Ride-Through and Delivery Point Study Requirements for High Impact Large Loads in Southwest Power Pool

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***Abstract*— The rapid growth of High Impact Large Loads (HILLs), such as data centers, cryptocurrency facilities, and AI computing hubs, presents new reliability and stability challenges for the bulk electric system (BES). These concentrated, power-electronic-based loads are highly sensitive to voltage and frequency disturbances, raising the risk of simultaneous tripping and large-scale load loss. To address this, Southwest Power Pool (SPP) developed HILL ride-through requirements and a structured HILL Delivery Point Study (HDPS) process. The two-stage HDPS integrates steady-state, dynamic, and electromagnetic transient analyses to evaluate system impacts and identify mitigation needs. This framework establishes consistent performance expectations and study procedures, supporting secure integration of large loads, enhancing grid resilience, and promoting transparent interconnection practices across the SPP footprint.**

Keywords— High Impact Large Load (HILL), HILL Delivery Point Study (HDPS), Ride-Through, Southwest Power Pool (SPP).

I. Introduction

The increasing penetration of HILLs, such as data centers, cryptocurrency facilities, and artificial intelligence computing hubs, introduces unprecedented challenges to the stability and reliability of the bulk electric system [1]. Unlike traditional industrial loads, these facilities exhibit high sensitivity to voltage and frequency disturbances and can disconnect simultaneously during grid events, leading to significant system imbalances [2]. Recent analyses by the North American Electric Reliability Corporation (NERC) and Regional Entities have documented several bulk power system disturbances during 2024–2025 in which unexpected reductions exceeding 1,000 MW of large load occurred. These incidents underscore the increasing reliability risks driven by the rapid growth and uncertain behavior of large, concentrated loads across the transmission grid [3]. Similarly, the blackout that occurred on April 28, 2025, in the Spanish Peninsular Electrical System highlighted the significant influence of Inverter based resources (IBRs) and large loads on overall system reliability and dynamic performance [4]. Establishing robust ride-through requirements and conducting comprehensive delivery point studies are therefore critical to ensure that these large, concentrated loads remain connected and behave predictably during system disturbances. Such studies enable the identification of potential reliability risks, evaluation of dynamic performance under contingency conditions, and development of appropriate mitigation measures to maintain system integrity. Within this context, SPP has developed a structured framework for assessing and enforcing HILL ride-through capabilities and delivery point performance to support reliable system planning and operation.

The addition of large new loads within the SPP region is governed by Attachment AQ of the SPP Open Access Transmission Tariff (OATT). To date, SPP has received over 26 GW of load requests exceeding 100 MW each, with approximately 7 GW (21 requests) advancing to executed service agreements (SAs) and targeting in-service dates between 2021 and 2027. This trend indicates that nearly 30% of the proposed large loads have been, or are expected to be, interconnected to the SPP transmission system. These requests span multiple sectors—including cryptocurrency mining, artificial intelligence (AI) data centers, industrial manufacturing, and municipal demand growth—though many applicants have yet to specify detailed load characteristics. Geographically, the Southeast region accounts for the highest concentration of new load activity, followed by the Southwest, Nebraska, Central, and North regions, reflecting rapid growth in high-impact, energy-intensive demand across the SPP footprint (see Fig. 1 for details) [5].

The SPP defines a HILL as a new or expanded commercial or industrial load at a single site, connected through one or more Points of Interconnection (POIs) or delivery points, that meets either of the following thresholds: (1) 10 MW or greater when connected at or below 69 kV, or (2) 50 MW or greater when connected above 69 kV. Electric Storage Resources are excluded from this definition.

