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

October 2021

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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

1 Arizona State University
2 Idaho National Laboratory
3 Lawrence Berkeley National Laboratory
4 Bonneville Power Administration
5 North American Electric Reliability Corporation

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Abstract

This report investigates how the addition of a large population of plug-in electric vehicles (PEV) to an existing residential distribution feeder might affect the load behavior that the feeder presents to the transmission grid. Simulations are made with a representative model of a residential distribution feeder combined with detailed modeling of existing loads (air conditioners) and modeling of charger controls based on tests with six commercially available PEVs.

The main conclusion of this investigation is that PEVs can be programmed to act during voltage dips in a way that, both, is friendly to the grid and causes no significant inconvenience to the operation of the vehicles. The report suggests voltage thresholds and timings that would be appropriate, in principle, for the programming of PEV charging systems supplied by a predominantly residential distribution feeder. Details of thresholds, timing, and logic will be determined by study of particular electric utility configurations; these studies should be undertaken with close cooperation between the electric power supply and motor vehicle industries.[1]

[1] PEV control strategies that would change over from charging to discharging have not been considered in this report, but should be considered in further investigations.

Executive Summary

Transmission operators are responsible for ensuring reliable operation of the integrated high-voltage or bulk electric power system. Carrying out this responsibility requires designing and operating the system so that it will initiate automatic, pre-planned actions to restore safe, stable operating conditions following unplanned, yet routine, disturbances in which failure to take immediate, decisive action risks initiating an uncontrolled, cascading blackout[1]. In 2005, preparing for these actions, and taking them when needed, became mandatory and enforceable with monetary penalties assessed by the North American Electric Reliability Corporation.

To fulfill this responsibility, transmission operators conduct extensive "what if" studies in which they anticipate and plan responses to the range of disturbances that the system must be capable of withstanding. The studies rely on detailed representations of how the elements of the system – generators, transmission facilities, and loads – behave during disturbances. The results of the studies are the basis for investments to harden the system (such as installation of automatic controls) as well as for procedures that must be followed so that control actions prevent blackouts.

Electrical faults on the transmission system that cause short depressions of voltage (typically lasting 7-9 cycles or 120-150 milliseconds) are a major focus of transmission planning studies. Historically, planning studies appropriately assumed that the majority of loads were "grid friendly," which meant that, following an electrical fault, loads would respond in a manner that facilitated rapid recovery of the grid to a stable operating condition.[2] The classic example is the incandescent lamp, which draws decreasing current as supply voltage is reduced. It is now widely recognized that a growing portion of load is "grid unfriendly," which means that, following a disturbance, it maintains (or adds) demand on the system and makes recovery more difficult.

Standard residential air conditioners in the U.S.[3] are an example of a grid unfriendly load when subjected to large dips in supply voltage. When a fault depresses voltage to 70 percent or less, standard residential air conditioners are likely to stall and draw many times their rated electrical current. This is an extreme example of grid-unfriendly behavior because greatly increasing load places additional stress on an already stressed grid.[4] Today, residential air conditioning accounts for a significant portion of load during the highest summer peak periods. In some portions of the United States, the grid-unfriendly behavior of residential air conditioners has led

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[1] Pre-planned, fully automated actions are essential because they must be initiated faster than human operators can direct.

[2] This definition of grid friendly is restricted solely to the specific issues pertaining to grid dynamics addressed in this report. It does not extend to address issues related to steady-state operations, interoperability, information sharing, or any other relevant facet that would be necessary for a more comprehensive definition of grid friendly.

[3] Standard residential air conditioners in the US refer to units that are connected to the grid via contactors. A small fraction of newer residential air conditioners sold in the US are connected to the grid via electronic inverters. This report does not address the responses of inverter-connected air conditioners to the behavior of plug-in electric vehicles.

[4] Following a large disturbance, the single-phase induction motors in residential air conditioners can stall and nearly instantaneously increase the load they place on the grid by a factor of 4 or more. As a result, instead of an immediate restoration of voltage following clearance of the fault, voltages remain depressed for many seconds. The resulting stressed condition is alleviated only by the actions of thermal protective devices in the air-conditioner motors that disconnect the units after 10-15 seconds in order to prevent permanent damage. This phenomenon is called "fault-induced, delayed voltage recovery" or FIDVR. See https://certs.lbl.gov/initiatives/fidvr.

transmission planners to install expensive additional equipment specifically to address the additional grid stress created by stalled air conditioners.

Plug-in electric vehicles (PEVs) represent a rapidly growing new type of load that transmission (and distribution) systems must be prepared to serve. Accordingly, transmission planners are now preparing to study future scenarios in which PEVs represent a significant portion of load. Whether planners find the behavior of PEVs to be grid friendly or grid unfriendly will have direct implications for future transmission investments and operating procedures.[1]

This report has two purposes. The first is to provide engineering counterparts in the PEV and electric vehicle supply equipment (EVSE) industry with insights into the types of PEV behaviors that are grid friendly or grid unfriendly during transmission faults.[2] The second is to show the range of grid friendly and grid unfriendly behaviors that currently exist in a selection of PEVs that are in production today.

To anticipate the conditions that the grid may be required to manage in the future, we studied a representative distribution feeder consisting of approximately 1,500 residences, many of which are equipped with standard air conditioning systems. We examined a future in which each household also has, and charges, a PEV from the household's power supply. We subjected the feeder to the rapid depressions of voltage (called voltage dips) that result when a fault takes place on the transmission system and is cleared in a normal manner. Voltage dips can cause residential air conditioners to stall and thereby delay the restoration of transmission system voltages. Delayed restoration of transmission voltages is a reliability concern that is studied routinely by transmission planners. We examined how six different types of PEVs affected the stalling behavior of air conditioners. If the addition of a large number of one type of PEV did not increase the number, or delay the recovery, of stalled air conditioners, we deemed the PEV grid friendly. If the addition of a large number of one type of PEV increased the number, or delayed the recovery, of stalled air conditioners, we deemed the PEV grid unfriendly.

We divided our findings into two distinct phases: The first phase is the very short period of time during which a voltage dip takes place, which lasts on the order of 7 to 9 cycles (120-150 milliseconds).[3] The second phase is the period immediately after the fault has cleared. Under favorable circumstances, the grid recovers nearly instantaneously to a safe, stable operating state one the fault has been cleared. Under the less favorable circumstances we examine, the

[1] The definition of "grid friendly" used to prepare this report is not comprehensive. It is restricted solely to the specific grid dynamics addressed in this report. In particular, it is restricted solely to the times when PEVs are drawing current from the grid (i.e., charging). The definition also does not extend to issues related to steady-state operations, interoperability, information sharing, or any other similar aspect.

[2] It is recognized that PEVs connect to the electricity grid through stand-alone (normally, stationary) electric vehicle supply equipment (EVSE). It is further understood that EVSEs may have control functions that are responsive to voltage dips. These functions may be independent of the control functions of a PEV, or they may operate in conjunction with the controls within a PEV. In either case, if EVSEs reinforce or, at least, do not compromise the PEV behaviors that this report deems are grid friendly, then the EVSEs are also grid friendly, in this same sense. Similarly, if EVSEs have the effect of causing PEVs to behave in a manner that this report deems grid unfriendly, then these EVSEs are also grid unfriendly.

[3] The exact duration depends on the type and location of the fault and the grid protective devices that have been installed to limit the fault's spread.

second phase can last many seconds, depending on the design of the transmission system, the penetration of residential air conditioners, and the depth and duration of the voltage dip.[1]

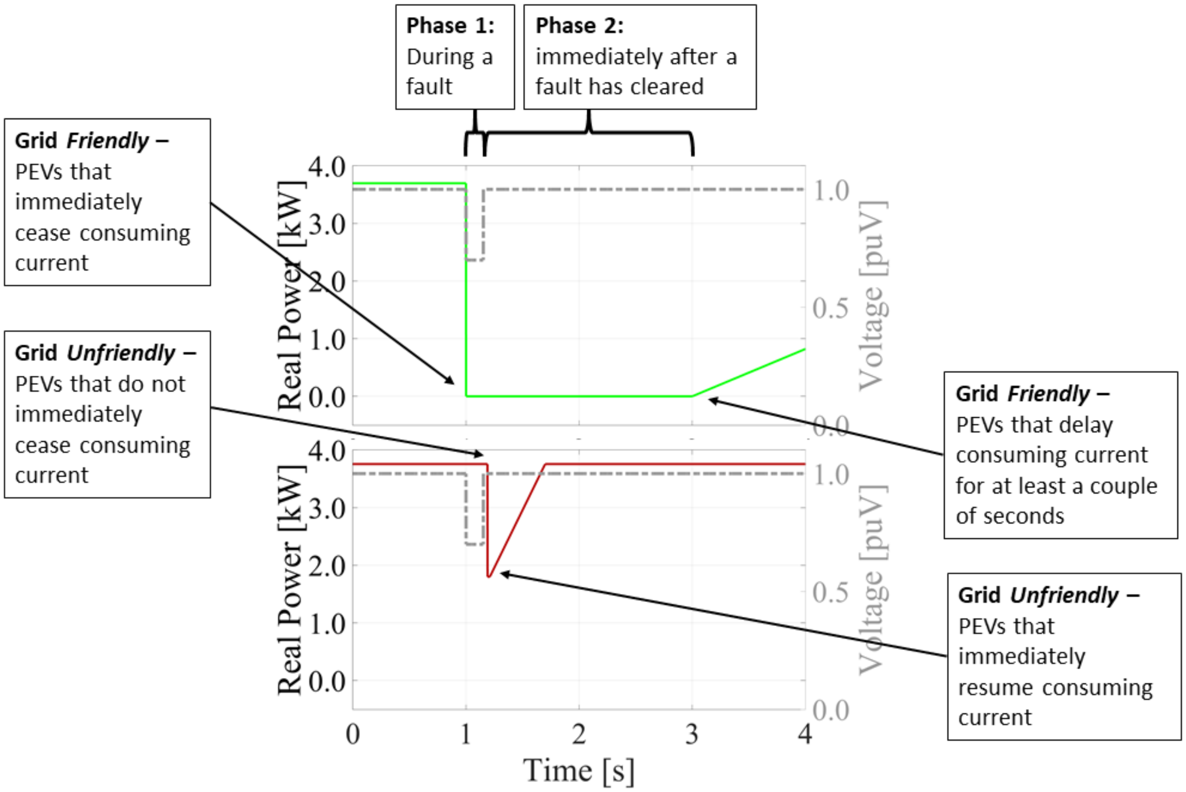

Figure EX-1 – Summary of Grid Friendly and Grid Unfriendly PEV Behaviors

Our findings on grid-friendly and grid-unfriendly PEVs are as follows (See Figure EX-1):

PEVs that immediately cease consuming current upon sensing a significant voltage depression are ***grid friendly***.[2] As noted above, faults place stress on the grid. End-use loads that decrease their power consumption during faults reduce stress on the grid.

PEVs that do not immediately cease consuming current upon sensing a significant voltage depression are ***grid unfriendly***. Additional load during this critical period adds to the stress on the grid. If PEVs, in fact, increase their consumption of current during the fault (e.g., in order to maintain constant power), doing so is ***highly grid unfriendly***.

PEVs that delay consuming current for at least a couple of seconds after the fault has cleared are ***grid friendly***. Managing acceptable post-fault voltage recovery is important for reliable grid operations. Drawing no or greatly reduced current supports the grid during this dynamic

[1] Stalled air conditioners will rapidly heat up and disconnect from the grid after a few seconds when internal thermal protective devices act to prevent permanent damage to the units. Once units have cooled down (after several minutes have passed), they will restart automatically.

[2] It is imperative that that PEVs cease consuming current immediately at the onset of a significant voltage dip. Delaying this action until the nadir of voltage can be determined is too late to prevent air conditioners from stalling. Instead, the action to cease current consumption must be initiated as soon, as it can be reasonably determined that a dip will be significant (e.g., to less than 85% nominal voltage).

recovery process. The return to pre-event consumption of current should be ramped over a period of several seconds.

PEVs that immediately resume (or continue) consuming current after the fault has cleared are ***grid unfriendly***. Adding load onto the grid during the critical post-fault period is detrimental to the restoration process.

This report suggests voltage thresholds and timings that would be appropriate, in principle, for the programming of vehicle chargers supplied by a predominantly residential distribution feeder. Details of thresholds, timing, and logic will be determined by study of particular electric utility configurations; these studies should be undertaken with close cooperation between the electric power supply and motor vehicle industries.

It is important to point out that the behaviors which make PEVs grid friendly or unfriendly during the times when they are charging do not extend to the times when they are discharging.

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Dr. Bernard Lesieutre, University of Wisconsin

All errors and omissions remain the responsibility of the authors.

Acronyms and Abbreviations

BES	bulk electrical system
DOE	U.S. Department of Energy
EV	electric vehicle
EVSE	electric vehicle supply equipment
FERC	Federal Energy Regulatory Commission
FIDVR	fault-Induced delayed voltage recovery
HELICS	Hierarchical Engine for Large-scale Infrastructure Co-Simulation
HVAC	heating, ventilation, and air conditioning
IBRPWG	Inverter-Based Resource Performance Working Group
IEEE	Institute of Electrical and Electronics Engineers
INL	Idaho National Laboratory
kHz	kilohertz
kV	kilovolt(s)
kW	kilowatt(s)
LBNL	Lawrence Berkeley National Laboratory
MVA	mega-volts ampere
MW	megawatt
NERC	North American Electric Reliability Corporation
PEV	plug-in electric vehicle
PNNL	Pacific Northwest National Laboratory
SAE	Society of Automotive Engineers
V	volt(s)
WECC	Western Electricity Coordinating Council

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1.0 Introduction

Transmission operators are responsible for ensuring the reliable operation of the integrated high-voltage or bulk electric power system. Carrying out this responsibility requires designing and operating the system so that it will initiate automatic, pre-planned actions to restore safe, stable operating conditions following unplanned yet routine disturbances when failure to take immediate, decisive action risks initiating an uncontrolled, cascading blackout.[1] In 2005, preparing for these actions, and taking them when needed, became mandatory and enforceable with monetary penalties assessed by the North American Electric Reliability Corporation (NERC).

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This report has two purposes. The first is to provide engineering counterparts in the PEV and electric vehicle supply equipment industry with insights into the types of PEV behaviors that are grid friendly and grid unfriendly.[1] The second is to show the range of grid friendly and grid unfriendly behaviors that currently exist in a selection of PEVs that are in production today.

The remainder of this report is organized as follows:

Section 2 introduces the modeling and simulation approaches that transmission planners use to study the transmission system's ability to withstand and recover from disturbances. The approach relies on representing electrical loads in a highly aggregated manner in a dynamic composite load model. The model assigns all the loads served by a distribution substation as contributing to one of a handful types of load, each of which behaves in a distinct, yet consistent fashion within the simulation study.

Section 3 describes the granular analysis approach used to conduct the current study. Rather than simulate the aggregated behavior of loads using a single model, as is done in a dynamic composite load model, our study simulates the individual behavior of each load served within a single, representative distribution feeder.

