NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Potential Bulk Power System Impact of Electric Vehicle Chargers

Preliminary Findings and Recommendations

January 2024

RELIABILITY | RESILIENCE | SECURITY

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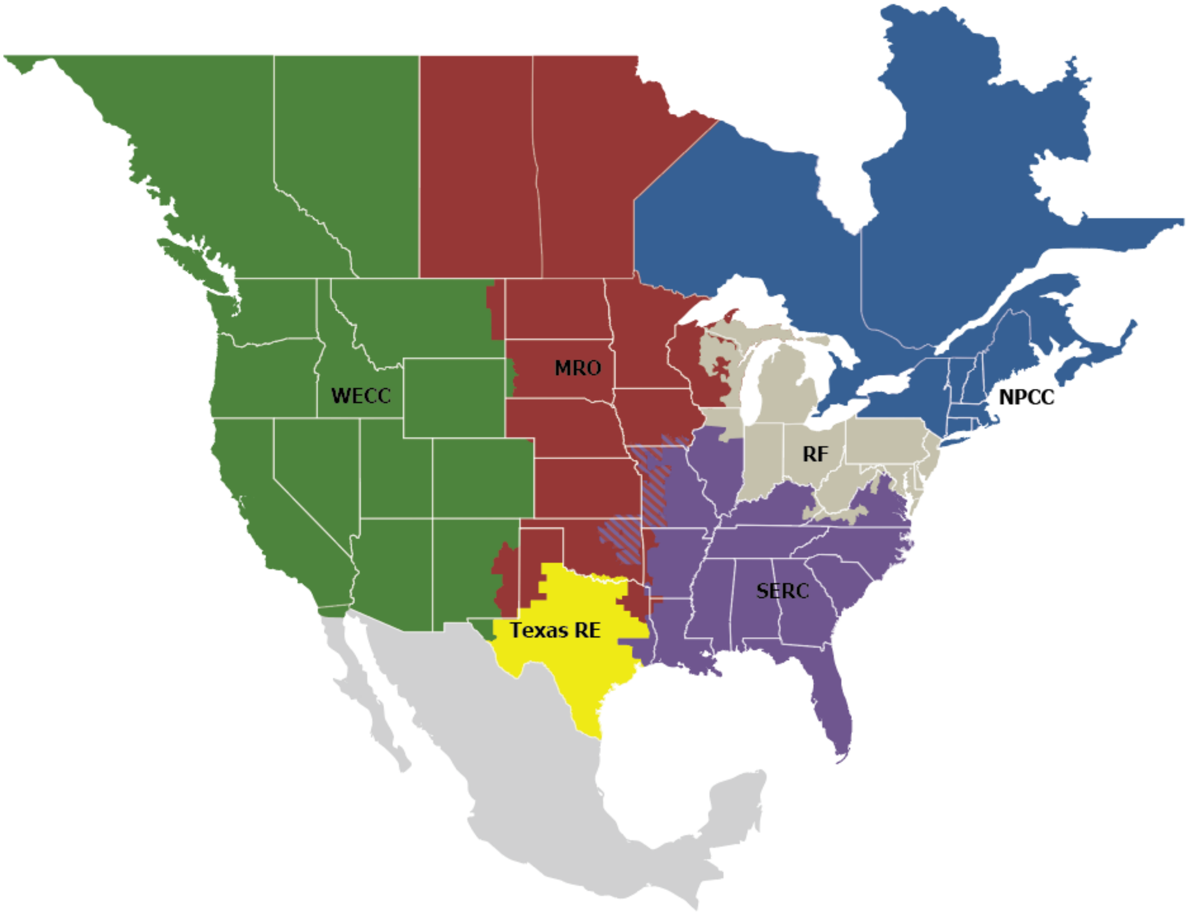
Preface

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

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

The North American BPS is made up of six Regional 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

NERC studies information from a variety of sources available to the ERO Enterprise to evaluate potential risks to reliability of the BPS. NERC completes these studies as part of executing its mission to ensure reliability of the BPS and in fulfillment of its responsibilities under section 215 of the Federal Power Act. Such assessments and studies do not seek to plan or propose fully realized solutions for the topic studied; rather, they provide stakeholders with engineering analysis on potential risks to reliability. Such studies provide key findings, guidance, and information on specific issues to promote and maintain a 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. NERC's studies 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 information supplied in this study.

Entities should review this study in detail and in conjunction with their evaluation of internal processes and procedures. Review of this study and such internal processes and procedures could highlight appropriate changes that should be made with consideration of system design, configuration, and business practices.

Executive Summary

NERC is publishing this white paper to help inform electric vehicle (EV) stakeholders and policymakers about the need for greater cross-sector collaboration regarding the potential effects of the rapid growth of EV charging on BPS reliability.

Growth in of Electric Vehicle Charging

As EVs become more numerous, their charging characteristics (i.e., where and how they charge) will have an increasing effect on the grid. Various studies have indicated that there will be significant EV growth through 2050.[1] Current projections and forecasts show that EV charging load can be dispersed throughout the BPS or at single points of interconnection. This white paper provides an overview of the potential adverse impacts of this growth on BPS reliability if not properly mitigated. **Chapter 1** contains a detailed discussion of projected EV growth.

Unique Traits of Electric Vehicle Charging

EV charging falls into one of four classification levels based on rate of charging.[2] NERC's initial study focus was primarily on Levels 1 and 2 based upon available data and projected near-term growth in these categories. However, it is important that future studies also address Level 3 and 4 chargers since the loads associated with these chargers (e.g., truck fleet charging) can be very significant.[3] A detailed discussion on charging levels is provided in **Chapter 1**.

The ability of EV owners to charge with their home charging systems as well as with public charging stations adds an element of uncertainty in electric load forecasting for given parts of the electric grid, potentially complicating BPS operations and planning. These forecasting challenges are further detailed in **Chapter 2**.

NERC, the National Laboratories, and others have conducted preliminary studies and concluded that EV charging can operate in either a grid-friendly or a grid-unfriendly manner.[4] However, if too many EV charging locations impact the grid in the unfriendly manner, BPS reliability could potentially be impacted.[5] Further details are in **Chapter 3**.

State of Industry Readiness

NERC has determined that there are significant gaps in both the electric utility and EV charging community's technical understanding, planning, and modeling of EV charging characteristics. While NERC has made efforts to address these knowledge gaps by working directly with EV manufacturers and other EV stakeholders, increased EV stakeholder awareness, engagement, and cross-sector collaboration is essential.

The following deficiencies are the most prevalent in modeling, standardization, and studies:

- **Modeling:** As it currently stands, there is only a single, generic electrical model to represent EV charging.[6] More work is needed to ensure that the electric system planners and operators have the quality of models needed.
- **Standardization:** Currently, EVs and their charging systems do not follow consistent control philosophies or performance. Simply put, two different EVs that use Level 2 chargers do not necessarily interact with the grid in the same way. This lack of standardization makes grid planning difficult. Efforts are under way within the electric industry to address this issue.[7]
- **Studies:** EVs and the effect of their charging systems on the grid have not been sufficiently studied.

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[1] *Annual Energy Outlook 2022*

[2] *Charger Types and Speeds*–Note that dc fast charging is broken into two subgroups, which other reports label Level 3 and Level 4.

[3] *Number of Public Electric Vehicle Charging Stations and Charging Outlets in the U.S. as of May 12, 2023*

[4] *Distribution-Level Impacts of Plug-in Electric Vehicle Charging on the Transmission System during Fault Conditions*

[5] *The Impact of Electric Vehicle Charging on Grid Stability*

[6] *A Positive Sequence Model for Aggregated Representation Electric Vehicle Charges*

[7] *ANSI Publishes Roadmap of Standards and Codes for Electric Vehicles at Scale*

NERC Electric Vehicles Study

To help address knowledge gaps about EVs and their charging systems, NERC undertook a study—based on the only model currently available on the subject—to determine how EV chargers interact with the electric grid and developed recommendations. Key findings and recommendations are presented below. Additional detail is provided in **Chapter 3**.

Key Findings and Recommendations

NERC has identified three key findings and recommendations for further action.

Key Finding 1

EV chargers can negatively impact BPS reliability depending on the way they draw current from the BPS (i.e., grid-friendly vs. grid-unfriendly).

Recommendation

To avoid reliability issues, EV and charging system manufacturers must increase their collaboration with electric utilities and establish performance criteria and standards regarding grid-friendly EV charging methods. Without greater collaboration, policymakers may need to act.

Key Finding 2

Reliability implications vary depending on the characteristics of the grid in specific locations and the number of EVs present. As a result, performance criteria are likely to vary based on location.

Recommendation

Transmission Planners (TP) will need to modify their planning criteria to indicate the types of charger performance criteria that are grid-friendly for their planning area. Different parts of North America will likely have different criteria for this, and it may be possible to address these criteria with EV charging software updates.

Key Finding 3

Knowledge gaps about EV charging behaviors create uncertainty in planning and understanding of the electrical impact that these devices may have on the BPS as well as associated policymaking.

Recommendation

Vehicle manufacturers, the electric industry, and policymakers must increase collaboration to close knowledge gaps and address reliability concerns and benefits.

Chapter 1: Electric Vehicle Charging Traits and Growth

The composition and nature of load models are rapidly evolving to represent the demand of the electrical system (i.e., BPS and distribution systems). These models started from as simple as polynomial/exponential mathematic models, to physics-based constant impedance, power, and current models (known as ZIP models or the polynomial load models), to modern motor and converter interfaced load models. With the rapidly increasing penetration of EVs, NERC evaluated the charging systems that interface EVs with the electric power system.[8] As with other rapid-moving technologies, early study and identification of potential BPS risks are essential to proactively mitigate any identified risk. This chapter highlights several insights into the growing sales and capacity of EVs and their charging systems. This chapter also identifies the potential impacts that this growth can have on the BPS.

Growing Penetration

The growth of EVs is not just a North American footprint phenomenon. Major areas throughout the world are rapidly electrifying their transportation sector, specifically light-grade vehicles used by most consumers during their day-to-day commutes or activities. **Figure 1.1**: Market Growth Projection (Source: Recurrent Auto) shows a market share report on battery EVs (BEV in the figure), plug-in hybrid EVs (PHEVs in the figure), full hybrid electric vehicles (HEV in the figure), and other types of EVs[9] alongside traditional internal combustion engine vehicles (i.e., diesel and gasoline powered). The electrical concern rises with BEVs and PHEVs as they draw current from the electric grid from which they charge. As the penetration of BEV, PHEV, and HEV[10] grows, the effect of their charging systems' characteristics on the electric system interconnections must be studied. As in **Figure 1.1**: Market Growth Projection (Source: Recurrent Auto), the global share of these vehicles by 2035 may reach above 50% of all vehicle purchases. Such projections are expected to be concentrated in the United States and European Union. While **Figure 1.1**: Market Growth Projection (Source: Recurrent Auto) does not provide market share for Canada, consideration of the EV growth in Canada will be an important component in assessing potential BPS reliability impacts within the ERO Enterprise footprint.

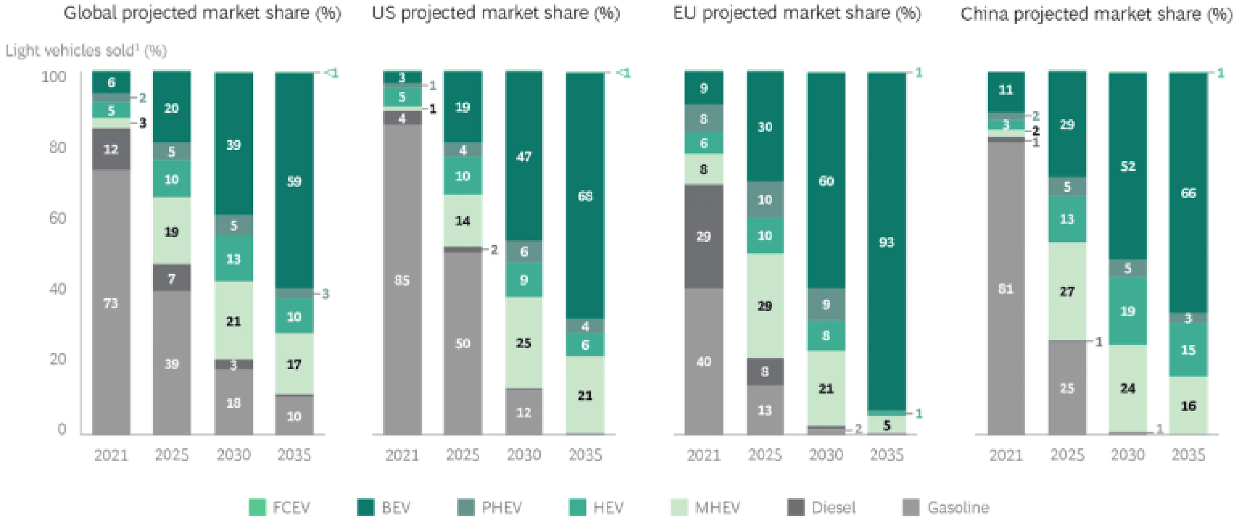

Figure 1.1: Market Growth Projection (Source: Recurrent Auto)

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[8] Referred to as electric vehicle supply equipment, generally. Exceptions to this term exist due to the rapid technology adoption of EVs. This report uses charging system due the electrical control logic potentially residing "on-board" the EV or "off-board" on electric vehicle supply equipment.

[9] The terms in the chart are explained in this article: EV Adoption, Trends & Statistics in the US.

[10] Although uncommon, some retrofit designs and post-manufacturing alterations by end users can modify an HEV to allow charging from the grid akin to a PHEV: *Electric Vehicle Conversions*.

What may be more telling is the adoption model for the EVs. Adoption models represent the percentage of consumers who will likely own a particular device or have access to a particular technology. For instance, while it took more than 15 years for half of the population to have access to an AM radio, smartphones passed half of the population adopting them within 10 years.[11] EVs are an emerging technology and may have many incentives for a rapid adoption like the smartphone. The Recurrent Auto organization performed four annually released projections to see how the expected sales rates (and thus adoption rates) were based on the year-over-year differences in consumer demand, supply chain enhancements, and other market factors. The projections for EV sale market share presented by the Boston Consulting Group (BCG) are in **Figure 1.2**.

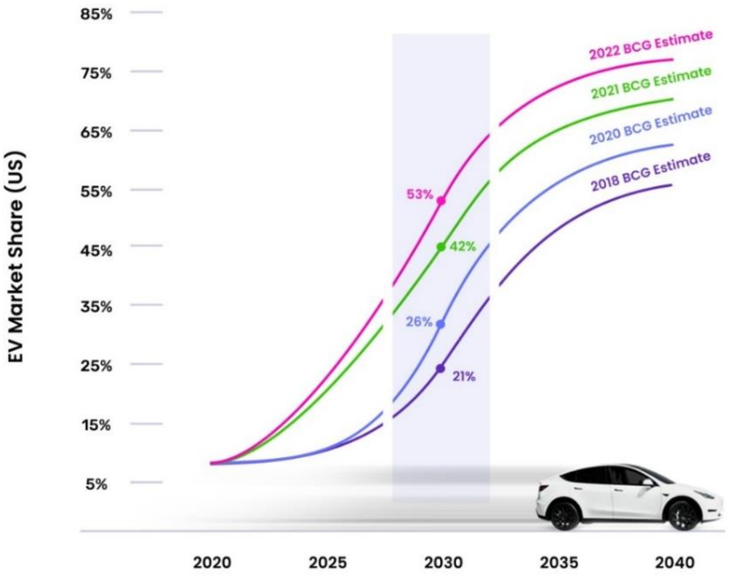

Figure 1.2: Projected U.S. Sales of EVs by 2040 (Source: Recurrent Auto)

The growing penetrations of EVs necessitate a study of the real or anticipated risks that the EVs with their charging requirements bring to the electric grid. This white paper aims to highlight the general risks to the electric sector in addition to demonstrating high-level, Interconnection-wide BPS impacts of specific charging paradigms.

Electric Vehicle Load Growth Impacts

One major finding from the growth projection reports is the impact that the charging infrastructure can have on the capacity requirements of the distribution and transmission systems; these are highlighted in **Figure 1.3** and are largely dependent on the ac vs. dc link from the EV's charging systems and the EV's battery management system. During single-phase ac charging, the estimated draw can be a maximum of 7 kW that, while large, would only require upgraded service if the EV's owner's residence contains significant major electrical appliances or draw,[12] such as an end-use customer using multiple electric heating, ventilation, cooling, and motor loads. Only when large amounts of end-use customers adopt these chargers are distribution upgrades required. In comparison, dc charging enables much greater charging capacity in the range from 50–350 kW, depending on the equipment; some chargers are slated to have 1 MW or greater charging capacity.[13] Chargers are categorized into "Levels" of charging capability and the electrical connection required to supply the power to the EV:

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[11] *Consumer Adoption*

[12] Assuming a 200 Amp supply, 7 kW is 14.58% of the rated supply. Typically, breaker ratings and end-use equipment is sized to the 200 Amp limit.

[13] These are Level 4 dc fast chargers generally used for commercial-grade equipment. It's likely these will be near more commercial areas while the slower chargers are for longer dwell time vehicles: Top Charger Article on Different Charger Levels

- **Level 1 Chargers:** A range of 2.6 kW for a single-phase ac supply generally using a three-pin socket, which is the slowest of chargers available to end users.
- **Level 2 Chargers:** A range of 7.4 kW with a single-phase ac supply or 11 kW with a three-phase ac supply (maximum for at home). A dc supply allows for up to 50 kW. These chargers require specialized equipment to be installed regardless of supply.
- **Level 3 Chargers:** A range of 60–100 kW for “rapid” and up to 350 kW for “ultra-rapid” chargers. These require a strong tie to the distribution substation or a connection for transmission service depending on the facility size and the total chargers in the location. These are generally public charging hubs or parking lots offering charging stations as an amenity for their users.
- **Level 4 Chargers:** Defined by 1 MW or greater charging capacity. These “megachargers” are in research and development and are planned for the trucking and other heavy equipment industries. Any facility of size (10 or more stalls) would require significant ties to a dedicated distribution substation and will likely need transmission infrastructure updates.

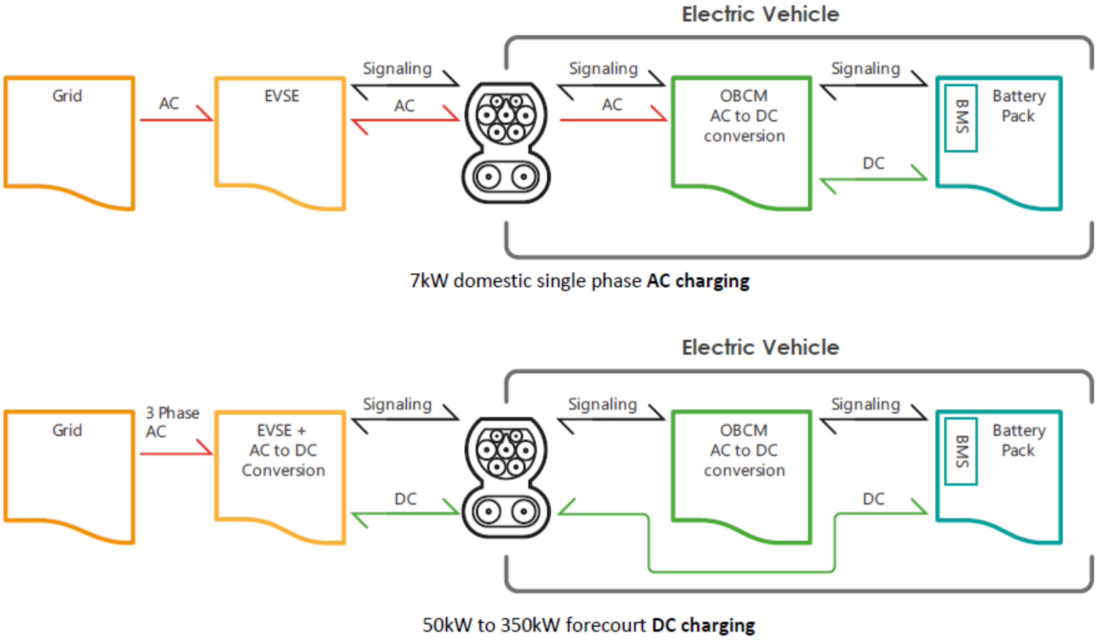

Figure 1.3: Difference in Capacity Needs for AC and DC Charging (Source: Sygensys)

The automotive industry is rapidly electrifying, and the generation, transmission, and distribution capacity and energy requirements for these new loads are trending upward. This added load and strain on the electrical grid has been projected to have vastly different outcomes depending on the scale of technology development, customer adoption, and the connection to the BPS. Larger EV charging loads are anticipated to use higher charging levels that necessitate direct connection to the BPS to supply a large EV charging load. However, EVs also are mobile and could charge at other end-user locations that use lower charging levels. The Energy Information Agency (EIA) provided some transportation electrification information in its *Annual Energy Outlook*.[14] The EIA has identified that EV sales will grow to add millions of vehicles each year between today and 2050 (see **Figure 1.4**). These sales each can be translated into at least a Level 1 charger to supply that EV with the needed energy for its end use, typically at distribution-level voltages. This white paper focuses on the aggregate impacts of dispersed EV charging load because of that translation; however, the characteristics and impacts of EV loads directly connected to the BPS can benefit from aggregate EV findings.

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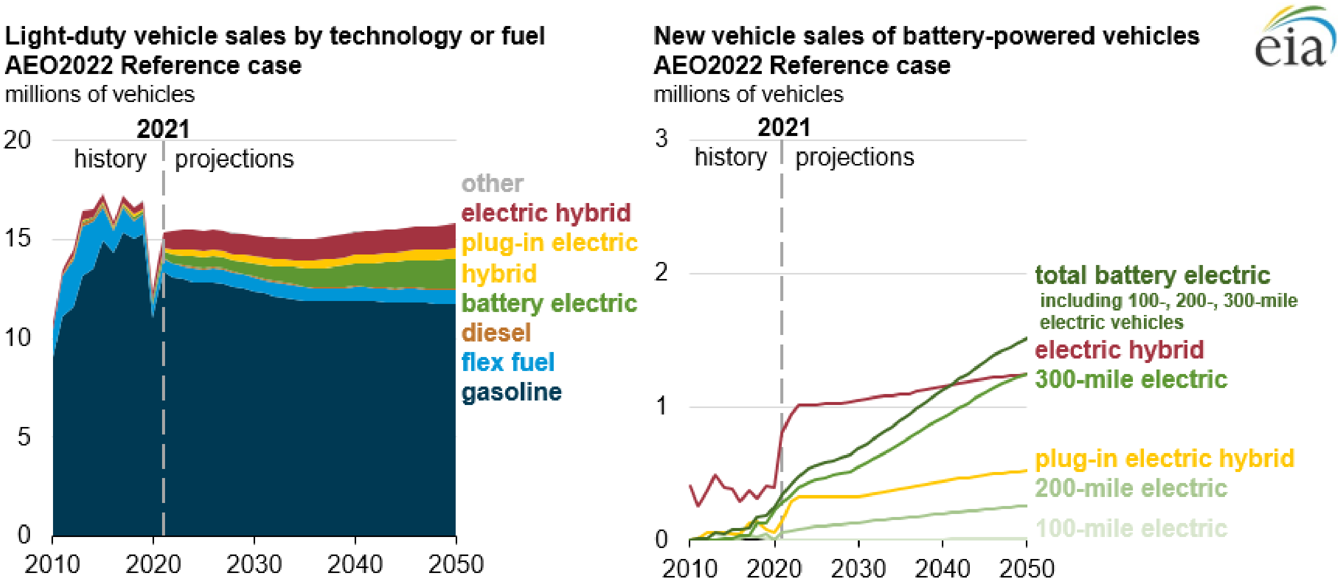
[14] The EIA *Annual Energy Outlook 2022* is an annual report that contains relevant energy policy information that sites information on EV consumption.



Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022* (AEO2022) Reference case

Figure 1.4: United States Light-Duty Electric Vehicle Growth (Source: EIA)

Cyber Security Considerations

The BPS impact of EV charging technology can differ depending on the connection point's voltage level, the aggregate response of specific controls, or the response of the equipment due to a malicious compromise. This white paper does not discuss the cyber security risk associated with EV charging in detail (e.g., reviewing threat intelligence), but the electric industry, through ongoing activities, seeks to analyze EV and charging system vulnerabilities and recommend areas of research to enhance security by design for the equipment. Proposed control recommendations for securing equipment include robust cyber-strong designs, the enabling of security patching, and managed security policy to mitigate vulnerabilities from exploitation by malicious threat actors.[15]

Research has been undertaken to explore potential electric system reliability risk associated with cyber attacks that affect EV charging equipment, including the potential for simultaneous equipment outages capable of inducing frequency or voltage disturbances. Some of the research reviewed focused solely on the interconnection effects of tripping a load block independent of the anticipated electrical response of surrounding EVs that did not trip off-line.[16] While this work robustly identified potential threats, vulnerabilities, and mitigations, other research reports assumed a more modest penetration of EVs and their charging systems.[17] These reviewed reports did not contain an analysis of the security posture coinciding with larger EV adoption and did not address security risk from a BPS perspective.

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[15] One example: *Cybersecurity of Smart Electric Vehicle Charging: A Power Grid Perspective*. See also: Roadmap of Standards and Codes for Electric Vehicles at Scale

[16] An example of the research reviewed: *Cybersecurity for Electric Vehicle Charging Infrastructure*

[17] As in: OSTI Document

Chapter 2: Industry Preparedness and Study Structure

This chapter provides background information relevant to the approach undertaken by the group of professionals who were engaged in performing the study presented in **Chapter 3**. Various assumptions were made based upon available information and the professional judgment of the study participants.

ANSI Roadmap of Electric Vehicle Standards

The American National Standards Institute (ANSI) outlined a variety of areas to enhance EV standards so that they are clear, consistent, and scalable for the rapid adoption of EVs.[18] The ANSI roadmap's intent is to "be broadly adopted by the user community" and "facilitate a more coherent and coordinated approach to the future development of standards for EVs." The roadmap covers everything from the onboard vehicle systems to the charging infrastructure as well as touching on concerns for grid interconnection and cyber security standards of EVs and their charging systems. Generally, the roadmap identified that the major cyber security concerns lie with the lack of clear regulatory application of existing cyber security frameworks and best practices, in addition to identifying no standard protocol for communication between EVs, end-use customers, utilities, and other third parties. Overall, while opportunities for significant enhancements to standardization exist, there are likely to be gaps in the understanding of technology and expected electrical performance. While the ANSI report presents some conclusions regarding electric system impacts of a malicious actor exploiting potential vulnerabilities, it does not identify the best corrective action for any grid-level impacts. The ANSI framework also identified that ride-through studies and requirements need clarity for EV applicability and desired outcomes.

This white paper speaks to the friendly versus unfriendly nature of various EV charging behaviors and presents recommendations based on the ANSI findings.

