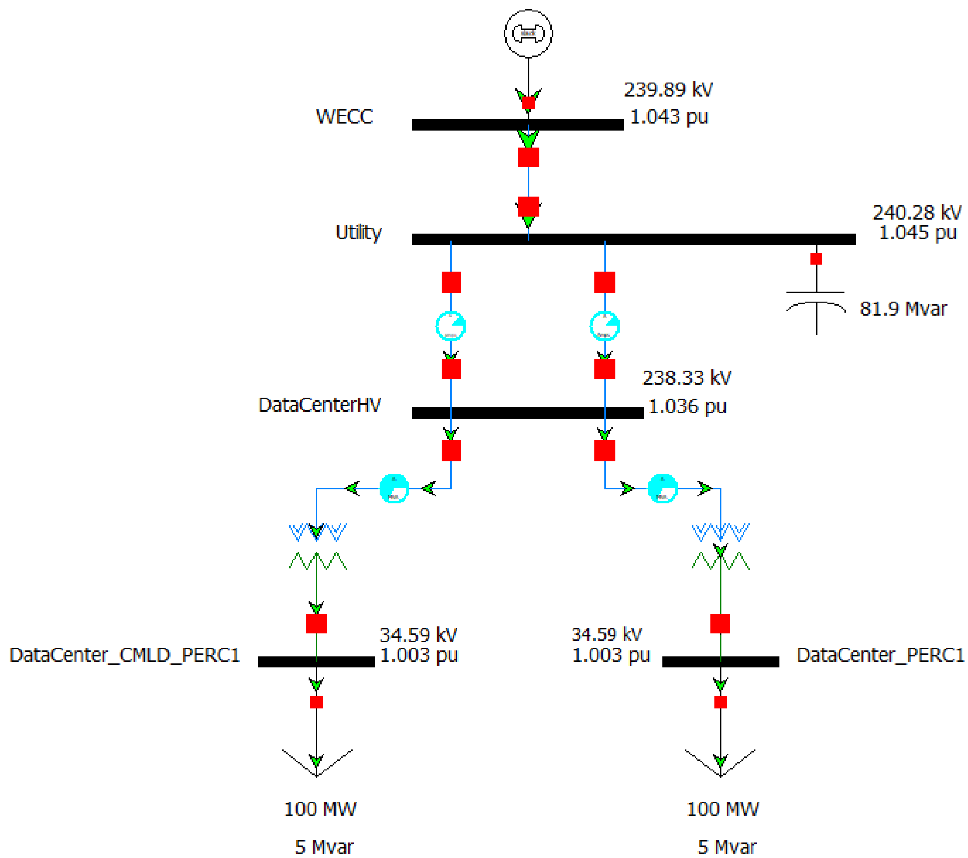


Figure 5.12: Example of data center powerflow model

Two approaches are used for dynamic load modeling. In the first case, the modular composite load model is used with 100% load fraction assigned to PERC1. In the second case, the PERC1 model is applied directly at the medium voltage bus.

Figure YY2 shows the PowerWorld dialog for the load with PERC1 model directly connected to the medium voltage bus.