Section 4 presents our simulation results and findings. We first simulate how standard residential air conditioners within the feeder respond to voltage dips (of varying depths and durations) with no PEVs present. Next, we add an identical type of PEV to each household and rerun the simulations. Six different types of PEVs are modeled. The model for each was developed from laboratory tests of commercially available PEVs from six different manufacturers. The development of these models is described in Appendices A and B.

Section 5 summarizes the conclusions from our investigation. PEVs are deemed grid friendly if they do not increase the number of air conditioners that stall initially and do not impede the ability of air conditioners to emerge from their stalled condition. Conversely, PEVs are deemed grid unfriendly if they either increase the number of air conditioners that stall initially or increase the number that remain stalled. In Section 5, we also contrast the insights that emerge from our study regarding PEVs when they are charging with those that industry prescribes for all electricity sources, including PEVs, stationary batteries, and solar PV, when they are discharging and injecting current into the grid.

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[1] It is recognized that PEVs connect to the electricity grid through stand-alone (normally, stationary) electric vehicle supply equipment (EVSE). It is further understood that EVSEs may have control functions that are responsive to voltage dips. These functions may be independent of the control functions of a PEV, or they may operate in conjunction with the controls within a PEV. In either case, if EVSEs reinforce or, at least, do not compromise the PEV behaviors that this report deems are grid friendly, then the EVSEs are also grid friendly, in this same sense. Similarly, if EVSEs have the effect of causing PEVs to behave in a manner that this report deems grid unfriendly, then these EVSEs are also grid unfriendly.

2.0 Background

This section describes the modeling and simulation approaches that transmission planners use to study the transmission system's ability to withstand and recover from disturbances and reviews known concerns planners have about the behavior of residential air conditioners during these events. The section also introduces related, emerging concerns regarding the impacts of growing loads from PEVs and concludes by explaining why the granular approach adopted by this study is required to explore these concerns.

2.1 Power System Planning and the Representation of Loads in Planning Studies

The electric power system experiences sudden disturbances whose character can be anticipated but whose timing cannot. These disturbances cause sudden voltage changes.

The behavior of the overall system is heavily dependent on the electrical characteristics of the bulk electrical system (BES) network, the dynamic characteristics of the generating plants connected to the BES, and the behavior of the myriad of individual electrical loads. Distribution substation loads are individually small but cumulatively have a dominant influence on BES behavior.

Analysis of the BES is based on simulations of the meshed transmission network at the scale of tens of thousands of nodes, thousands of individual power plants, and tens of thousands of load-serving substations. The scale of the simulations is such that representation of individual load entities is impractical, except for a relatively few very large industrial loads. Current practice is to recognize the behavior of loads by attaching condensed models representing collective load behavior to the network nodes where power is supplied from the meshed BES to radial sub-transmission and distribution systems.

An electric power system is made up of a single, large, meshed BES and a large number of radially connected distribution substations. Each distribution substation supplies one or more distribution feeders, as illustrated by the red portions in Figure 1.

Distribution system loads are modeled in a composite manner that represents the distribution substations where the radial parts of the system are connected to the meshed transmission system. The principal elements of a composite load model, as illustrated in the blue portions of Figure 1, are:

- a transformer connected on its supply side to the bulk transmission system and on its load side to a distribution bus
- a single section of distribution line running from the distribution bus outward to a concentration of load elements
- load elements representing the collective power consumption of classes of loads that are supplied by the distribution feeders

The single distribution line section in the composite load model is used to acknowledge the impedance, and therefore voltage difference, between the substation distribution bus and the locations[1] of the load elements.

The load classes represented in current implementations of the composite load model are:

- simple resistance load (incandescent lighting, resistive heating)
- three-phase induction motors that drive fans, pumps, conveyers, etc.
- single-phase induction motors that drive residential air conditioners
- miscellaneous electronic load such as television sets, computers, and light-emitting diode lighting

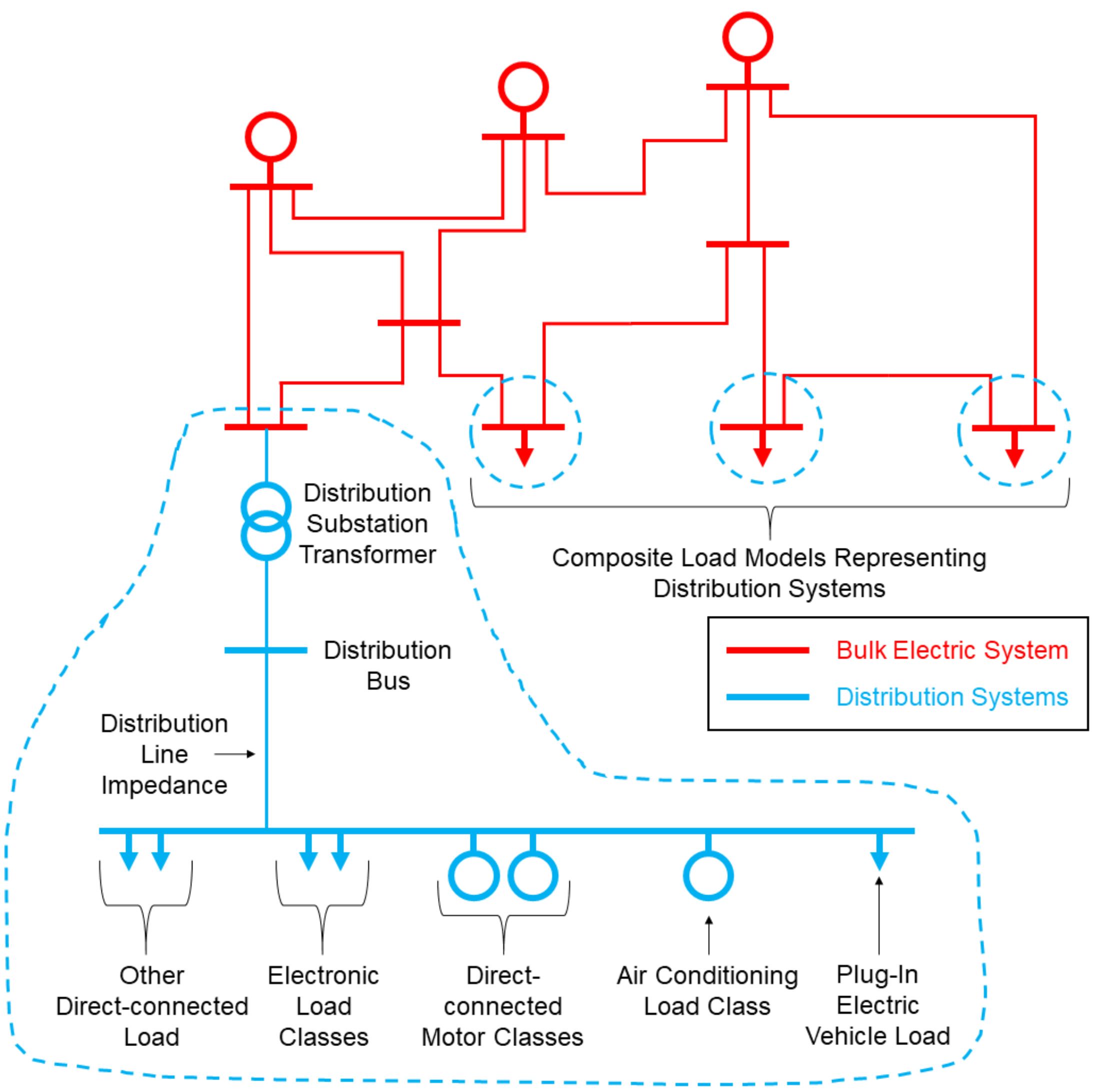


Figure 1 – Bulk Electrical System and Composite Load Model Components

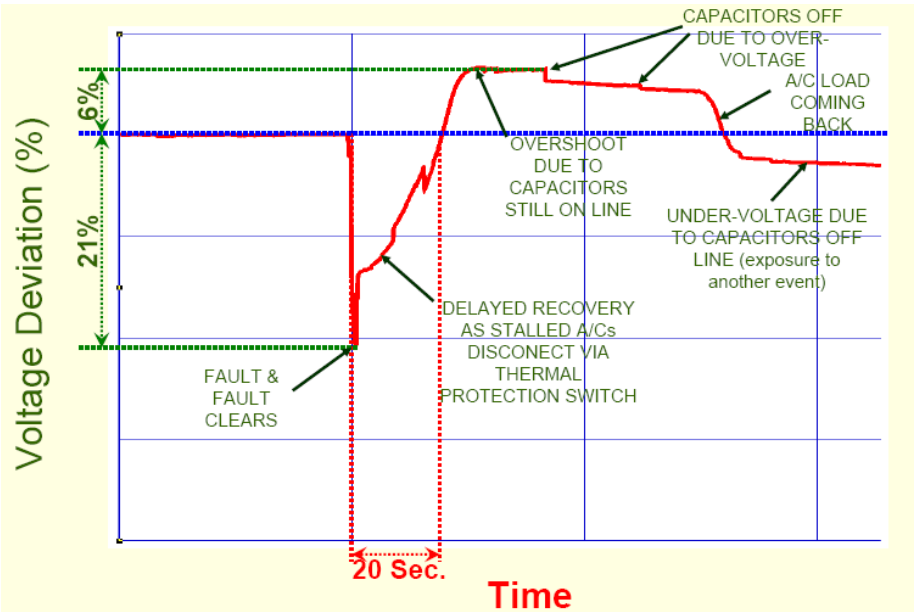
[1] Figure 1 shows PEVs as a distinct class of loads. Currently, PEVs are included in electronic loads.

2.2 Residential Air Conditioning is a Grid-Unfriendly Load

The ability of the grid to withstand disturbances and continue to supply power is affected by the behavior of the electrical loads that it serves. As described above, simple loads, like resistive heating and lighting, respond to voltage disturbances in a way that aids the restoration of normal grid conditions. These loads are “grid friendly.” Other significant types of load respond to voltage disturbances in ways that do not aid, and can impede, a return to normal operation. These loads are “grid unfriendly.” Residential air conditioners are a well-studied example of a grid-unfriendly load.

According to NERC (2009):

> Fault Induced Delayed Voltage Recovery (FIDVR) is the phenomenon whereby system voltage remains at significantly reduced levels for several seconds after a transmission, sub-transmission, or distribution fault has been cleared See Figure [below] for a typical FIDVR. Significant load loss due to motor protective device action can result, as can significant loss of generation, with a secondary effect of unacceptably high, potentially damaging system voltage sometimes following the load loss. A severe event can result in fast voltage collapse.
>
> FIDVR is caused by highly concentrated constant torque induction motor loads which stall in response to low voltages resulting from system faults. The stalled motors draw excessive reactive power from the grid and require five to six times their typical steady-state running current in this locked-rotor condition. Across many motors, this state can cause the system voltage to be significantly depressed for several seconds after the fault is cleared and this can lead to cascading system failure.



The compressor motors used in standard, U.S. residential air conditioners are the predominant form of high-torque induction motor that causes FIDVR events.[1] These single-phase motors are directly connected to the power supply by contactors. Because their inertia is low, these compressor motors decelerate very quickly when supply voltage reduces. If a voltage depression is too deep or lasts too long, these motors will stall. Depending on the nature of the voltage recovery and the type of air conditioner compressor, the motors may not restart. Induction motors that remain connected to the power supply while stalled present the electricity system with real and reactive power loads that are several times greater than the motors' normal running load. This high reactive load pulls down the voltage at the point of connection, compromising the security of the BES. The stalling of air conditioner motors is, therefore, a major concern in regard to the behavior of the distribution load as seen from the BES.

2.3 Growing Loads from Plug-in Electric Vehicles: Grid Friendly or Unfriendly?

It is anticipated that the loads from PEVs will become a significant, and at certain hours, dominant part of overall electrical load. The characteristics of PEVs are reasonably well known, and, because PEVs operate in various different modes depending on circumstances, we anticipate that they will have a favorable effect on the response of the electric power supply system in some situations and an unfavorable effect in others.

PEV load is expected to become a major part of power system load in all climates. One concern is the effect of this load where it is superimposed on existing "traditional" residential air conditioning load. Accordingly, this study looks at how the addition of a large amount of PEV load to the existing load on a distribution feeder serving air-conditioned homes would affect the behavior seen at the distribution substation that supplies the feeder.

2.4 Study of the Grid-Friendliness of PEV Requires Detailed Simulation of the Distribution System

The composite load models used in transmission planning studies have been well calibrated for substations serving legacy loads but not yet calibrated for substations that serve a significant PEV loads. An important objective of this study is to contribute to the development of dynamic composite load modeling procedures to examine the reliability impacts of greatly increased loads from PEV.

As noted, the composite load model classifies all loads served by a distribution substation as one of a handful of types. Each load type is, itself, a model that represents the aggregate behavior of all loads that belong to that load category. Although it is natural to think of the model of any particular load type for, say, residential air conditioning as a single (albeit, very large) induction motor, in fact, the model must also account for the operating diversity among the hundreds or thousands of individual residential air conditioners that are served by a distribution substation.

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[1] A small fraction of newer residential air conditioners sold in the U.S. are connected to the grid via electronic inverters. This report does not address the responses of inverter-connected air conditioners to the behavior of PEVs.

Transmission planners account for this diversity by adjusting the modeling parameters for individual load types. These parameters specify, for example, what fraction of the total residential air conditioning load served by a distribution substation will stall at a given voltage.

These parameters are specified and calibrated through a combination of laboratory experiments involving staged testing of individual machines, field observations of the behavior of many machines as seen from a single aggregation point, detailed simulations of individual feeders, and sensitivity studies conducted using transmission planning models.[1]

The current study relies on a simulation-based approach that models the individual behavior of each load served by a representative distribution substation. This approach is necessary because the load behaviors we seek to understand involve the interactions between residential air conditioners and PEVs, as well as the electrical distance between the head of the distribution feeder and the location of these loads within the feeder.

[1] See: Bravo et al. (2009), Bravo et al. (2013), Bravo et al. (2014), Kueck et al. (2014), Ravikumar et al. (2016), and Tenza et al. (2016) for examples of how the listed approaches were followed to develop appropriate composite load model parameters for the residential air conditioning load type.

3.0 Study Approach

To evaluate the impact of PEVs on the larger transmission system, details of their behavior within an individual distribution feeder were needed. A population of PEVs was deployed in a model of a single, representative distribution feeder. The electrical responses of the loads within the feeder (including residential air conditioners, both with and without PEVs present) were then simulated in response to a transmission-level fault. This approach enables any nuances of individual PEV responses to the fault event to be properly represented in future aggregate models used in wide-area transmission system studies.

Section 3.1 describes the modeling tools that were employed to execute the study, and Sections 3.2, 3.3, and 3.4 describe elements of the representative distribution feeder that we studied. Two appendices supplement the material presented in this section. Appendix A describes the Caldera tool, which models the behavior of individual PEVs. Appendix B describes the laboratory tests that were used to develop parameters that describe the behavior of different types of PEVs in the Caldera model.

3.1 GridLAB-D, Caldera, and HELICS

FIDVR originates from within distribution systems because that is where the single-phase induction motors used in residential air conditioners, which stall and cause FIDVR, are connected to the grid. Hence, FIDVR must be studied by simulating the stalling behavior of these motors (and the impacts of PEV on the voltages that cause motors to stall) in distribution systems.