Industry Understanding of Electric Vehicle Charging Impacts

While industry has performed some work in understanding the impact and importance of rising EV growth as detailed in **Chapter 1**, improvements are needed in the modeling of EVs and clarity in EV equipment standards necessary to support BPS reliability as well as stakeholder understanding of the potential electric system impacts of EV policies.[19] NERC has identified three important areas for further focus:

- **Modeling of EV Charging Behaviors:** The available models that represent EV behavior are inadequate. Through research, development, and iterative improvement, a proper representation of EV electrical behavior should be capable of accurately being modeled.
- **Vehicle-to-Grid Programs:** Operators have the need to integrate vehicle-to-grid (V2G) programs and impacts into their operational planning assessments or real-time assessments such that the assessments reflect policymaker-approved equipment standards for their footprint. EV original equipment manufacturers (OEM) should strive for greater standardization and integrate emerging technology into current operator systems, especially since EVs cross operator and/or Interconnection boundaries.
- **Transmission Studies:** There are no robust transmission studies to capture the impact that EVs and their charging systems have on common planning problems. Through beta studies that focus on EV impacts and improved study procedures, NERC anticipates that TPs will need to undertake recurring studies to accurately capture reliability risk for their areas.

The above three topics and associated milestones of improvement are further detailed in **Appendix C**. This white paper should be considered the first milestone in the transmission modeling and studies pillars.

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[18] *Roadmap of Standards and Codes for Electric Vehicles at Scale*

[19] While distribution system impacts will need to be addressed, those are not the focus of transmission studies. Rather, the purpose of transmission studies is to ensure reliable delivery of power to the distribution system and other end-use loads.

Study Objective and Previous Study Follow-Up

With the rapid growth of EVs across the ERO Enterprise footprint, the impact of coincident charging and response to various grid disturbances on the BES needs to occur at both an Interconnection level as well as at a local load bus. A study of EV chargers and their responses to "deep"-level faults has already been documented in the Pacific Northwest National Lab (PNNL) report titled *Distribution-Level Impacts of Plug-in Electric Vehicle Charging on the Transmission System during Fault Conditions.*[20] The report classifies six charger types, and an EV model has been developed to broadly characterize them.[21] Due to the expected EV to be charged from the distribution system, the model takes an aggregate approach to reflect the response to the transmission and distribution interface (T-D Interface). The description of the model controls is found in the *A Positive Sequence Model for Aggregated Representation Electric Vehicle Chargers* report.[22] These controls were implemented by the positive sequence load-flow software used by the NERC EV Study Team (Study Team), and the block diagram is shown in **Figure 2.1**[23] for the aggregate model's active power components. The reactive power control block is the same, minus the droop control block, and it uses Q_o and V_{filt} as its inputs rather than P_o and V_t. There is a direct control of the initialization fraction for the P to Q consumption of the aggregate.

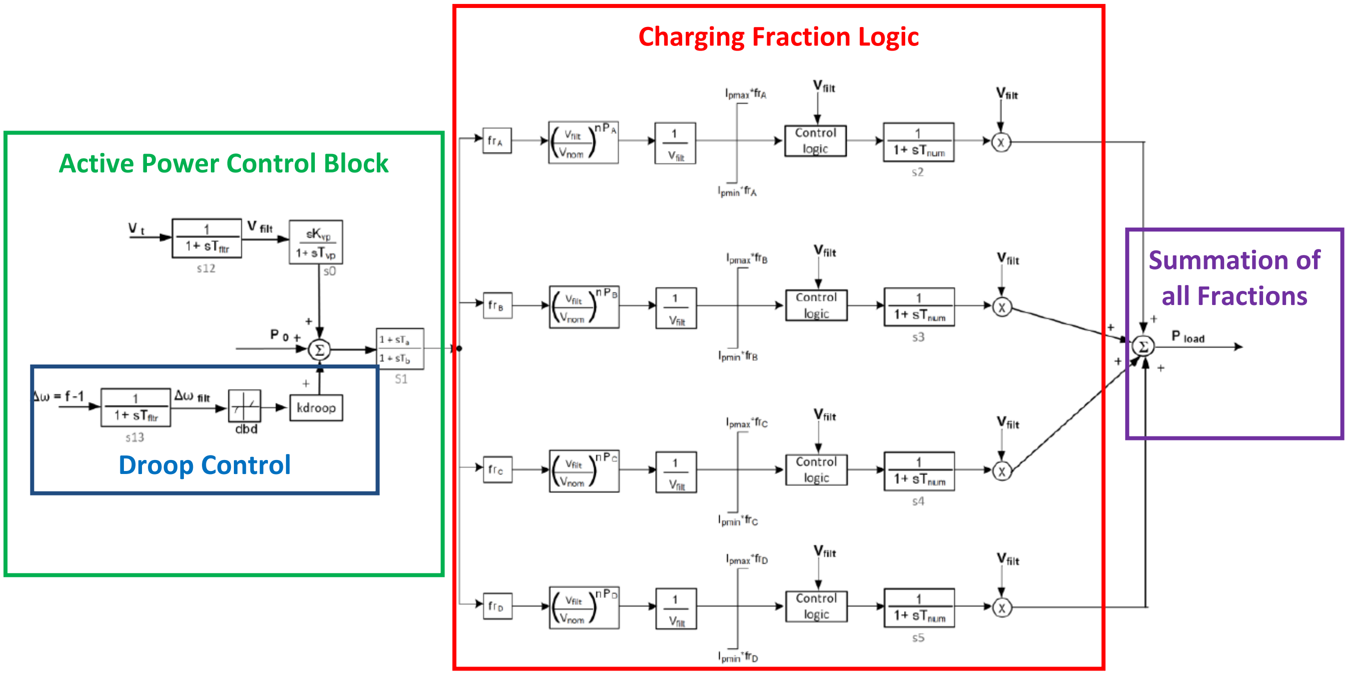

Figure 2.1: Block Diagram of Aggregate EV Model Active Power Logic (Source: General Electric)

In April 2023, a cross-sector EV grid reliability working group formed by the California Mobility Center published a paper—with the support of WECC and NERC[24]—that identified recommended EV charging behaviors. These recommendations included providing fault ride-through and promoting "grid-friendly" behavior. These behaviors typically indicate that the EV should ride through low-voltage conditions as much as possible (expected down to 0.75 p.u. nominal voltage) and if there is a need to trip, they should recover quickly once the voltage returns to a percentage of nominal. This study and model seek to test those behaviors in a major adoption case and see if the study results can confirm various recommended behaviors.

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[20] *Distribution-Level Impacts of Plug-in Electric Vehicle Charging on the Transmission System during Fault Conditions*

[21] *Positive Sequence Model for Aggregated Representation Electric Vehicle Chargers*

[22] *Positive Sequence Model for Aggregated Representation Electric Vehicle Chargers*

[23] GE, "*GE PSLF User's Manual*," General Electric Int. Ltd., Schenectady, NY, USA, Oct. 2012.

[24] *Electric Vehicle Dynamic Charging Performance Characteristics during Bulk Power System Disturbances*

This white paper further evaluates the electric system impacts that these recommended EV charging behaviors can have when most of the coincident load is composed of both motor load and EV charging. While motor loads may dominate the load composition today, EV charging loads are expected to increase as states and provinces continue to promulgate policies supporting EV adoption. EV charging may impact the BPS if the charging equipment is not programmed to respond to faults and other grid disturbances in a grid-friendly way. This white paper focuses on providing recommendations on charging profiles necessary to maintain electric system stability.

Study Method, Assumptions, and Inputs

Transmission engineering studies evaluating the reliability impact of specific phenomena require models with populated information reflective of installed facilities and equipment. Some equipment has a direct representation of its parameters, and others are represented by an electrical equivalent, typically done at the connecting edges of the Interconnections. For example, the set of transmission models does not typically model in detail the sub-transmission or distribution system in their area but rather summarizes the electrical quantities at the nearest BPS-connected bus (e.g., 115 kV bus). Far more often, the sub-transmission is modeled rather than a distribution system, and even then, primarily with electrical equivalents to capture well-known and understood phenomena (e.g., the collector system of a solar PV plant). While the interconnection point is typically the distribution system, load records still need to be represented in these transmission models and electrical equivalences typically incorporate their impact.

When assessing distribution-connected EV charging systems and their aggregate impact on the BPS, the component-load model (or composite-load model) with aggregate modeling of lumped distribution parameters is considered the most appropriate and practical approach for this white paper. The high-level component modeling is provided in **Figure 2.2**.[25]

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[25] Source: PSLF. GE, "*GE PSLF User's Manual,*" General Electric Int. Ltd., Schenectady, NY, USA, Oct. 2012.

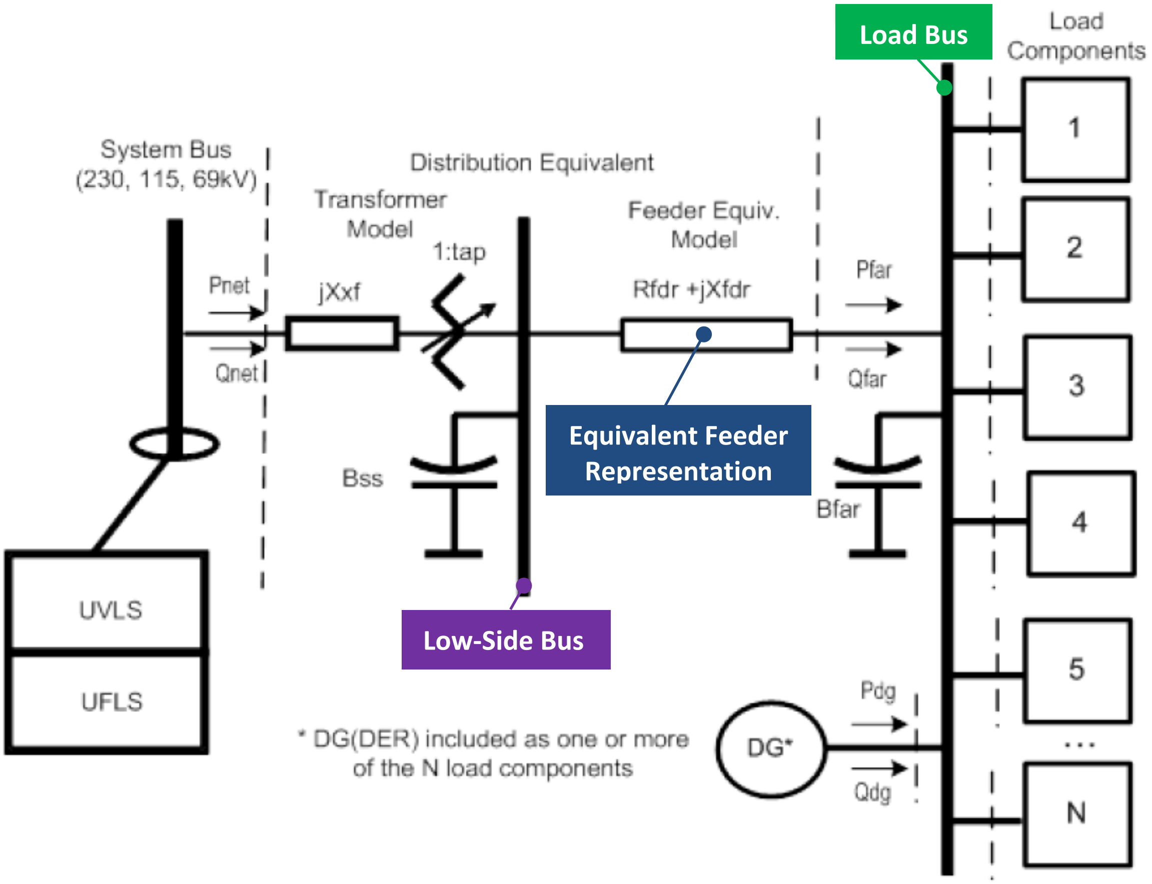

Figure 2.2: Component Load Model (Source: PSLF)

The load record is first expanded into a T-D transformer with a low-side bus, equivalent feeder representation, and a load bus at the end of the feeder equivalent. These models are each described in the GE Positive Sequence Load Flow (PSLF) software manual[26] that comes with the software installation. Typically, the composite load model is used to produce the equivalent feeder and expands the representation for the engineer on initialization of the composite load model. Notice that distributed energy resources (DER) can also be linked to the load components; based on the system planning impacts from the DER Working Group, this would be a good method to model the retail-scale DER behind a transmission-distribution interface. This white paper represents both the load and DER components of the load via the **cmpldw2** model, which is depicted in Figure 2.3. This high-level aggregate EV model is one of these load components among three-phase motors, single-phase motors, and static-load components.

This white paper includes a fault response analysis and a generation loss response to a set of interconnection-wide models. The ability to mitigate against fault-induced delayed voltage recovery, overvoltage, and frequency response metrics are used to characterize the BPS impact these chargers have.

Electrical Characteristics of Level 1 and Level 2 Chargers

Level 1 chargers contain a different expected response to electrical service disruption from Level 2 chargers as identified in the Global Power System Transformation (G-PST) Consortium's report,[27] which is the outcome of research directed at the modeling and analysis of DERs that included work on the electrical characteristics of Level 1

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[26] GE, *"GE PSLF User's Manual,"* General Electric Int. Ltd., Schenectady, NY, USA, Oct. 2012.

[27] Consortium information available here: *Australia's Global Power System Transformation (G-PST) Research Roadmap*. Specifically, GPST Topic 9 – DER and Stability identifies EV behavior as part of the equipment studied.

and Level 2 residential chargers. The two chargers (a Level 1 and a Level 2) and their tested equipment are summarized in **Table 2.1** with the ride-through characteristics to various duration and depth of faults. The G-PST tested the two chargers for fault depths ranging from 0.8 to 0.2 p.u. voltage and 80 ms, 120 ms, and 220 ms durations.[28]

Table 2.1: Level 1 vs. Level 2 EV Charger Capabilities

Quantity	Level 1 Charger	Level 2 Charger
Active Power Consumption	2.2 kW	7.4 kW
Power Factor	0.93 leading	0.99 leading
Ride-through mode for an 80 ms 0.5 p.u. voltage dip	No interruption, ride-through in constant current	No interruption, ride-through in constant current
Ride-through mode for a 220 ms 0.5 p.u. voltage dip	Cease consumption for 7 seconds	No interruption, ride-through in constant current
Ride-through mode for an 80 ms 0.2 p.u. voltage dip	Cease consumption for 32 seconds	No interruption, ride-through in constant current
Ride-through mode for a 220 ms 0.2 p.u. voltage dip	Cease consumption for 32 seconds	No interruption, ride-through in constant current

Notably, the 0.5 p.u. depth faults showed that the tested chargers would not disconnect or momentarily cease charging during depressed voltage conditions. Rather, we see that the ride-through characteristic tested was a Q priority on-fault condition. The Level 1 charger's on-fault response recording is found in **Figure 2.3**, and the Level 2 charger's on-fault response is found in **Figure 2.4**; these figures show the active or reactive power (**blue** lines) against various faults (shown with the **red** voltage trace) applied to Level 1 or Level 2 chargers. Level 1 charging demonstrated that the short-duration fault to 0.5 p.u. did not interrupt the charger's service. This behavior stays the same for the Level 2 charger for even deeper voltage dips. The Level 1 charger, however, enters different ride-through behavior as the fault duration increases and depth of the voltage dip exceeds 0.5 p.u. voltage.

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[28] Note that the G-PST tested these chargers on a 50 Hz system, meaning that these fault durations are 4 cycles, 6 cycles, and 11 cycles, respectively. These durations range from a normally cleared fault to a delayed clearing fault and thus simulate expected real-world behavior.

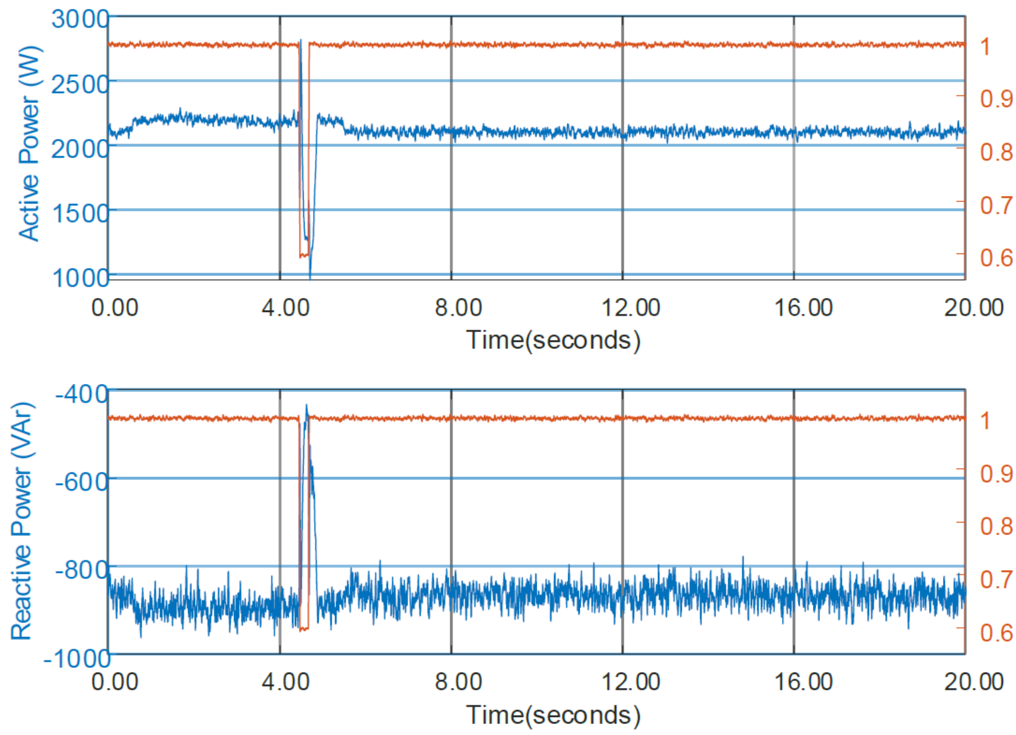

Figure 2.3: Level 1 Charger On-Fault Behavior to 0.5 p.u. Voltage Dip (Source: G-PST)

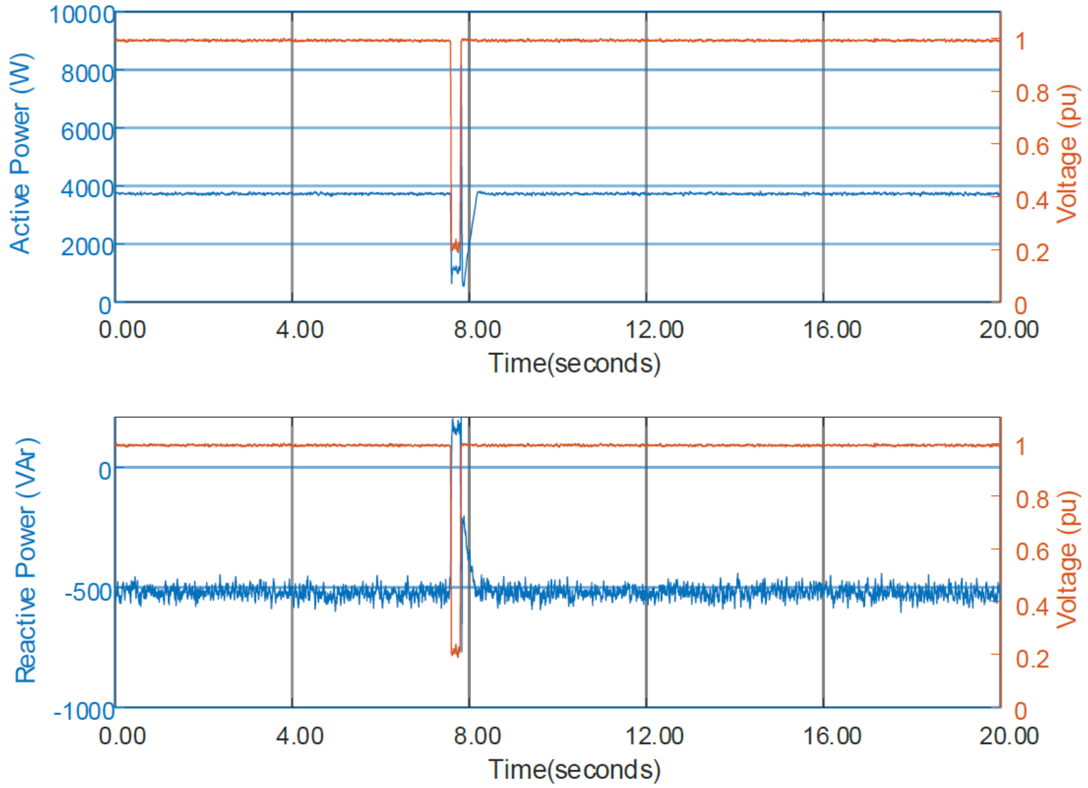

Figure 2.4: Level 2 Charger On-Fault Behavior to 0.2 p.u. Voltage Dip (Source: G-PST)

The change in Level 1 behavior with steep voltage dips (at or below 0.5 p.u.) results in the charger disconnecting for 7–32 seconds, depending on the duration and depth of the fault. At 0.5 p.u. voltage dip, the Level 1 charger would ride through faults that were 80 ms but momentarily ceased charging for 7 seconds if the duration of the dip was greater than 120 ms. Beginning at 0.3 p.u. voltage dips, the Level 1 charger would disconnect for 32 seconds if the fault duration was 80 ms or higher. This is highlighted in the comparison in **Figure 2.5**, which follows the same color conventions as **Figure 2.4** and **Figure 2.5**.

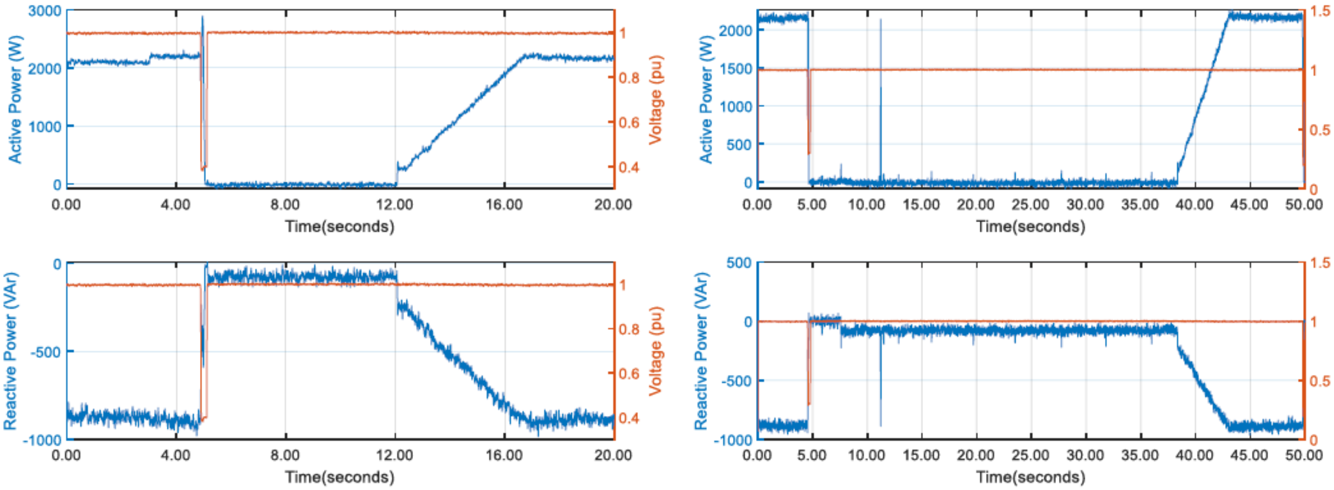

Figure 2.5: Level 1 On-Fault Behavior for Long Duration (Left) and Deep (Right) Voltage Dips (Source: G-PST)

Counter to the findings in the G-PST report, Idaho National Labs (INL) tested different chargers as part of the PNNL report[29] detailed in the **Study Objective and Previous Study Follow-Up** section. The chargers tested at INL exhibited a broader set of charging behavior; however, the INL team only tested 0.5 p.u. voltage dips for nine cycles when charting the electrical behavior. They identified six broad behaviors as demonstrated in **Figure 2.6**. These six broad behaviors are also further simplified into four categories if the immediate on-fault simulation time step is not as important as the on-fault and post-fault behavior. One of these four categories causes a negligible reduction of power to a fault (0.5 p.u. voltage), shown in the green and yellow plots in **Figure 2.7**. The remaining three charger categories consist of a reduction of power in response to the fault with varying ramped return-to-service periods. Thus, these tests validate the model development overviewed in the **Study Objective and Previous Study Follow-Up** section of this white paper that demonstrates the positive sequence model used to represent this charging behavior.

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[29] *Distribution-Level Impacts of Plug-in Electric Vehicle Charging on the Transmission System during Fault Conditions*

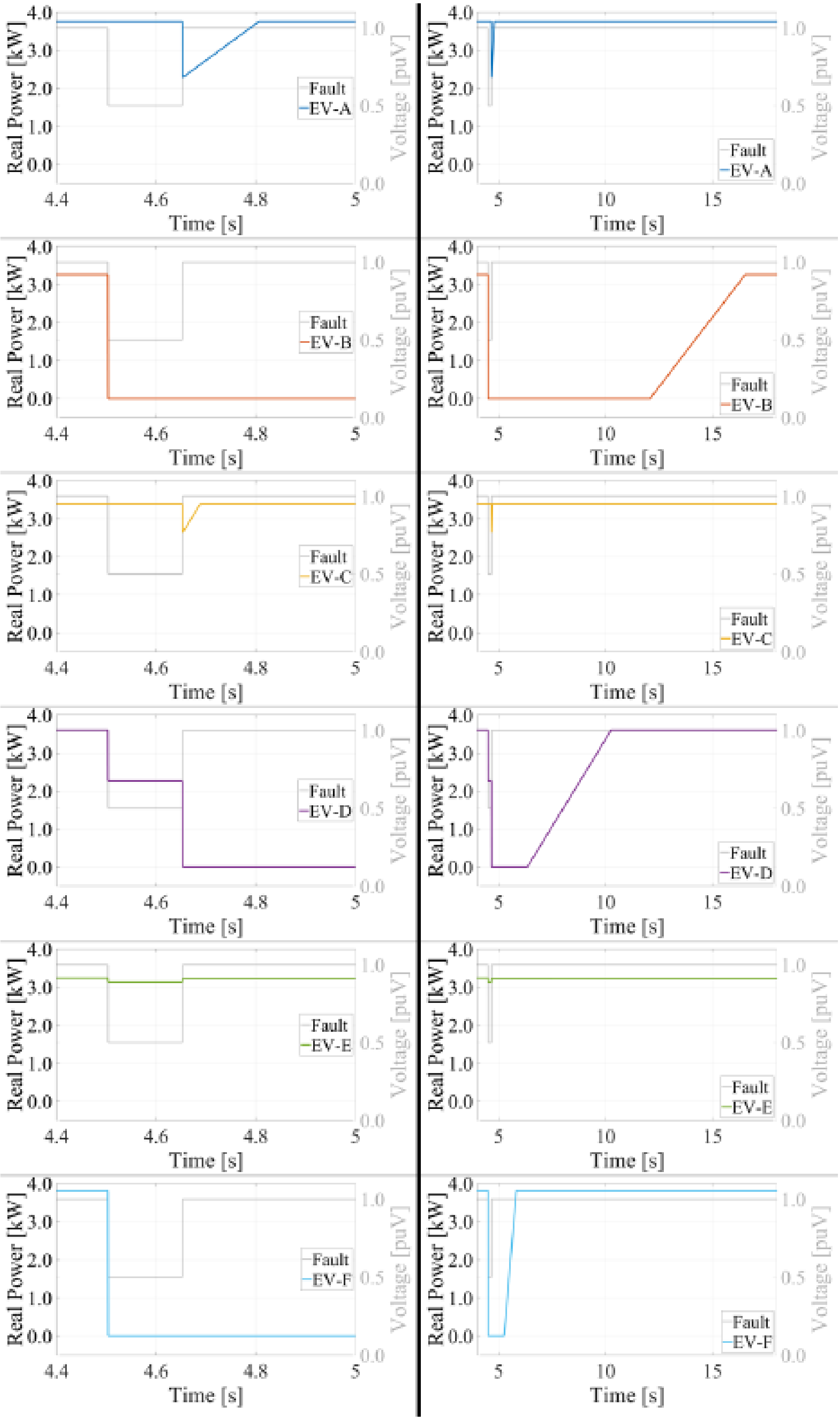

Figure 2.6: INL Real and Reactive Power Response for Tested EV Chargers (Source: PNNL)

Anticipated Electric Vehicle Profiles

The time of day that EVs charge is a major factor in EV steady-state and stability studies for transmission-level studies. The California Energy Commission has identified a load duration profile to be used to identify which level of EV charger the end-use consumer is using at a given time. As shown in **Figure 2.7**, there is an anticipated rise in residential Level 1 and Level 2 charging toward the evening hours that will dissipate as vehicles reach full capacity. In the daytime, the EVs are more likely to be plugged into Level 2 chargers at a public parking facility or in a workplace garage with the current rollout of charging locations. Additionally, Level 3 chargers ("Fast Charging" in **Figure 2.8**) will have inter-hour peaks due to their ability to rapidly charge the EV battery.