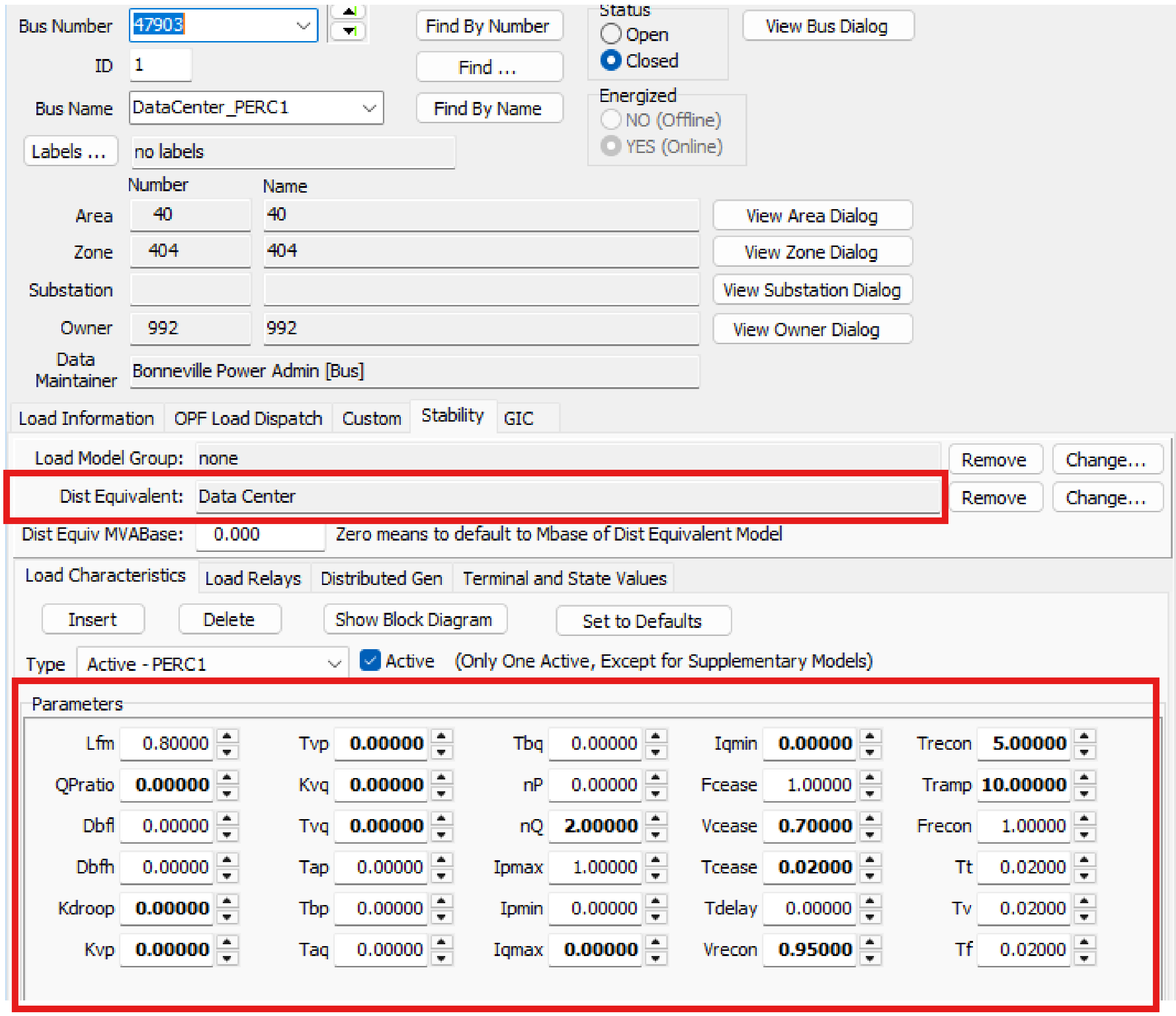


Figure 5.13: PERC1 data center model data

Model data is parameterized based on the OEM presentations at NERC Load Modeling Working Group meeting. Please contact your data center operator on site-specific UPS control settings.
Model also includes a distribution equivalent "Data Center", which has a typical medium-low voltage transformer with 5.75% impedance and low voltage distribution network impedance of 2%.

Figure 5.13 shows the PowerWorld dialog for the composite load model with PERC1. The model references Load Model Group "IND_DC1" and distribution equivalent model "Data Center".