The distribution-level simulations, including the power-flow calculations and residential load behavior, were all conducted using the GridLAB-D™ distribution analysis software tool (Chassin et al. 2018). GridLAB-D is U.S. Department of Energy (DOE)-developed analysis software that includes power system models, detailed residential building and end-use load models, and energy-market simulation capabilities.

The single-phase induction motor model used in GridLAB-D to represent the behavior of residential air conditioners is a physics-based model implemented using dynamic phasor techniques (Lesieutre et al., 2008). Specifically, it is a dynamic-phasor-based model with torque defined by (1).

$$\text{Mechanical\_torque\_per\_unit} = 0.85 + 0.15 \cdot (\text{rotor\_speed\_per\_unit})^4 \quad (1)$$

Currently, GridLAB-D does not contain the detailed PEV models required to conduct our analysis. Therefore, we used a new software tool, Caldera (Pennington 2020), which is a PEV simulation platform developed for DOE by the Idaho National Laboratory (INL), to model the behavior of PEV during and after voltage depressions. Caldera is a generalized state-transition model that can represent the behavior of a wide variety of PEVs. Appendix A provides an overview of Caldera. Appendix B describes the laboratory test findings that were used to specify the Caldera modeling parameters for each of the six types of PEVs we studied.

To interface the two software tools, we used the Hierarchical Engine for Large-scale Infrastructure Co-Simulation (HELICS) (Palmintier et al. 2017).). HELICS is a DOE-developed platform that handles information and time coordination between different software elements, allowing a combination of domain-specific or domain-detailed capabilities to integrate into a larger system representation.

Figure 2 shows the block diagram of the GridLAB-D and Caldera interactions through HELICS. GridLAB-D calculates voltage at PEV interconnection points and passes this information to Caldera via the HELICS interface. Caldera then uses these values to simulate PEV behavior during that scenario. This behavior is translated into a current load, which is then passed via HELICS back to GridLAB-D, which uses this information to calculate the next set of voltages. This process continues for each time step in the simulation. A dynamic-capable PEV model could be developed and integrated directly into GridLAB-D, but using HELICS allowed us to directly leverage domain-appropriate simulators (GridLAB-D for power flow and buildings, and Caldera for PEVs).

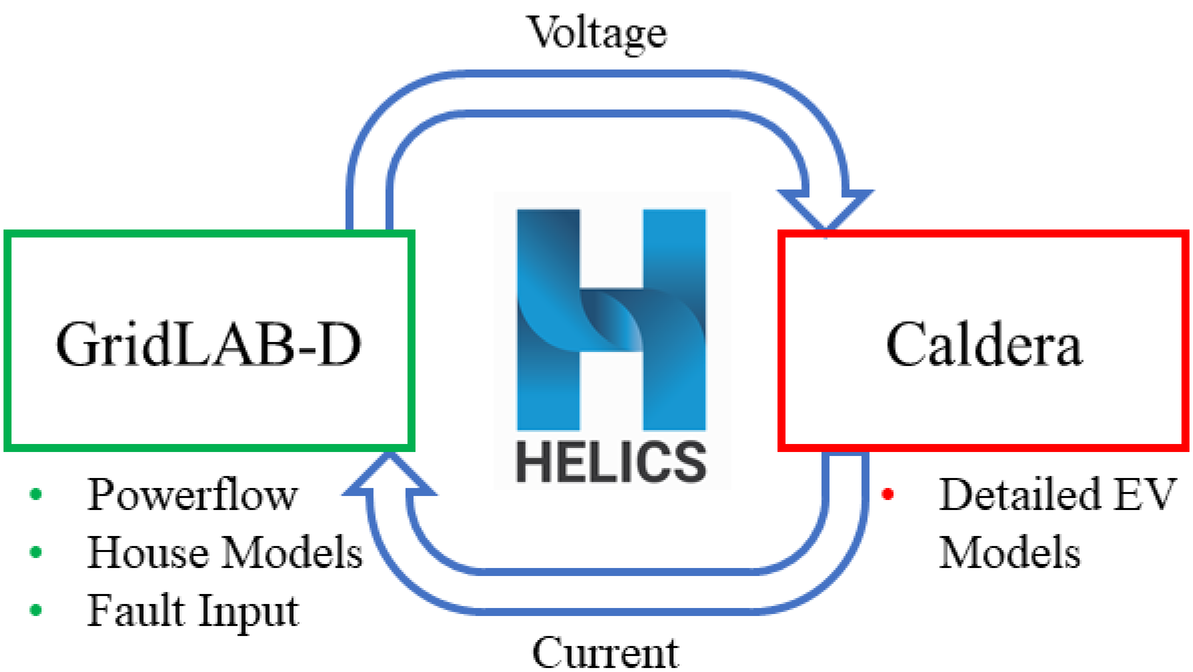

Figure 2 – Block diagram of GridLAB-D, Caldera, and HELICS interactions

3.2 A Representative Distribution Feeder

The distribution feeder that we simulated is based on the topology of the R1-12.47-1 feeder from the Taxonomy of Prototypical Feeders (Schneider et al., 2008). This feeder represents a moderately populated suburban and rural area with mostly residential loads and a small amount of light commercial and agricultural load.

Figure 3 shows the topology of the feeder. The power supply is connected to the feeder by an equivalent transformer as indicated by the inset in the figure. The power supply is modeled by a single-source bus representing the point of supply from the BES and an equivalent transformer. The Thevenin impedance of the source bus is low; the Thevenin impedance of the supply at the 12.47-kilovolt (kV) head bus of the feeder is represented by the equivalent 69/12.47-kV transformer. The equivalent transformer impedance is kept constant at 5 percent with respect to its own base mega-volt ampere (MVA), and the effective supply impedance is adjusted by adjusting the size of the transformer.

Events occurring in the BES are imposed on the distribution feeder by changing the voltage of the source bus. Voltage dips are described by the level to which the source bus voltage drops, and the time period during which the bus remains at the lower level.

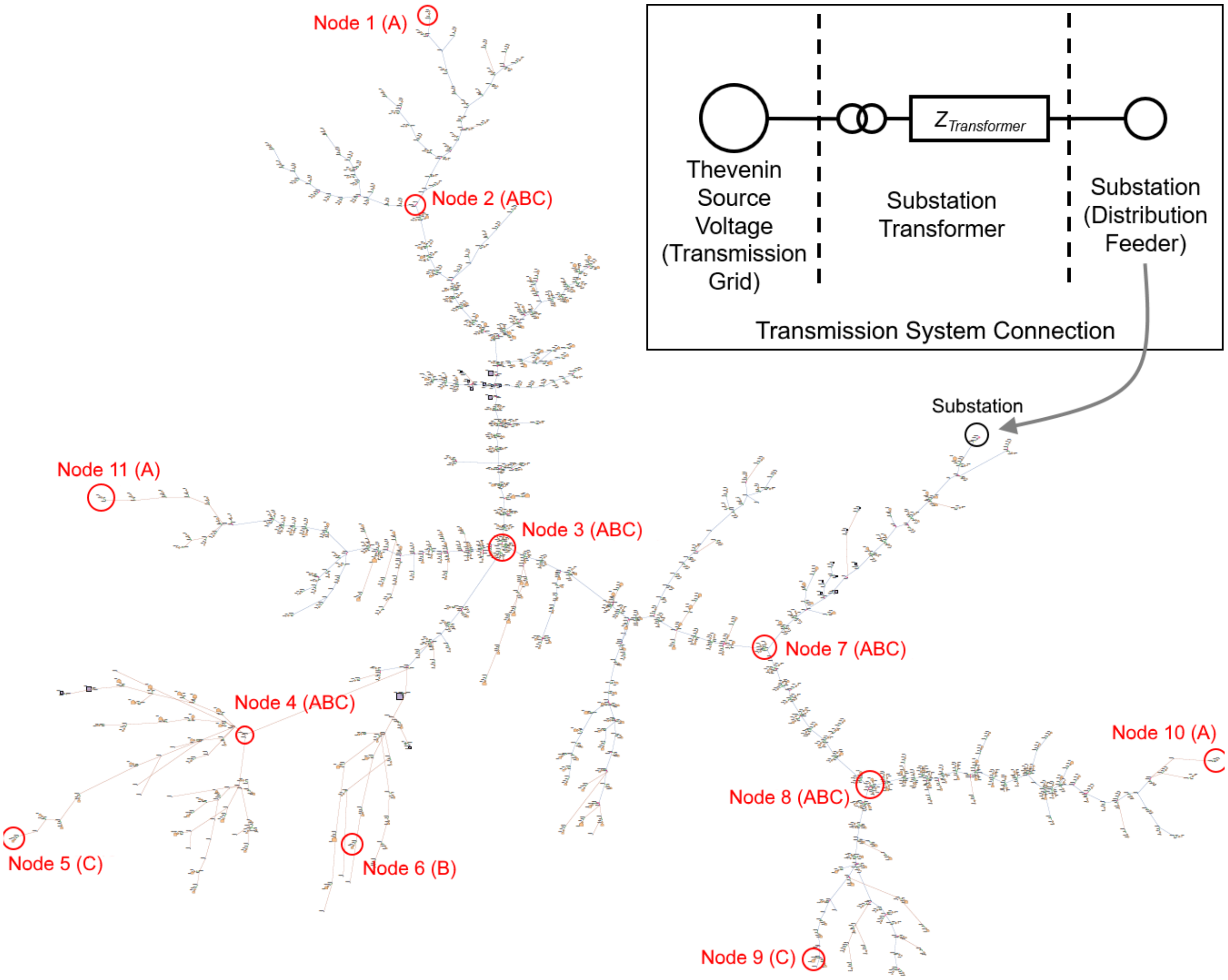

Figure 3 – Topology of R1-12.47-1 feeder

Table 1 – General Properties of Simulation Feeder

Property	Value
Overall Information	
Geographic Area	11.75 square miles
Base Load	5.57 megawatts
Load Composition	
Residential	93.4%
Commercial	5.7%
Agricultural	0.9%
Distribution Line Lengths	
Overhead Line	14.24 miles
Underground Line	11.35 miles
Triplex (service) Line	3.40 miles

Table 1 lists the general features of the feeder. The feeder is populated with 1,594 single-residential homes that have characteristics typical of the Phoenix, Arizona region. Details of the overall population process are available in Fuller, Prakash Kumar, and Bonebrake (2012). The individual homes were populated with a detailed thermal model; a heating, ventilation, and air conditioning (HVAC) system that includes a standard residential air conditioning compressor; and an appropriate assortment of electrical loads on usage schedules. A PEV was added to each household.

Based on current practices used in Western Electricity Coordinating Council (WECC) system studies, it was assumed that approximately 45 percent of the residential load is in single-phase induction motors driving air conditioner compressors. (WECC, 2019).

Based on this WECC assumption, 766 of the residential homes on the feeder were equipped with detailed induction motor models to represent potential motor stalling or starting transients resulting from the fault scenarios. For all scenarios explored, a "worst case" load scenario is studied, with all PEVs and air conditioning units active.

The load on U.S. distribution feeders is often not balanced evenly across all three phases (Kersting, 2017). The feeder modeled here fits this description. Figure 4 shows the phase loading for the baseline scenario, which does not include the PEVs. Figure 4 also shows the breakdown of the baseline load into commonly recognized categories. The overall feeder loading is 5.73 megawatts (MW). Phase C is the most heavily loaded, so its quantities and measurements will be of the most interest.

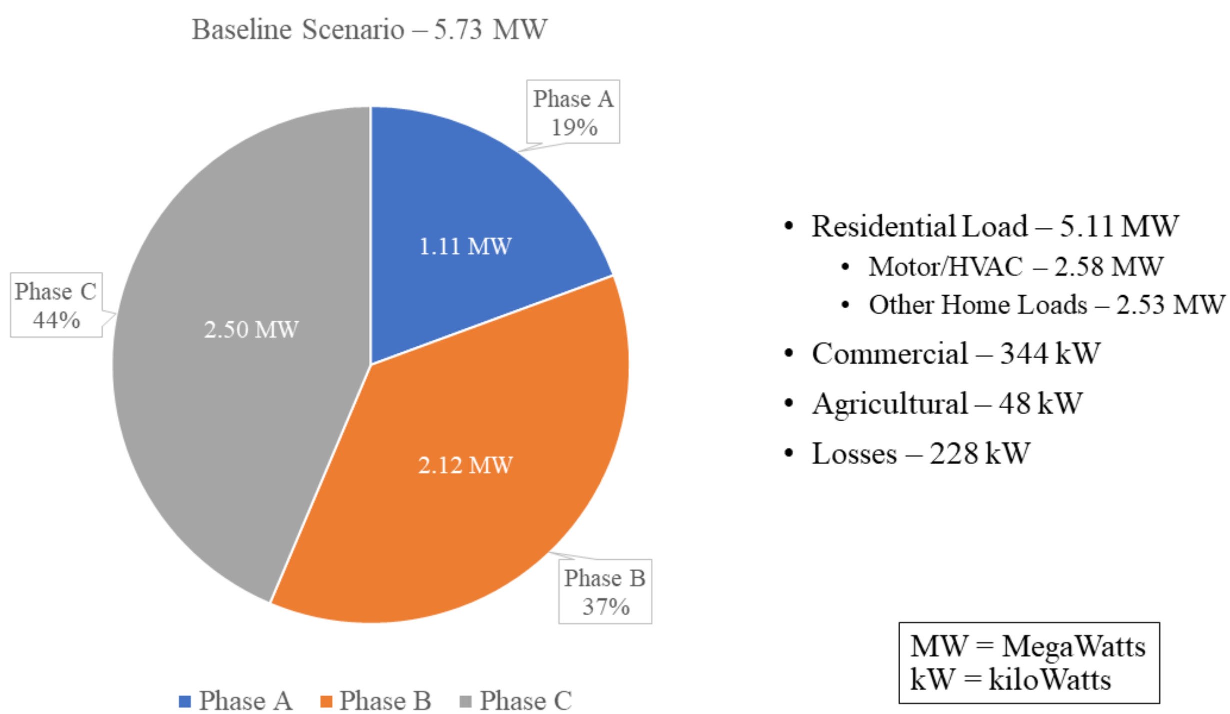

Figure 4 – Baseline feeder phase loading

PEVs were deployed uniformly at every residence on the feeder, adding 1,594 PEVs of the exact same type to the system. Figure 5 compares some of the load quantities for the baseline and PEV-populated feeder. The charge rate for the PEVs can vary, but the PEVs in this example had an average charge rate of 3.52 kW. Figure 5 shows the loading of the feeder during peak load conditions after the addition of the PEVs, and the comparison against baseline parameters of the feeder is shown in Table 2. Given that the feeder is almost completely residential, the overall loading-by-phase relationship was retained, with Phase C still accounting for the bulk of the load.

Given the size of the PEVs, adding one to each household essentially doubles the load served by the distribution substation. The doubling of load on this feeder necessitated an increase in the strength of the power supply at the substation. This was accomplished in the model by adjusting the rating of the equivalent transformer, as discussed in the next subsection.