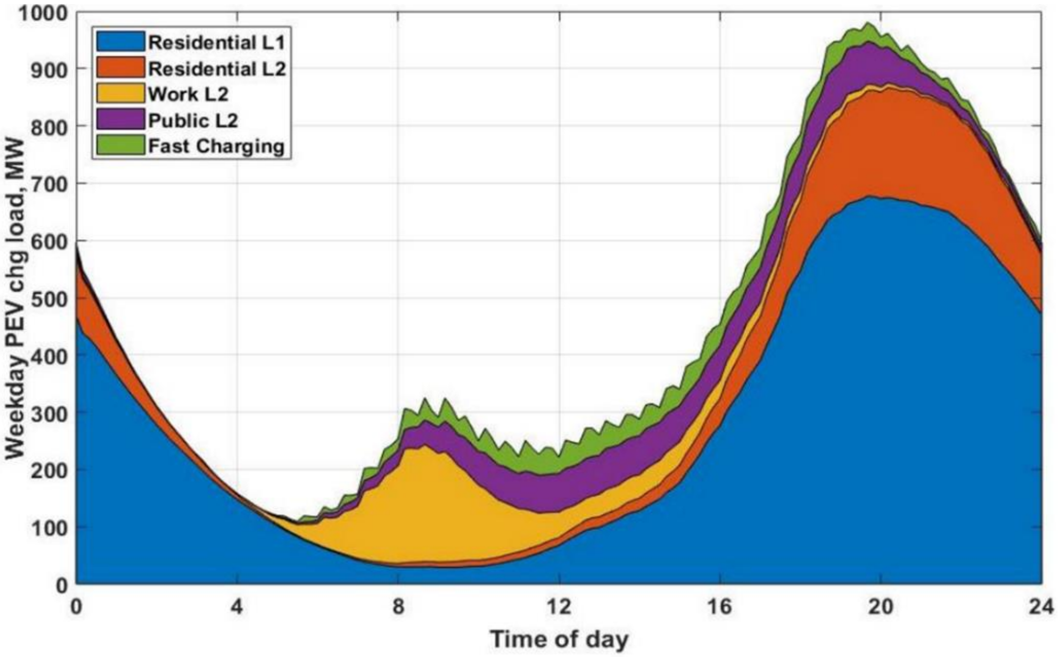

Figure 2.7: California Energy Commission Electric Vehicle Charging Profile (Source California Energy Commission and NREL)

Figure 2.7 shows that there are two different potential study conditions. One will be at the peak near the evening and another at the early morning to midday peak. The evening peak will use residential Level 1 or Level 2 chargers primarily with a mixture of other Level 2 and some Level 3 chargers as public places. Based on **Figure 2.7**, the Study Team identified that of the nearly 1,000 MW of capacity tracked in this profile, roughly 850–870 MW of the evening peak was Level 1 chargers with the remainder being Level 2 or Level 3 chargers. For simplicity, 85% of evening peak was identified to be made up of Level 1 chargers with the remaining 15% of EV load to be Level 2 or Level 3. In the midday, this percentage composition is much different. In **Figure 2.7**, the midday peak of roughly 300 MW contains only about 50 MW of Level 1 charging with the remainder being Level 2 or Level 3 chargers. This equates to 17%, which is 15% of the EV load as Level 1 chargers with the remaining 85% to be Level 2 or Level 3 chargers. Comparing the two peaks in magnitude shows that the evening peak is roughly three times greater than the midday peak; however, this can change depending on how additional infrastructure buildouts for public charging stations, industrial charging capabilities, and workplaces adopt faster chargers. The general peak load conditions that are to represent the times of 4:00–8:00 p.m. local time will generally need Level 1 chargers modeled, while the midday hours would need the model to be majority Level 2 chargers.

Electric Vehicle Chargers and Growth

As all forecasts come with some uncertainty, there are many different projections for the anticipated growth of the charging stations available to EV owners. Most EV owners currently rely on their at-home end-use charging station (typically a Level 1) to charge their EVs for use during the following day; however, some EV owners elect to use the public charging stations. Based on current installed equipment, **Figure 2.8** shows that roughly three times as many end-use charging outlets are installed as there are public charging stations, yet the number of fast chargers are anticipated to increase as the technology advances to higher power draw devices.[30]

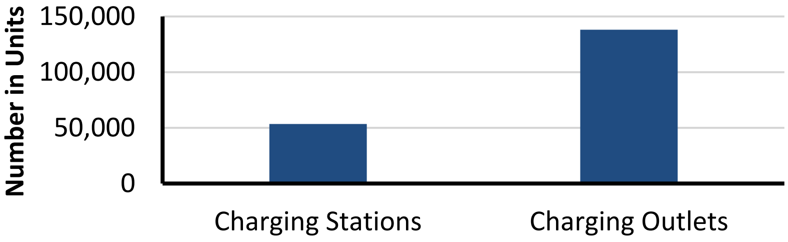

Figure 2.8: Electric Vehicle Public Charging Stations vs. Charging at Home (Source: Statista)

Assuming all of the **Figure 2.8** charging stations and outlets are Level 2 chargers, 1,417 MW of EV charging load is already installed or, in other words, EV charging load is currently less than 1% of peak load for most Interconnections. Some have projected this load to move from the meager 1 GW into 100 GW of EV load,[31] which would indicate a shift to 30% of peak load conditions (or even potentially most of a lower load condition) to be needed to serve EVs. The current breakdown and rapid adoption of EVs indicate that the Study Team should begin to look at these higher-percentage penetration studies to observe what Interconnection-wide performance changes occur depending on the amount of EV load served.

Study Setup

In this white paper, the Study Team used a single base case to represent the Western Interconnection[32] and made a few alterations to situate the long-term planning cases to assess current EV projections and their potential impact to grid reliability. The set of models was altered to reflect large-scale EV adoption and tested the impacts of electrification of the transportation sector at an Interconnection-wide level. **Table 2.2** summarizes the cases.

Table 2.2: Study Case Comparison

Case Description	Total Load	Total EV Load	EV Percentage of Load
Long-term Horizon Heavy Summer Conditions	199,110 MW	37,748 MW	18.96%
Near-term Horizon Light Spring	121,759 MW	19,941 MW	16.38%
Long-term Horizon Heavy Summer with High EV Adoption	199,110 MW	105,673 MW	53.07%
Near-term Horizon Light Spring with High EV Adoption	121,759 MW	55,792 MW	45.82%

The Heavy Summer and Light Spring Case are indicative of time-of-day charging. Heavy summer conditions stress the loading of the transmission system and have historically occurred in summer months for the Western

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[30] *Number of Public Electric Vehicle Charging Stations and Charging Outlets in the U.S. as of May 12, 2023*

[31] *The EV Transition Explained > Engineering a New Cyberphysical System at Scale Poses Daunting Challenges*. Replacement of 1.3 billion vehicles with EVs yields very high GW penetrations. Even at 30% coincident loading and only half of the vehicles replaced, this would be 432 GW.

[32] WECC cases are available to those with the prerequisite access to their information here: https://www.wecc.org/SystemStabilityPlanning/Pages/BaseCases.aspx

Interconnection.[33] Light loading conditions generally happen during off-peak conditions and are coupled with maintenance outages in the spring and fall months, demonstrating a propensity for voltage problems. With EVs being projected in the **Anticipated Electric Vehicle Profiles** section, the penetration of EVs currently lies at less than 1% of load. With the EIA projecting EV sales growth in the near term, 100 GW of demand would be on the high end of the projections. This would be at most 30% of coincident load for the above cases (adding the new load to current load). However, these projections may be underestimating the adoption rate of EVs, so the Study Team tested moderate and very high adoption rates for their cases. The adjusted cases reflect high EV adoption to quantify the bulk grid impact of the rapid adoption of light, medium, and heavy vehicle class EVs. The altered percentage load reflects the percentage of load in a system that has sufficient resources to meet a given MW target, so the Study Team did not adjust for any resource shortages that may occur should generation not keep up with a demand set by high EV adoption. As EVs are being added in addition to other load growth, it is likely that both the percentage composition and the total load of these cases will change.

Electric Vehicles and Distributed Energy Resources

The study cases in **Table 2.2** contain a small amount of DERs in the Base Case model, reflective of current WECC projections of DER for these cases. While EVs are growing at an extreme rate, so is the rate of adoption of DERs. Furthermore, V2G capabilities allow for the charging of EVs to export active power and become a source of electric power on the distribution system. This indicates that distribution-connected EV chargers or charging stations can act as DERs, so they can be considered in future aggregate DER projections if there are robust V2G requirements and studies. This study does not evaluate the impacts from V2G capabilities; it solely considers impacts in response to EVs when they are in charging mode. The involvement of V2G impacts is detailed in the **Study Objective and Previous Study Follow-Up** section, but this is not part of the study work in this white paper. Studies of distribution-connected EVs performing as load and generation should use the DER modeling practices in NERC System Planning Impacts of DERs Working Group reliability guidelines[34] and account for the handoff between consumption and generation of power seamlessly. Both technologies (EVs and non-EV DERs) are further compelled by virtual power plant (VPP) growth, and the individual responses studied in the cases are not reflective of control centers or entity interactions outside of the end-use device electrical characteristics.

Documented Workarounds and Case Corrections

During the transient dynamic simulations, some modeling issues arose while testing the integration of the EV model into the Interconnection-wide transmission planning models. The following issues were identified:

- **Unstable Models**: Some generator models become unstable during model testing of grid response to disturbances. Typically, model testing for stability in these widespread models includes a flat run (also called a "no disturbance" run) and a small bump test. When running a baseline response for the conventional resource loss portion of this white paper, a growing generator bus voltage emerged coupled with an angular separation of this generator with the rest of the system. As this was the only generator model (**Figure 2.9**) that exhibited this particular response, load netting the generator was warranted. A different valid workaround models out-of-step protection for all generator models. The Study Team load netted this generator but recommends resolving the modeling errors under normal model verification procedures. MOD-032 designees should ensure that their Interconnection-wide model representations that represent the transmission system and the impacts of the sub-transmission and distribution systems are numerically robust and are valid responses for Interconnection-wide study.

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[33] Although they have a winter-peaking section of their system to the north, the entire Interconnection generally is summer peaking when considering all coincident load of the Interconnection.

[34] RSTC Guidelines Website

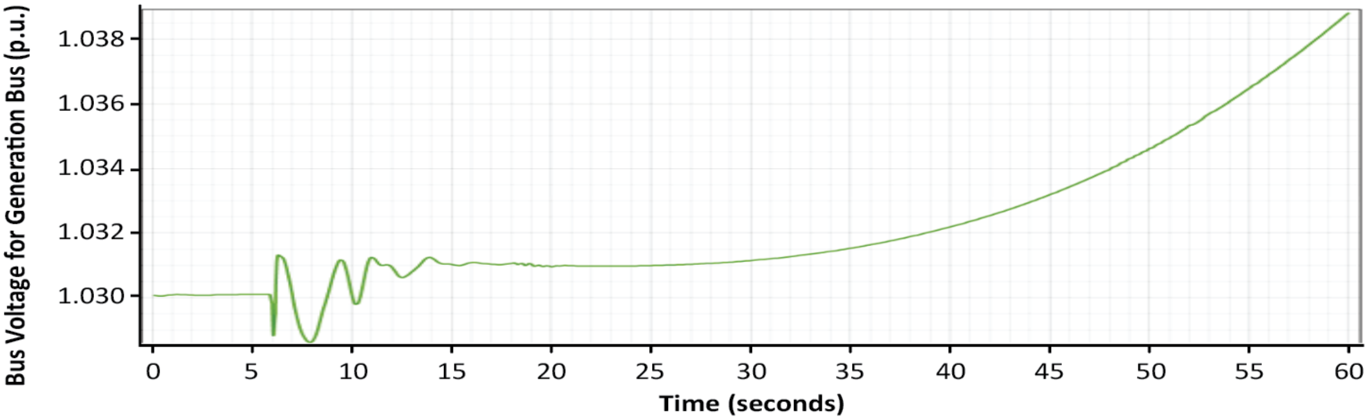

Figure 2.9: Generator Instability Found by Study Team

- **Model Size Too Large with Added EV Models:** The number of models was too high for the power flow software to assign an aggregate EV model to each load in the case. The Study Team determined a reasonable cutoff threshold for the EV model such that the power flow software limits are respected but still analyze the impacts of high EV penetrations and their charging behavior. TPs should model these areas with greater fidelity (i.e., lower workaround thresholds) than other areas, should modeling issues occur. Software vendors may be able to increase the model table sizes; however, this may also affect the computational burden of the software.

Key Takeaway

Software vendors should account for total current limits opposed to decoupling active and reactive current limits for an aggregate EV model. EVs are a current-limited converter-based technology, so EV models should respect the current limitations of EVs and EV charging equipment.

- **Available active and reactive current limits in EV models**: Decoupling of P and Q loading for the EV chargers, while robust, does not account for a single aggregate device limitation for current limited devices. Thus, should a TP wish to study a device that has a P-priority ride-through characteristic, they will need to set the Q-limits to near zero. However, as the limit cannot be dynamically updated to reflect the total current of the device, there is an inability to model the reactive current response in instances where there is not a full use of the active current limit. The Study Team ran a sensitivity study to see if the lack of reactive current (0 p.u. limit) versus a 1.1 p.u. limit can alter the simulation significantly under 1.1 p.u. active current limits with high EV penetration conditions. In this sensitivity study, the steady-state power factor target was unity, resulting in a 0 p.u. reactive current target, yet allowing for transient spikes based on the reactive current limits. The simulation had a similar trajectory for both the 1.1 p.u. reactive current limit and the 0 p.u. reactive current limit. The model insufficiently addressed total current limits of EVs, a currently limited converter technology, but this did not compromise the analysis results. That said, it would be beneficial for the model software to be altered to account for the total current limits rather than decoupling the limits.

- **Modular Load Component Model**: The Study Team attempted to use a variety of models to represent the load composition of the Interconnection-wide case and primarily focused on using the PSLF centric “data maintainer” models that enable one set of data to apply to multiple load records. While good for wide-area studies, these types of models do not provide access to individual load models and their parameters; they only represent a wide area. Thus, modifying only one dynamic representation of the wider area load model was limited to turning off the entire load rather than modifying specific parameters. No workaround to this was identified, but a change of study scope can accommodate the software limitation encountered. The user experience for load models should be continually improved.

Chapter 3: Electric Vehicle Charger Study Results

The Study Team placed the EV model into Interconnection-wide cases to determine which charging and high-level behaviors from EVs and their charging equipment are grid-friendly or grid-unfriendly. Where applicable, this report provides recommendations on preferred EV and charging equipment behavior.

Historical Background Technical Reports

As highlighted in the previous chapters, EV adoption in the European Union is set to outpace the United States and Canada, so transmission-level impacts have already been investigated to some degree by the European Union. One such investigation is a two-part study prepared for the National Grid ESO: *The Impact of Electric Vehicle Changing on Grid Short-term Frequency and Voltage Stability, and Cascade Fault Prevention and Recovery* report.[35] The report seeks to evaluate the transmission grid impacts posed by rapid electrification and summarizes six impacts on the transmission grid as shown in **Figure 3.1**.

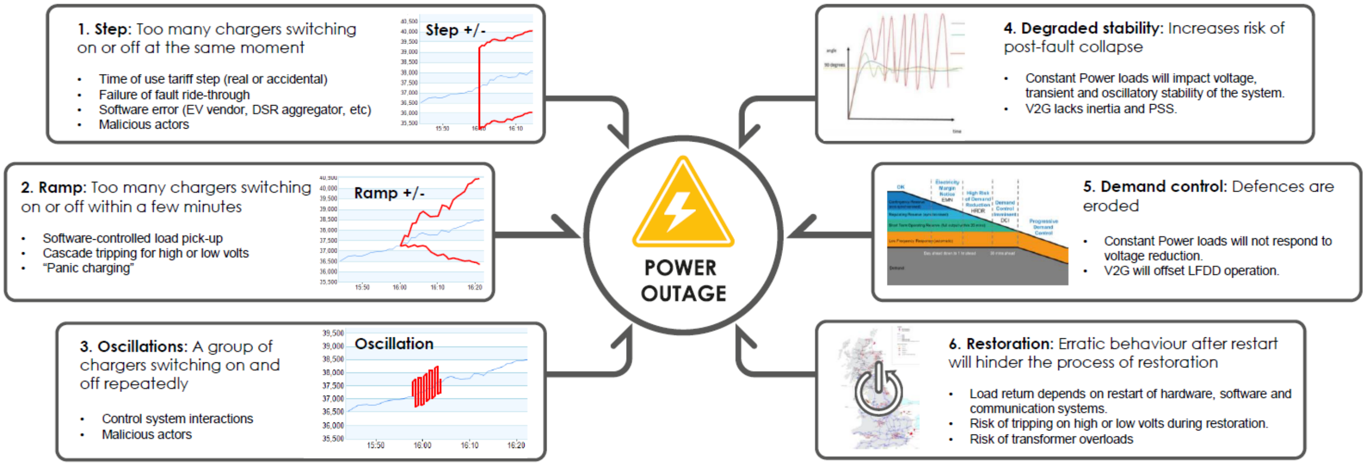

Figure 3.1: Electric Vehicle Charger Impacts to Grid Reliability (Source: Sygensys)

These six components in **Figure 3.1** are shown to lead to a power outage; the report attributed these six components as being related to the common-mode behaviors of EVs when switching on and off, the fact that EVs are designed for customer needs and not grid requirements, the fact that EVs depend on interconnection software platforms, and the incentives for decarbonization.

While the report identifies very specific risks to the transmission grid, the risks are largely summarized by the impact of switching the EV chargers on and off, policy-level impacts to their demand control program efficacy, and the uncertain operating characteristics of the devices in specific conditions. The report findings identify that, while the risks may be more granular, the need for well-understood EV charging behavior, clear performance standards with operator training, and regular planning study assessments are needed to achieve a reliable future in the Great Britain's electric system; these findings should be strongly considered for North American grid planning.

Rate of Change of Frequency, Inter-Area Oscillations, and Electric Vehicles

One of Sygensys's interesting findings is the regional variation in the rate-of-change-of-frequency (RoCoF) behavior in various areas of the Great Britain system. Further complicating the matter is that dc tie tripping can lead to high RoCoFs when the dc tie is heavily loaded. Sygensys reported this phenomenon in its report and identified that the growth of EV charging load can exacerbate RoCoFs and have different magnitudes throughout the system. Shown in

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[35] Sygensys report: *The Impact of Electric Vehicle Changing on Grid Short-term Frequency and Voltage Stability, and Cascade Fault Prevention and Recovery*

Figure 3.2, the variation of RoCoF is correlated to the physical location of the generator. For EV charging, this means that their observable frequency during large generation losses is not only dependent on the size of the loss but also where the load is served from the transmission system. V2G EV disconnections during this time due to RoCoF would exacerbate the disturbance and lead to a potential blackout.

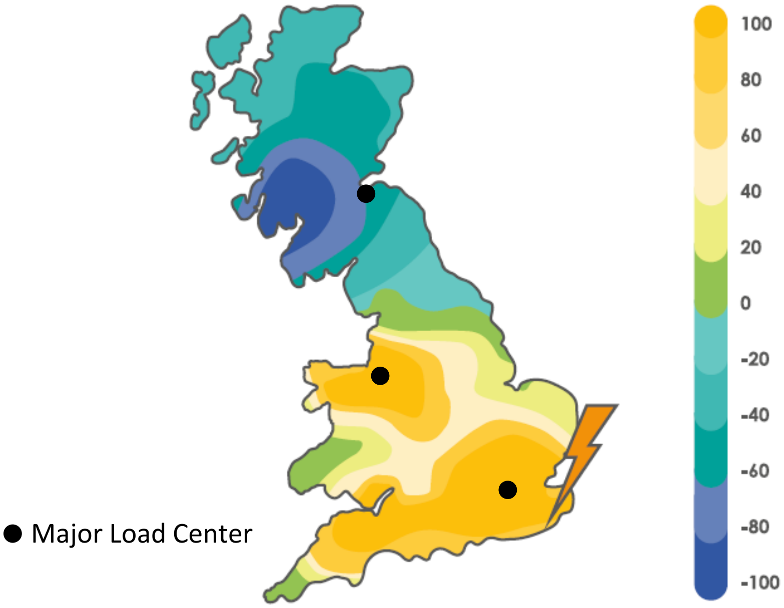

Figure 3.2: RoCoF Differences Based on Location for a Grid Disturbance (source: Sygensys)

The Great Britain results are a reminder that transmission planning staff should understand the oscillatory modes seen in the ERO Enterprise footprint and identify if the RoCoF increases from high amounts of inverter-based resources (IBR) and converter-based resources could trip generation. Previous events[36] in the Great Britain system, such as in 2019, signaled that some distributed generation trips off-line at 0.125 Hz/s. This tripped roughly 350–430 MW of generation in the event and triggered the first stage of Ofgem's underfrequency load shedding (UFLS)[37] program. As rising RoCoFs increase risk throughout the world, planners need to pay particular attention to the impact EV charging has when exporting to the grid in V2G modes or when EV chargers are drawing energy from the grid in charging modes.

The oscillatory modes in WECC are comparable to those seen in Great Britain, so emulating Sygensys's study methods in WECC can identify potential reliability risks. In WECC's case, the oscillatory modes are caused by a generation-rich portion of the grid that is connected to the load-rich portion of the grid through both ac and dc ties. Disturbances in either area can create inter-area oscillatory modes, primarily the north-to-south oscillatory modes of the WECC system. This white paper's conclusions are informed by comparisons of RoCoF in the various EV penetrations in a modified WECC system. Further, the conclusions are generalized in a way that is applicable to the entire ERO Enterprise and not solely the WECC system.

Electric Vehicle Charger Response to BPS Fault

As some of the most common grid events are transmission faults, the Study Team started by assessing the response of various charging behaviors of EVs and their charging systems. EVs generally fall into categories that will ride through faults or cease their charging characteristics and ramp back to service. The specifics on how the EV returns

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[36] *Investigation into 9 August 2019 Power Outage*

[37] The Ofgem report refers to UFLS as "Low Frequency Demand Disconnection."

to service is dependent on the OEM; however, the six broad characteristics identified in EV INL testing[38] were used to parameterize the aggregate EV model to represent one of the following charging behaviors and classifications:

- Ride-through in constant power (Constant P)
- Ride-through in constant current (Constant Current)
- Cease charging until voltage recovers for 10 seconds and ramp back to pre-disturbance output in another 10 seconds (Long Recovery)
- Cease charging until voltage recovers for 1/4 second and ramp back to pre-disturbance output in another 10 seconds (Fast Recovery Long Ramp)
- Cease charging until voltage recovers for 1/4 second and ramp back to pre-disturbance output in another second (Fast Recovery Fast Ramp)
- Cease charging until voltage recovers with no delay and ramp back to pre-disturbance output in another second (No Delay Fast Ramp)

Furthermore, there are two separate fault conditions—one to test for the general BPS fault at a 500 kV substation and one to test a known fault-induced delayed voltage recovery (FIDVR) location (also a 500 kV substation). While the most common type of fault is single-line-to-ground, the simulation was aimed to stress the system and EV response, so 3phase bus faults are used for both types of faults, a 10-cycle duration for the General Case, and a 4-cycle fault for the FIDVR Case. These faults were simulated and plotted for the above charging characteristics of the EV charger power response for the heavy summer condition in **Figure 3.3** and the voltage trajectory in **Figure 3.4**. A "noEV" baseline in the voltage plots allows the comparison between such a baseline and other charging behaviors to see where the voltage recovery is better or worse.