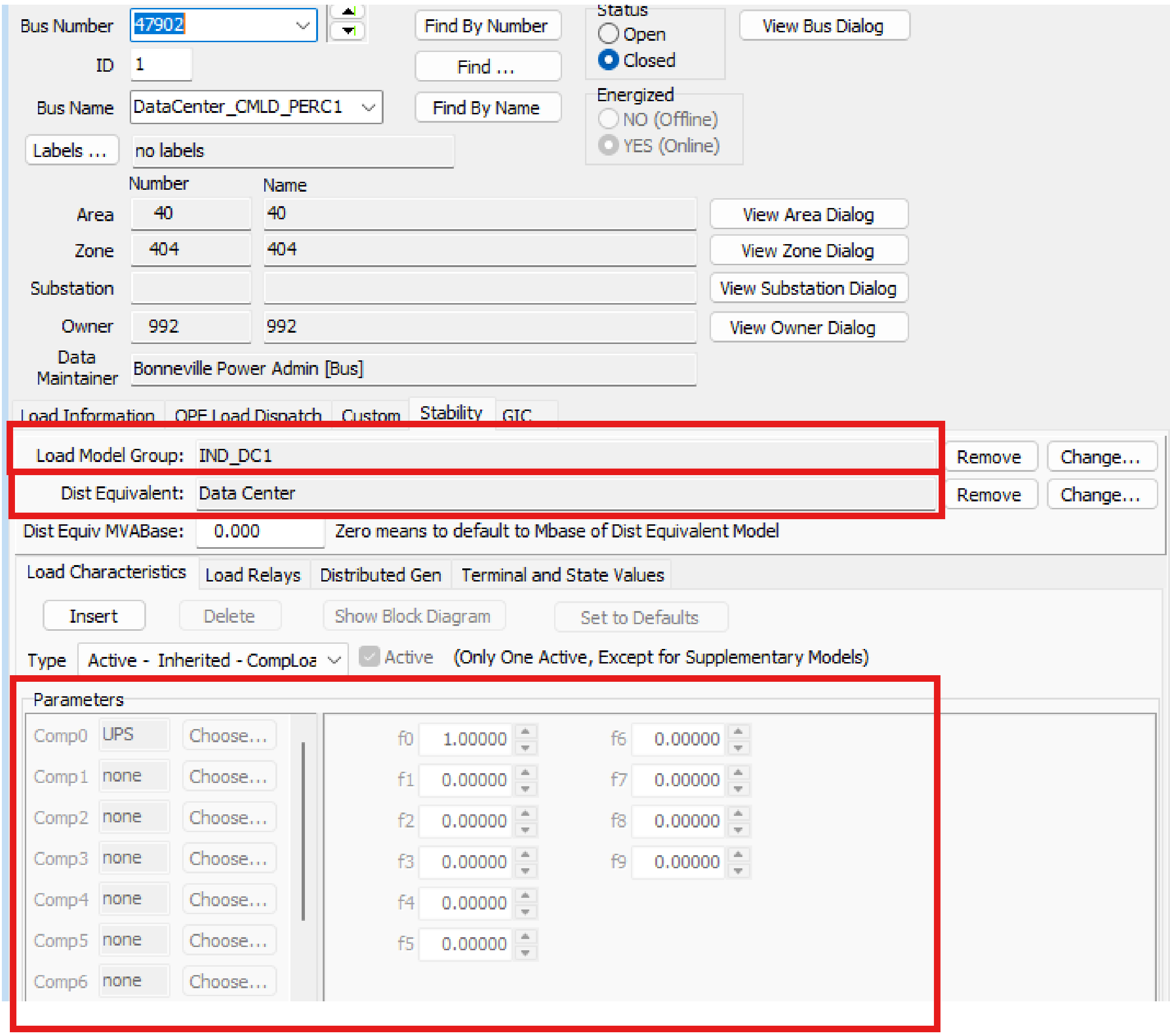


Figure 5.14: PowerWorld dialog for the composite load model that includes 100% share of model PERC1

For the distribution equivalent model “Data Center”, a typical medium to low voltage transformer is assumed with 5.75% impedance, and the low voltage distribution system with 2% impedance.
In the Load Model Group “IND_DC1”, 100% of load is assigned to PERC1 model.

PowerWorld Simulator has play-in capabilities where the simulated bus voltage and frequency can be made to follow a pre-defined voltage and frequency profiles. Figure 5.14 shows the play-in of a simulated voltage sag at the “WECC” bus.

Figure 5.15 compares the simulated voltages, active and reactive power for the two approaches for data center modeling (blue PERC1 is a part of CMLD, and red PERC1 is stand alone, green is the play-in voltage). For the simulated voltage sag, PERC1 model connected directly to medium voltage bus and PERC model imbedded in CMLD produced identical responses.

Figure 5.16 shows play-in of a simulated voltage swing at “WECC” bus. As before, PERC1 model connected directly to the medium voltage bus and PERC model imbedded in CMLD produced identical responses. The UPS is modeled at 80% load factor.

Both instances of the PERC1 models are identical.