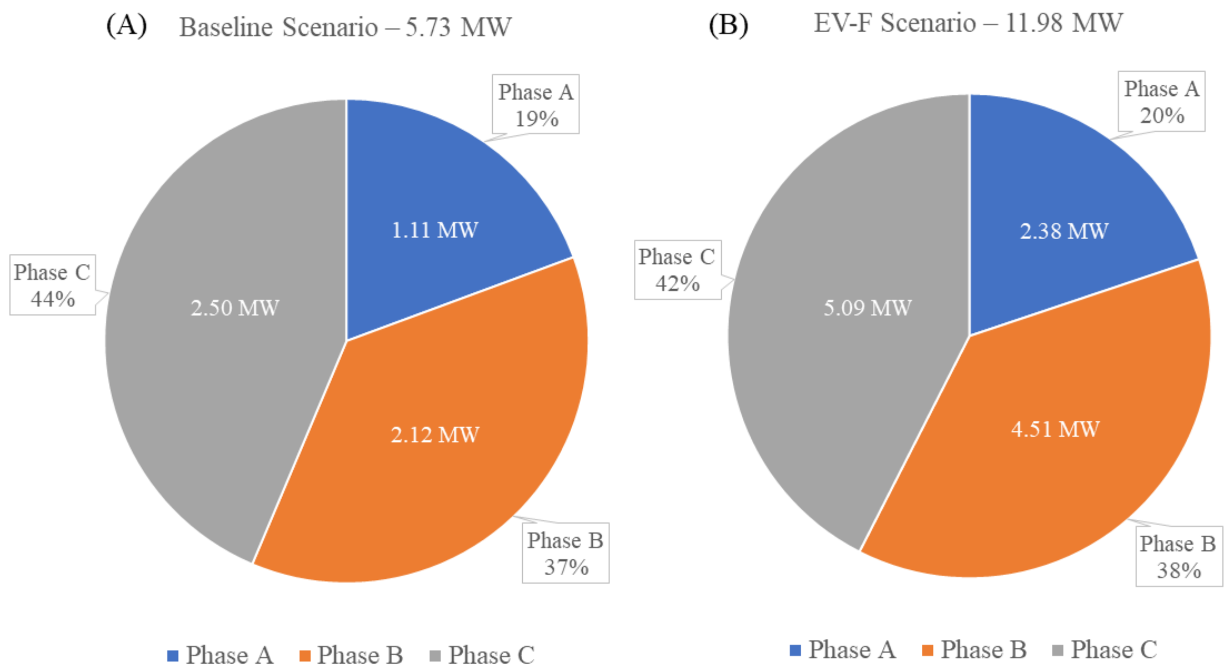

Figure 5 – (A) Baseline and (B) sample PEV loading scenarios

Table 2 – Load Properties for Baseline and PEV Loading Scenarios

Property	Baseline Scenario	EVSE Loading Scenario
Overall Load	5.73 MW	11.98 MW
Residential Load	5.11 MW	10.95 MW
Residential – Motor/HVAC	2.58 MW	2.57 MW
Residential – Other Home	2.53 MW	2.46 MW
Residential – EVSE	N/A	5.92 MW
Commercial Load	344 kW	312 kW
Agricultural Load	48 kW	48 kW
Losses	228 kW	670 kW

3.3 Substation Modeling

Our simulations were made by playing-in the voltage at the “grid” side of the substation supplying the distribution feeder shown in Figure 3. The bulk generation and transmission system (red in Figure 1) was not represented by a mathematical model. Rather, the played-in voltage was chosen to be a pro-forma example of the voltage dip that would be produced by a fault event somewhere in the transmission system.

The supply substation is represented by a Thevenin equivalent made up of a programmed voltage source and a 69/12.47-kV transformer, as shown in Figure 3. Various values of power supply Thevenin impedance, as seen at the 12.47-kV head of the distribution feeder, were achieved in simulations by adjusting the MVA base of the equivalent transformer.

Simulations shown in Section 4 were made with the 5.5 MVA equivalent transformer in the base cases without PEV load and with the 11 MVA transformer base when the PEV load was added. Increased feeder currents increase real power losses from 228 kW to 670 kW.

Voltage dip events on the BES were simulated by reducing and restoring the voltage of the programed source. Note that voltage dip events are described by the level to which the supply voltage has been reduced.

3.4 Form of Simulated Feeder Behavior

Figure 6 shows the behavior of the feeder in response to a dip of supply voltage to 0.55 per unit for 12 cycles (200 milliseconds).

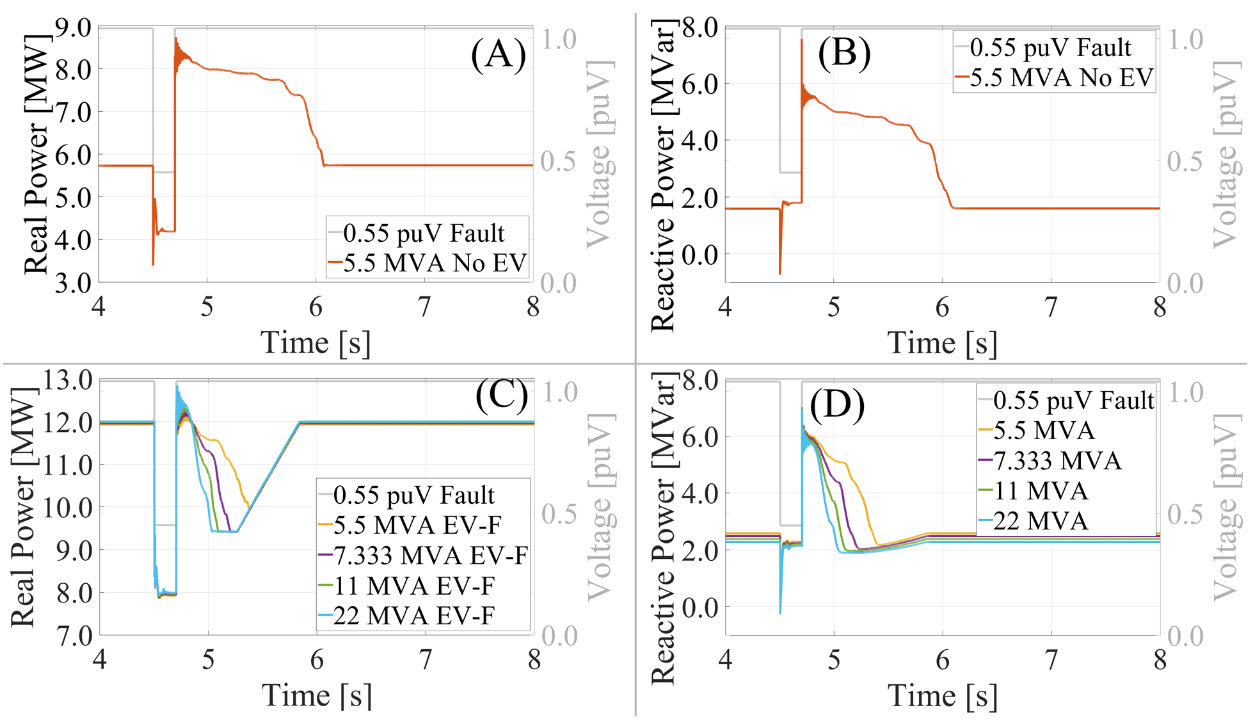

Figure 6 – Form of response to applied voltage dip

First, consider Figure 6(A) and Figure 6(B) which show the variation of real and reactive power flow into the feeder when there is no PEV load. During the voltage dip, the real power is sharply reduced, and the reactive power is slightly increased. The increase in reactive power reflects the increased reactive power consumption of air conditioner motors whose speed runs down quickly while voltage is depressed. When the voltage recovers, real and reactive power both increase to levels above the pre-event level, reflecting the re-acceleration of the air conditioner motors. In this example all air conditioner motors re-accelerate successfully in a little more than two seconds, and real and reactive power return to their pre-event values.

Figure 6(C) and Figure 6(D) show the behavior of the feeder during the same voltage dip event when the load is augmented by PEV type EV-F. Type EV-F ceases to draw current immediately at the leading edge of the voltage dip. This is reflected in the real and reactive power during the dip.

EV-F does not start to draw current at the end of the voltage dip. Real power jumps up at the end of the voltage dip as air conditioner motors re-accelerate. The cyan trace in Figure 6(C) shows that, with strong power supply, re-acceleration is completed quickly at 5.0 seconds, substantially before the EV-F starts to ramp its draw of current back to the pre-event level. The green and purple traces in Figure 6(C) show how higher power supply impedance (smaller equivalent transformer) increases the time needed for re-acceleration. The gold trace shows that with an undersized power supply equivalent transformer, re-acceleration is not completed by the time the PEV load starts to ramp back on.

4.0 Findings

Using the simulation tools and distribution feeder model described in Section 3, we first simulate how residential air conditioners within the feeder respond to voltage dips (of varying depths and durations) when no PEVs are present. Next, we add identical PEVs (one of six different types) to each household and rerun the simulations. We tabulate the impacts of the voltage dips on the number of air conditioners that stall. We also tabulate the number of air conditioners that are unable to re-accelerate and remain in stalled condition.

We simulated 12 voltage-dip scenarios: three voltage dips to 0.55, 0.50, and 0.45 pu, and, for each voltage dip, four durations of 5, 7, 9, and 12 cycles, respectively. These scenarios span a range that is representative of situations that are studied routinely by transmission planners as well as situations that cause standard residential air conditioners to stall.

This section describes the findings from the above simulations. For brevity, only results from voltage dips on Phase C of the distribution feeder are presented. Section 4.1 describes the behavior of residential air conditioners without PEVs present. Section 4.2 describes the behavior of residential air conditioners with PEVs present. Section 4.3 summarizes our findings.

In reviewing the results in this section, it is of utmost importance to bear in mind that the simulations we conducted are intended only to be representative of the behaviors of standard residential air conditioners and PEVs relative to one another. *No representation is made regarding the absolute numerical values that emerge from the simulations. The numerical values are presented only to indicate the directional behavior of the permutations we studied.* For example, in presenting the results for our baseline case in Section 4.1, we seek only to illustrate that deeper and longer voltage dips lead to greater numbers of air conditioners stalling than do voltage dips that are less deep or shorter in duration. Similarly, in Section 4.2, we are interested only in showing whether PEVs of one type causes greater or fewer air conditioners to stall or remain stalled than do PEVs of another type. We do not, in either section, seek to predict the exact number of air conditioners that will (or will not) stall in any particular real-life feeder or the precise conditions under which they will or will not stall.

4.1 Residential Air Conditioner Stalling without PEVs Present

Two aspects of residential air conditioner stalling behavior are of interest: the number of units that stall immediately upon experiencing the dip in voltage caused by a fault and the number that remain stalled after the fault has cleared. In the first instance, the air conditioners stall as a direct result of the dip in voltage. In the second instance, they remain stalled because, even though the fault has been cleared, voltages have not recovered sufficiently to allow the units to re-accelerate to a normal operating state. Residential air conditioners that remain stalled will continue to draw excess real and reactive power for 10 to 15 seconds until they heat up to the point that they trip off line because of internal thermal protective devices that act to prevent permanent damage to the motor.

Table 3 shows the number of residential air conditioners that stall immediately upon experiencing the dip in voltage. The table illustrates how both the depth of the voltage dip and its duration contribute to the number that stall. On the one hand, deeper dips in voltage, if all else remains equal, cause more to stall. On the other hand, longer durations, if all else remains equal, also cause more to stall.

In reviewing Table 3, bear in mind that Phase C of the distribution feeder contains a total of 331 residential air conditioners. When voltage dips to 0.55 pu, no air conditioners stall until the dip lasts 12 cycles. When voltage dips to 0.50 pu, no air conditioners stall until the dips last 9 and 12 cycles. When they last 9 cycles, nearly 2/3 of the air conditioners stall; when they last 12 cycles, all air conditioners on the circuit stall. When voltage dips to 0.45 pu, no air conditioners stall until the dips last 9 cycles or more. But when they last 9 cycles or more, all air conditioners on the circuit stall.

Table 3 – Number of Residential Air Conditioners that Stall During Voltage Dips

Depth of Voltage Dip	Duration of Voltage Dip			
	5 cycles	7 cycles	9 cycles	12 cycles
0.55	0	0	0	272
0.50	0	0	199	331
0.45	0	0	331	331

Figure 7 depicts the speeds of the residential air conditioner motors during the 9-cycle voltage dip to 0.50 pu. The figure shows all motors slowing down initially, but some of them do not stall (i.e., the speed of the motors does not drop all the way to zero) and these motors re-accelerate. A second group is visible that stalls (i.e., the speed of the motors drops to zero), but then, in less than one second, they all re-accelerate to normal operating speed. Figure 8 depicts the counts of stalled and running motors during this same time period.

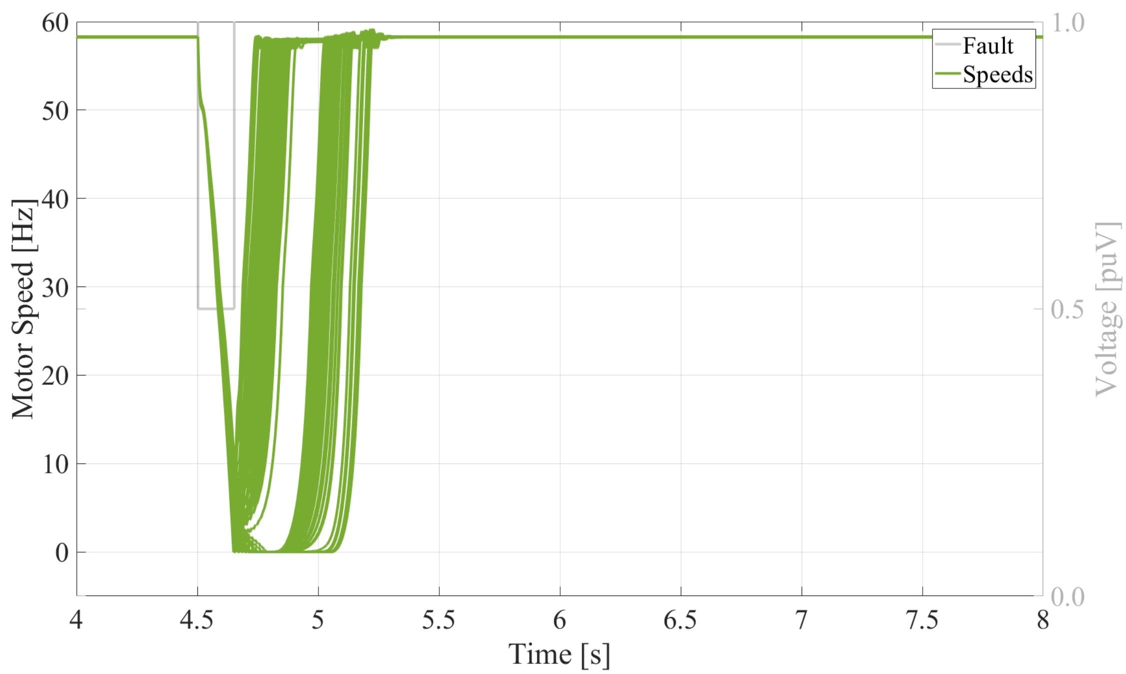

Figure 7 – Residential Air Conditioner Motor Speeds – 9-cycle voltage dip to 0.50 pu