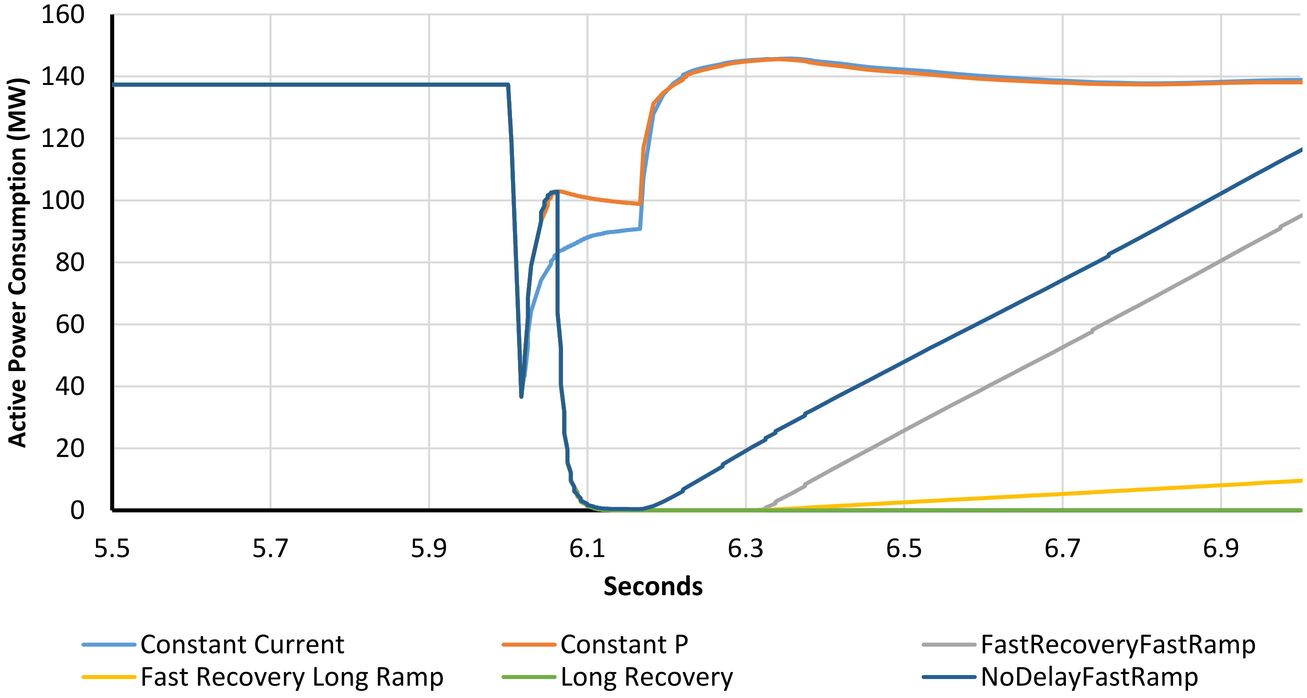

Figure 3.3: Electric Vehicle Power Response to Bulk Grid Fault Conditions—Heavy Summer

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[38] More information on the report this testing came from is provided in the **Study Objective and Previous Study Follow-Up** section.

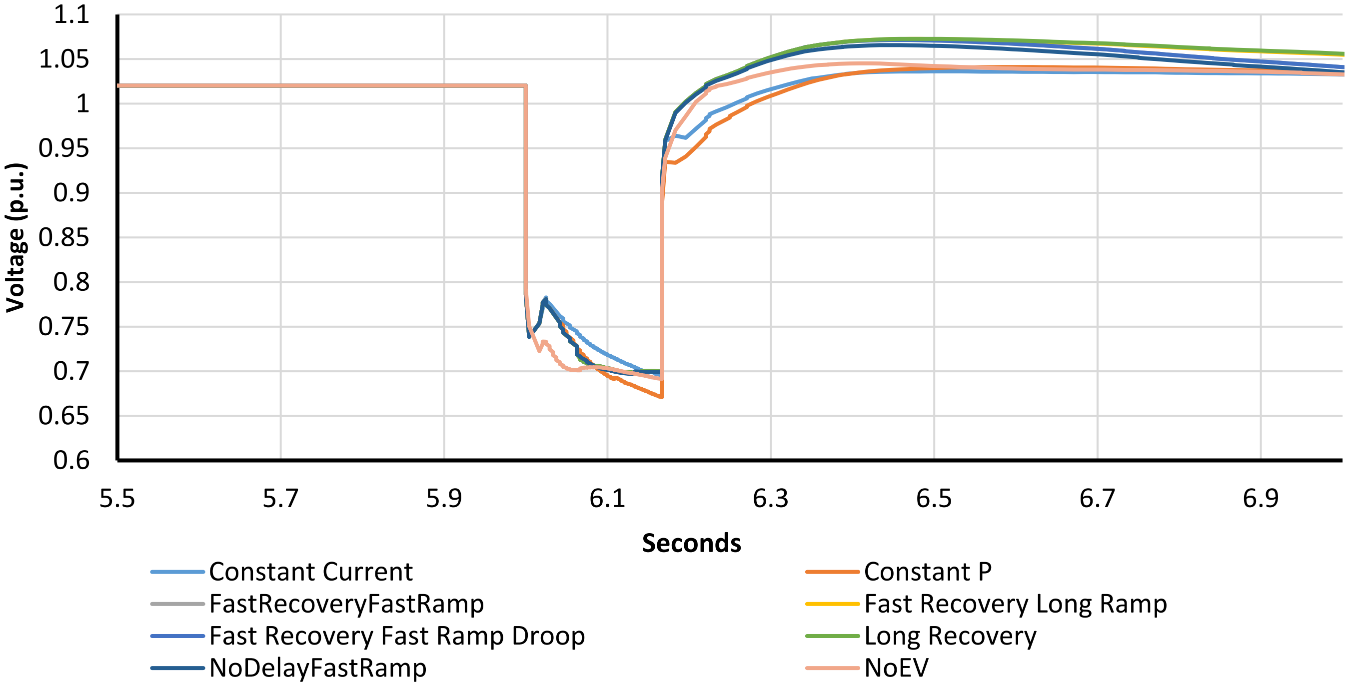

Figure 3.4: High-Side Transformer Voltage Trajectory—Heavy Summer

There is a tendency for ceased EV chargers to create small voltage overshoot conditions that cease during a fault as indicated by **Figure 3.4**. However, the constant power or constant current ride through does not create overvoltage conditions. Granted, such ride-through characteristics do lengthen the time for the BPS to recover voltage immediately following a fault, just not by significant enough margins to consider it a delayed recovery. Should the EV chargers cease charging, the No Delay Fast Ramp control logic performed better than the other controls and matched the "noEV" baseline performance. The same controls were tested on a light load condition to see if the voltage recovery impact on the same load bus is dependent on the magnitude of load in the case. **Figure 3.5** and **Figure 3.6** plot the EV charging system's power response and voltage trajectory, respectively.

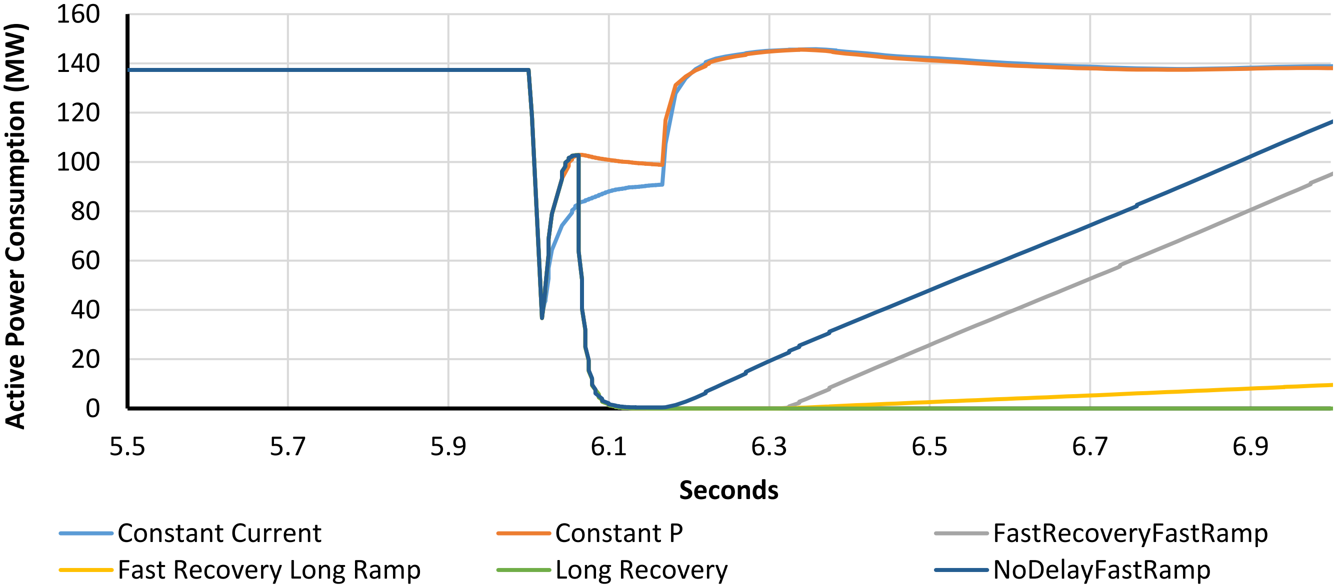

Figure 3.5: Electric Vehicle Power Response to Bulk Grid Fault Conditions—Light Load

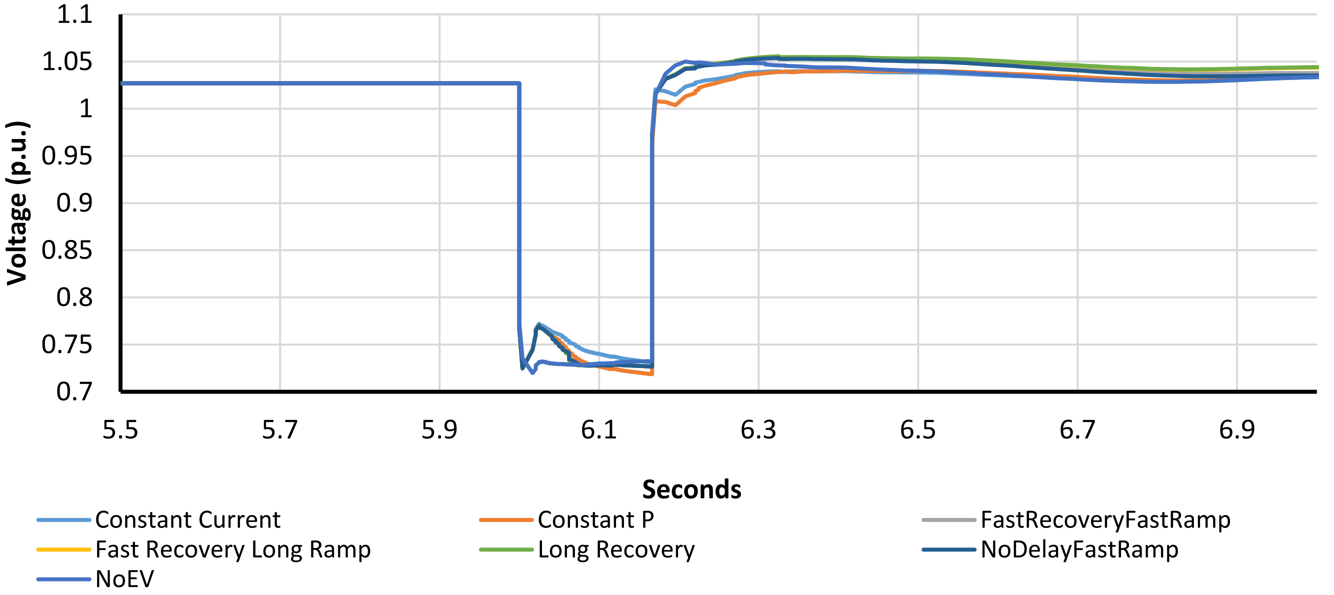

Figure 3.6: High-Side Transformer Voltage Trajectory—Light Load

In the light load condition, the voltage dip is not as great as in the heavy loaded condition; however, it is still sufficient to potentially cause EV charging equipment to enter current cessation. As with the heavy summer conditions, the constant current mitigates against the immediate voltage overshoot condition after the fault clears, which is an improvement over the noEV baseline performance. The No Delay Fast Ramp control logic does not mitigate the impact to the extent it did in the heavy loading conditions. While still useful in heavy conditions, there is a strong recommendation to ride through the fault in either constant current or constant power conditions. The Study Team also tested these fault conditions near a bus that was known to create FIDVR conditions. Rather than a 10-cycle fault being applied to a nearby bus, system exposure lowered the exposure of the fault to 4 cycles. The EV charging power is in **Figure 3.7**, and the voltage recovery is in **Figure 3.8** with a zoomed-in portion in **Figure 3.9**.

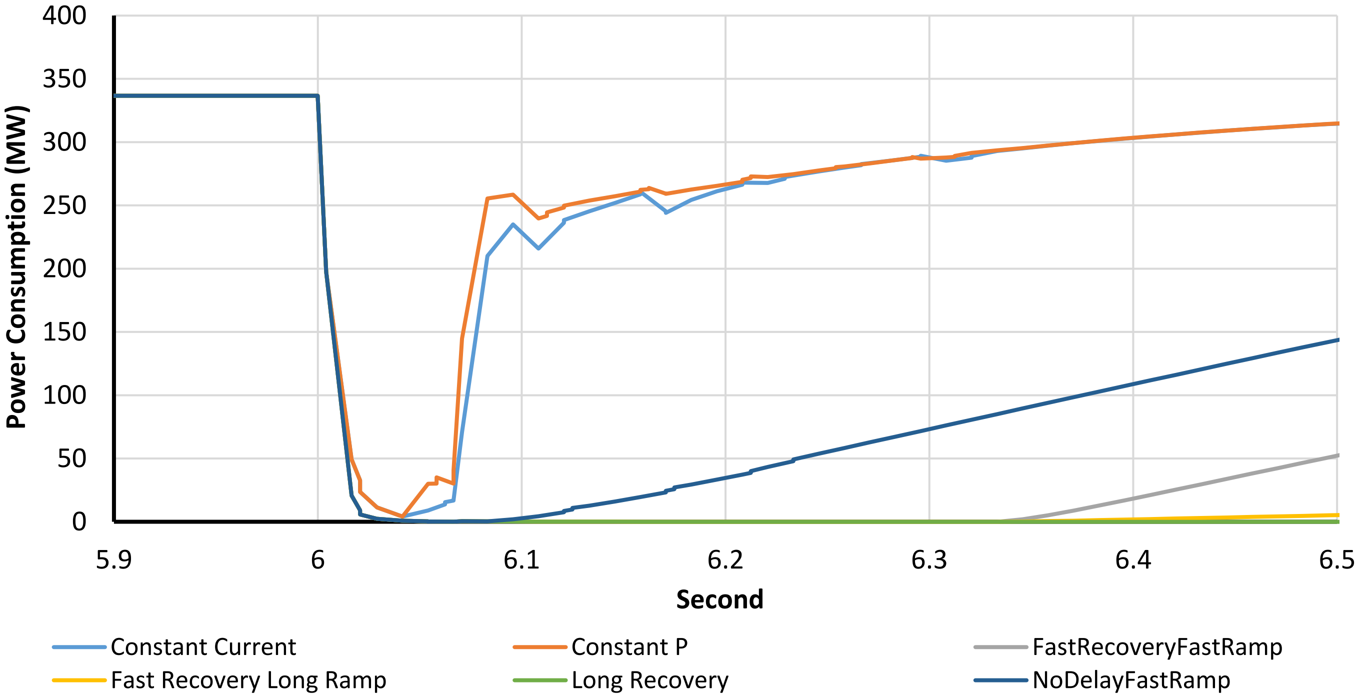

Figure 3.7: Electric Vehicle Power Response to Bulk Grid Fault Conditions—FIDVR

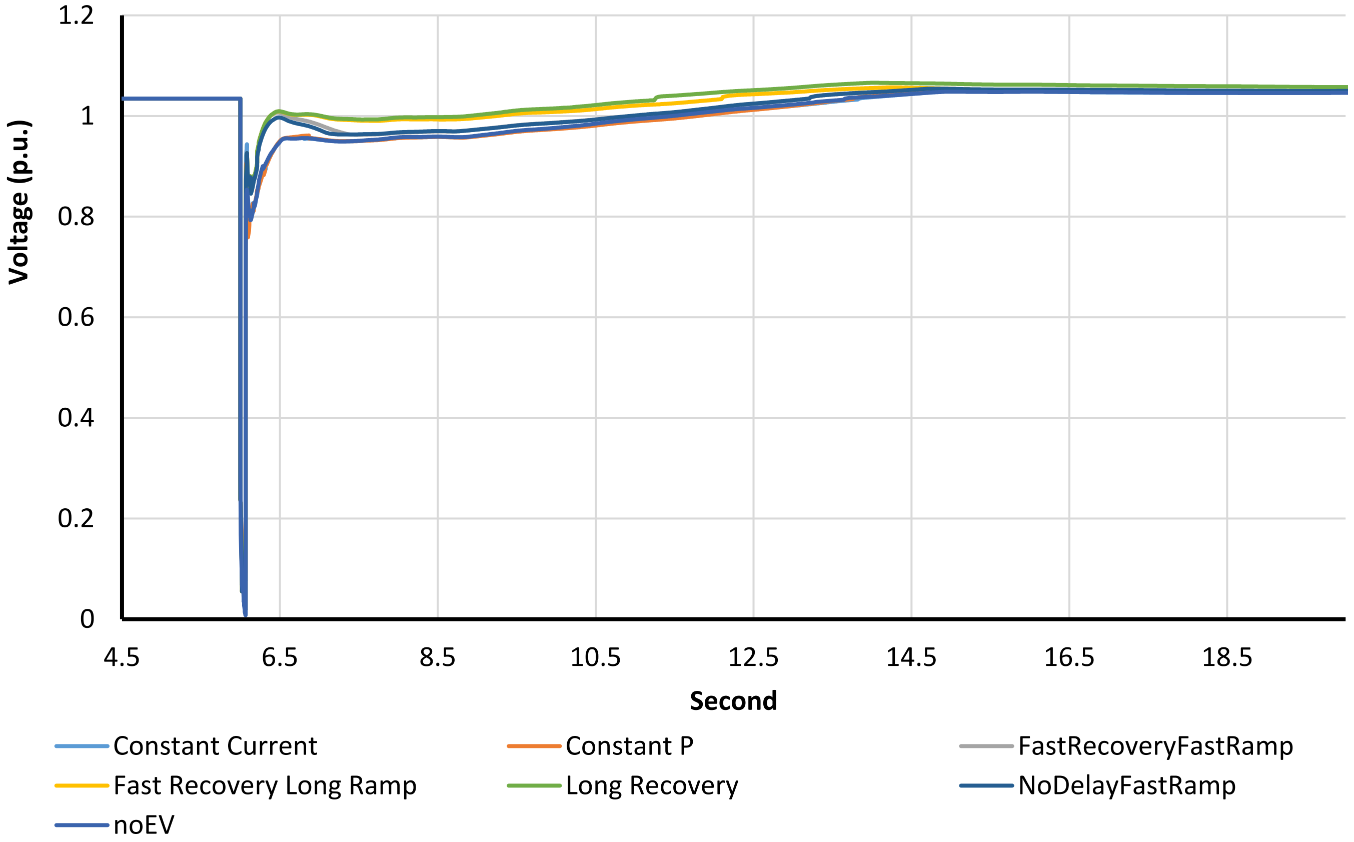

Figure 3.8: High-Side Transformer Voltage Recovery—FIDVR

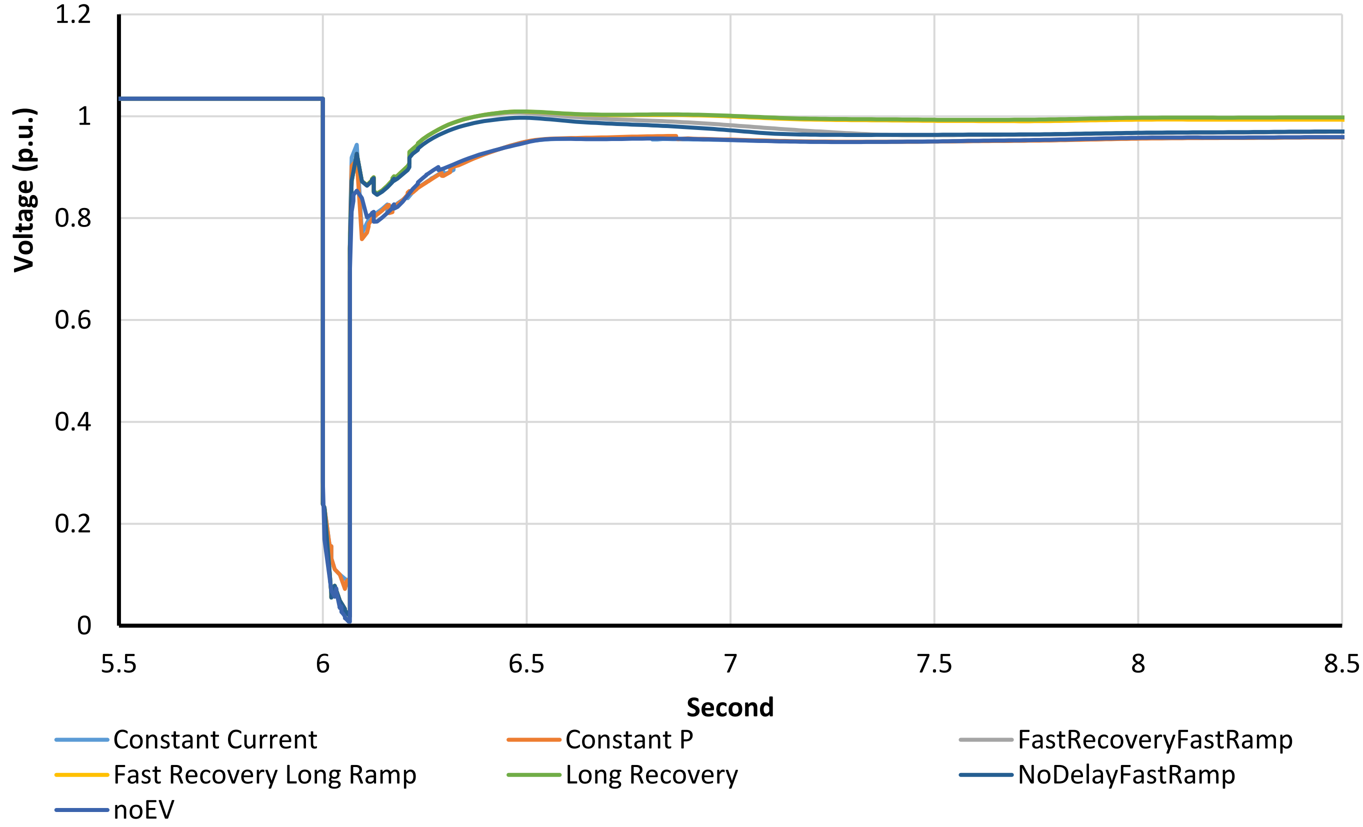

Figure 3.9: High-Side Transformer Voltage Recovery, Zoomed in—FIDVR

As seen in the voltage recovery for **Figure 3.7**, **Figure 3.8**, and **Figure 3.9** for the FIDVR condition, the high-side transformer voltage has a much stronger and faster recovery when the EV charger takes a longer time to return to its pre-disturbance power set point. This confirms findings in previous EV charging reports[39] that ceasing power consumption during FIDVR conditions is a grid-friendly behavior for this penetration of EV charging. As evident in the active voltage recovery figures, the slowest to recover is the constant current with no cessation during fault condition controls. However, the voltage does recover by 15 seconds with minimal changes between the types of response at that time post-disturbance. The FIDVR recommendation to have EV chargers cease charging and remain off-line for a long period post-disturbance conflict with preferred characteristics in portions of the BPS that do not tend to exhibit FIDVR. Therefore, each TP should identify the preferred mode of fault ride through their system performance based on their most dominant conditions.

Note that the improvements from chargers ceasing consumption during these conditions is already an improvement over the baseline noEV performance, which is closely tied with the trajectories of the constant power or constant current trajectories in the figures. Therefore, the Study Team does not believe that (for the conditions studied above) an alteration to the general recommendation of having EVs and their charging equipment ride through faults would bring significant harm to the nuanced conditions of FIDVR. Rather, the trajectories show that EV charging can help the FIDVR condition by turning off under FIDVR conditions yet riding through the FIDVR conditions showed no deterioration of the voltage recovery. This concept is explored more in **Fault-Induced Delayed Voltage Recovery at High Electric Vehicle Penetrations.**

Recommendations Based on Fault Disturbances

The Study Team poses the following recommendations based on EV charger and EV equipment response to bulk grid faults. These recommendations are generalized and should be reviewed by individual TPs and incorporated as appropriate. TPs and EV OEMs should do the following:

- Require EVs to ride through common grid faults via constant power or constant current with a preference to constant current.
- Where necessary to trip, TPs should ensure that the EVs or their charging equipment do not add intentional time delay when voltage returns above the recovery threshold.
- EV recovery should also return to 100% pre-disturbance charging within one second of initiating recovery.
- In areas where FIDVR is a concern, the EV OEMs should coordinate with the TP to determine the required voltage ride-through characteristic and if V2G support can help mitigate FIDVR conditions. In general, if the charger cannot support mitigation of FIDVR conditions, post-disturbance charging should cease to allow for motor load recovery.

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[39] *Electric Vehicle Dynamic Charging Performance Characteristics during Bulk Power System Disturbances*

Electric Vehicle Charger Frequency Response and Impact

As frequency is a widely shared electrical quantity across the simulation, the Study Team determined that the EV model would need to be evaluated for both wide-area and local-area impacts to evaluate the frequency performance impact to the Interconnection. The Interconnection load response and the median system frequency demonstrate wide-area performance with a median system frequency nadir, RoCoF, and frequency response trajectory measured for each simulation. In the local area view, one of the high-side buses with the EV load is looking at the voltage magnitude and the damping ratio of any oscillation. The generation loss of two major units in the Interconnection-wide case was simulated, totaling 2,750 MW of generation. As these were base load generators, the dispatch changes between the cases did not alter the total generation dropped between the heavy summer and light load conditions. For the simulation that tested droop control, the EV model used a 5% droop characteristic with a 17 mHz deadband. **Figure 3.10** holds the analyzed Interconnection-wide load; the median simulation frequency is in **Figure 3.11** and demonstrates that droop control benefits the nadir.