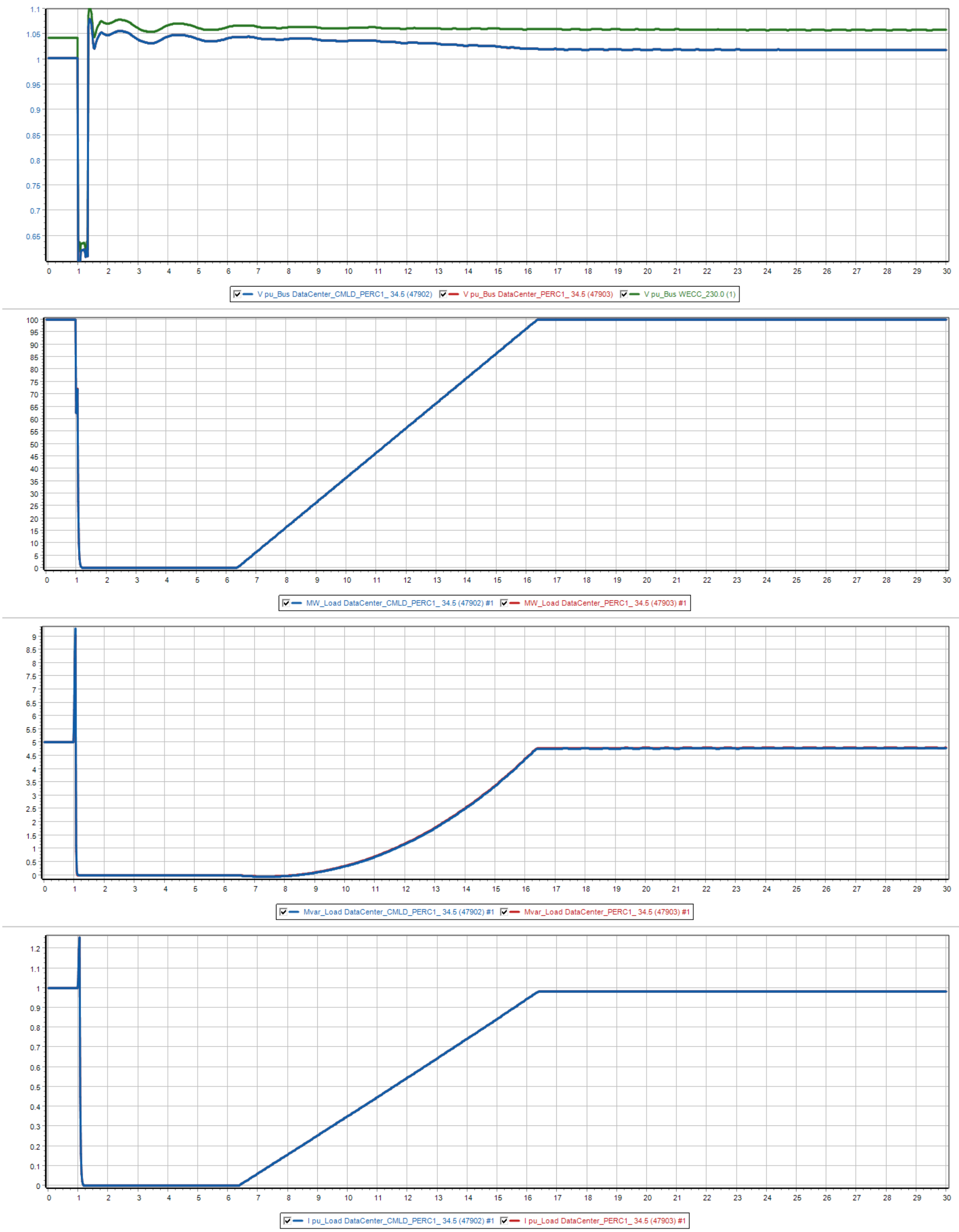


Figure 5.15: simulation of voltage sag responses of CMLD with PERC1 (red) and the stand-alone PERC1 models (blue), to voltage Volt2 signal (green) a)Voltages b)Active power c) Reactive power d) Current

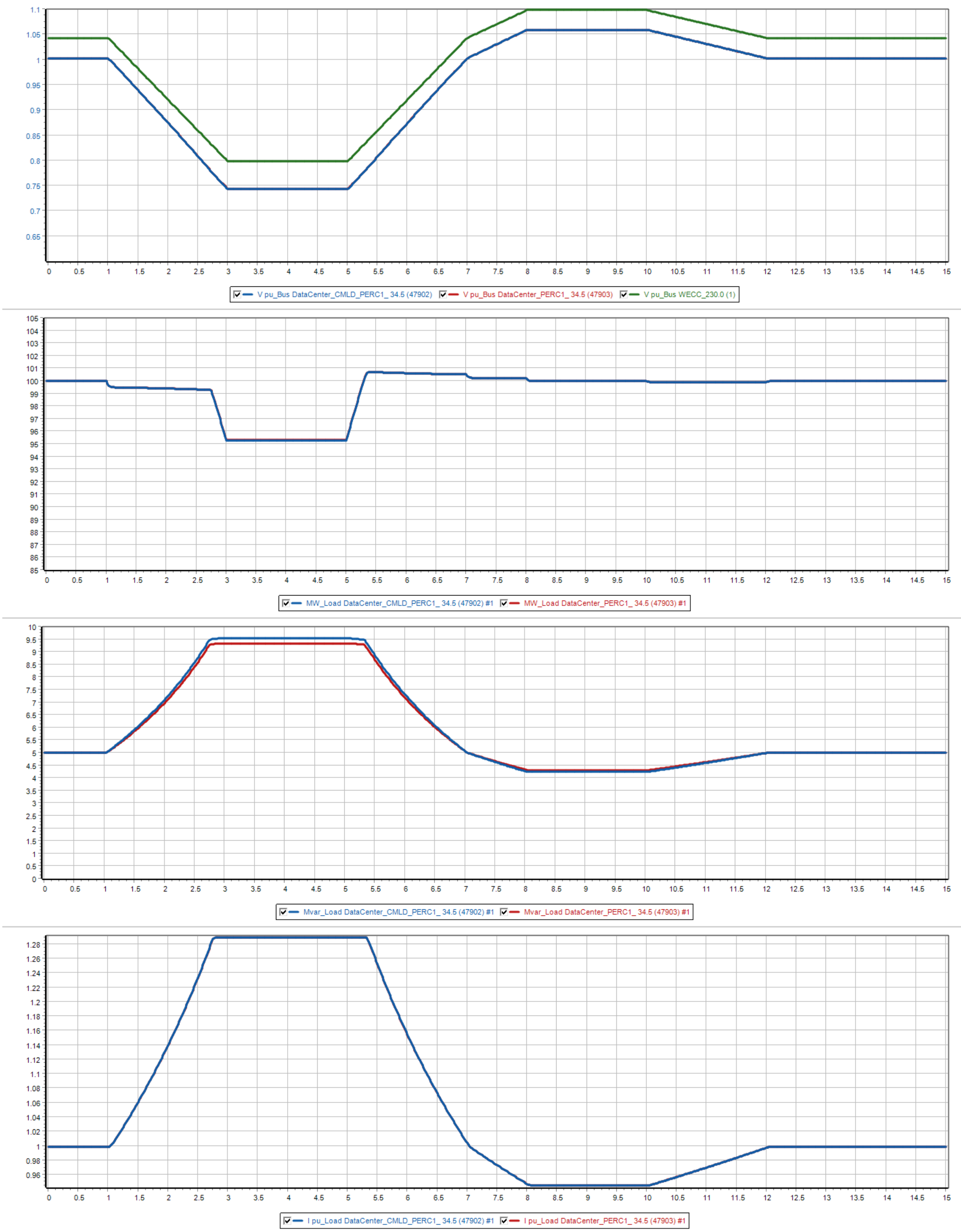


Figure 5.16: simulation of voltage swing responses of CMLD with PERC1 (red) and the stand-alone PERC1 models (blue), to voltage Volt4 signal (green) a)Voltages b)Active power c) Reactive power d) Current