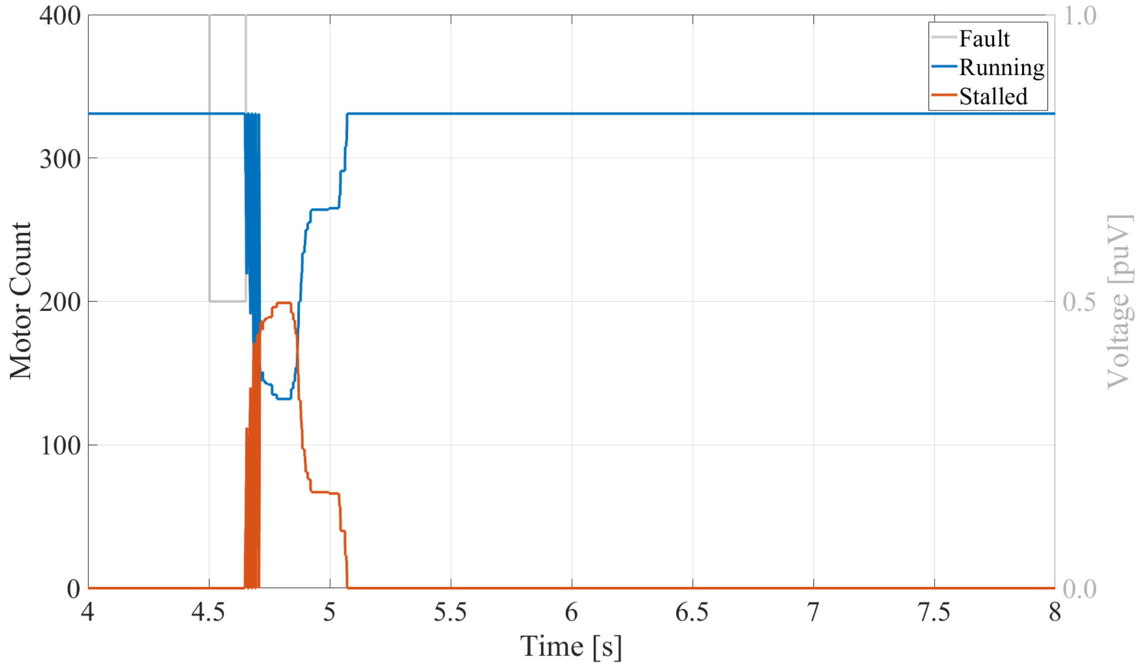

Figure 8 – Residential Air Conditioner Running and Stalled Motor Counts – 9-cycle voltage dip to 0.50 pu

To understand why some air conditioners stall and others do not (or, as we shall see, some remain stalled), it is necessary to recall that each load within a distribution feeder responds to the local voltage conditions to which it is subjected, and these conditions vary depending on the electrical distance of the air conditioner from the head of the distribution feeder.

Figure 9 shows the voltages that are seen at various locations (nodes) within the distribution feeder during the 9-cycle voltage dip to 0.50 pu (see Figure 3 in Section 3 for a map of the feeder showing the location of these nodes). Figure 9 shows that all voltages within the feeder are lower than those at the substation. The lowest voltages are experienced at the nodes that more electrically distant from the substation. It is also important to observe that, during the dip, voltages at locations within the feeder are not constant; they drop slightly throughout the time that the dip is taking place.

The electric motor models we have used in our simulations cause motors to stall once voltage has dipped to a certain level. When the voltage dip, as measured at the head of the feeder, is shallow (e.g., less than 0.55 in our simulations), the threshold at which air conditioner motors stall is never crossed within the feeder. However, when the dip, as measured at the head of the feeder, is close to the threshold, then the threshold will be crossed depending on how electrically distant the location is from the head of the feeder. Deeper dips, especially those that last longer, increase the likelihood that voltages at more locations within the feeder will fall below the threshold, causing more motors to stall.

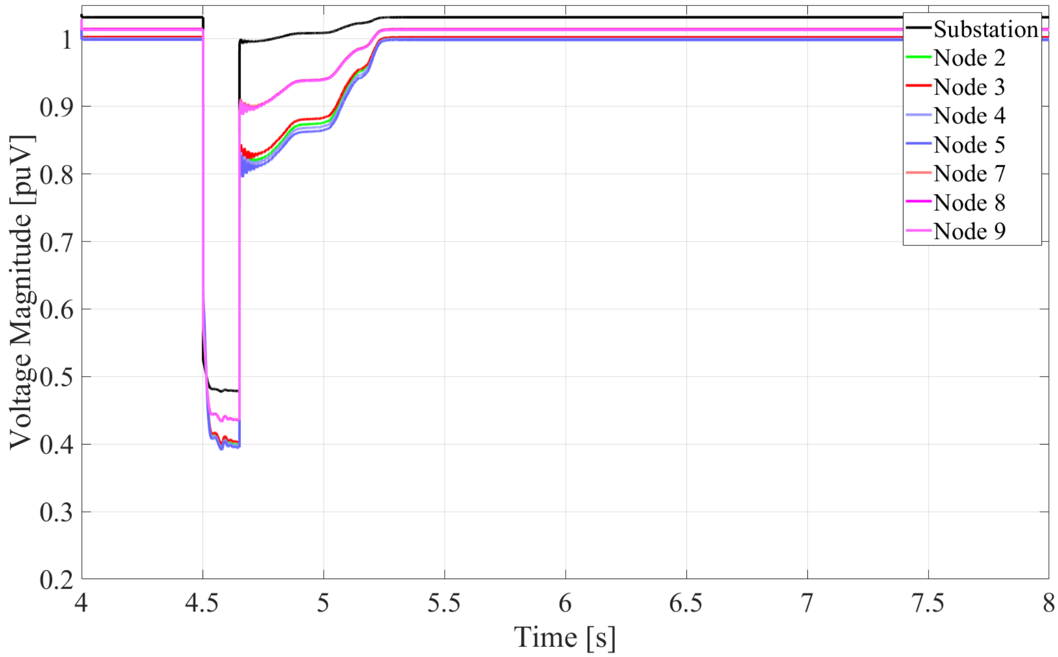

Figure 9 – Voltages at Selected Locations – 9-cycle voltage dip to 0.50 pu

There are also feedback effects. As air conditioner motors begin to stall, they greatly increase their real and reactive power consumption. This further depresses voltages, which, in turn, will cause other air conditioners to stall.

Once the motors in residential air conditioners begin to slow down or stall, they will try to re-accelerate automatically. If voltage has recovered sufficiently, they will be successful and quickly return to a normal operating state. But if voltage has not recovered sufficiently, these motors will continue to slow down or remain in a stalled condition.

Figure 9 shows how stalled air conditioners continue to depress voltage after the fault has cleared (and the voltage dip has ended). The recovery of voltage directly traces the re-acceleration of air conditioner motors seen in Figure 7 and Figure 8.

This is another example of the feedback effect just mentioned. As the motors re-accelerate and return to a normal operating state, they reduce their real and reactive power consumption and cease placing downward pressure on voltage. This, in turn, will allow other air conditioners to experience higher voltages and to also emerge from their stalled state and re-accelerate to a normal operating state.

Figure 10, Figure 11, and Figure 12 follow the format of Figure 7, Figure 8, and Figure 9, respectively, for a more severe scenario (a 12-cycle dip to 0.50 pu). These figures show that all the motors stall initially. But, as with the less severe scenario, after stalling, they all re-accelerate within less than 2 seconds. Note that, compared to Figures 7 and 8, the motors here restart in distinct groupings rather than all at once. Figure 12 shows that the different rates at which voltages return to nominal, which in turn depends on the locations at which voltages are observed within the feeder, are the reason that the motors re-accelerate in these groupings.

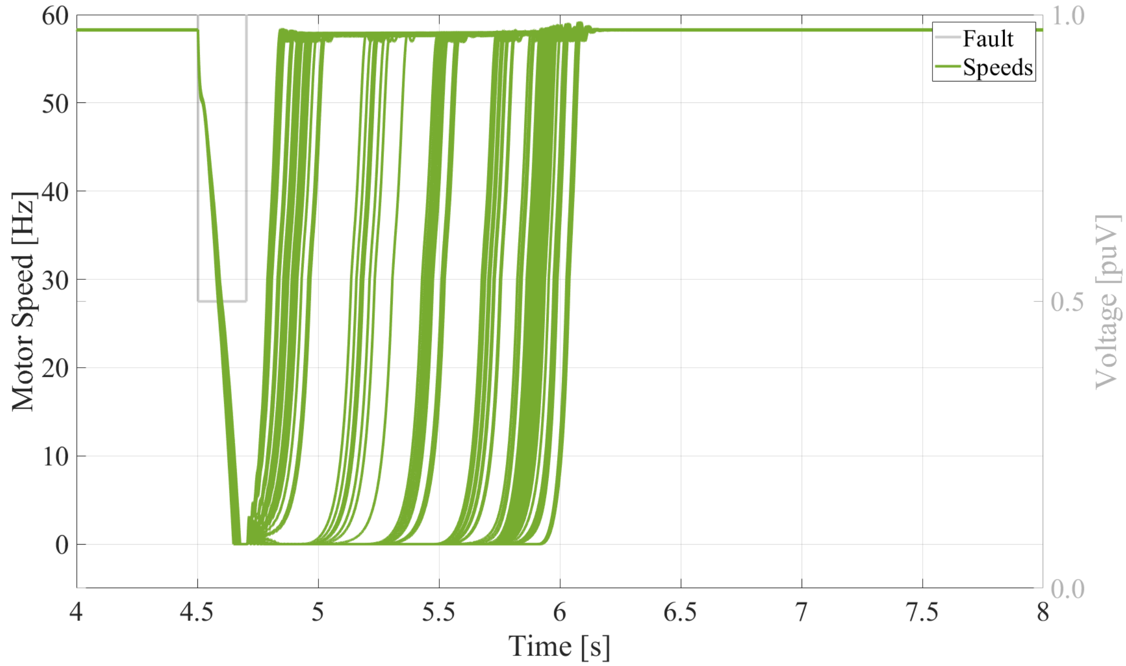

Figure 10 – Residential Air Conditioner Motor Speeds – 12-cycle voltage dip to 0.50 pu

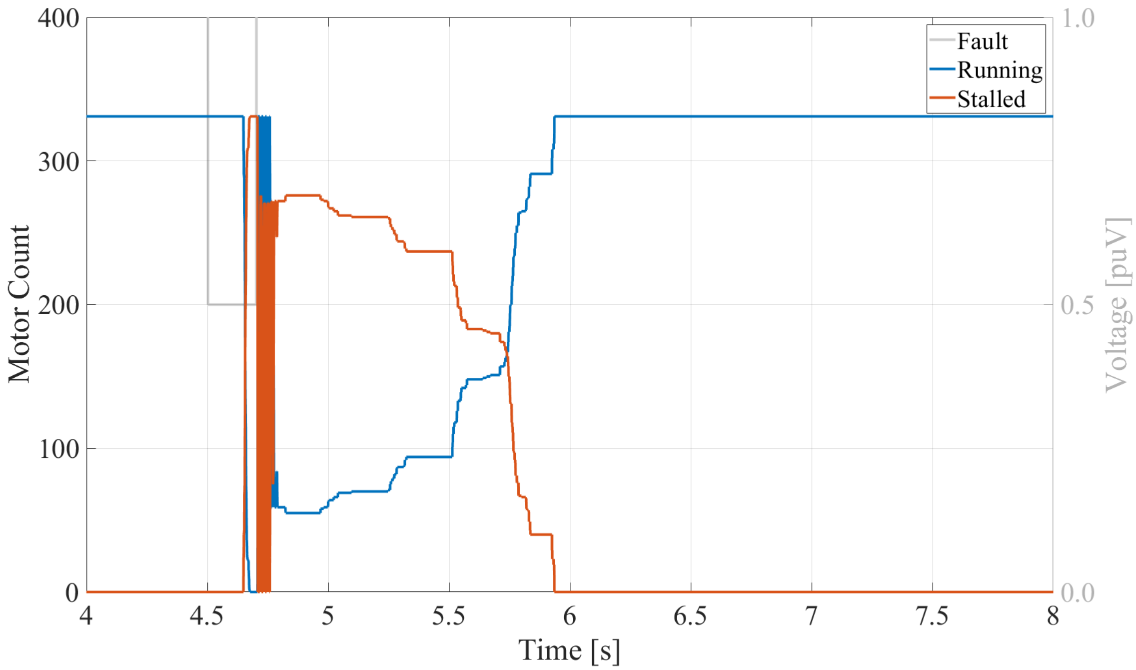

Figure 11 – Residential Air Conditioner Running and Stalled Motor Counts – 12-cycle voltage dip to 0.50 pu

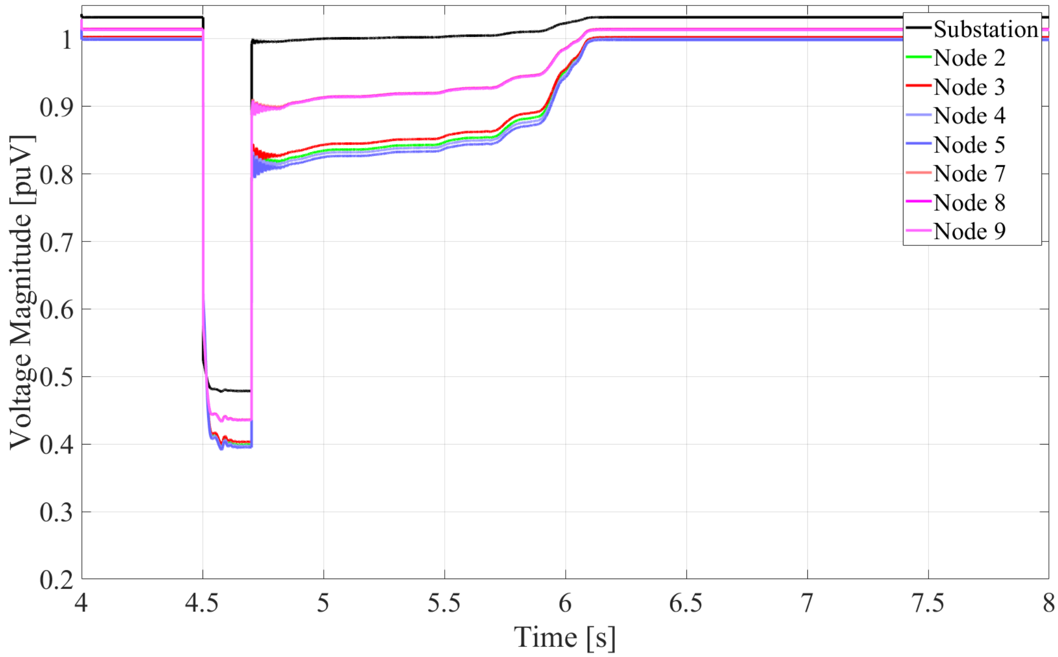

Figure 12 – Voltages at Selected Locations – 12-cycle voltage dip to 0.50 pu

4.2 Residential Air Conditioner Stalling with PEVs present

Table 4 and Table 5 incorporate the information in Table 3 and add the results from re-running each of the voltage-dip scenarios with one of the six types of PEVs. The grid-friendliness of PEVs can be assessed by comparing the number of stalled residential air conditioners resulting from the addition of each type of PEV to the number of air conditioners that stall (or do not stall) initially in response to the voltage dip and those that re-accelerate (or remain stalled) in the baseline (with no PEVs present).