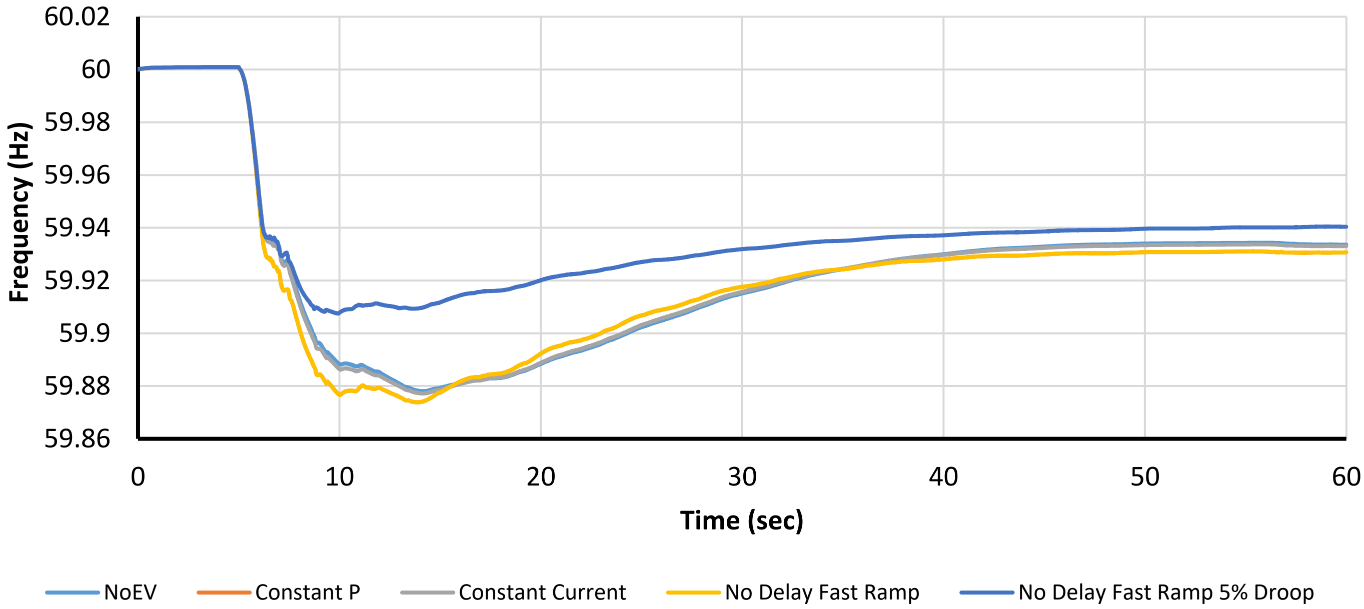

Figure 3.10: Interconnection-Wide Load Response to Conventional Generation Loss for Heavy Summer Case

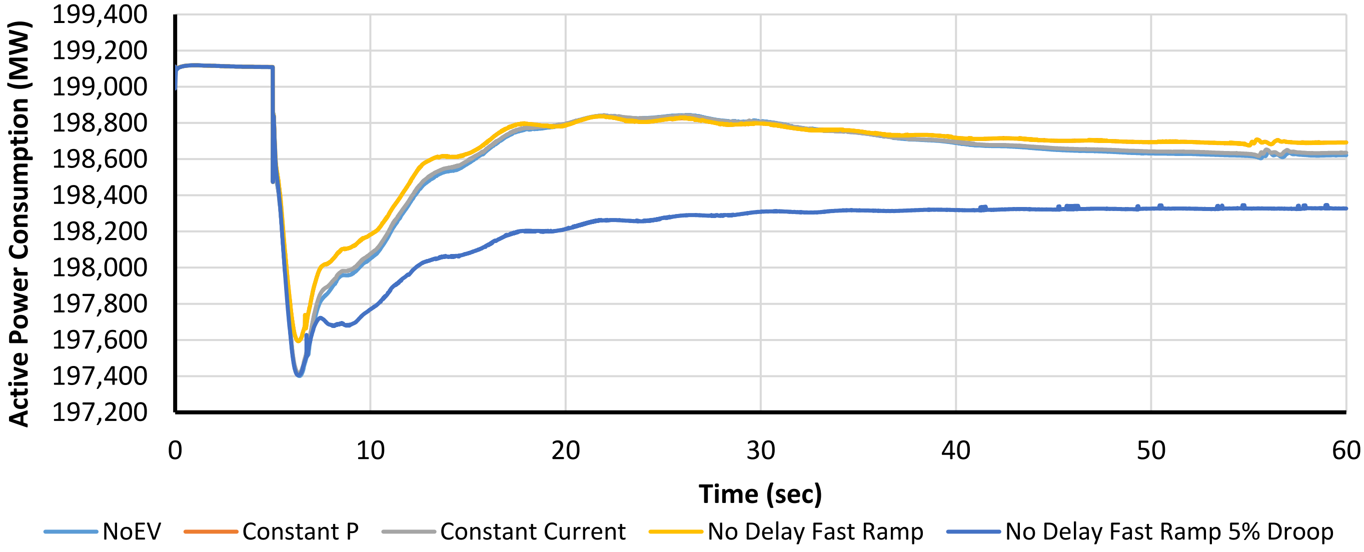

Figure 3.11: Median Simulation Frequency to Conventional Generation Loss for Heavy Summer Case

Based on the wide-area look at adding EV to the simulation, there is a small degradation in the simulated median frequency nadir when adding the EV model as a portion of the Interconnection-wide load. The constant P and cessation logic of no intentional time delay with a return to pre-disturbance output by one second had the same trajectory. There were no instances where a voltage change placed the charger into its cessation logic. Thus, both runs essentially were constant power for the entire simulation. Constant current charging behavior generally kept the nadir and damping ratio right around the noEV benchmark. However, there was a significant benefit for adding in the 5% droop with a 17 mHz deadband. Not only did the nadir rise by roughly 30 mHz, but the oscillatory behavior of the high-side bus voltage was also reduced at a wide area, and the post-disturbance steady-state conditions were closer to nominal. Looking at the local behavior of the Heavy Summer Case, the same damping ratio improvements can be seen in the voltage magnitude plot (**Figure 3.12**) and in the EV power output (**Figure 3.13**). Note that the constant current steady state is 1 MW off its' pre-disturbance value due to the slightly lowered post-disturbance settling voltage.[40]

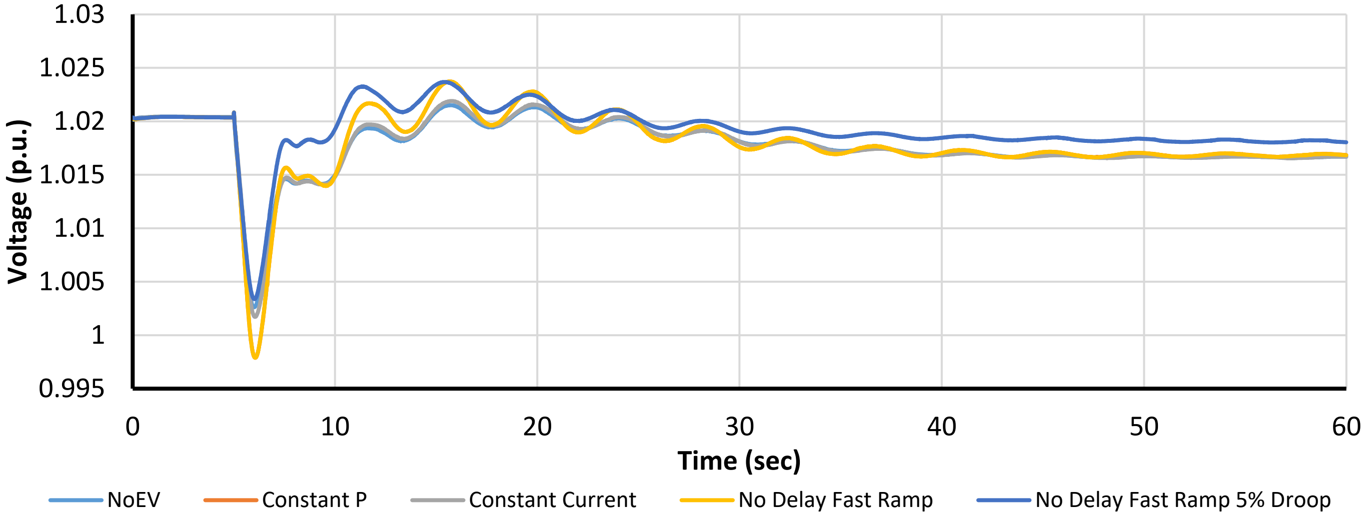

Figure 3.12: High-Side Voltage Magnitude for Conventional Generation Loss—Heavy Summer

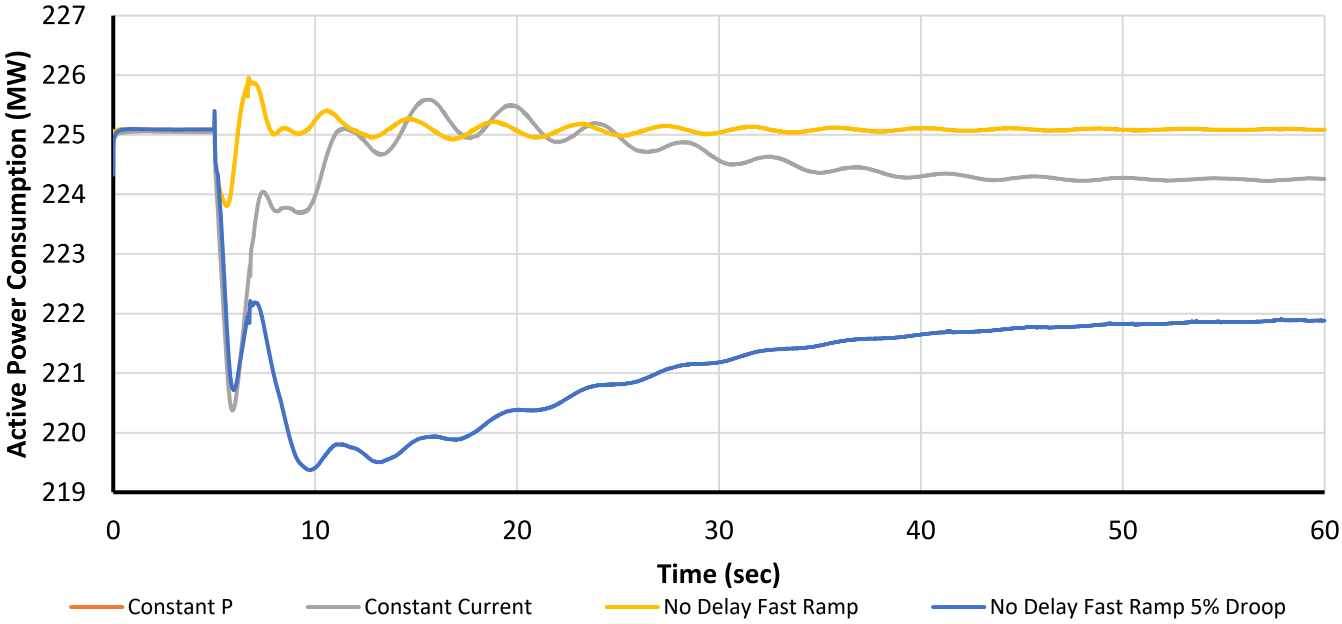

Figure 3.13: EV Active Power during Conventional Generation Loss—Heavy Summer

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[40] This is because dc power is dc voltage multiplied by dc current. To keep a constant dc current with a lowered dc voltage, the overall charging power needs to reduce.

The Study Team further tested the response of the EV model for light load conditions with the same parameters as the heavy summer conditions. The Interconnection-wide load response is found in **Figure 3.14** and the median frequency is in **Figure 3.15**. In contrast to the Heavy Summer Case, the median simulation frequency settles to roughly the same value; however, the nadir improvement is better by 20 mHz (total 50 mHz benefit from noEV baseline).

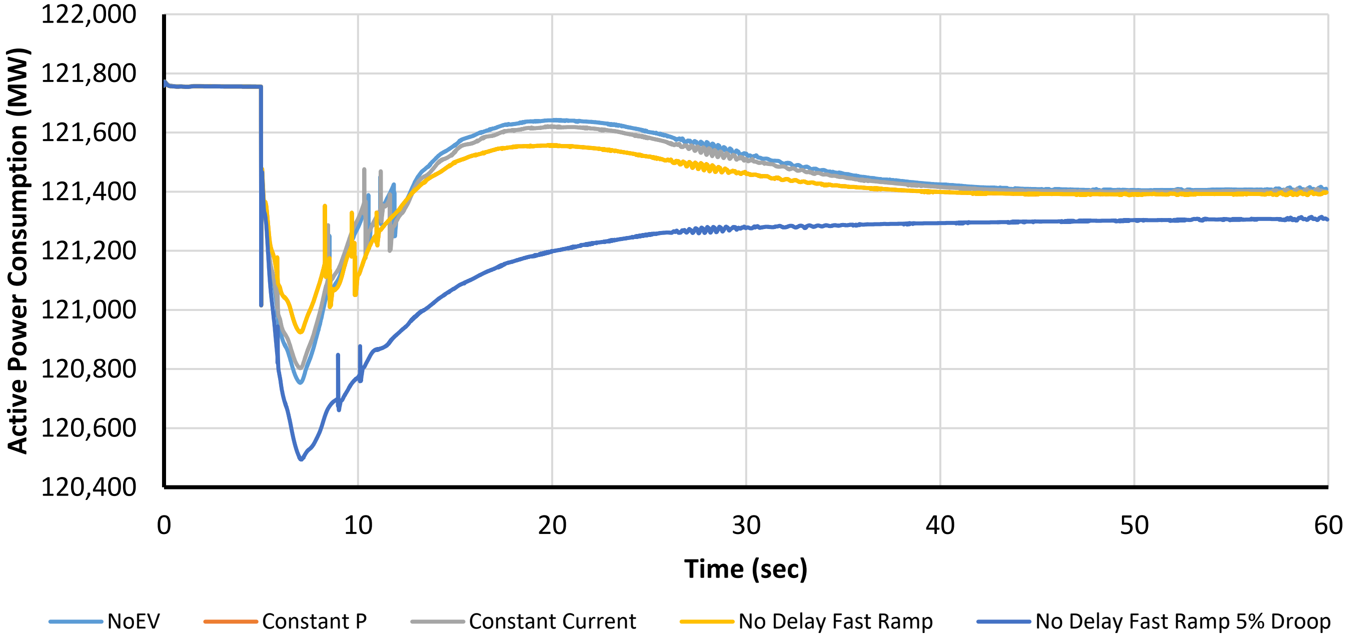

Figure 3.14: Interconnection-Wide Load during Conventional Generation Loss—Light Load

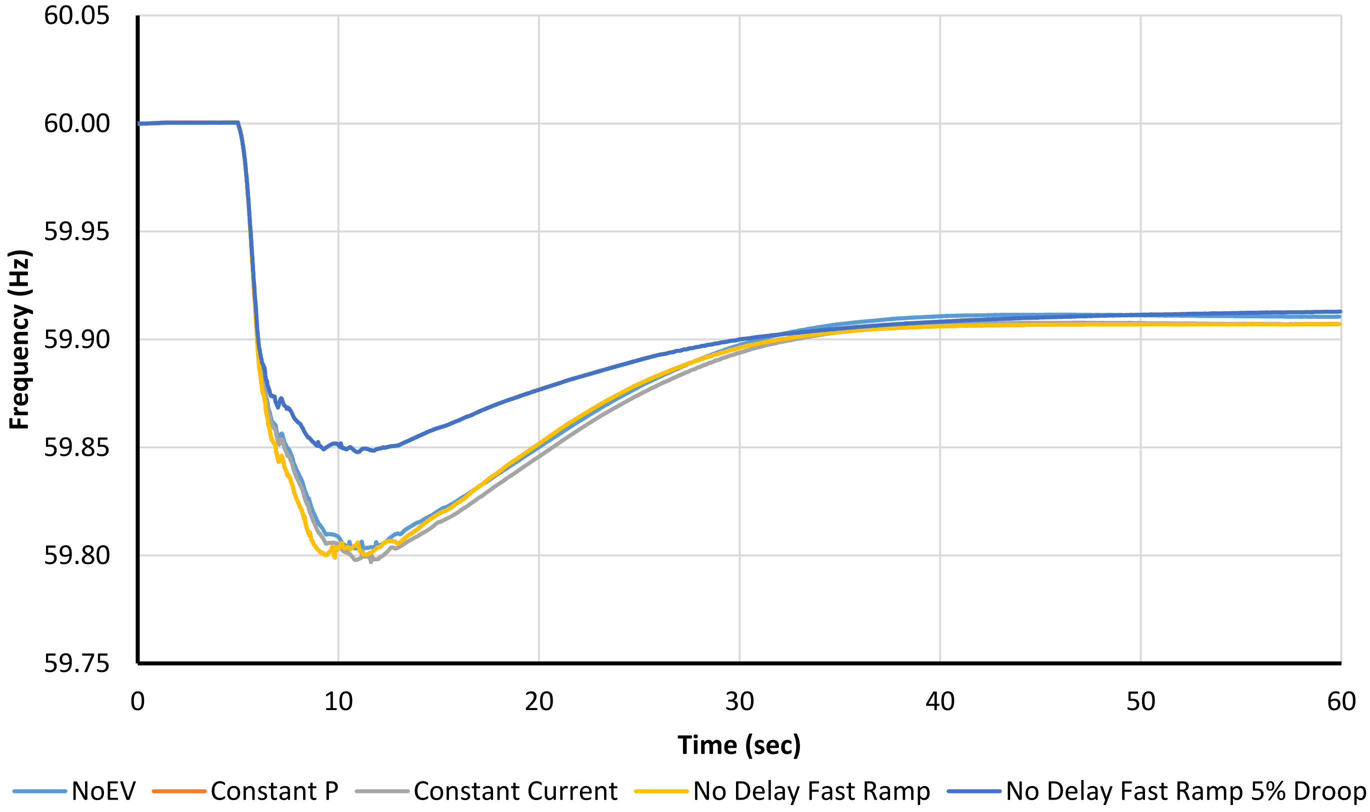

Figure 3.15: Median Simulation Frequency during Conventional Generation Loss—Light Load

Looking at the local behavior of the Light Loading Case, the high-side voltage magnitude plot (**Figure 3.16**) shows that the droop setting of 5% leads to a slight overvoltage (~0.02 p.u.), but the overshoot settles to nominal voltage at the end of the simulation. The EV power output (**Figure 3.17**) also shows that the output power generally did not move in response to the simulation frequency (as expected with no droop) while the droop performance showed a 3 MW reduction post-disturbance compared to the pre-disturbance value with a maximum reduction of nearly 6.5 MW.

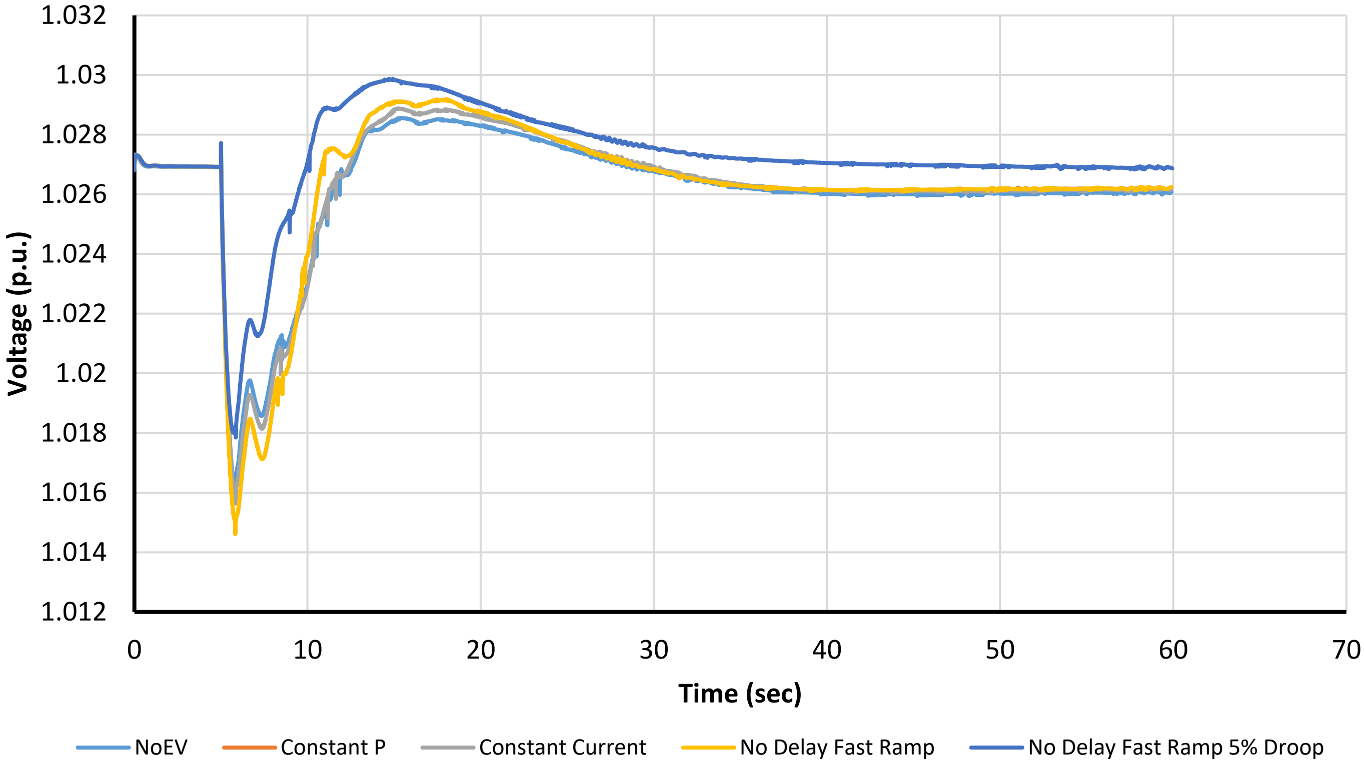

Figure 3.16: High-Side Voltage Magnitude for Conventional Generation Loss—Light Load

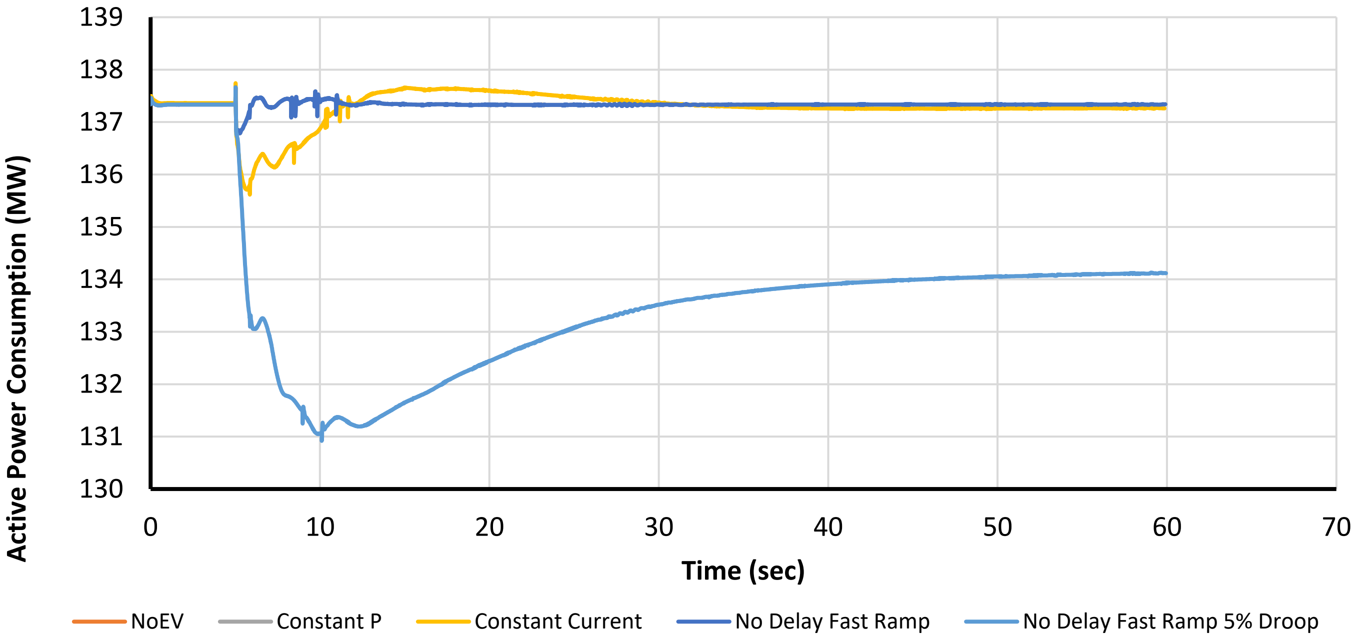

Figure 3.17: EV Active Power during Conventional Generation Loss—Light Load

Table 3.1 compares the nadir differences, RoCoF, settling frequency values, overvoltage, relative damping ratio (to the noEV simulation), and EV charger reduction for all transient dynamic simulations. The RoCoF value is calculated as the linear slope between the starting frequency of the event and half a second after the contingency was applied. Generally, including the 5% droop characteristic is grid-friendly to help arrest the frequency decline during conventional generation loss events.

Table 3.1: Frequency Response Impacts of EV Charging Behavior

Simulation Run Name	Frequency Nadir (Hz)	Delta from NoEV Run (mHz)	RoCoF (Hz/s)	Delta RoCoF from noEV Run (Hz/s)	Post-disturbance Overvoltage (p.u.)	Relative Damping Ratio	EV Charger Active Power Reduction
Heavy Summer							
No EV	59.87806	0	0.02729	N/A	0.00119	N/A	N/A
Constant P	59.87386	-0.0042	0.028908	-0.001618	0.0034	=	0.01 MW
Constant Current	59.87719	-0.00087	0.027519	-0.000229	0.00159	=	0.807 MW
No Delay Fast Ramp	59.87385	-0.00421	0.028908	-0.001618	0.00341	=	0.01 MW
No Delay Fast Ramp 5% Droop	59.90747	0.02941	0.028503	-0.001213	0.00335	+	2.447998 MW
Light Load							
No EV	59.80297	0	0.067619	N/A	0.001617	N/A	N/A
Constant P	59.79895	-0.402	0.069664	-0.002045	0.002366	=	0.01 MW
Constant Current	59.79678	0.619	0.068169	-0.00055	0.002053	=	0.08 MW
No Delay Fast Ramp	59.79895	-0.402	0.069733	-0.002114	0.002373	=	0.007 MW
No Delay Fast Ramp 5% Droop	59.84779	0.04482	0.067917	-0.000298	0.00306	+	3.22258 MW

From Table 3.1 above, it is readily shown that the impact on the RoCoF is not altered significantly between the baseline (No EV) to the addition of EVs, even those that had a 5% droop characteristic. However, the relative damping ratios of the system and the improvement to the frequency nadir demonstrate that the droop characteristic significantly improves the stability of the interconnected system under resource loss, and the total number of megawatts reduced by an individual EV model is a relatively high percentage (about 97% or more) of the pre-disturbance charging condition. Thus, for the benefit of arresting and recovering from a frequency excursion, the droop characteristic provides a significant (29–45 mHz) benefit to the system. In perspective, the UFLS scheme begins at 59.1 Hz, and the margin to that frequency for the Light Load EV simulation run is about 703 mHz, so the 45 mHz benefit the droop curve provides increases that margin from 703–748 mHz, a 6.4% increase.

Recommendations Based on Frequency Response Study

The Study Team was able to use the above findings and trajectories to identify a few recommendations on the frequency support capabilities of EV chargers. TPs should ensure that any of the small signal stability concerns are also addressed for the rising penetration of constant power loads. One solution may be to incentivize constant current behavior of the devices such that higher-level controllers do not induce underdamped (or undamped) oscillations on the grid. The following high-level recommendations are based on the findings in the **Table 3.1**:

- EVs and their charging equipment collectively should be able to have the capability to enable frequency droop control:
  - This control should be enabled as a default to aid in BPS reliability.
  - This control should be set to a 5% droop characteristic unless a TP-specific study supersedes this recommendation.
- TPs should study local overvoltage by enabling droop characteristics on EVs and their charging equipment. These studies should identify any corrective action on the BPS to mitigate against overvoltage behavior or to adjust the droop characteristic curve as most appropriate and cost effective.

Electric Vehicle Charger Scenario Analysis

To help qualify the results and findings for the above analysis, the Study Team identified a few different scenarios to run and compared how these scenarios affected the results of the Interconnection-Wide Case. This section holds the findings of this scenario analysis.