The addition of HILLs to the SPP grid—without sufficient consideration of planning, operational, and market impacts—has the potential to turn an opportunity for regional growth into a risk to system reliability and stability. Recognizing these emerging challenges, in June 2025, SPP established a cross-functional strike team to identify existing gaps and to develop the necessary requirements, processes, and services to address them. Through two Revision Requests (RRs), the team proposed updates to the SPP OATT and associated governing documents, as well as several new services intended to create a more streamlined and efficient interconnection pathway for large-load transmission customers. At the time of this writing, the revisions contained in one RR remain pending before the Federal Energy Regulatory Commission (FERC) [6], while the second is under active review by SPP stakeholder Working Groups (WGs) [7]. To provide the technical foundation for these initiatives, SPP has developed comprehensive frameworks for HILL ride-through requirements and the HDPS process. While several European system operators—such as France (RTE), Ireland (EirGrid), Denmark (MYEN), and the European Union—have already established or proposed voltage ride-through grid codes for large loads [8–11], similar initiatives are still emerging in North America. Both the Electric Reliability Council of Texas (ERCOT) [12] and the Alberta Electric System Operator (AESO) [13] are currently

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developing large-load ride-through and interconnection requirements, which remain under internal review and approval.

This paper presents the SPP's comprehensive framework for integrating HILLs through the development of ride-through requirements and the HDPS process. It outlines the motivation, methodology, and technical considerations behind these efforts, highlighting how they enhance system reliability, support consistent interconnection practices, and align with emerging regional and international approaches for large-load integration.

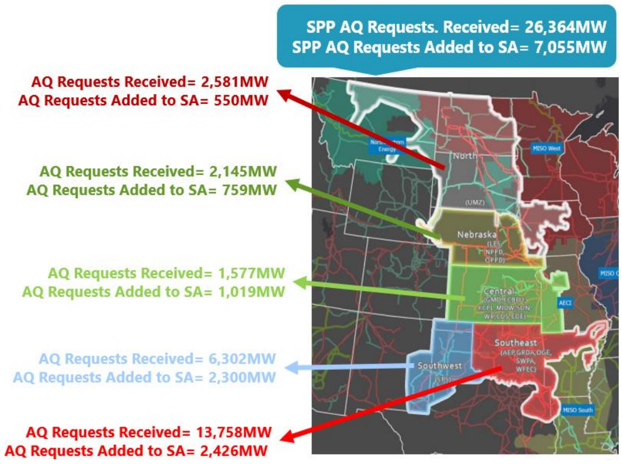

Fig. 1 SPP Load Requests by Region (≥100 MW) [5]

II. SPP HILL Ride-Through Requirements

SPP developed the HILL Ride-Through Requirements to establish consistent, technically justified performance expectations for large industrial and commercial loads interconnecting to the bulk transmission system. Historically, load facilities were not required to remain connected during transmission faults. However, with the increasing concentration of large electronic and power-electronic-based loads, uncontrolled tripping events have emerged as potential contributors to widespread disturbances. To mitigate this risk, SPP established clear ride-through and control performance requirements analogous to those applied to generation resources.

A. Ride-Through Performance Expectations

SPP aligned its technical framework with IEEE 2800-2022, NERC PRC-024-4, NERC PRC-029-1, and ERCOT's proposal [12] and AESO's proposal [13], ensuring regional consistency. IEEE 2800-2022, NERC PRC-024-4, NERC PRC-029-1 are scoped for IBRs. Selected performance requirements are adapted by SPP for HILLs. This adaptation is made to support system reliability and does not imply applicability of these standards to load facilities.

Voltage Ride Through: HILLs must withstand temporary voltage deviations consistent with the Information Technology Industry Council (ITIC) curve (formerly the CBEMA curve). SPP adopted this modified ITIC curve based on the ERCOT proposal [12]. The corresponding performance criteria are summarized in Table 1 and Fig. 2.

Table 1. HILLs RMS Voltage Ride-Through Requirements as Measured at POI

Root Mean Square Voltage (pu. of nominal at POI)	Minimum Ride-Through Time (Seconds)
V>1.20	N/A (May ride-through or trip)
1.10<V≤1.20	0.50
0.90≤V≤1.10	Continuous operation, no trip.
0.80≤V<0.90	2.00
0.50≤V<0.80	0.50
V<0.50	0.15

To address the limitations of variable-speed drives (VSDs) and provide greater flexibility in adopting these requirements, SPP has exempted HILLs equipped with VSDs—such as oil and gas pumping stations—from the requirement listed in the last row of Table 1, provided the HDPS demonstrates that granting the exemption will not adversely affect the reliability of the SPP transmission system.