Table 4 shows that EV-B and EV-F are initially grid friendly and that the other four types of PEVs are initially grid unfriendly. EV-B and EV-F are initially grid friendly because the number of air conditioners that stall immediately is either lower than or unchanged from the number in the baseline. For example, in the 12-cycle voltage dip to 0.50, the actions of EV-B and EV-F caused fewer air conditioners to stall than the number that stall in the baseline.

The other four types of PEVs (EV-A, EV-C, EV-D, and EV-E) are initially grid unfriendly because all of them cause more air conditioners to stall than in the baseline. In several scenarios (e.g., voltage dip to 0.55 pu lasting 7 and 9 cycles), these types of PEVs caused significant numbers of air conditioners to stall that did not stall in the baseline under identical voltage-dip conditions.

Table 5 shows that, after the fault has cleared (and the voltage dip has ended), EV-B and EV-F continue to be grid friendly, and that EV-D is also grid friendly. These three types of EVSE are grid friendly because they do not prevent any of the air conditioners from re-accelerating to their normal operating state. The other three types of EVSE (EV-B, EV-C, and EV-E) remain grid unfriendly because they prevent some or all of the air conditioners from re-accelerating to their normal operating state.

Table 4 – Initial Number of Air Conditioning Units Stalled in Simulation

	Fault Scenario		Initial Number of Units Stalled						
#	Depth	Duration	Baseline	EV-A	EV-B	EV-C	EV-D	EV-E	EV-F
1	0.55	5	0	0	0	0	0	0	0
2	0.55	7	0	100	0	72	0	0	0
3	0.55	9	0	330	0	320	167	309	0
4	0.55	12	272	331	40	331	331	331	234
5	0.50	5	0	0	0	0	0	0	0
6	0.50	7	0	309	0	309	35	260	0
7	0.50	9	199	331	0	331	331	331	0
8	0.50	12	331	331	331	331	331	331	331
9	0.45	5	0	0	0	0	0	0	0
10	0.45	7	29	331	0	331	309	331	0
11	0.45	9	331	331	331	331	331	331	331
12	0.45	12	331	331	331	331	331	331	331

Table 5 – Number of Air Conditioning Units Stalled After Recovery from Fault

	Fault Scenario		Number of Units Stalled at T_{Fault}+2.0s						
#	Depth	Duration	Baseline	EV-A	EV-B	EV-C	EV-D	EV-E	EV-F
1	0.55	5	0	0	0	0	0	0	0
2	0.55	7	0	0	0	0	0	0	0
3	0.55	9	0	291	0	307	0	300	0
4	0.55	12	0	291	0	307	0	303	0
5	0.50	5	0	0	0	0	0	0	0
6	0.50	7	0	272	0	295	0	256	0
7	0.50	9	0	291	0	307	0	300	0
8	0.50	12	0	291	0	305	0	300	0
9	0.45	5	0	0	0	0	0	0	0
10	0.45	7	0	297	0	301	0	295	0
11	0.45	9	0	303	0	307	0	300	0
12	0.45	12	0	307	0	307	0	300	0

4.3 Identifying PEV Behaviors that are Grid Friendly and Grid Unfriendly

The simulations show that PEVs can be both grid friendly and grid unfriendly. Two types of PEVs (EV-B and EV-F) were initially grid friendly and were joined by a third type that exhibited grid-friendly behavior after the fault cleared (EV-D). The remaining three types of PEVs were initially grid unfriendly and remained grid unfriendly after the fault cleared. To understand the reasons, we review the actions of the PEVs during and after the voltage dip.

EV-B was found to be grid friendly initially because it prevented air conditioners from stalling during voltage-dip conditions that had caused a number of units to stall in the baseline.

Figure 13 shows the operating states of EV-B, which ceased drawing current immediately when voltage dipped. By taking its load off the feeder, EV-B prevented the air conditioners from slowing down to the point of stalling and also enabled all of them to return to a normal operating state immediately following the voltage dip. See Figure 14 (compare to Figure 7).

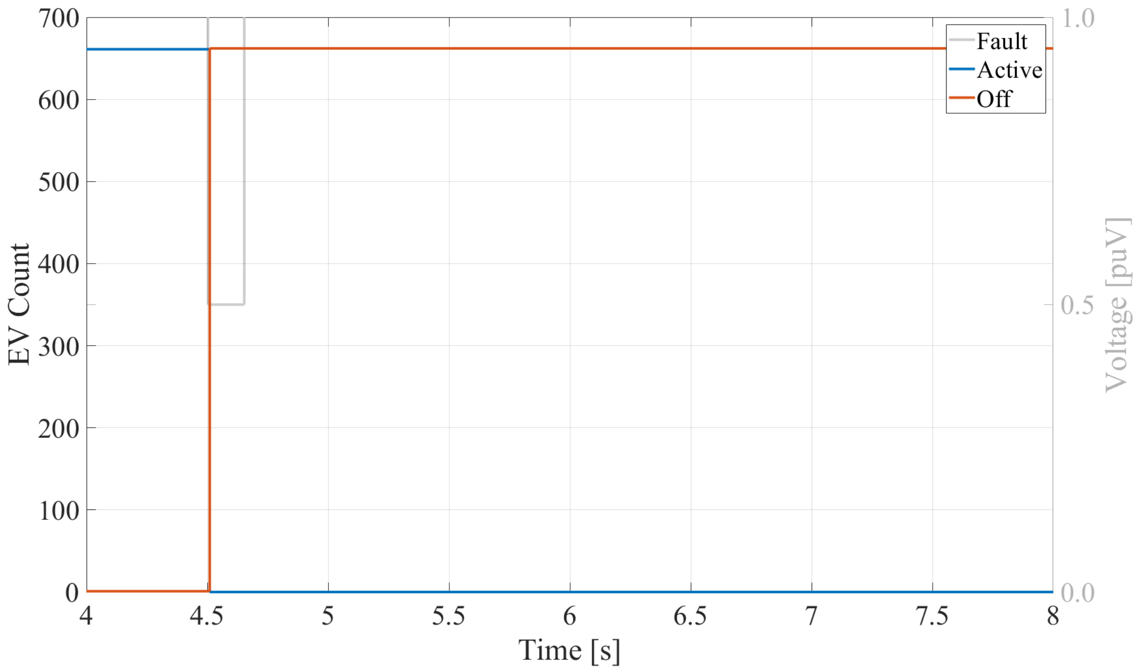

Figure 13 – Operating States of EV-B – 9-cycle voltage dip to 0.50 pu

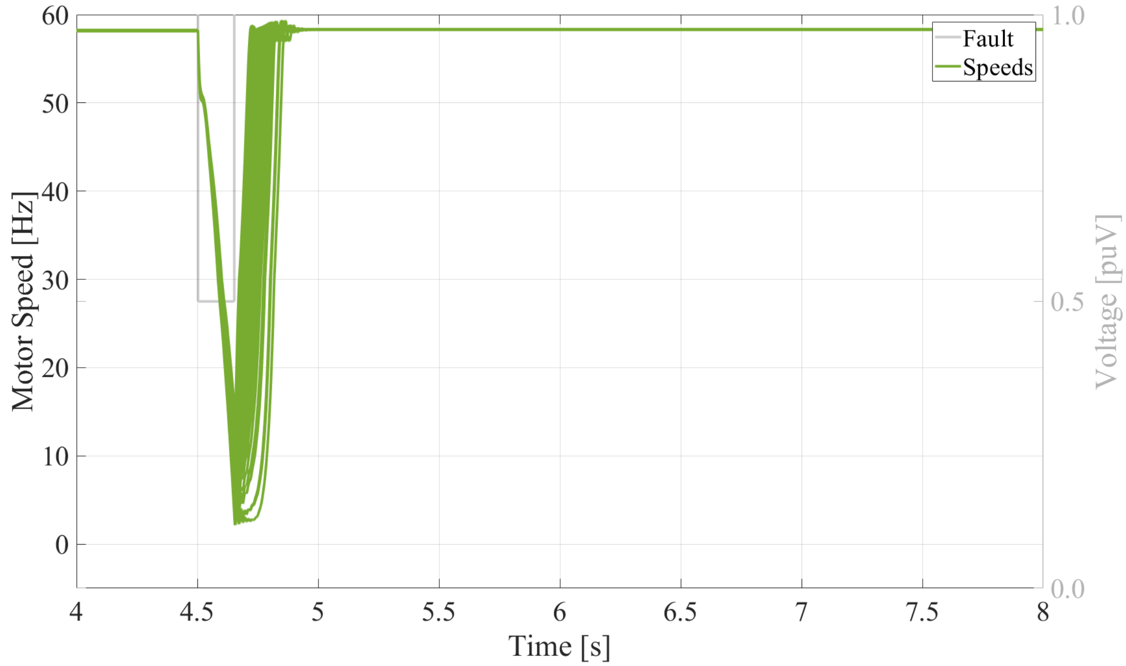

Figure 14 – Residential Air Conditioner Motor Speeds with EV-B – 9-cycle voltage dip to 0.50 pu

EV-A was found to be grid unfriendly initially because it caused air conditioners to stall during voltage dip conditions under which no units stalled in the baseline.

Figure 15 shows the operating states of EV-A during the 9-cycle voltage dip to 0.50. The figure shows that EV-A continues operating during and after the voltage dip, causing more air conditioners to stall (and stay stalled) that did not stall (or re-accelerated after stalling) when EV-A was not present. See also Figure 16 (compare to Figure 8).

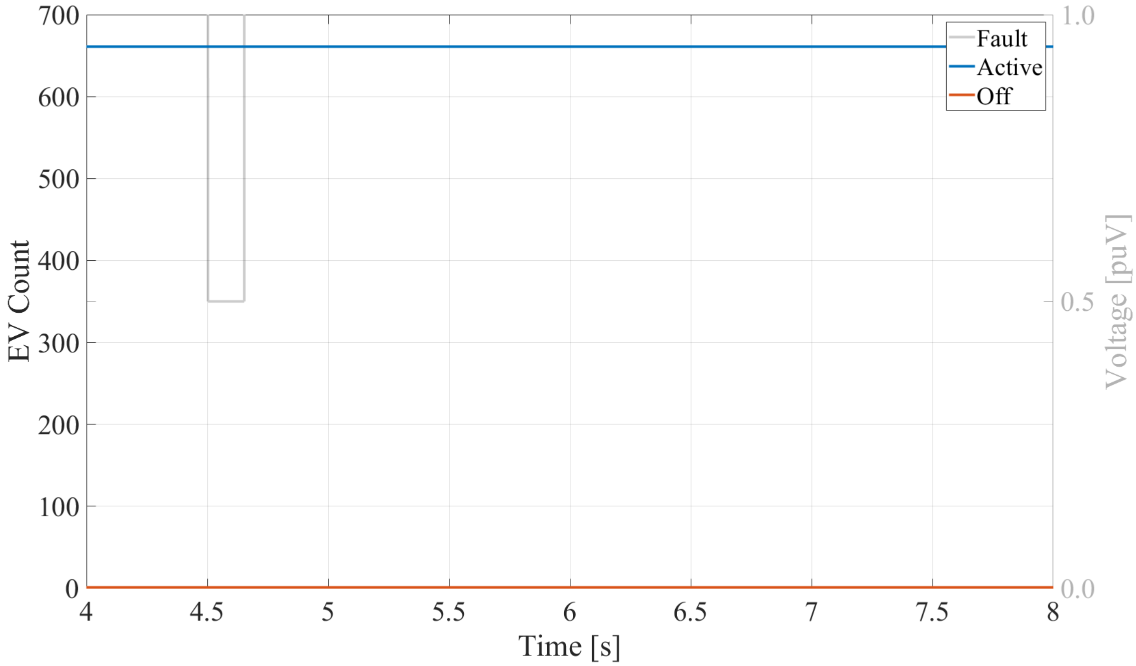

Figure 15 – Operating States of EV-A – 9-cycle voltage dip to 0.50 pu

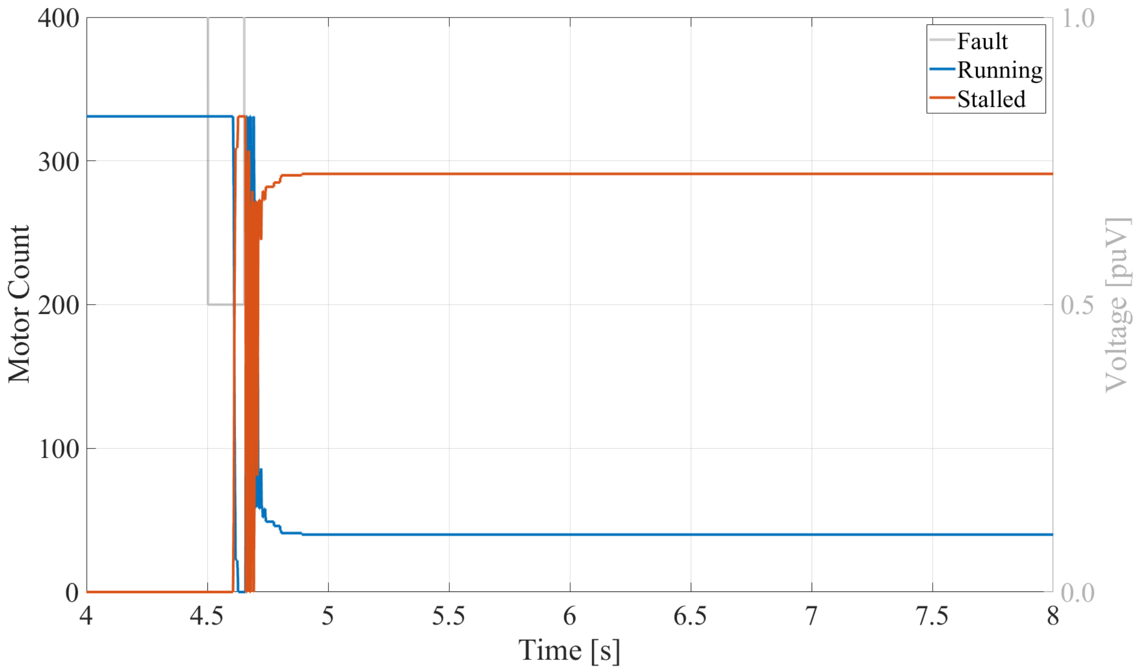

Figure 16 – Residential Air Conditioners Running and Stalled Motor Counts with EV-A – 9-cycle voltage dig to 0.50 pu

EV-D was found to be grid unfriendly initially but grid friendly after the fault cleared because EV-D's behavior enabled air conditioners that had stalled initially to re-accelerate after the fault had cleared.