Benchmarking between PTI PSS®E and PowerWorld Simulator

Powerflow model shown in **Figure 5.12** was implemented in PTI PSS®E version 36.5. Same voltage sag and voltage swing were simulated in PSS®E using play-in function. Figure YY6 compares PTI PSS®E and PowerWorld simulation for voltage sag

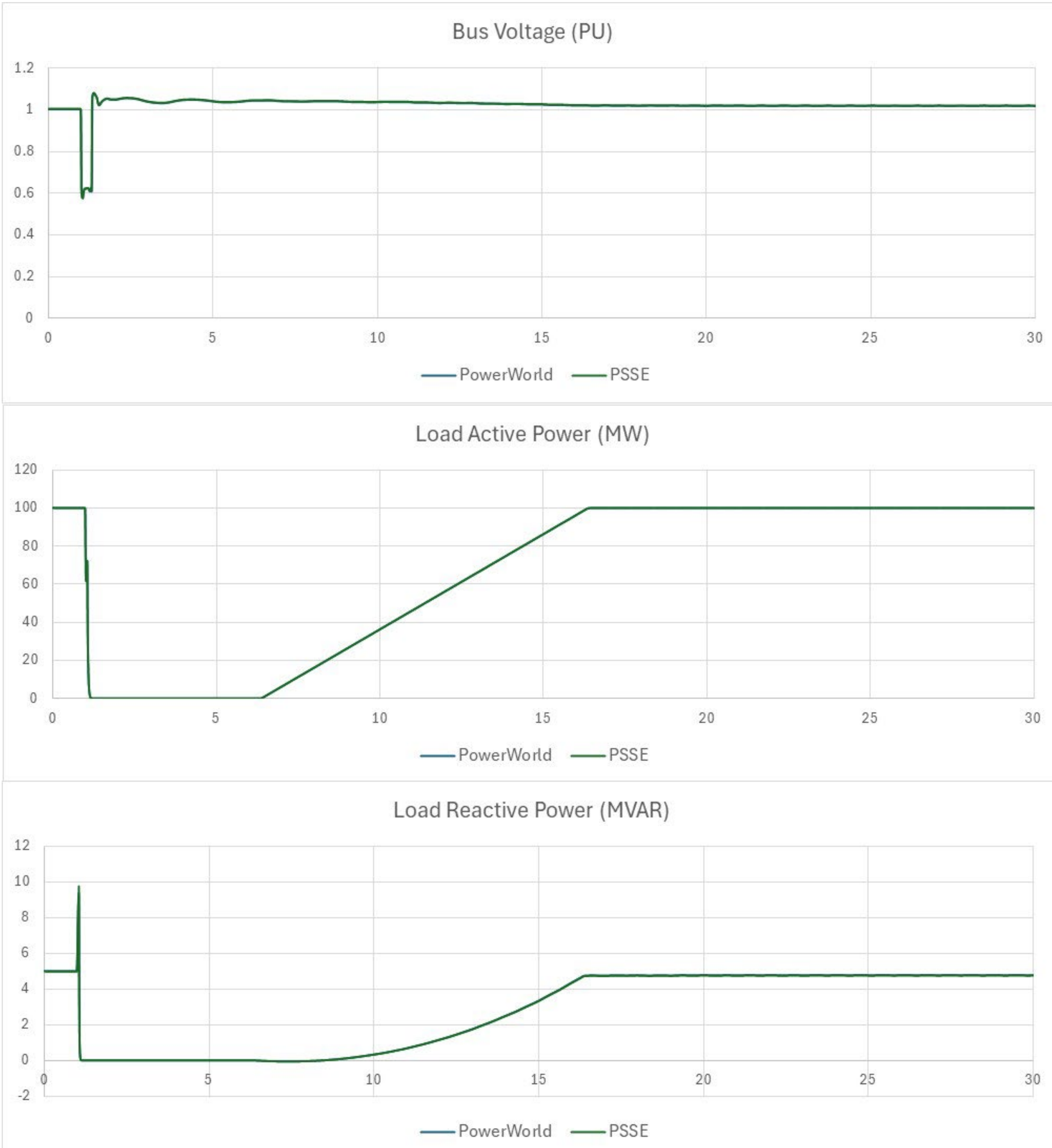


Figure YY6: simulated voltage sag responses in PTI PSS®E and PowerWorld Simulator