Delay of Response to Sensed Fault

As EVs and their charging equipment need to be able to detect and respond to a fault to enact their ceasing logic, the Study Team varied a delay parameter to the vehicle’s sensed voltage and when the charge stops its consumption. As it was recommended to either ride-through faults or rapidly return to pre-disturbance output with no intentional time delay, excluding FIDVR conditions, the Study Team ran just the recommended charging characteristic for this scenario and tested the following time delays on both the Heavy Summer and Light Spring Cases:

- 8 ms delay, equating to 1/2 electrical cycle
- 16 ms delay, equating to 1 electrical cycle
- 50 ms delay
- 250 ms delay

Figure 3.18 contains the high-side transformer voltage for each of the above conditions for the Heavy Summer and **Figure 3.19** for the Light Spring Case.

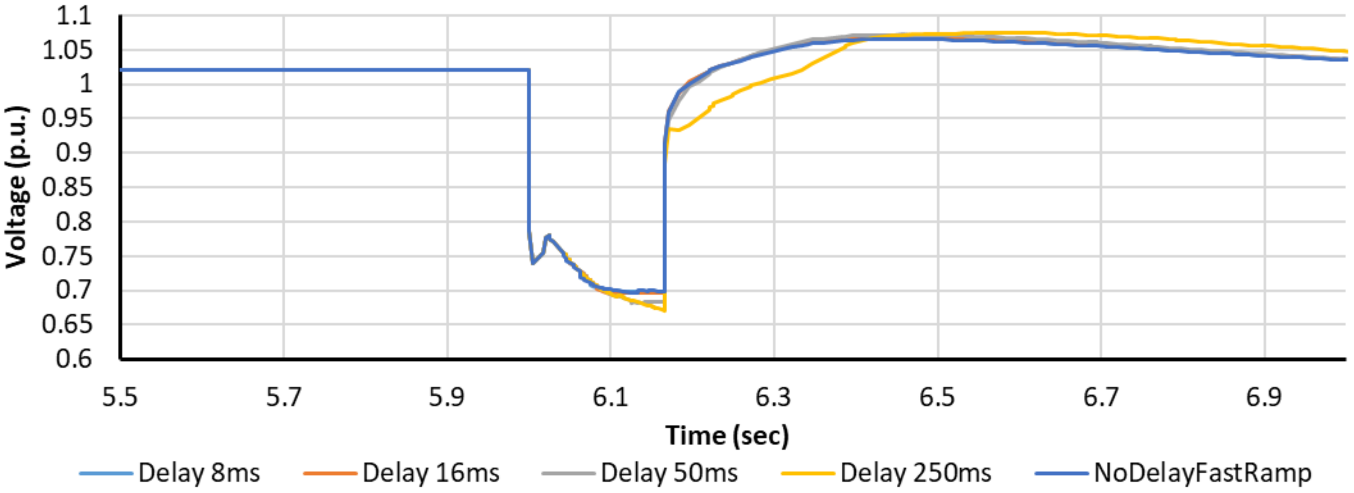

Figure 3.18: Voltage Recovery with Sensing Delay of BPS Fault—Heavy Summer

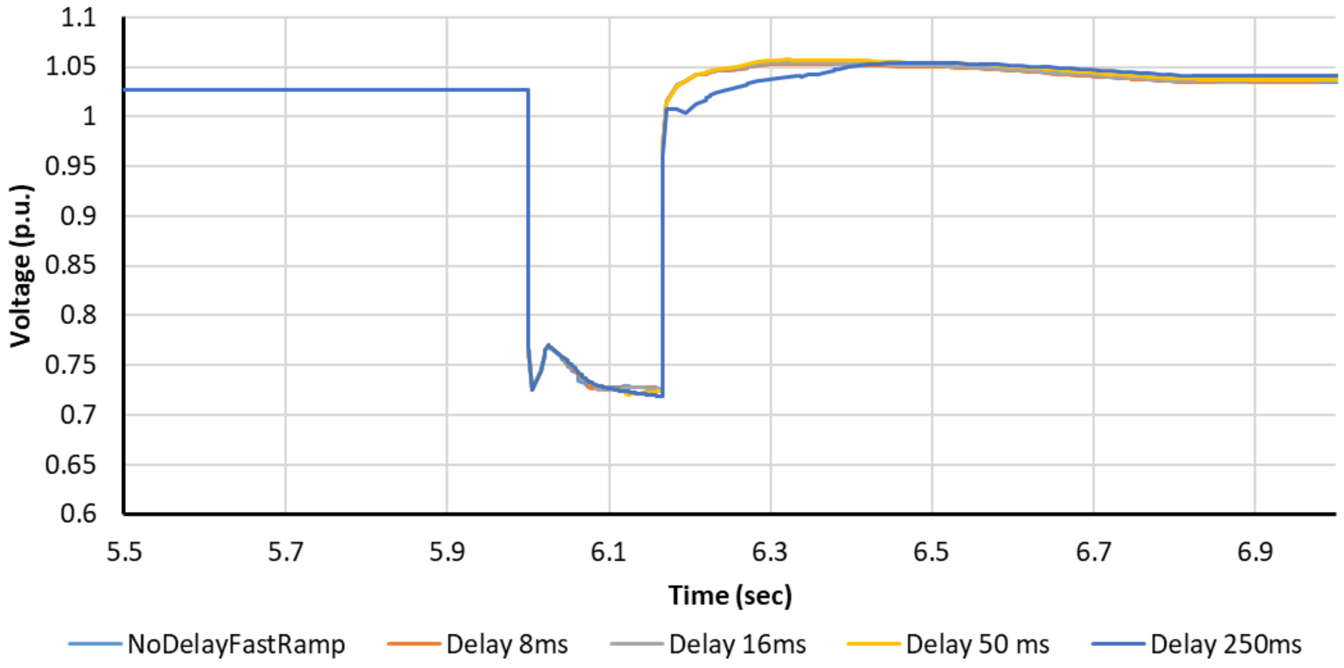

Figure 3.19: Voltage Recovery with Sensing Delay of BPS Fault—Light Spring

As demonstrated, only the 250 ms sensing delay influenced the voltage recovery of the voltage where the 250 ms delay coincided with a reduction after the fault cleared from the system (as demonstrated by **Figure 3.20**).

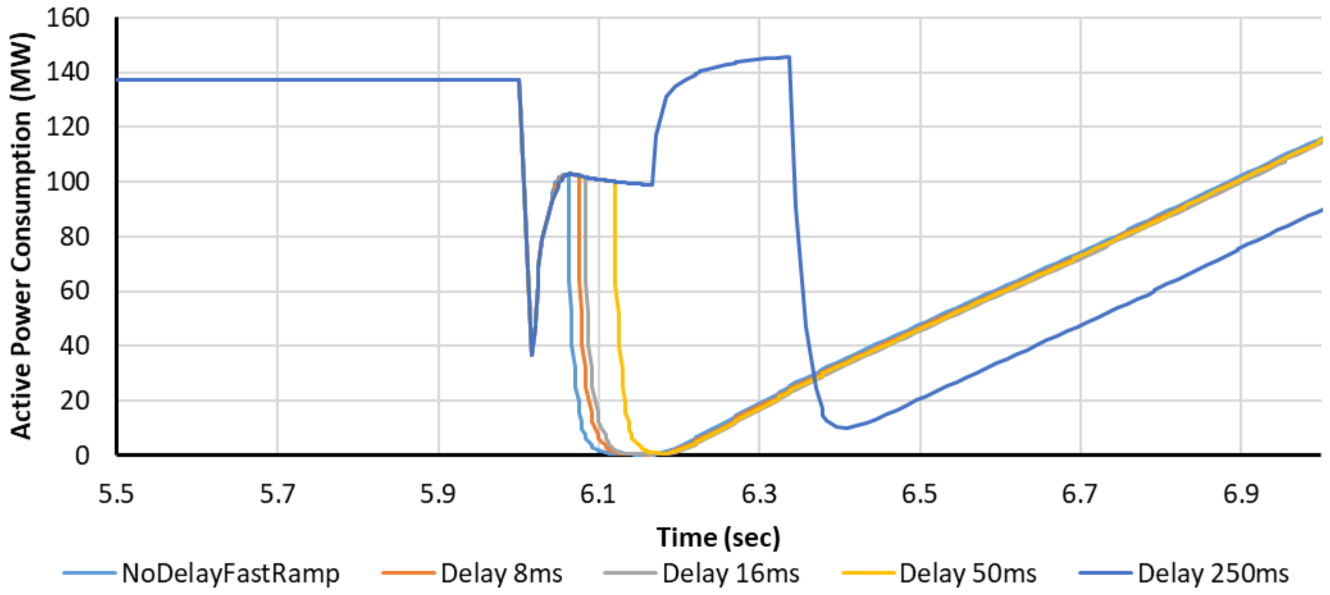

Figure 3.20: EV Power Recovery with Various Sensing Delays

Key Takeaway

EV responses should be quick to sense a fault and perform a ride-through behavior or tripping mode change. Delay in mode changes can negatively impact the voltage recovery post-disturbance.

Thus, the Study Team identified that any sensing delay associated with the EVs or their sensing equipment to detect a fault at or above 250 ms would deteriorate the benefits of having a zero-delay and one-second return to pre-disturbance behavior. As little delay as possible should be implemented when detecting a fault condition when implementing a cessation of charging characteristic.

The Study Team also recommends that constant power or constant current ride through of these faults is preferred over the quick recovery characteristic, should a hard 250 ms technical feasibility limitation be in place on fault detection. Furthermore, anti-islanding protection schemes may also factor into play for specific EVs with V2G capabilities that may trip EVs. As identified in the fault responses, delay of power recovery to pre-disturbance risks overvoltage; however, this is in the current draw state. In V2G modes, the EV or its charging system is feeding into the distribution system pre-disturbance. Such a lack of current may exaggerate a voltage depression akin to DER tripping. NERC has a separate study looking at the characteristics of DERs separate from the work performed to characterize the load behavior.[41]

High Electric Vehicle Adoption Cases

The Study Team analyzed the impact of most of the load served being composed of EVs and their charging systems; these cases represent an EV penetration of roughly 55% and 35%, respectively. The near tripling of the served EV load can quantify how the electrical characteristics of the Interconnection can change depending on the ride-through and response of the EVs and their charging systems to grid disturbances.

Key Takeaway

EVs should implement a droop curve characteristic regardless of their fault ride-through behavior to compensate for frequency deviations. It is recommended to implement ride-through in constant current with a 5% droop curve from these findings.

Figure 3.21 holds the response of the EVs to a large generation resource loss for the heavy summer conditions, and **Figure 3.22** compares the same responses to this large generation loss during the Light Spring Case. As demonstrated, the increasing EV penetration exacerbates the findings in the **Electric Vehicle Charger Frequency Response and Impact** portion of this white paper. Based on the higher penetration EV case to exacerbate the nadir of median system frequency for generation losses, the recommendation to require a droop curve response to frequency excursions to arrest a frequency decline is further reinforced.[42]

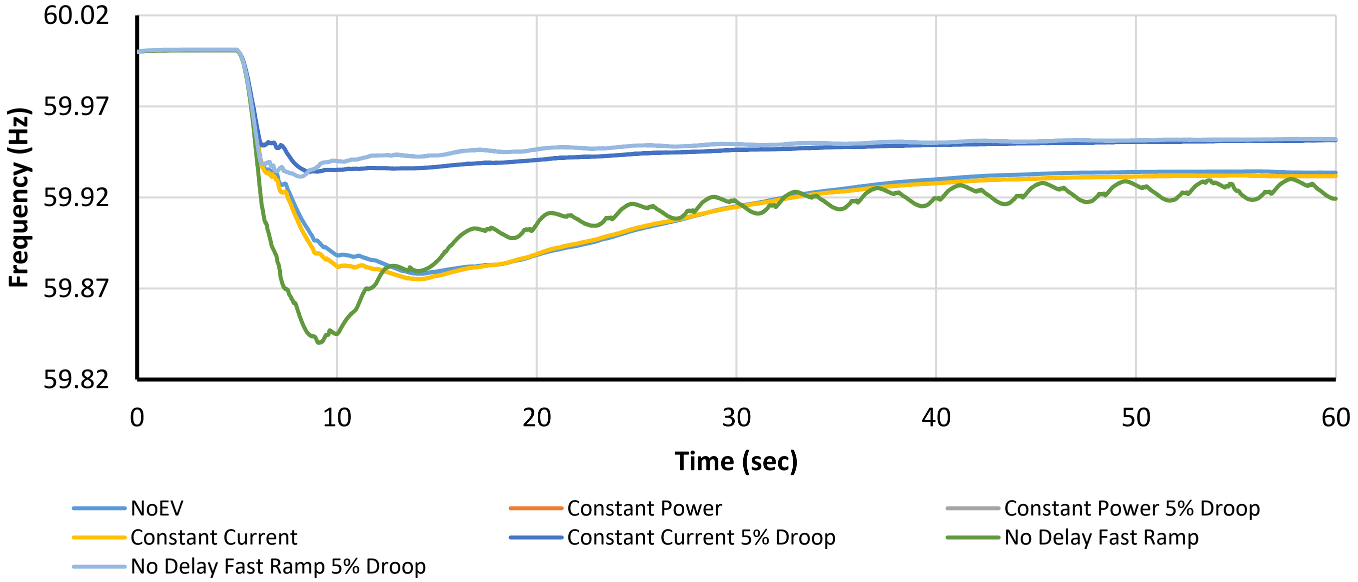

Figure 3.21: Median Simulation Frequency to Conventional Generation Loss for Heavy Summer with High EV Adoption

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[41] DER Modeling Study

[42] Conversely, this droop response can also mitigate an under-arrested frequency rise.

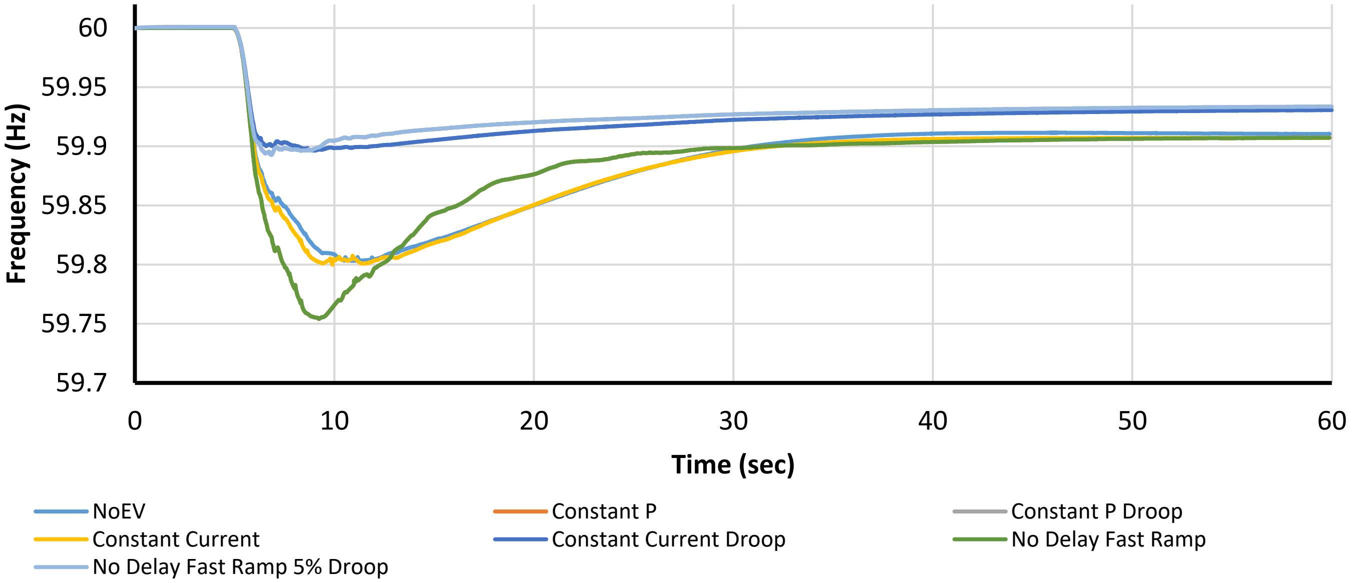

Figure 3.22: Median Simulation Frequency to Conventional Generation Loss for Light Spring with High EV Adoption

Furthermore, the anticipated constant power load or swapping to a constant current load performs worse in oscillatory behavior without any droop control. The opposite holds true when adding in the same 5% droop curve. That is, ride through in constant power or constant current load with a 5% droop curve was the best outcome for the median simulation frequency as the orange and green colored trajectories are the same as the constant current trajectory. This finding reinforces that it is a grid-friendly behavior to ride through in constant power or current with a droop curve enabled for these chargers. Due to the potential for small signal stability issues, constant current is preferred to constant power. Future studies should investigate how constant power or constant current loads behave under various droop settings to confirm if this finding is only valid for EV chargers or for other constant power or constant current loads as well.

The high-side bus voltages (and thus the voltages seen in the distribution equivalent model) can contain an underdamped or undamped voltage oscillation in the 60-second simulation depending on the type of load and charging behavior. This voltage behavior is demonstrated in **Figure 3.23**, which plots the High EV Adoption Heavy Summer Transformer High-Side Voltage Case. Similarly, **Figure 3.24** holds the same high-side voltage trajectory for the high EV adoption Light Spring Case. The constant power and constant current representations perform better than the no-delay fast ramping charging characteristic; however, the frequency droop setting of 5% adds damping to this voltage oscillation regardless of charging characteristic.

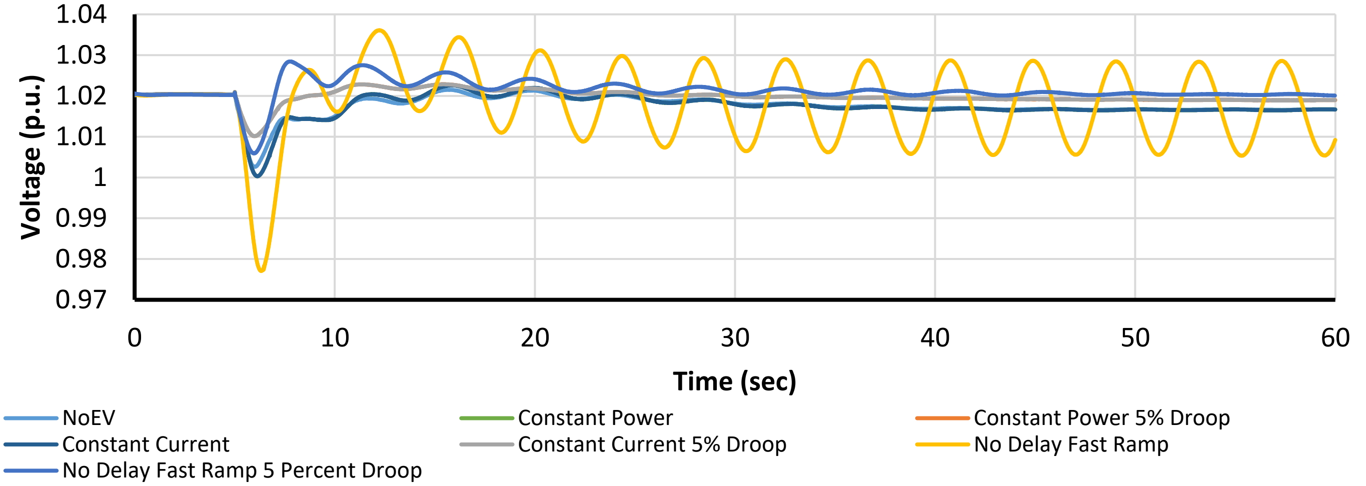

Figure 3.23: High-Side Voltages during Conventional Generation Loss for Heavy Summer with High EV Adoption

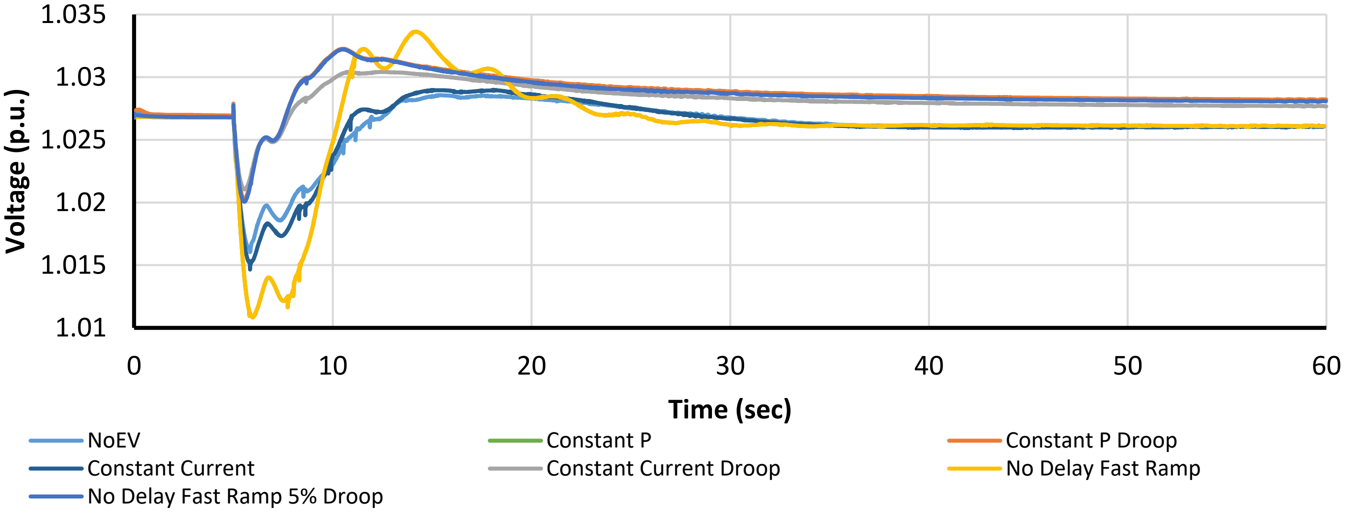

Figure 3.24: High-Side Voltages during Conventional Generation Loss for Light Spring with High EV Adoption

The Study Team also notes that the no-delay fast ramp charging characteristic is placed over a constant power representation for this study, and the undamped voltage oscillation in this scenario run can be attributed to the interaction of the power recovery and constant power normal operating mode. The no-EV run is plotted to demonstrate that there is some oscillatory behavior native to this load from the large frequency disturbance. The constant current or constant power coupled with the 5% droop setting smoothed the oscillation faster than the no-EV run, further reinforcing that a droop setting should be enabled for all EV chargers to mitigate the voltage stability concern in addition to mitigating the frequency nadir of a frequency excursion. For the Light Spring Case, the undamped oscillation was not initially present; however, the added droop smoothed the voltage trajectory in all simulation runs. These findings reassert the recommendation to ride through in constant current with frequency droop enabled.

Key Takeaway

In general, a long delay before recovery is grid-unfriendly. EVs should ride-through BPS faults and quickly return to pre-disturbance conditions with no intentional delay if needed.

Additionally, the Study Team looked at the response of these high-penetration cases to the same faults as in **Figure 3.25** and **Figure 3.26** contain the high-side voltage of the T-D interface for the Heavy Summer High-EV Adoption Scenario for the various charging paradigms. As demonstrated, when the EV percentage rose, the overvoltage potential was exacerbated due to a larger share of the load ceasing its charging.

This further reinforces the recommendation to ride through in constant current mode for BPS faults and highlights that the solution to FIDVR conditions (i.e., cease charging until motor load can recover) can create grid-unfriendly conditions when applied generically. This is especially evident in the voltage trajectory when the EV power takes a long time to recover to pre-disturbance conditions as shown in **Figure 3.25**. The long recovery charging characteristic did not fully settle by the end of the 60-second simulation, but the oscillatory behavior of the voltage was damped. TPs should study their T-D Interfaces and determine if ride through in constant current[43] or immediately ceasing current draw and waiting for a recovered voltage is a better solution.

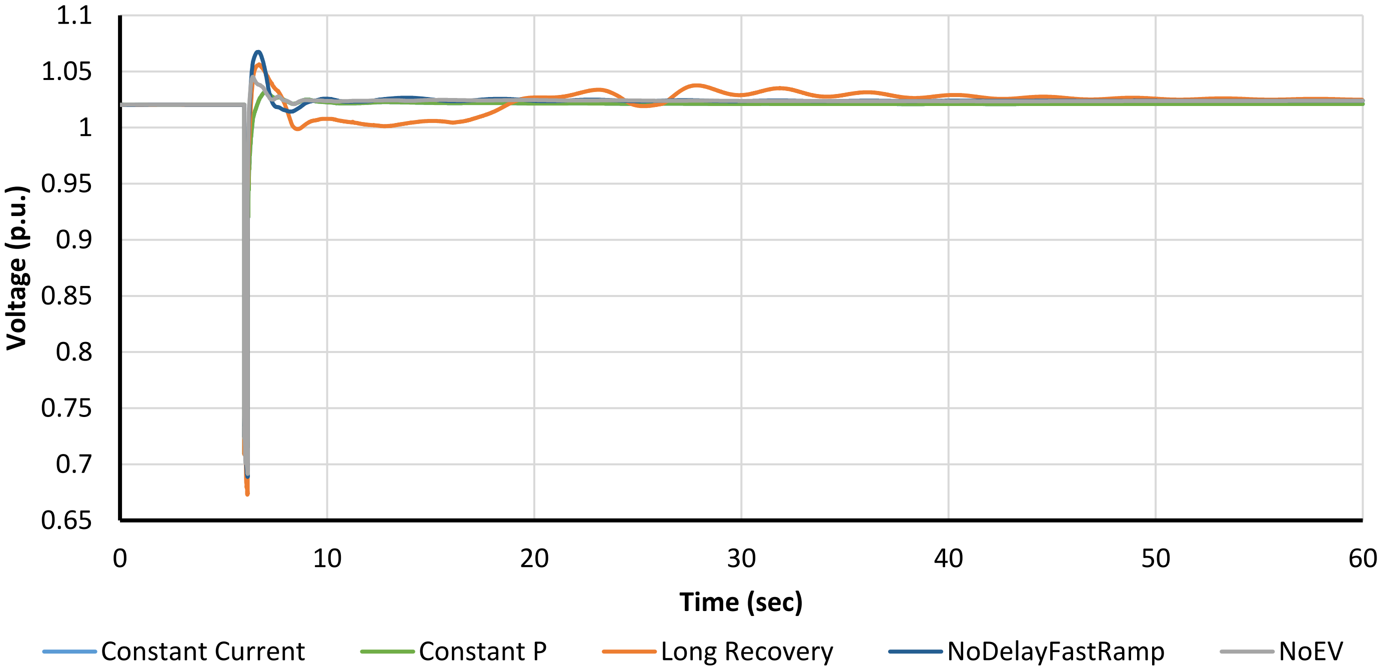

Figure 3.25: High-Side Voltage Response to Bulk Grid Fault Conditions Heavy Summer with High EV Adoption

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[43] This study also highlights that ride through in constant power is also acceptable, generally. However, there are known stability issues with constant power load, namely in small signal stability concerning undamped voltage oscillations. For this reason, the study team did not recommend ride through in constant power under the extreme EV adoption scenario.