Figure 17 shows the operating states of EV-D, which continues operating during the voltage dip but ceases drawing current for a period of time after the fault clears (i.e., after the voltage dip ends). By taking its load off the feeder after the fault clears, EV-D enables air conditioners that had stalled to re-accelerate to normal operating speeds. See also Figure 18 (compare to Figure 8).

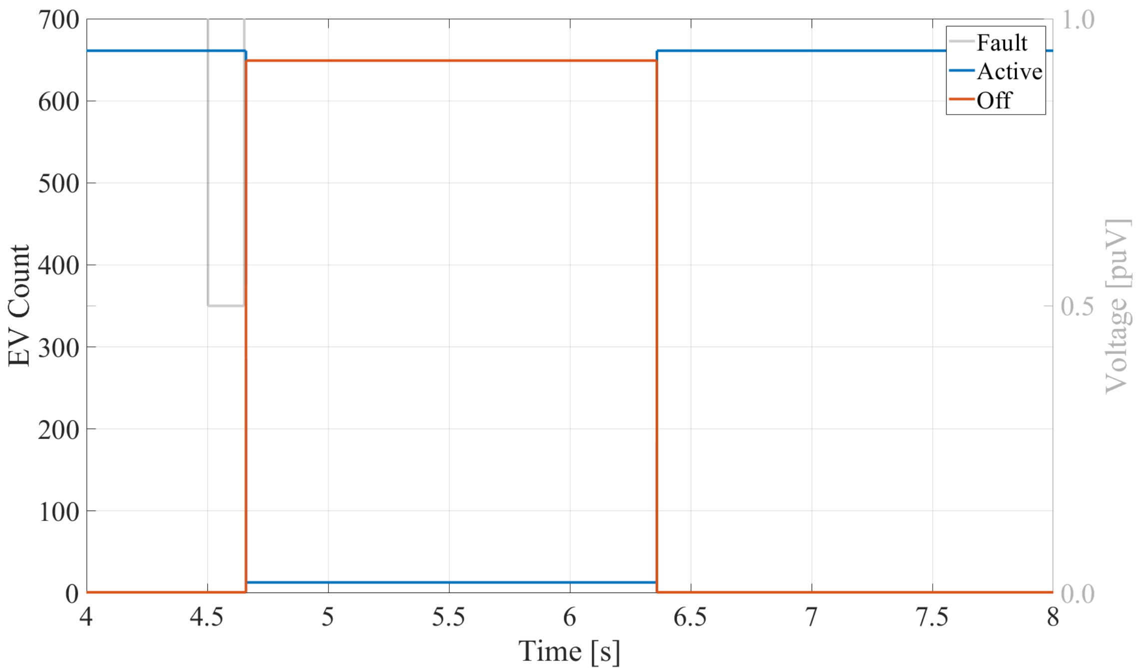

Figure 17 – Operating States of EV-D – 9-cycle voltage dip to 0.50 pu

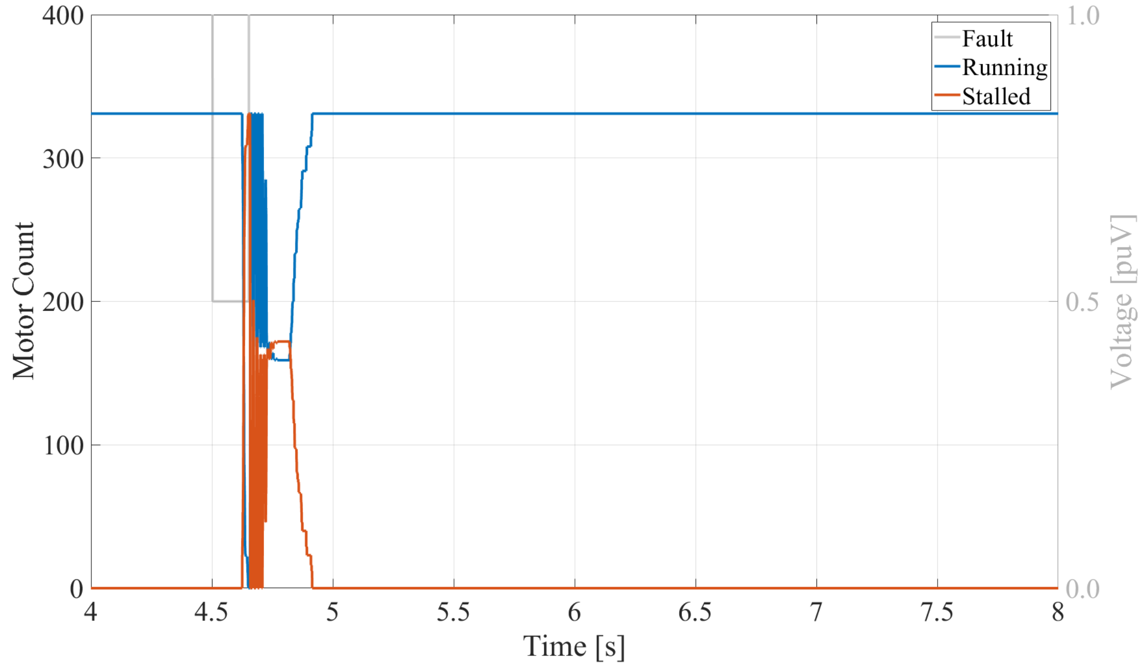

Figure 18 – Residential Air Conditioners Running and Stalled Motor Counts with EV-D – 9-cycle voltage dip to 0.50 pu

4.4 Phases of Grid Friendly and Grid Unfriendly PEV Behaviors

The 'measure' of grid friendliness, or grid unfriendliness, used in this discussion has been the number of air conditioner motors that stall. This measure is an indication of the extent to which the voltages available to the individual loads on the distribution feeder are pulled down below the voltage at the transmission supply point where the voltage depression is applied. Grid friendly loads cause only minimal additional depression of voltages along the feeder, and thus, have a minimal detrimental effect on the ability of the feeder to support its loads during and in the wake of the initiating disturbance. Grid unfriendly loads act in ways that increase voltage drops along the feeder and thereby reduce its ability to support its load.

It is helpful to consider the behavior of PEV loads in two phases:

The first phase is the very short period of time during which a voltage dip takes place, which lasts on the order of 7 to 9 cycles (120-150 milliseconds).[1]

In this phase, both the depth of the transmission voltage dip and the timing, on the scale of milliseconds, of actions taken by the PEV charging controls are important. A reduction of charging current that is very helpful when implemented at the leading edge of a voltage depression may have no beneficial effect if its implementation is delayed by a few tens of milliseconds. The voltage dip threshold for unfavorable response of the feeder may be sharply dependent on such small changes in the timing of charging control actions.

[1] The exact duration depends on the type and location of the fault and the grid protective devices that have been installed to limit the fault's spread.

The second phase is the period immediately after the fault has cleared. Under favorable circumstances, the grid recovers nearly instantaneously to a safe, stable operating state once the fault has been cleared. Under the less favorable circumstances we examine, the second phase can last many seconds depending on the design of the transmission system, the penetration of residential air conditioners, and the depth and duration of the voltage dip.[1] In this phase the voltage available to the feeder loads is still being pulled down by high load currents (drawn by stalled air conditioner motors); the timing of control actions taken by PEVs is important on a scale of seconds.

Figure 19 presents the behavior of all six types of PEVs during a 9-cycle voltage dip to 0.50. The first column shows the PEV's behaviors during the first phase (a period lasting about one-half second). The second column shows the PEV's behaviors during this phase, as well as during the second phase that follows immediately (a period lasting about 15 seconds).

We can now summarize the grid friendliness of each of the six types of PEVs:

EV-A is grid unfriendly during both phases. EV-A "rides through" and draws current throughout the voltage dip. This behavior causes more air conditioners to stall compared to the situation when no PEVs are present. EV-A reduces its draw of current at the end of the voltage dip, but this action is too late to prevent air conditioners from stalling initially. EV-A then immediately ramps up its current draw back to nominal within less than one-quarter second. This behavior causes more air conditioners to remain stalled compared to the situation when no PEVs are present.

EV-B is grid friendly during both phases. EV-B ceases to draw current immediately and does not resume drawing current until more than 5 seconds after the fault clears. This behavior causes no additional air conditioners to stall during the voltage dip and also enables air conditioners to re-accelerate in numbers that are comparable to the situation when no PEVs are present.

EV-C is grid unfriendly during both phases. EV-C, like EV-A, "rides through" and draws current throughout the voltage dip. This behavior causes more air conditioners to stall compared to the situation when no PEVs are present. EV-C, like EV-A, also reduces its draw of current at the end of the voltage dip, but, again, this action is too late to prevent air conditioners from stalling initially. EV-C also immediately ramps its current draw back up to nominal within less than one-quarter second. This behavior, like EV-A's, also causes more air conditioners to remain stalled compared to the situation when no PEVs are present.

EV-D is grid unfriendly during the first phase and grid friendly during the second phase. EV-D is grid unfriendly during the first phase because, like EV-A and EV-C, it "rides through" the voltage dip, albeit at a reduced level. Referring to Table 3, even at this reduced level, EV-D causes more air conditioners to stall compared to the situation when no PEVs are present. EV-D is grid friendly during the second phase because EV-D delays drawing current for a couple of seconds before ramping back to nominal. This short delay of only a couple of seconds is sufficient to enable all the air conditioners that have stalled to emerged from their stalled condition and re-accelerate to normal operating speeds.

[1] Stalled air conditioners will rapidly heat up and disconnect from the grid after a few seconds when internal thermal protective devices act to prevent permanent damage to the units. Once units have cooled down (after several minutes have passed), they will restart automatically.

EV-E is grid unfriendly during both phases. EV-E, like EV-A and EV-C, “rides through” and draws current throughout the voltage dip as well as after the dip has ended. This behavior causes more air conditioners to stall initially and more air conditioners to remain stalled compared to the situation when no PEVs are present.

EV-F is grid friendly during both phases. EV-F ceases to draw current immediately and delays drawing current for about 1 second after the fault clears. This behavior causes no additional air conditioners to stall during the voltage dip and this even shorter delay in drawing current after the fault (e.g., compared to EV-A and especially EV-D) still enables air conditioners to re-accelerate in numbers that are comparable to the situation when no PEVs are present..

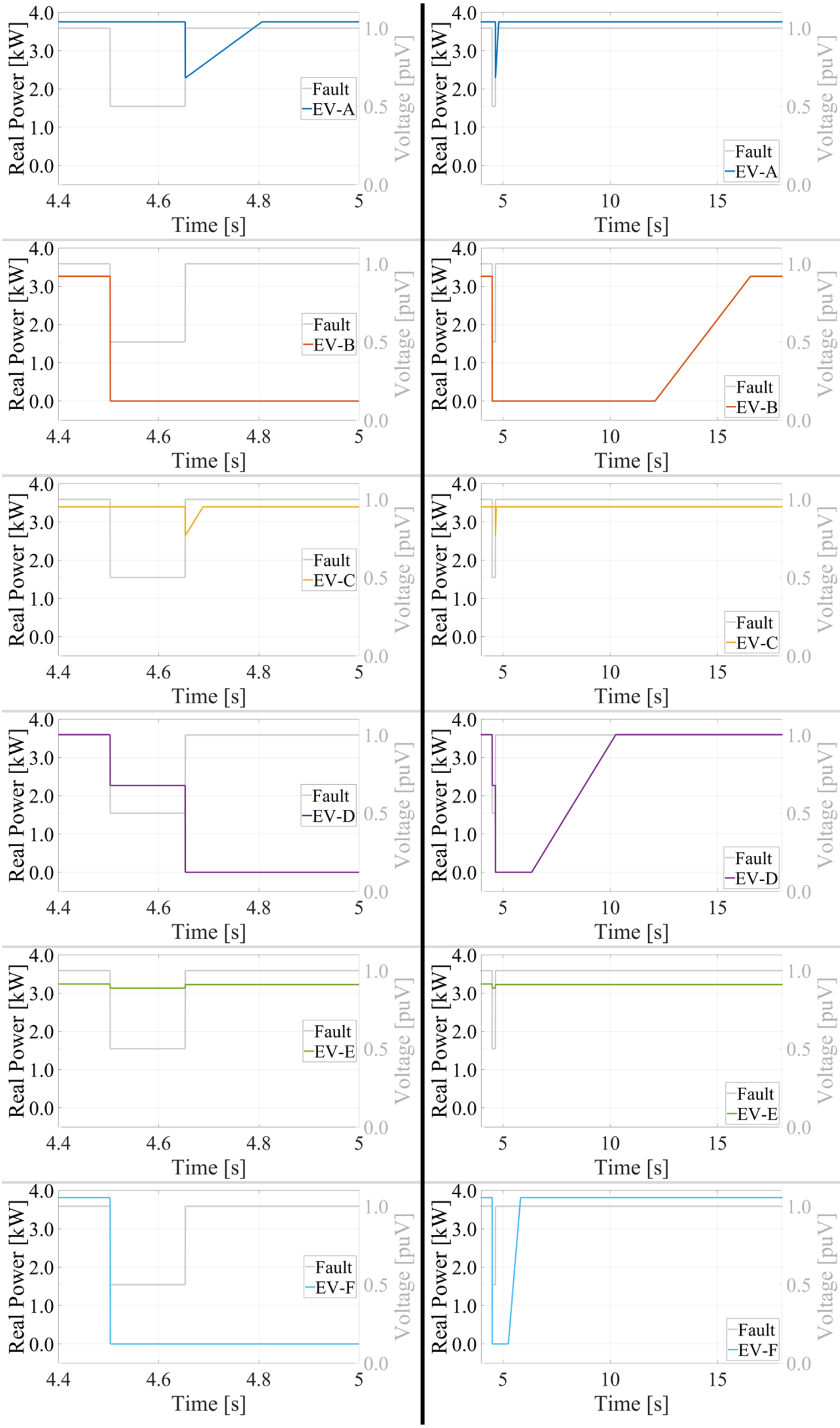

Figure 19 – Summary of PEV Behaviors – 9-cycle voltage dip to 0.50 pu

4.5 From Grid Friendly Principles to Application

This report has been concerned with the possible interactions among load on a distribution feeder and with the assessment of the credibility of the composite load models that are presently used in large-scale grid simulations. The modeling used in the work described here to represent individual PEVs has been at the level of equipment characteristics in principle, but not in detail.

As an example of matters not pursued in this work, the PEV charger modeling considers control actions to be implemented at the inception or ending of a voltage dip, which is an idealization of the way a PEV controller would have to function. In practice a controller would have to:

- First, recognize that a significant voltage dip is in progress; and
- Second, having recognized that a dip is in progress, act to change the operation of the charger within a time scale that may be as brief as 16 milliseconds.

Methods of voltage measurement that are accurate and appropriate for use when controlling a charger for normal operation may take too long to be useful in implementing control actions of the type that we have described here in principle. The trade-offs between accurate measurement, quick detection, and reliable discrimination may be different from those that have guided the design of controls for normal operation.

Communication between EVSE and PEV may be an issue; timing and thresholds that are appropriate when "plugging in", "plugging out", and in normal operation may take too long for coordination between EVSE and PEV to work effectively in situations like those considered here.