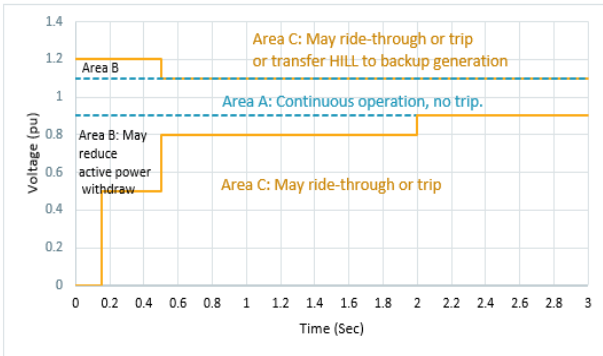

Fig. 2 HILLs RMS Voltage Ride-Through Requirements as Measured at POI

In Fig. 2, Area A represents the continuous operation region, where the HILL shall not trip. Area C allows the HILL either to ride through or trip or transfer to backup generation, depending on system conditions. Area B consists of two sub-regions: in the upper part, the HILL shall ride through; however, in the lower part of Area B, the HILL shall meet the following performance requirements:

1. The HILL shall continue consuming power from the grid during shallow voltage sags between 0.5 pu and 0.8 pu, with power consumption reduced proportionally to the voltage dip.
2. During deep voltage sags (below 0.5 pu), the HILL may switch to uninterruptible power supply (UPS) or trip. After voltage recovery (≥ 0.9 pu), it shall restore at least 90 % of pre-disturbance power within one second. The default active power recovery time is one second, but it may be extended under weak grid conditions with SPP and transmission owner approval to prevent oscillations and maintain stability. VSDs may be exempt from the one-second recovery requirement if justified by the HDPS and shown not to impact SPP grid reliability.
3. The load shall not operate in constant-power mode in this region; instead, it shall operate in constant-current mode with an appropriate current limitation. However, VSDs may be exempt from this

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requirement, provided the HDPS demonstrates that granting such an exemption will not adversely impact on the reliability of the SPP grid.

Transient Overvoltage Ride Through: The HILL shall ride through transient overvoltage that does not exceed the fundamental frequency overvoltage ride-through requirements specified in Table 1 and Fig. 2 and for which the greater of individual phase-to phase or phase-to-ground instantaneous voltage magnitudes do not exceed the cumulative durations (minimum time) specified in Table 2. Table 2 is identical to Table 14 in the IEEE standard 2800-2022. The cumulative duration shall only include the sum of durations for which the instantaneous voltage exceeds the respective threshold over a 1-min time window. VSDs may be exempt from these transient overvoltage ride through requirements, provided the HDPS demonstrates that granting such an exemption will not adversely impact the reliability of the SPP grid.

Table 2. HILLs Transient Overvoltage Ride-Through Requirements as Measured at POI

Instantaneous Phase to Phase or Phase to Ground (p.u. of nominal at POI)[a]	Minimum Ride-Through Time (milliseconds)[b]
V>1.80	May ride through or trip
V>1.70	0.2
V>1.60	1.0
V>1.40	3.0
V>1.20	15.0

a Specified voltage magnitudes are the residual voltages with surge aresters applied.
b Cumulative time over a 1-min time window.

Frequency Ride Through: HILLs should remain connected and continue consuming power within the frequency profiles shown in Table 3. Table 3 shows the requirements pointed out by NERC standard PRC-029-1. Tripping for frequency excursions within these boundaries should not occur unless required by internal protection schemes.