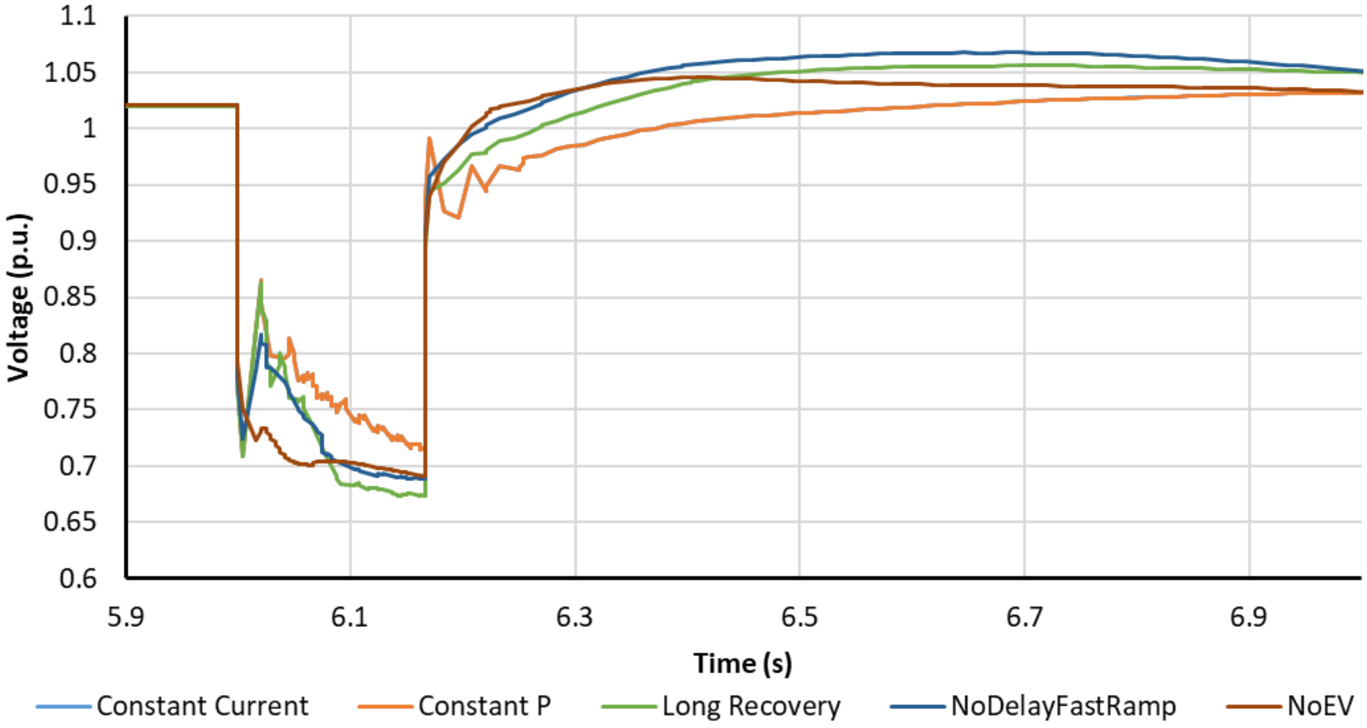

Figure 3.26: High-Side Voltage Response to Bulk Grid Fault Conditions Heavy Summer with High EV Adoption–Zoomed In

The Light Spring High EV Adoption Case reinforced the same findings in the Heavy Summer Case. Figure 3.27 and Figure 3.28 demonstrate the transformer high-side voltage trajectory to the BPS fault. Note that the overvoltage conditions are more prone in the Light Spring Case than the Heavy Summer Case; however, they exist in both scenarios. While the voltage recovery of the high-side BPS bus was concerning, the findings do not warrant EV charging requirements under either loading condition.

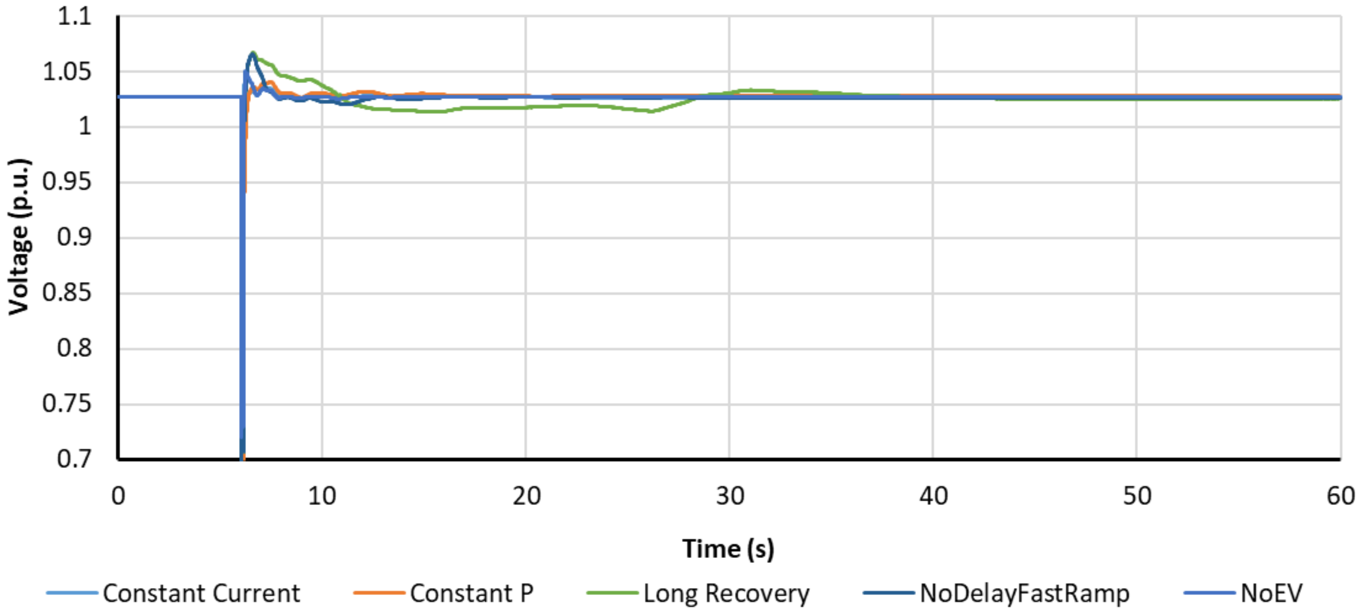

Figure 3.273: High-Side Voltage Response to Bulk Grid Fault Conditions Light Spring with High EV Adoption

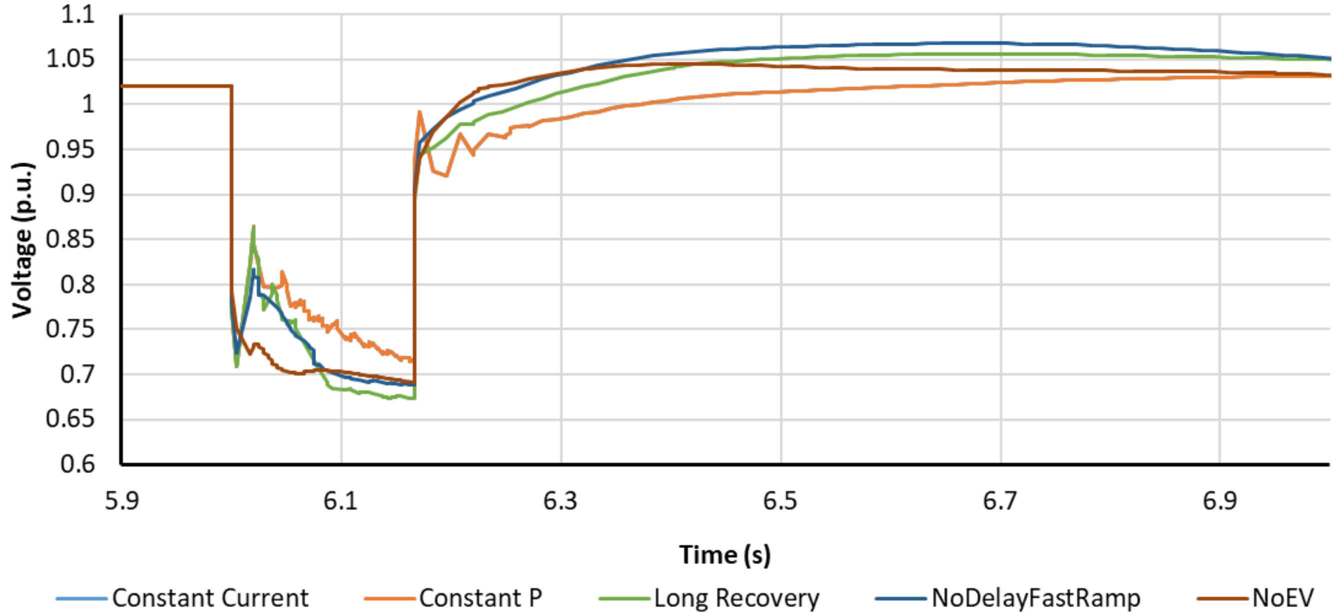

Figure 3.28: High-Side Voltage Response to Bulk Grid Fault Conditions Light Spring with High EV Adoption—Zoomed In

Fault-Induced Delayed Voltage Recovery at High Electric Vehicle Penetrations

The Study Team wanted to see the difference between the extreme EV adoption cases and the cases with lower EV penetrations that pertained to the FIDVR conditions. As this FIDVR study only revealed partial or marginal differences between the noEV runs and other charging behaviors, whether this holds up at the major penetrations is important.

The recommended charging behavior changes from the base assessment and this scenario analysis. As seen in Figure 3.29, the voltage recovery between the charging behavior that takes a long time to recover (10 seconds of a recovered voltage with another 10 seconds to ramp back to pre-disturbance behavior) and the one that adds no delay with a 1-second ramp to pre-disturbance does not significantly impact the immediate voltage post-disturbance. One thing to note is that, while the constant power and constant current trajectories overlap and seem better initially, those runs had the **lsdt9** model (a UFLS protection model) tripping the electrical bus's load. As the UFLS relay tripping the load is not a desired outcome, ride through in constant current or constant power in FIDVR-prone areas is not a grid-friendly behavior[44] (see Figure 3.30).

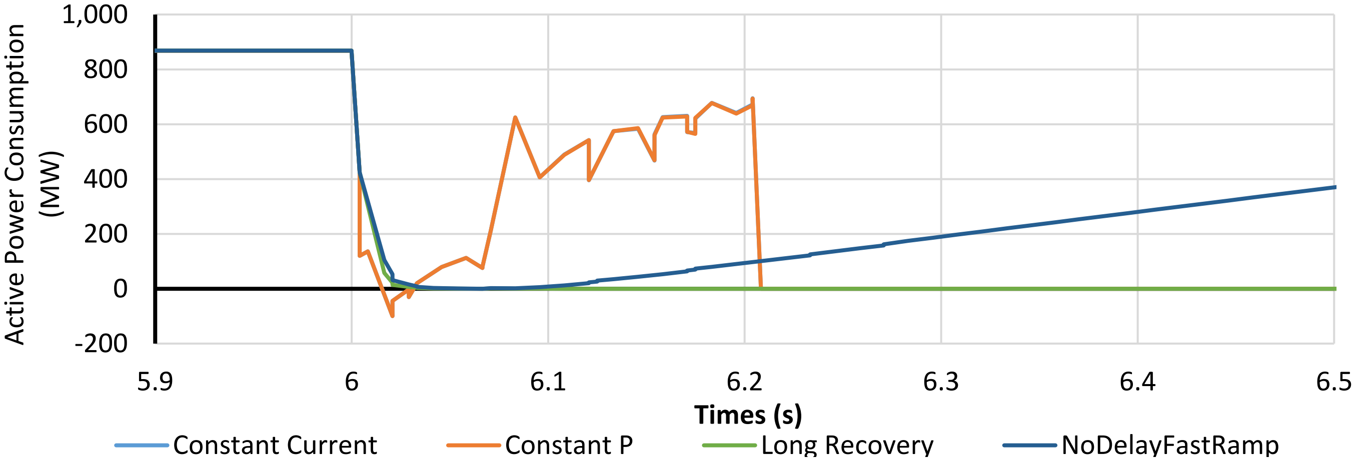

Figure 3.29: High-Side Transformer Voltage Recovery–FIDVR at High EV Penetration

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[44] This is a change from initial findings in the lower penetration portion of this report.

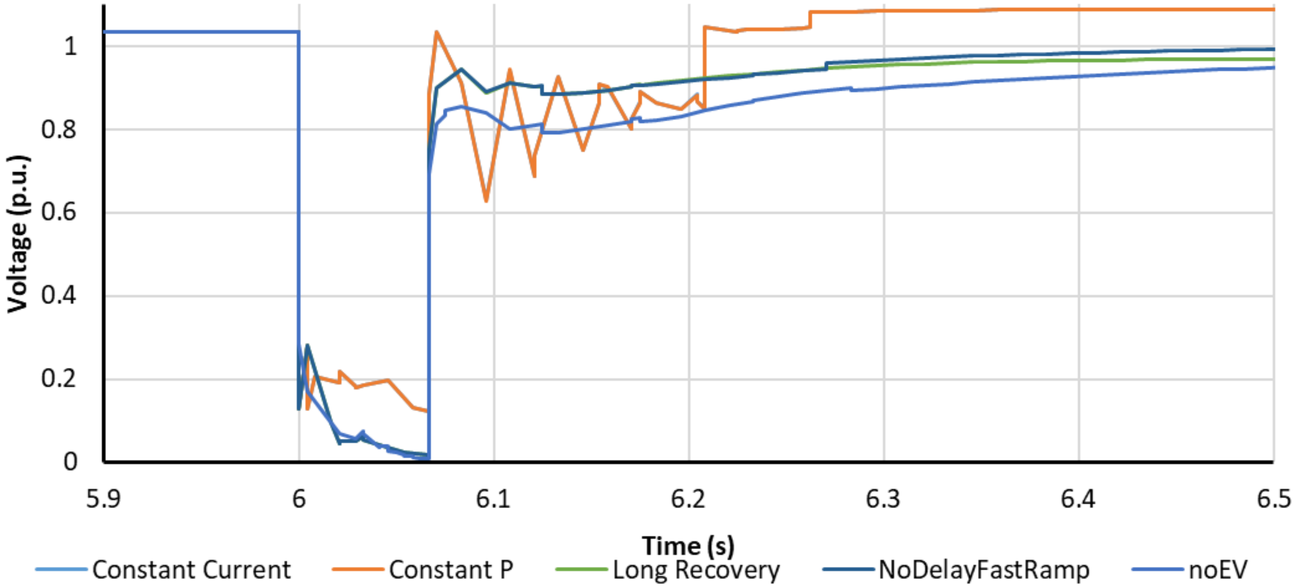

Figure 3.30: Electric Vehicle Power during FIDVR at High Penetrations

Key Takeaway

In FIDVR conditions, ride-through in constant power or constant current is grid-unfriendly and risky. No intentional delay should be added when recovering within one second to pre-disturbance consumption over a longer recovery.

Furthermore, the Study Team assessed if there is a difference between the long recovery versus the no intentional delay and fast ramp charging behavior far after the grid fault. At roughly nine seconds (three seconds post-disturbance) in the simulation, all the noEV, long recovery, and no intentional delay charging behaviors coincided until five seconds after the disturbance. This is plotted in **Figure 3.31**. Then, the long recovery EV charging characteristic maintained a depressed voltage from the noEV simulations and the no delay behavior recovered better than the noEV runs. For high adoption rates of EVs, the FIDVR condition still exists, and very long recovery times do not necessarily mean that the high side recovers faster. Instead, a charging behavior that momentarily ceases power consumption during FIDVR conditions should not add intentional time delay to its recovery; ramping back to pre-disturbance power within one second is the preferred EV charger response. The long recovery charging behavior also contains other grid-unfriendly behavior in the non-FIDVR fault portion of this study, and the marginal post-disturbance benefit does not warrant recommending such behavior in FIDVR conditions.

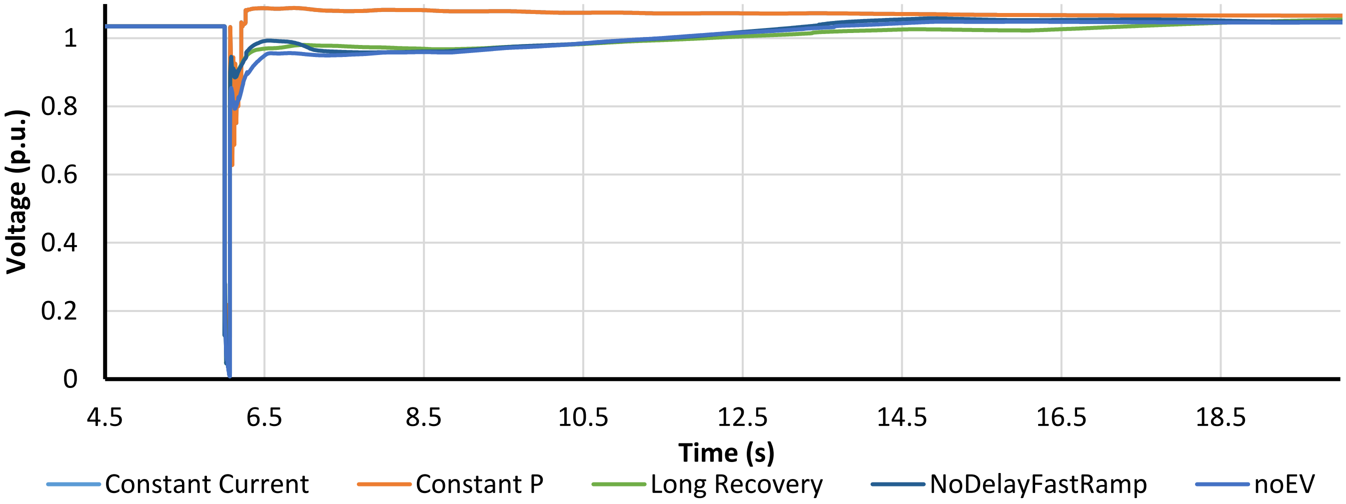

Figure 3.31: High-Side Transformer Voltage Recovery during FIDVR at High EV Penetrations–Zoomed Out

Return-to-Service Characteristic Post-Fault Behavior

Some EV charging stations have a lockout where the customers would need to reset their equipment via a physical switch rather than with a digital reset. Thus, after a 50–100 ms fault or voltage excursion, there is a probability that some EV chargers will enter a lockout that prevents the load from returning to service. This is only desirable for FIDVR-heavy conditions and is generally not grid-friendly behavior. The Study Team recommends not implementing a needed physical reset of equipment where possible; the ability to digitally reset the equipment or to enable automatic restoration behaviors that do not require a person to re-enable normal operating modes is preferable. The added delay in restoration leads to grid unfriendly behavior as the Study Team demonstrates in the High Electric Vehicle Adoption Cases section. As the EV penetration increases, the delay in load recovery can potentially destabilize the voltage[45] of the BPS. The Study Team recommends that no intentional delay in recovery or lockout of equipment is placed on EVs and their charging equipment. This may need to be balanced with distribution standards and requirements to ensure that distribution system protection is sufficient and aligned with other distribution anti-island performance[46] requirements.

Cyber Security Implications

With ongoing discovery of exploitable vulnerabilities identified across EV OEM equipment and software,[47] the Study Team wanted to test the sudden loss of a major block of EVs in a high-adoption scenario. To do so, the Study Team added a few new assumptions.

- **Assumption 1:** A threat actor maliciously gains access to a single OEM's application infrastructure after compromise of any downstream customer EV system or public charging station and then issues a wide disconnect signal to all applicable endpoints.
- **Assumption 2:** Any mitigating cyber security controls have failed to prevent the initial intrusion and have no impact on preventing the disconnect signal. Rather, the Study Team wanted to determine if bus voltages or frequencies became unstable with the associated load drop.
- **Assumption 3:** The single OEM compromise was roughly 20% of a single area in the Interconnection-wide models to test the impact such a load drop had on the simulation. For the heavy summer high EV penetration case tested, this equated to 14,016 MW of sudden load disconnection and the load trajectory is plotted in **Figure 3.32**.

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[45] This is particular to the finding in that section stating the long recovery settings never fully settled by the end of the 60-second simulation.

[46] This is particularly true for EVs that have V2G capability and are exporting power to the grid. This study and model representation did not look at EV charger export as part of this study.

[47] *Cybersecurity of Smart Electric Vehicle Charging: A Power Grid Perspective*

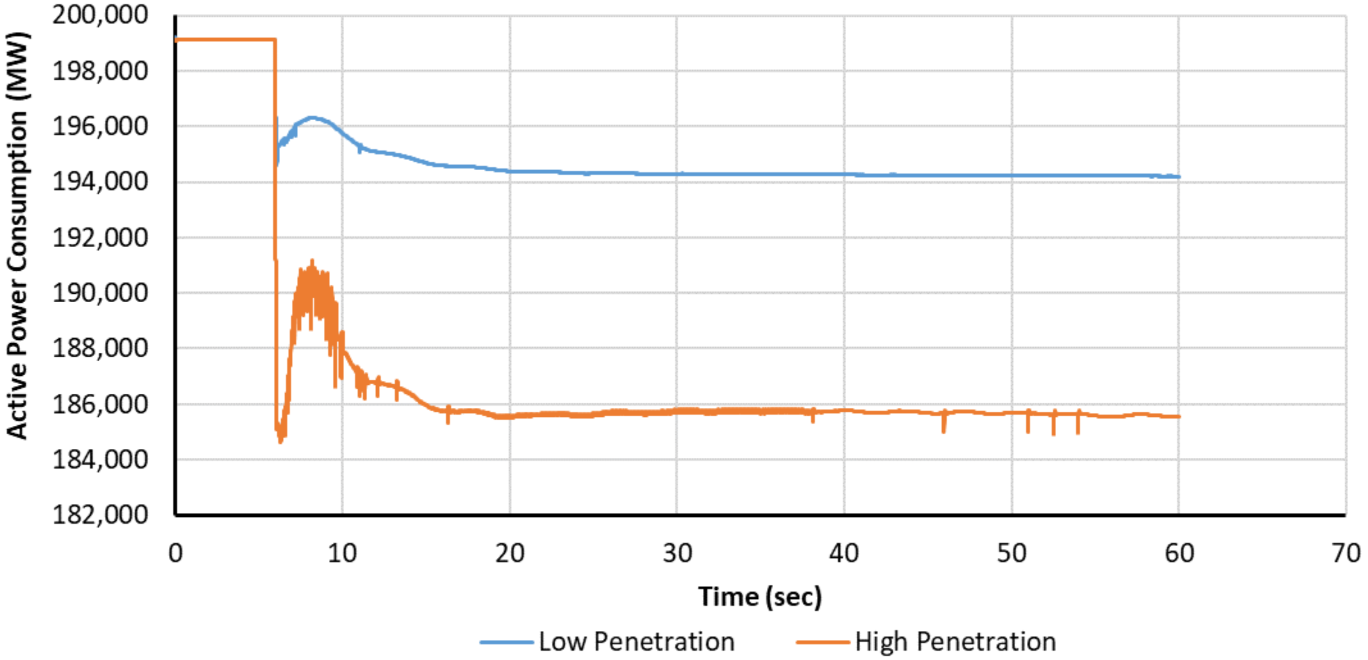

Figure 3.32: Load Trajectory of Potential Cyber Security Compromise of One EV OEM

With the load drop, the median simulation frequency (**Figure 3.33**) did increase; however, the most telling response is near the bus with the most load dropped, which increased the high-side transformer voltage found in **Figure 3.34**. In the heavy summer low EV penetration case tested, the load drop was MW and similar conditions were observed; however, the Study Team noticed generator bus voltage spikes above the instantaneous high voltage cut out per NERC PRC-024[48] in the heavy penetration EV simulation.