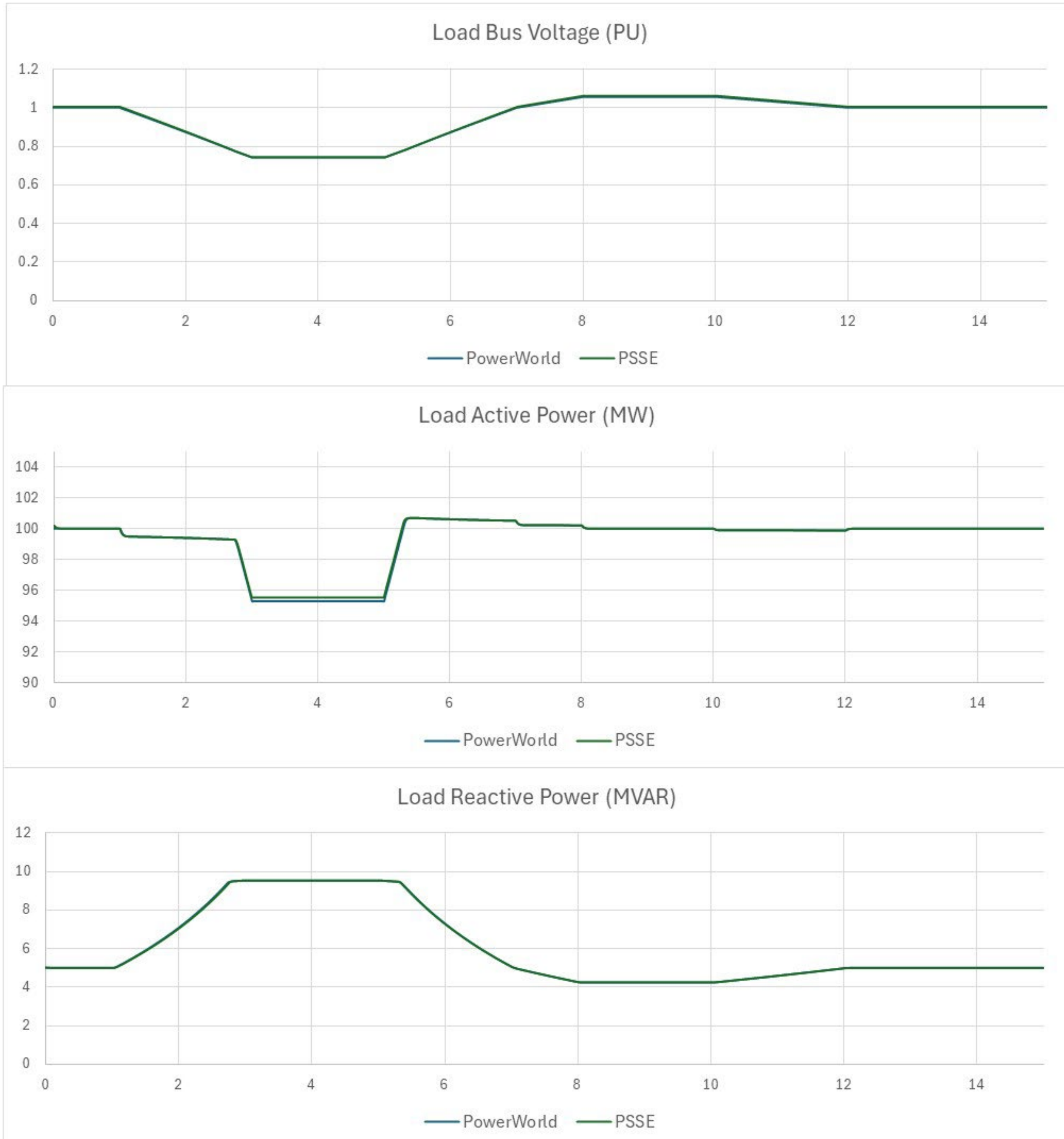


Figure YY7: simulated voltage swing responses in PTI PSS®E and PowerWorld Simulator

Table below shows PERC1 model data in PSS®E:

	Con Value	Con Description
1	0.8000	Ldfact, load factor (to calculate load MVAbase)
2	0.0000	QPratio, Q/P ratio to determine the initial load Q
3	0.0000	dbfl (pu), frequency deadband lower threshold (pu frequency deviation) (<= (
4	0.0000	dbfh (pu), frequency deadband upper threshold (pu frequency deviation) (>=
5	0.0000	Kdroop (pu), reciprocal of droop for real power
6	0.0000	Kvp (pu), P-path wahsout gain
7	0.0000	Tvp (s), P-path washout time constant (> 0)
8	0.0000	Kvq (pu), Q-path wahsout gain
9	0.0000	Tvq (s), Q-path washout time constant (> 0)
10	1.0000	Tap (s), P-path lead-lag block lead time constant
11	1.0000	Tbp (s), P-path lead-lag block lead time constant
12	1.0000	Taq (s), Q-path lead-lag block lead time constant
13	1.0000	Tbq (s), Q-path lead-lag block lead time constant
14	0.0000	nP, P-path voltage exponent
15	2.0000	nQ, Q-path voltage exponent
16	1.0000	Ipmax (pu), Maximum active current
17	0.0000	Ipmin (pu), Minimum active current
18	0.0000	Iqmax (pu), Maximum reactive current
19	0.0000	Iqmin (pu), Minimum reactive current