Table 3. HILLs Frequency Ride-Through Requirements as Measured at POI

System Frequency (Hz)	Minimum Ride-Through Time (Seconds)
f≥61.8	May ride through or may trip
f≥61.2	299
f≤ 61.2 and f≥ 58.8	Continuous
f< 58.8	299
f< 57.0	May ride through or may trip

B. Ride-Through Performance for Reources Supporting a HILL Behind a Common POI

The ride-through requirements from IEEE 2800-2022, or PRC-024-4 are considered applicable to IBRs and non-IBRs supporting HILL facilities that are electrically coupled with one another at a common bus. Since the resources and the HILLs share the same POI, they shall coordinate their ride through performance to ensure system reliability and stability during grid disturbances, preventing adverse interactions between the HILL, onsite generation, and the BES.

IBRs Paired with HILLs: The IBR Plants paired with HILLs shall adhere to IEEE 2800-2022 Clause 7 requirements.

Non-IBRs Paired with HILLs: The ride-through requirements from PRC-024-4 are applicable to synchronous generators, Type 1 and Type 2 wind resources, and synchronous condensers supporting a HILL and are electrically coupled with one another at a common bus.

C. Control Methodology for HILLs

For HILLs consisting primarily of power electronic devices and/or variable-speed drives (VSDs):

1. HILLs shall use constant current control during disturbances and avoid constant power control, which can result in increased current draw during voltage sags and exacerbate local or system-wide instability; and
2. HILLs should not enable protection schemes or protection logic that may lead to the disconnection of the HILL from the SPP system during or following multiple voltage deviations resulting from automatic reclosing operations as long as the voltage measured at the POI remains within the limits specified in the ride-through requirements. If such a protection scheme must be activated to safeguard the equipment or due to the limitations of the equipment, the HILL must at least be capable of remaining connected to the system for a minimum of six voltage fault-clearing attempts within a 90-second period.

III. HDPS PROCESS

The HDPS process aligns with the SPP OATT, and it supports SPP Planning Criteria [14] and compliance with relevant NERC standards to cover technical study requirements for HILLs interconnections. It provides clear guidance for study engineers, HILL customers and stakeholders by outlining modeling requirements, evaluation steps, and decision triggers. The goal is to establish a transparent and consistent approach to assessing HILLs and also supporting secure system operations. Fig. 3 provides an overview of the technical studies necessary for HDPS evaluations. It outlines the key study types—including steady-state power flow, short circuit, transient stability, Electromagnetic Transient (EMT) screening, and supplemental studies. These requirements ensure consistency, reliability, and compliance throughout the HDPS process. The HDPS process includes base and supplemental stages (Fig. 3). If the HILL request fails to pass the EMT screening, supplemental studies shall be performed.

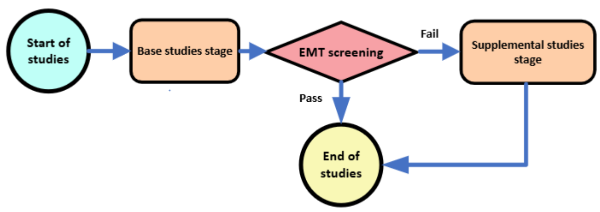

Fig. 3 Overview of HDPS Stages

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A. *Base Studies Stage*

This stage involves five studies (Fig. 4), including thermal overload study, voltage stability steady state study, Root Mean Square (RMS) dynamic performance study, and EMT screening. These studies should be conducted by SPP at the expense of the HILL Customer.