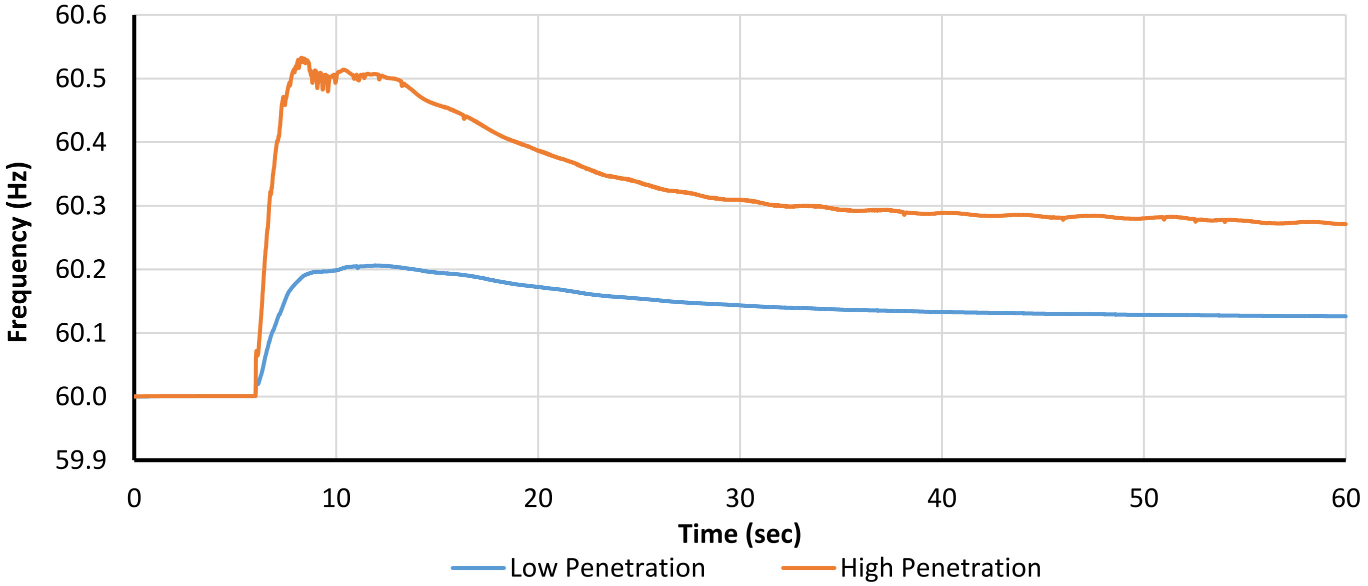

Figure 3.33: Median Simulation Frequency Due to Cyber Security Compromise

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[48] NERC PRC-024

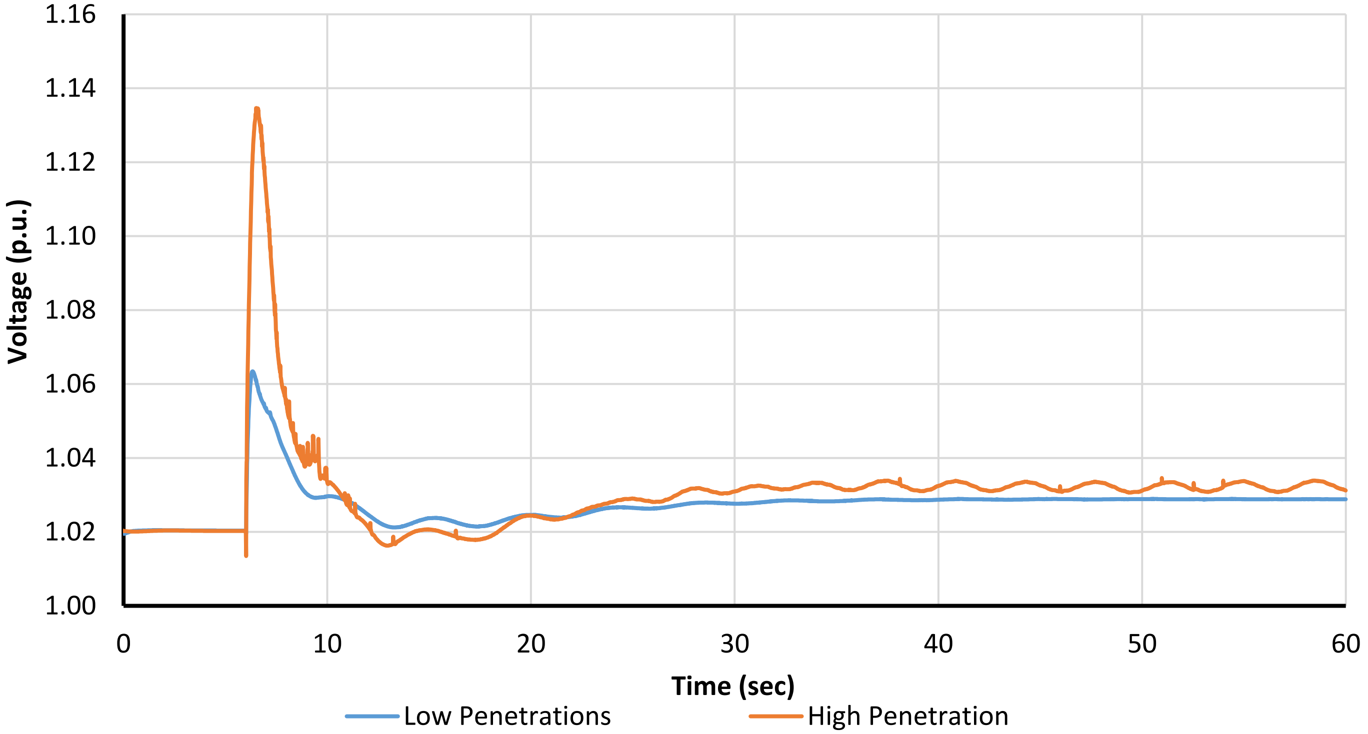

Figure 3.34: High-Side Bus Voltage at Largest EV Tripping Due to Cyber Security Compromise

As seen in **Figure 3.32**, **Figure 3.33**, and **Figure 3.34**, the potential voltage perturbation may create conditions where generator overvoltage protection enacts, leading to potential cascading. In the low-penetration case, zero generators experienced a 1.2 p.u. or higher voltage, but 18 generators lost 406 MW of generation in many different areas for the heavy EV penetration case. Due to how the BPS is modeled for these transient dynamic simulations and the major assumptions made for this scenario, this finding does not indicate that generators will trip given these conditions. Rather, the amount of EV penetration and their potential compromise by a malicious actor may lead to insecure grid conditions that can result in cascading. Therefore, EV manufacturers should increase their security posture to prevent compromise.

Chapter 4: Risks, Solutions, and Recommendations

The Study Team compared the results from the previous chapters as well as the identified EV roadmap to propose a set of risk-informed recommendations. The team first looked to see if there were other identified solutions for high EV adoption to see what lessons might advise recommendations.

Current Attempted Solutions and their Results

In Great Britain, there is a smart charging[49] effort that requires EVs to be able to respond to operator control signals. There, the electrical system has both a transmission system operator and a distribution system operator that can leverage this control to manage the EV charging ports. This current effort, however, does not specify the vehicles to return to service (i.e., no digital restart) nor other protocol and capability requirements. There are similar standards and solutions in the ERO Enterprise footprint that are generally utility driven with rate structures to incentivize end-use customers to participate in off-peak charging. These are all classified as a form of demand response and seem effective to limit EV charging by tying it to time of use or other rate structures. However, Sygensys identified this solution[50] as another potential threat to the electrical grid as the sudden charging onrush can be significant. **Figure 4.1** demonstrates the jump of EV charging power with a-time-of-use rate over a generalized EV consumption profile that did not contain the time-of-use rate. Currently, there is activity to move away from the time-of-use rates that promote large steps into other solutions that do not incentivize sudden spikes in EV power consumption. Outside of this one solution, there are efforts to specify more technical electrical ride-through specifications and mandatory charging behavior through cross-sector collaboration. Therefore, many organizations tackling the rapid adoption of EVs are taking a collaborative solution between utilities, regulators, and vehicle manufacturers.

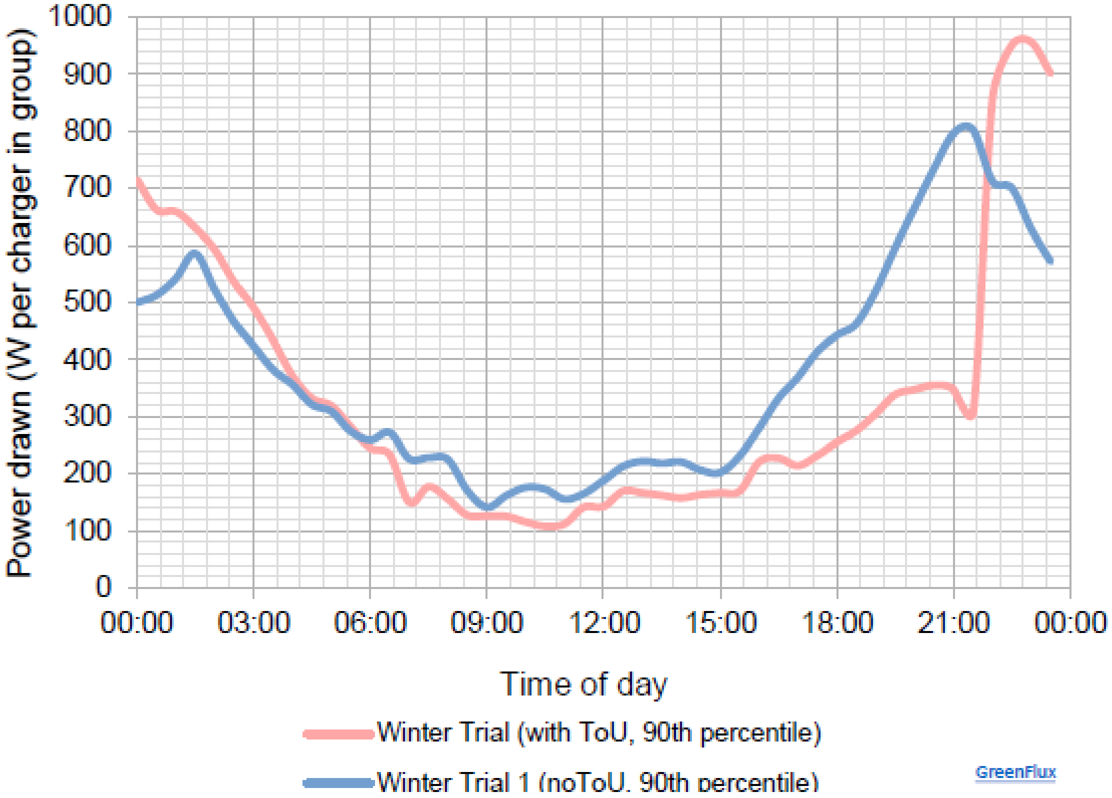

Figure 4.1: Time-of-Use Rate Impact on EV Charging (Source: Sygensys)

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[49] Great Brittain's smart charging effort helps manage the EV charging impacts by allowing operators to disconnect specific blocks of EV chargers during needed times for grid reliability.

[50] *The Impact of Electric Vehicle Charging on Grid Stability*

Potential Risks to the Electrical Grid

Collaboration among OEMs and utilities is needed to reduce any identified risk to the electrical grid; however, there are some charging behaviors that are more grid-friendly than others. The Study Team classified the various charging behaviors into grid-friendly and grid-unfriendly behavior in Table 4.1 and identified that there are charging behaviors not relevant to this table as a separate charging behavior better accomplishes the task. The fast-recovery-fast-ramp method of charging should use the no-delay fast ramp behavior and the fast recovery long ramp is very similar to the general long recovery charging behavior.

Table 4.1: Grid-Friendly or Grid-Unfriendly EV Charging Behavior

EV Charging Behavior	Base Case Grid Fault	Base Case FIDVR	Base Case Generation Loss	High EV Adoption Grid Fault	High EV Adoption FIDVR[51]	High EV Adoption Generation Loss
Heavy Summer						
Constant Power	Friendly	No change	No change	Friendly	Unfriendly	Slightly unfriendly*
Constant Current	Friendly	No change	Slightly friendly	Friendly	Unfriendly	Slightly unfriendly*
No Delay Fast Ramp	Friendly	Slightly friendly	Slightly unfriendly*	Friendly	Friendly	Unfriendly*
Long Recovery	Slightly unfriendly	Friendly	N/A	Unfriendly	Slightly friendly	N/A
Light Load						
Constant Power	Friendly	No change	Slightly unfriendly	Slightly friendly	N/A	No change*
Constant Current	Friendly	No change	Slightly friendly	Slightly friendly	N/A	Slightly unfriendly*
No Delay Fast Ramp	Friendly	Slightly friendly	Slightly unfriendly*	Slightly friendly	N/A	Unfriendly*
Long Recovery	Slightly friendly	Slightly friendly	N/A	Unfriendly	N/A	N/A

*This is a friendly behavior with a 5% frequency droop enabled. This is most notable in the extreme EV adoption cases for the major generation loss simulation.

Table 4.1 demonstrates that the friendliest charging behavior does not introduce intentional time delay and returns to pre-disturbance output in one second with a 5% frequency droop control enabled. Another friendly behavior is for the chargers to ride through in constant current mode with a 5% droop curve; however, such behavior can lead to load loss under FIDVR conditions.

The previous chapters also contain an EV roadmap to describe the desired outcome that is reproduced in Figure 4.2: Industry Position Relative to Identified EV Roadmap with a blue arrow pointing to where the NERC footprint is in the various stages of implementation. As seen in Figure 4.2 and Table 4.1, there is a need to mitigate the grid-level impacts that EV charging equipment can have on the BPS. Collective and collaborative industry engineering efforts

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[51] The constant power and constant current charging behavior caused the simulation to enact UFLS protection, dropping a major load bus in the simulation.

to understand EV charging behaviors should use this roadmap to improve on the modeling and studies portions. NERC should continue to assess and provide guidance on any identified risk for V2G technology and other similar policies in addition to maintaining awareness of equipment standards that can affect the electrical performance and ride-through of EV charging equipment.

Figure 4.2: Industry Position Relative to Identified EV Roadmap

Major Findings and Recommendations

Based on the results of the model testing and various charging paradigms, the Study Team drew a few conclusions and recommendations of specific features beneficial (i.e., grid friendly) to proactively identify the support needed for large penetrations of EVs for the various scenarios identified in the study. The conclusions and recommendations are summarized below:

- EV charger ride through for grid disturbances is the preferred charging characteristic for the Base Case, and EV charging equipment should default to riding through bulk grid faults if possible. NERC recommends the following actions:
    - TPs should identify areas where FIDVR conditions would change recommended EV and charging system ride-through characteristics.
    - If EV chargers and their equipment need to cease charging, they should not introduce a time delay when voltage recovers and returns to pre-disturbance charging levels within one second.
    - As the EV penetration increases, EVs and charging systems should return to pre-disturbance levels within one second of seeing a recovered voltage if needing to cease consumption.
- EV frequency response has an impact on the Interconnection-wide load, and EVs can support system-level frequency depending on droop settings. NERC recommends the following actions:
    - EVs and their charging systems should allow and enable a 5% droop characteristic.
    - A reasonable deadband should be implemented for this frequency droop behavior, starting at 17 mHz.
    - TPs should identify if a different droop parameter is needed for their areas to adjust EV and charging system response for frequency excursions.
- Voltage sensing delay does not affect post-disturbance recovery unless it is longer than the recovery time. The following action is recommended:

    - No intentional delay to recovery should be added when sensing a recovered voltage. In line with that recommendation, EVs should not contain a large voltage sensing delay to enable that fast response.

- The industry is in the early stages of understanding the electrical impact of large-scale adoption of EVs. NERC recommends the following actions:
    - NERC should build a collaboration effort with EV manufacturers to understand the technology so that planners and operators have sufficient understanding to perform their objectives.
    - NERC and its technical stakeholder committees should continue to study EV electrical response, especially concerning V2G capabilities.
    - TPs and PCs should identify planning practice enhancements to incorporate state and federal policies to electrify the transportation sector. These should ensure that Transmission Operators have sufficient flexibility to operate during many different scenarios.
    - NERC and its technical stakeholder committees should evaluate EVs and their charging systems for the risk posed by the cyber security posture of EVs and their charging systems. Where appropriate, NERC should provide reliability-focused recommendations to help improve BPS reliability.

The above points are categorized by their recommendations with additional notes. The Study Team found it useful to provide the necessary nuance to implement the recommended charging behavior. As seen in **Table 4.2**, some of the key findings can be influenced by future studies and factors as utilities and NERC improve their understanding of emerging EV technologies.

Table 4.2: Key Findings and Recommendations

Key Finding	Recommendations	Implementation Notes
EV charging systems can negatively impact the voltage recovery of the load bus depending on their charging characteristic. FIDVR concerns have a different, conflicting, preferred charging characteristic that can be set depending on the penetration of EVs at that bus.	• Ride-through of EV chargers is preferable for bulk faults. • If necessary, EV charging systems should not introduce physical lockouts or other intentional time delays and return to pre-disturbance charging behavior in one second. • Where FIDVR is a concern at lower EV penetrations, the TP should identify the preferred charging behavior outside of the above key finding. • At higher EV penetrations in FIDVR conditions, EV charging systems should cease charging during the disturbance and then return to pre-disturbance conditions with no intentional time delay and ramp back to pre-disturbance conditions.	Of the six charging characteristics, ride-through is the preferred constant current behavior; however, for heavy penetration cases, the Study Team recommends using no intentional delay with a one second ramp to pre-disturbance output. Proactive establishment of grid-friendly EV charging system characteristics allow for a reliable future grid. While there is leeway in the preferred characteristic at low penetrations, TPs should consider adoption of no intentional delay and one second ramp to pre-disturbance levels for their conditions. At higher penetrations, other studied charging behaviors led to some measure of grid-unfriendly behavior. However, the no intentional delay with a one-second ramp to pre-disturbance consumption did not lead to unfriendly behavior.
EV charging systems can provide major benefit in frequency excursions when using a 5% droop characteristic and prevent grid unfriendly behavior.	• EV and vehicle supply equipment OEMs should ensure their equipment has the capability for frequency droop and default to a 5% characteristic.	As frequency response is a BA's duty, TPs should use their input into the exact deadband and droop settings for their footprint. Then, TPs should study the reliability impacts that may arise at their buses due to that load response.

Table 4.2: Key Findings and Recommendations		
Key Finding	**Recommendations**	**Implementation Notes**
	• Balancing Authorities and TPs should study the impact other droop characteristics have and set a reasonable frequency deadband.	
Growing Penetrations of EVs indicate growing uncertainty in policy, planning, and electrical impact these devices may have on a utility's grid	• NERC and its technical stakeholder committees should continue to study the electrical impact of growing EV penetrations and new EV technology. • TPs and PCs should prepare for and enhance their planning practices to incorporate electrification of the transportation sector.	This white paper touches on the Interconnection-wide impacts of EV chargers but only outlines next steps for policy and TP enhancements.

Future Study Work

The Study Team was unable to obtain OEM-specific settings and confirmations of performance for this study. As such, the findings and recommendations of this white paper can be confirmed through collaboration between the electric vehicle manufacturers, regulatory bodies, and utilities. The following actions are recommended for future collaborative efforts:

- Further studies should obtain OEM-specific settings and compare against the "grid-friendly" behaviors. The future study should use such specific settings and populate the aggregate EV model to represent different OEM penetrations and their impact on the voltage and frequency recovery in similar grid conditions. EV OEMs and TPs will need to collaborate to understand the electrical representation of the EV charging system to ensure it is studied correctly in the planner's footprint.
- Further studies should investigate the cyber security posture of EVs and their charging systems and determine the impact a potential cyber compromise may have on the electrical system in greater detail. One such avenue to explore is the ERO Enterprise's report on *Cyber-Informed Transmission Planning*.[52]
- Industry should develop more specific models to represent V2G behaviors that are widely implemented in software platforms. The current models are not a good representation of both reduction of load and increase in generation and, as such, a generic aggregate model that can accomplish all aspects of the EV representation should be explored. Dynamic models for aggregate DERs exist and can potentially be useful to inform the proposed new model's development. Model benchmarking studies should be performed as part of this process.

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[52] ERO Enterprise White Paper Cyber Planning 2023

Appendix A: Contributors

NERC would like to acknowledge the following people who contributed to the study and review of this white paper. The Study Team would also like to thank those in **Table A.1** for their technical review and contributions to enhancing this report.

Table A.1: Contributors

Name	Company
NERC EV Study Team	
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Appendix B: List of References for Further Reading

NERC is sharing dashboards and other useful references for further reading. These are presented here for further education on penetrations, use cases, and other relevant technical material on the electrical performance of EVs and potential grid impacts outside of those mentioned in the white paper.

EV WATTS Station Dashboard | Energetics:[53] This shows a dashboard to highlight the utilization trends depending on type of charger, etc. These are useful to show that EVs are used at different venues depending on time of day but look to narrow out the total load (i.e., All will charge about the same if added all up and leveraged, so the load is the same; it just moves around after transportation use.).

IEEE Guide for Energy Storage:[54] The 1547.9-2022 standard includes electric storage DER and would include the interoperability for electric vehicles. The work in the IEEE 1547 family of standards is ongoing; however, the practices contained in the guide and clarifications on energy storage can be useful in how the utility sector views the V2G technology.

Statistica's Electric Vehicle Charging Infrastructure in the United State | Statistics & Facts:[55] This paid report includes various statistics and is regularly updated to reflect the EV rollout in the United States. The report serves as a good source to keep track of various integration stages in the United States outside of utility programs and additional statistical information on the rate of EV adoption.

California Energy Commission's Demand Analysis Working Group:[56] This working group has forecasts, policy briefs, and some EV statistics for California in addition to other energy products it tracks. This is a good source for state-level efforts tracking the EV rollout in their state. Readers are able to subscribe to the working group's distribution list.

The NERC Load Modeling Working Group:[57] The NERC Load Modeling Working Group is under way to develop additional models, parameters, and information to depict the electrical behavior of EVs and their charging systems with greater accurately. This group is active, and readers can subscribe to the observer list to see the latest in load modeling efforts in the NERC technical stakeholder groups.

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[53] EV WATTS Station Dashboard

[54] IEEE Guide for Using IEEE Std 1547 for Interconnection of Energy Storage Distributed Energy Resources with Electric Power Systems

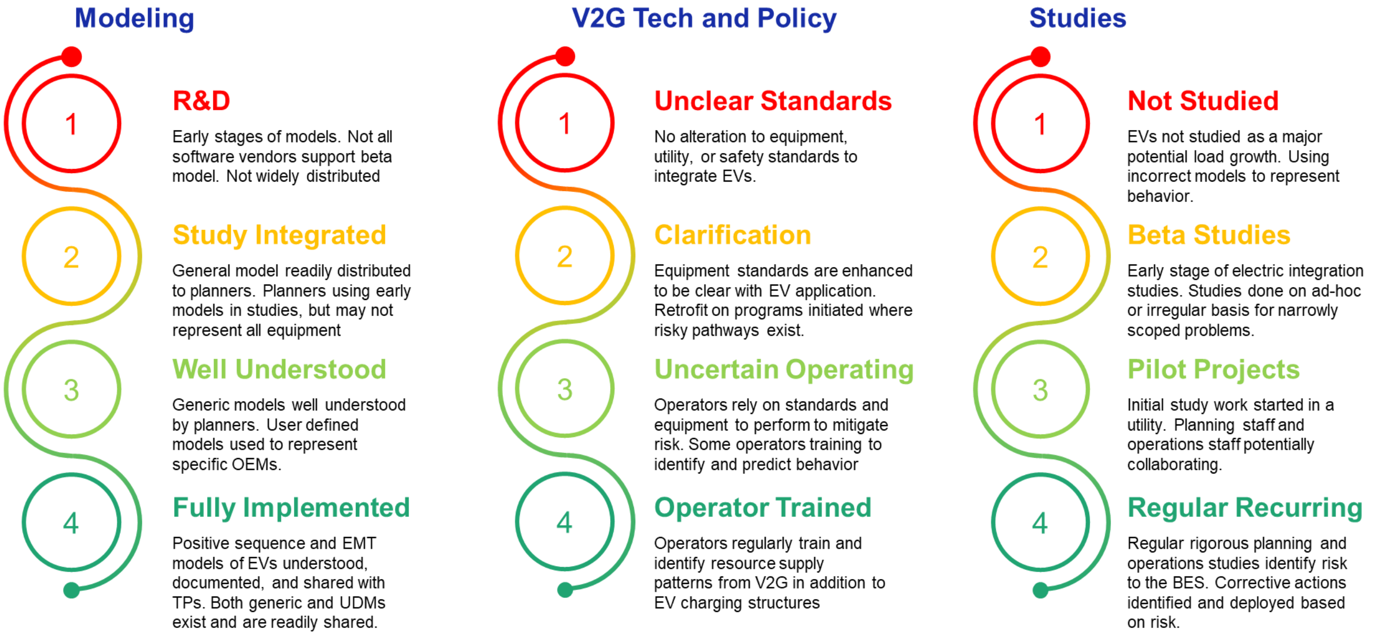
[55] Electric vehicle charging infrastructure in the United States - statistics & facts

[56] Demand Analysis Working Group (DAWG)

[57] Load Modeling Working Group (LMWG)

Appendix C: Desired Steps for Electric Industry Improvement

The modeling, V2G, and transmission studies pillars and associated milestones are mapped between the current (undesired) situation and the desired reliability outcome in **Figure C.1**. The figure highlights the steps that NERC and EV stakeholders can take to move between the undesired situation and the desired outcome with various milestones highlighted. NERC finds that it is essential to have a fully implemented model reflective of a consensus understanding of common EV charger characteristics, standardized treatment of EVs in operator platforms, and recurring transmission-level electrical studies capable of identifying specific risks as well as to recommend appropriate corrective actions.



Modeling

1 **R&D**
Early stages of models. Not all software vendors support beta model. Not widely distributed

2 **Study Integrated**
General model readily distributed to planners. Planners using early models in studies, but may not represent all equipment

3 **Well Understood**
Generic models well understood by planners. User defined models used to represent specific OEMs.

4 **Fully Implemented**
Positive sequence and EMT models of EVs understood, documented, and shared with TPs. Both generic and UDMs exist and are readily shared.

V2G Tech and Policy

1 **Unclear Standards**
No alteration to equipment, utility, or safety standards to integrate EVs.

2 **Clarification**
Equipment standards are enhanced to be clear with EV application. Retrofit on programs initiated where risky pathways exist.

3 **Uncertain Operating**
Operators rely on standards and equipment to perform to mitigate risk. Some operators training to identify and predict behavior

4 **Operator Trained**
Operators regularly train and identify resource supply patterns from V2G in addition to EV charging structures

Studies

1 **Not Studied**
EVs not studied as a major potential load growth. Using incorrect models to represent behavior.

2 **Beta Studies**
Early stage of electric integration studies. Studies done on ad-hoc or irregular basis for narrowly scoped problems.

3 **Pilot Projects**
Initial study work started in a utility. Planning staff and operations staff potentially collaborating.

4 **Regular Recurring**
Regular rigorous planning and operations studies identify risk to the BES. Corrective actions identified and deployed based on risk.

Figure C.1: Anticipated Risk and Steps to Success

These three pillars highlight potential, anticipated risk as the BPS undergoes rapid transportation electrification. Historic loads (and generation for the V2G technology) were geographically static (i.e., There was not generally an electrical movement between the load and its designated BES bus serving the load.).[58] In comparison to historic loads, EVs are mobile and can charge from home to public or alternative charging systems. EV mobility leads to an uncertainty to where the charging load will materialize on the electric system. The growing penetration of EVs indicates that clarity in enhanced modeling, clear policy, and increasing studies are the first steps toward solving the uncertainty and unknowns that electrifying the transportation sector brings to the BPS reliable operation. The broad potential risks and roadmap in **Figure C.1** are not the only potential risks when moving to the above NERC-desired outcome for models, V2G technology and policy, and studies. Potential areas of investigation that will be informed by milestones in **Figure C.1** include the following:

Key Takeaway

Growing penetrations of EVs indicate a growing uncertainty in the policy, planning, and electrical impacts of EVs and their charging equipment. Clarity enhancements are the first step to a reliable future BPS.

- Treatment of EVs during emergency operation times, particularly cold weather
- Identification of EV charging systems operating independent of or dependent on a separate entity (e.g., price-responsive charging or used in demand response programs)

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[58] Obvious exceptions to this are the reconfiguring schemes to ensure load is served under specific contingencies. However, these are set up and studied in advance of operation. Such certainty is a stark difference with the nature of EV loads throughout the day.

- Role in TP corrective action plans[59] that are the results from regularly recurring transmission planning studies

As with all emerging technologies in the electricity sector, uncertainty qualifies not only the electrical characteristics of the technology but also the pathway needed to mitigate any uncovered reliability risk to the BPS. Utilities and EV OEMs are encouraged to share information on the electrical impact of this emerging technology and proactively encourage grid-friendly behavior as EV adoption rises.

Electric Vehicles and Virtual Power Plants

While this white paper focuses on the impacts of EV charging requirements independent of other growth, EV participation is growing in virtual power plants (VPPs).[60] These plants are another technology that effectively has another entity (i.e., the VPP) interface between the utility procuring energy to serve the EV charging demand and the EV end-use device. VPPs can leverage control over EV output, so EV growth increases the capacity potentially under the control of a VPP or similar entity and further incentivizes VPP growth. VPPs span multiple technology types and may include generation and load as part of their design. Even with the tie-in for VPPs, the three broad topics that should be addressed for the growing EV technology are not changed. Rather, their application while under the control of a VPP versus independent control for their charging characteristics is incorporated into the steps in **Figure C.1**.

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[59] Particularly any CAP that cannot account for the potential shift of EVs to a separate BES bus may not fully alleviate the added load consideration EVs place onto a TP's planning footprint.

[60] VPPs have a variety of definitions, but the Department of Energy has a report highlighting the load, generation, and other components of a VPP. Available here: DOE Report on VPPs