Table below shows distribution equivalent DISTBL model data model data:

	Con Value	Con Description
1	-1.0000	Load factor or Load MVA
2	0.0000	Bss, Substation shunt (pu on Load MVA base)
3	0.0000	Rfdr, Feeder resistance (pu on Load MVA base)
4	0.0200	Xfdr, Feeder reactance (pu on Load MVA base)
5	0.0575	Xxf, Transformer Reactance (pu on load MVA base)
6	1.0000	Tfixhs, High side fixed transformer tap (pu)
7	1.0000	Tfixls, Low side fixed transformer tap (pu)
8	0.9000	Tmin, LTC transformer minimum tap (on low side)
9	1.1000	Tmax, LTC transformer maximum tap (on low side)
10	0.0050	Tstep - LTC step (on low side)
11	1.0250	Vmin, LTC lower end of regulated range side (pu)
12	1.0400	Vmax, LTC high end of regulated range side (pu)
13	300.0000	TD, LTC Control time delay (s)
14	300.0000	TC, LTC Tap adJustment time delay (s)
15	0.0000	Rcmp, LTC compensating resistance (pu on load MVA base)
16	0.0000	Xcmp, LTC compensating reactance (pu on load MVA base)

Appendix G: Inadequacy of the simple Power electronic Model to represent data center disturbance response

In Figure 5.17 the green curve is the voltage at the data center POI, the red curve is the response from the PERC1 model and the green curve is the response from the Pel model. Based on the results it is clear that a data center modeled with the simple power electronic model will show optimistic results in a frequency stability study.

Figure 5.18: PE model compared to PERC1 model.

Appendix H: UPS PERC1 Parameters

Parameters for Toshiba UPS

Parameter	Suggested generic (typical) value	Minimum (if a range is available)	Maximum (if a range is available)
V_{cease} (pu)	0.8	0.78	0.8
T_{cease} (s)	1.5		
T_{delay} (s)	0.0005	0.0001	0.0009
V_{recon}(pu)	0.9	0.9	0.92
T_{recon} (s)	3 (default)	1 (adjustable)	3600 (adjustable)
T_{ramp} (pu/s)	10 (default)	1 (adjustable)	30 (adjustable)

Type of UPS (3 phase or 1 phase):	3
Nature UPS (OCP or central double conversion):	Double Conversion
OEM/Model number/sub model number of the power conversion device:	Toshiba G9000
Size of a unit of the power conversion device (kW):	1000kW / 1050kVA
Facility rating Site 1 (MW, critical):	48
Facility rating Site 2 (MW, critical):	24
Facility rating Site 3 (MW, critical):	36

Representative UPS parameters from Equinix

Table 1: Parameters to represent Ceasing and Reconnection logic of a typical data center/UPS

Note: some of the below are not settings, but related to the response of the hardware. Tcease is a good example of that.

Parameter	Suggested generic (typical) value	Minimum (if a range is available)	Maximum (if a range is available)
Vcease (pu)	0.9	0.7	0.9
Tcease (s)	0.1s	0s	0.2s
Tdelay (s)	0	0	0
Vrecon(pu)	0.95	0.9	1
Trecon (s)	10s	0s	30s
Tramp (pu/s)	~0.06 pu/s	~ 0.03 pu/s	0.1 pu/s

Parameters for Vertiv UPS

Today's UPS

Parameter	Suggested default (typical) value	Minimum (if a range is available)	Maximum (if a range is available)
V_{cease} (pu)	0.70	0.70	0.90
T_{cease} (s)	1 line cycle	1 line cycle	1 line cycle
T_{delay} (s)	0.0	0.0	0.0
V_{recon}(pu)	0.85	0.85	0.95
T_{recon} (s)	5.00s	2.25s	10.0s
T_{ramp} (pu/s)	15.0s	1.50s	30.0s

Fault Ride Through UPS (goal, UPS requalifies, restarts, and ramps up in less than 1 second)

Parameter	Suggested default (typical) value	Minimum (if a range is available)	Maximum (if a range is available)
V_{cease} (pu)	0.70	**0.30**	0.90
T_{cease} (s)	1 line cycle	**1/4 line cycle**	1 line cycle
T_{delay} (s)	0.0	**0.0**	0.0
V_{recon}(pu)	0.85	**0.60**	0.95
T_{recon} (s)	5.00s	**0.80s**	10.0s
T_{ramp} (pu/s)	15.0s	**0.10s**	30.0s

Type of UPS (3 phase or 1 phase):	3
Nature UPS (OCP or central double conversion):	Double Conversion
OEM/Model number/sub model number of the power conversion device:	Vertiv EXL S1
Size of a unit of the power conversion device (kW):	1000kW / 1000kVA
Facility rating Site 1 (MW, critical):	96