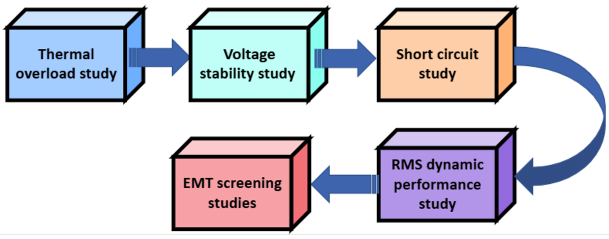

Fig. 4: Base Studies Stage

- **Thermal Overload Study:** Assesses whether project-related power flows cause transmission line or equipment overloads under various contingencies.
- **Voltage Stability Study:** Evaluates steady-state voltage performance to ensure no violations occur and identifies needed reinforcements if voltage support is insufficient.
- **Short Circuit Study:** Analyzes changes in fault current levels due to the HILL project to ensure compliance with NERC TPL-001-5.1 and determine if mitigation is required.
- **RMS Dynamic Performance Study:** Examines the project's effects on dynamic behavior—frequency, voltage recovery, transient stability, and fault ride-through—to confirm compliance with SPP and NERC performance standards.
- **EMT Screening:** Identifies fast transient and control interaction risks not captured in RMS or steady-state studies. SPP uses short circuit ratio (SCR), weighted SCR (WSCR), Composite SCR (CSCR), and Critical Clearing Time (CCT) thresholds (<3.0 and <0.15 s) to flag weak interconnections requiring detailed EMT studies, supported by tools such as EPRI's GSAT [15] for assessing system strength and stability.

B. *Supplemental Studies Stage*

Fig. 5 shows the necessary supplemental studies that should be done in this stage. All these studies should be conducted by SPP at the expense of the HILL Customer if the HILL fails the EMT screening.

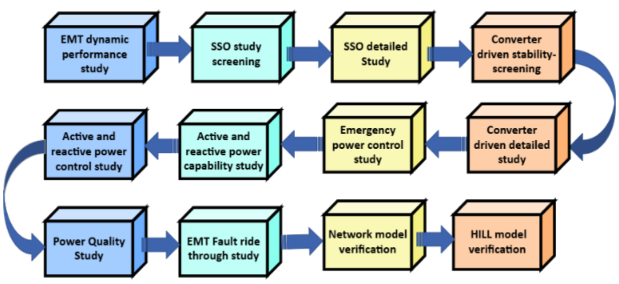

Fig. 5: Supplemental Studies Stage

- **EMT Dynamic Performance Study:** Uses detailed EMT models to assess HILL impacts on frequency, voltage recovery, and transient stability under various scenarios.
- **Sub-Synchronous Oscillation (SSO) Studies:** Include screening (impedance scans per CIGRE 909 [16] to detect sub synchronous resonance (SSR)/ sub synchronous control interaction (SSCI) risks and detailed analyses (using EMT simulations and damping assessments) to evaluate oscillation behavior and identify mitigation needs.
- **Converter-Driven Stability (CDS) Studies:** Screening uses SCR and weighted multi infeed interaction factor (wMIIF) metrics to detect converter interaction and weak-grid risks; detailed EMT studies are conducted if issues are found to resolve control and system interaction problems.
- **Emergency Power Control (EPC) Study:** Verifies EPC function, ramping capability, and compliance with performance requirements using EMT models.
- **Active & Reactive Power Capability Study:** Confirms converter active/reactive limits and steady-state capability, including under voltage ride through (UVRT), transient overvoltage (TOV), and unbalanced fault responses.
- **Active & Reactive Power Controller Study:** Validates power and voltage control performance via EMT/RMS simulations and response tests..
- **Power Quality Study:** Assesses harmonics, voltage steps, and unbalanced operation to ensure compliance and equipment compatibility.
- **Fault Ride-Through Study:** Evaluates HILL response to fault scenarios using EMT models to verify compliance with ride through requirements.
- **Network Model Verification:** Confirms alignment between SPP's RMS and EMT network representations.
- **HILL Model Verification:** Ensures RMS and EMT HILL models behave consistently and accurately reflect the actual project.

IV. Conclusion

The integration of HILLs presents both opportunities for economic growth and challenges for bulk system reliability. SPP's framework of ride-through requirements and the HDPS process provides a structured, technically robust approach to evaluate HILL impacts, ensure consistent performance, and maintain system stability. Base and supplemental studies—including steady-state, dynamic, and EMT analyses—identify potential reliability risks and necessary mitigations. Future work will focus on refining ride-through criteria, enhancing modeling of emerging power-electronic and converter-based technologies, and improving assessment methods for HILL interactions in weak-grid conditions. These efforts will support secure, efficient, and reliable integration of large loads across the SPP footprint.

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