Parameters for Eaton UPS

Typical Eaton UPS without Fault Ride Through capabilities

Parameter	Suggested generic (typical) value	Minimum (if a range is available)	Maximum (if a range is available)
V_{cease} (pu)	0.7	0.7	0.9
T_{cease} (s)	0.001		
T_{delay} (s)	0.001		
V_{recon}(pu)	0.9		
T_{recon} (s)	5	0.2	*
T_{ramp} (pu/s)	0.2	**	50

Typical Eaton UPS with Fault Ride Through capabilities

Parameter	Suggested generic (typical) value	Minimum (if a range is available)	Maximum (if a range is available)
V_{cease} (pu)	0.5	0.5	0.9
T_{cease} (s)	0.001		
T_{delay} (s)	0.001		
V_{recon}(pu)	0.9		
T_{recon} (s)	0.2	0.1	*
T_{ramp} (pu/s)	20	**	50

* UPS reconnection time is configurable
** UPS input power ramp-up time is configurable

Depending on UPS loading, the input active power consumption may reduce as voltage decreases as the UPS rectifier limits input current and draws the required additional energy from batteries. At full load, the rectifier current limit is typically hit around 0.85 pu input voltage.

I think the above mentioned parameters apply quite generally to our Data Center UPSs, and here I only made the split between FRT-enabled and FRT-disabled UPSs. FRT capabilities are something that we have been actively working on, and have already demonstrated with the 9395P UPS. We are currently developing similar FRT capabilities for our newer models as well. Note that the faster reconnection only applies to short FRT-type under/over voltages and the UPS recovery would be according to the first table after longer outages.

Type of UPS (3 phase or 1 phase): 3
Nature UPS (OCP or central double conversion): Central **Double conversion**
OEM/Model number/sub model number of the power conversion device: Eaton 9395P, Eaton 9395XC, Eaton 9395XP
Size of a unit of the power conversion device (kW): 250 – 1200 kW for 9395P, 1125 – 2250 kW for 9395XC, 1000 – 1700 kW for 9395XP
Facility rating (MW): Could range anywhere from few MW to hundreds of MW.

Parameters for Schneider UPS

Parameter	Suggested generic (typical) value	Minimum (if a range is available)	Maximum (if a range is available)
V_{cease} (pu)	0.5	0.5	0.85
T_{cease} (s)	0.003	0.003	0.2
T_{delay} (s)	0.001		
V_{recon}(pu)	0.5	0.5	0.85
T_{recon} (s)	1		
T_{ramp} (pu/s)	0.1	0.0033	1

Contributors

NERC gratefully acknowledges the contributions and assistance of the following industry experts in the preparation of this guideline.

Name	Entity
Robert J O'Keefe	AEP
Brett Ross	PNNL
Rahul Anilkumar	Danovo (formerly Quanta)
Eric Meier	ERCOT
Dmitry Kosterev	BPA
Nick Hatton	WECC
Parag Mitra	EPRI
Poria Astero	Gridstrong
Kannan Sreenivasachar	ISO-NE
Ryan Howard	levitate
Bernard Lesieutre	UWM (Uni Winsconsin)
Jackson Daly	Idaho power
Lakshmi Sundaresh	EPRI
Saurav Talukdar	Verrusdata
Jayapalan Senthil	Siemens PTI
Lasantha Meegahapola	RMIT Australia
Shilpa Marti	Verrusdata
Kaustav Chatterjee	PNNL
Anurag Jivanani	Schneider Electric
Jim Simonelli	Schneider Electric
John Stratton	Equinix
James Myers	Stackinfrastructure
Haritha Yearuva	Stackinfrastructure
Aleksi M Karjalainen	Eaton
Janne Paananen	Eaton
Joshua Buzzell	Eaton
Keith Watson	Eaton
Brian Heber	Vertiv
Steve Unger	Toshiba
Maryclaire Peterson	Entergy
Mengxi Chen	GE Vernova
John Wiggins	SERC
Li Peiyan	Powertech
Jeff Bloemink	Powertech
James Weber	Powerworld
Bathiya Jayasekara	Manitoba Hydro
Kishan Guddanti	EPE
Fabio Rodriguez	Duke

Mostafa Sedighizadeh	SPP
This list will be filled completely after review with the chapter leads. If you are a contributor and not yet included in this list – please provide your information for the chapter leads to review by filling this short form.	https://app.smartsheet.com/b/form/019d4584bc1678bc8a38be775c21b591

Guideline Information and Revision History

Guideline Information	
Category/Topic: [NERC use only]	Reliability Guideline/Security Guideline/Hybrid: [NERC use only]
Identification Number: [NERC use only]	**Subgroup:** [NERC use only]

Revision History		
Version	**Comments**	**Approval Date**

Metrics

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

Baseline Metrics

All NERC reliability guidelines include the following baseline metrics:

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

Specific Metrics

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

- [Insert metrics specific to the content of this reliability guideline here]

Effectiveness Survey

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

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

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

Guideline Effectiveness Survey [insert hyperlink to survey]

Errata