With regard to discrimination, continuity of supply to a PEV is unlikely to be critical in the way that it is to safety-related loads. Reluctance to take protective action until discrimination of true events from false is complete may not be appropriate; it may be better to cease charging for, perhaps, 30 seconds to be sure not to aggravate a grid event, than to attempt to ride through, fail, and cause the aggravation in any case. The important characteristic of the PEV/EVSE combination would be an assured ability and protocol to restart after a brief interruption.

The detection and response capabilities that we have found in principle to be desirable for PEV charging are similar to those under consideration by the NERC Inverter-Based Resource Performance Working Group (IBRPWG) and the Institute for Electrical and Electronics Engineers (IEEE) draft Standard P2800 (IEEE, 2021). The voltage thresholds and timings that have been used in this work are consistent with guidelines promulgated by the IBRPWG for reactive current-voltage performance by inverter-based resources during large disturbances.

5.0 Summary and Conclusions

This report has two purposes: 1) to provide engineering counterparts in the PEV industry with insights into the types of PEV behaviors that are grid friendly and grid unfriendly, and 2) to show the range of grid friendly and grid unfriendly behaviors that currently exist in a selection of PEVs that are in production today.

To anticipate the conditions that the grid may be required to manage in the future, we studied a representative distribution feeder consisting of approximately 1,500 residences, many of which are equipped with air conditioning systems. We examined a future in which each household also has, and charges, a PEV from the household's power supply. We subjected the feeder to the rapid depressions of voltage (called voltage dips) that result when a transmission-system fault takes place and clears normally. We examined how six different types of PEVs affect the stalling behavior of air conditioners. If the addition of a large number of PEVs did not increase the number or delay the recovery of stalled air conditioners, we deemed the PEVs grid friendly. If the addition of a large number of PEVs increased the number or delayed the recovery of stalled air conditioners, we deemed the PEVs grid unfriendly.

We divided our findings into two distinct phases. The first phase is the very short period of time during which a voltage dip takes place, which lasts on the order of 7 to 9 cycles (120-150 milliseconds).[1] The second phase is the period immediately after the fault has cleared. Under favorable circumstances, the grid recovers nearly instantaneously to a safe, stable operating state once the fault has been cleared. Under the less favorable circumstances we examined, the second phase can last many seconds depending on the design of the transmission system, the penetration of residential air conditioners, and the depth and duration of the voltage dip.[2]

Our findings on grid-friendly and grid-unfriendly PEVs are as follows (see Figure 20):

PEVs that immediately cease consuming current upon sensing a significant voltage depression are ***grid friendly***.[3] As noted above, faults place stress on the grid. End-use loads that decrease their power consumption during faults reduce stress on the grid.

PEVs that do not immediately cease consuming current upon sensing a significant voltage depression are ***grid unfriendly***. Additional load during this critical period adds to the stress on the grid. If PEVs, in fact, increase their consumption of current during the fault (e.g., in order to maintain constant power), doing so is ***highly grid unfriendly***.

PEVs that delay consuming current for at least a couple of seconds after the fault has cleared are ***grid friendly***. Managing acceptable post-fault voltage recovery is important for reliable grid operations. Drawing no or greatly reduced current supports the grid during this dynamic

---

[1] The exact duration depends on the type and location of the fault and the grid protective devices that have been installed to limit its spread.

[2] Stalled air conditioners will rapidly heat up and disconnect from the grid after a few seconds because internal thermal protective devices will act to prevent permanent damage to the units. Once units have cooled down (after several minutes have passed), they will restart automatically.

[3] It is imperative that that PEVs cease consuming current immediately at the onset of a significant voltage dip. Delaying this action until the nadir of voltage can be determined is too late to prevent air conditioners from stalling. Instead, the action to cease current consumption must be initiated as soon as it can be reasonably determined that a dip will be significant (e.g., to less than 85% nominal voltage).

recovery process. The return to pre-event consumption of current should be ramped over a period of several seconds.

PEVs that immediately resume (or continue) consuming current after the fault has cleared are ***grid unfriendly***. Adding load onto the grid during the critical post-fault period is detrimental to the restoration process.

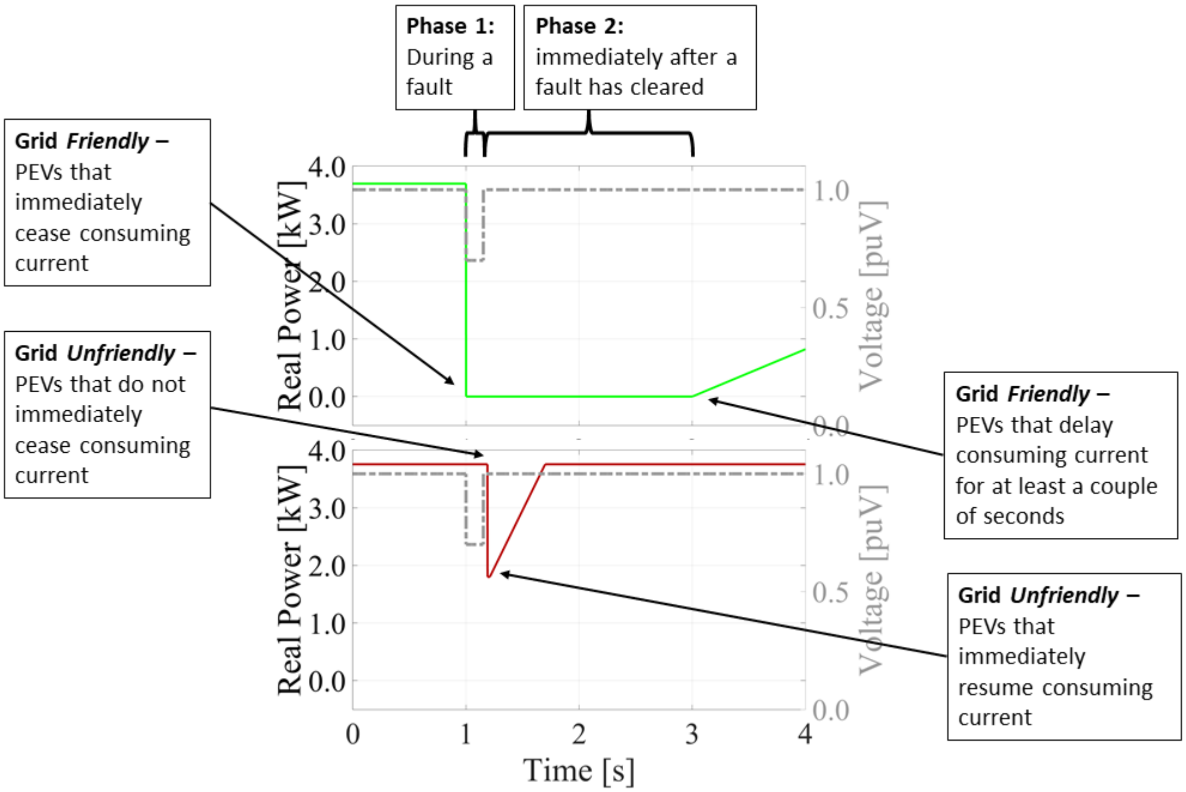

Figure 20 – Summary of Grid Friendly and Grid Unfriendly PEV Behaviors

This report suggests voltage thresholds and timings that would be appropriate, in principle, for the programming of vehicle chargers supplied by a predominantly residential distribution feeder. Details of thresholds, timing, and logic will be determined by study of particular electric utility configurations; these studies should be undertaken with close cooperation between the electric power supply and motor vehicle industries.

It is important to point out that the behaviors which make PEVs grid friendly or unfriendly during the times when they are charging do not extend to the times when they are discharging.

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Appendix A – Electric Vehicle Model Structure

This appendix contains a presentation prepared by Don Scoffield, “Simplified Model of PEV Charging During a Voltage Sag.” This presentation was released by Idaho National Laboratory as document number INL/EXT-19-55665.

The presentation describes how the testing results described in Appendix A were translated into the PEV model parameters that were incorporated into the Caldera model used to conduct this study. The presentation also illustrates how different PEV types operate during different grid conditions.

Simplified Model of PEV Charging During a Voltage Sag

Don Scoffield

2019-09-06

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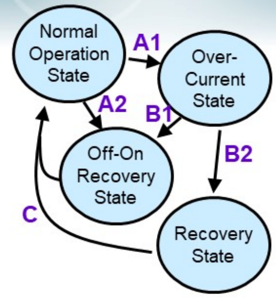
Voltage Sag Model Overview

Voltage Sag Model Overview

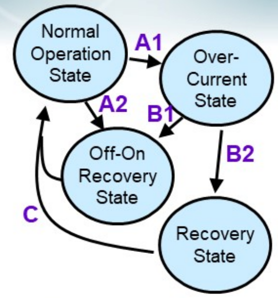


- Model is a good first order approximation of PEV charging under the following conditions:
  - **Level 2 PEV Charging (240 Volt single phase)**
  - **Voltage Sag duration is less than 200 ms (0.2 seconds)**
- Model is a state machine with following 4 states:
  - Normal Operation State
  - Over-Current State
  - Off-On Recovery State
  - Recovery State
- State Transitions occur at 3 points in time
  - Transition A1 and A2 occur the moment the voltage sag starts.
  - Transition B1 & B2 occur the moment the voltage sag ends.
  - Transition C occurs when the vehicle charging has recovered to its normal charging state

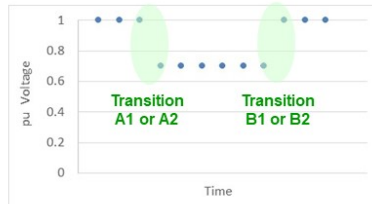
Summary of Model Parameters

- To fully define the voltage sag model 13 parameters are required.
- These parameters will be highlighted in blue and are describe in detail in the following slides:
- The 13 parameters are:
  - **charge_current_at_nominal_voltage**
  - **pu_voltage_charging_mode_boundary**
  - **OVER_CURRENT_STATE_max_PEV_current**
  - **OFF_ON_RECOVERY_STATE_off_time_sec**
  - **OFF_ON_RECOVERY_STATE_recovery_time_sec**
  - **RECOVERY_STATE_initial_current_offset_as_percent_of_recovery_current**
  - **RECOVERY_STATE_recovery_time_sec**
  - **prob_A1_trans_step_change_in_puV_LB**
  - **prob_A1_trans_step_change_in_puV_UB**
  - **prob_A2_trans_step_change_in_puV_LB**
  - **prob_A2_trans_step_change_in_puV_UB**
  - **prob_B1_trans_step_change_in_puV_LB**
  - **prob_B1_trans_step_change_in_puV_UB**

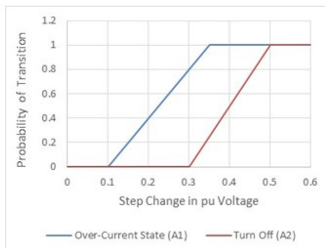
State Transition Logic (A1 and A2)



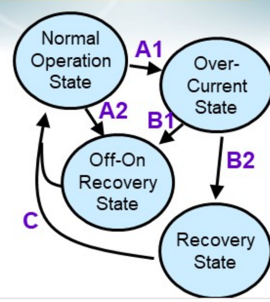
- A **large abrupt** change in voltage is required to push a PEV charger into a 'transient response'
- Transitions A1 and A2 are determined using a stochastic model that is based on the magnitude of the step change in pu Voltage.
- The stochastic model assigns a probability of taking transition A1 and A2 as a function of the step change in pu Voltage.
- For each large abrupt change in voltage the following process is used:
  1. Sample to decide if transition A2 will occur
  2. If A2 does not occur sample to decide if A1 will occur
- Example (see table and chart below)



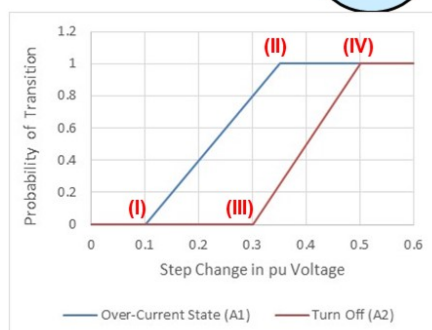
Step Change in pu Voltage	Probability of Transition A1	Probability of Transition A2
0.15	0.2	0
0.2	0.4	0
0.3	0.8	0
0.4	1	0.5
0.5	1	1



State Transition Parameters (A1 and A2)



- As mentioned in the previous slide: the stochastic model assigns a probability of taking transition A1 and A2 as a function of the step change in pu Voltage.
- This probability is defined with two pu Voltage values (a lower bound and upper bound).
  - If step_change_in_pu_V < lower_bound then
    - probability_of_transition = 0
  - If step_change_in_pu_V > upper_bound then
    - probability_of_transition = 1
  - If step_change_in_pu_V between lower_bound and upper_bound then
    - probability = line between lower_bound and upper_bound
  - Note: The stochastic behavior can be removed by making the upper_bound infinitesimally larger than the lower bound.
- The state transitions are defined by the following parameters.
  - **(I) prob_A1_trans_step_change_in_puV_LB** = 0.1
  - **(II) prob_A1_trans_step_change_in_puV_UB** = 0.35
  - **(III) prob_A2_trans_step_change_in_puV_LB** = 0.3
  - **(IV) prob_A2_trans_step_change_in_puV_UB** = 0.5



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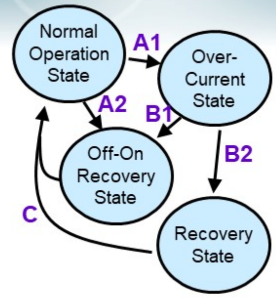
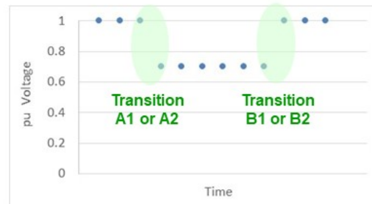
State Transition Logic (B1 and B2)

- Transition B1 & B2 occur the moment the voltage sag ends.
- If the PEV stops charging at the end of the voltage sag then transition B1 is taken otherwise transition B2 is taken.
- Transitions B1 and B2 are determined using a stochastic model that is based on the magnitude of the step change in pu Voltage.
- The stochastic model assigns a probability for the PEV to stop charging at the end of the voltage sag as a function of the step change in pu Voltage.
- For each large abrupt change in voltage the following process is used:
    1. Sample to decide if transition B1 will occur
    2. If B1 does not occur take transition B2





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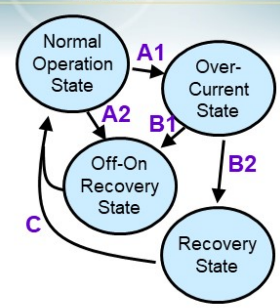
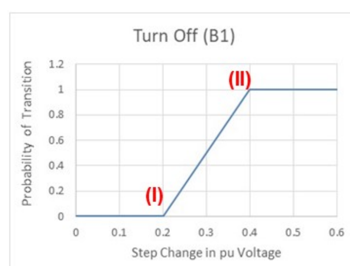
State Transition Parameters (B1 and B2)

- As mentioned in the previous slide: the stochastic model assigns a probability of taking transition B1 as a function of the step change in pu Voltage.
- This probability is defined with two pu Voltage values (a lower bound and upper bound).
    - If step_change_in_pu_V < lower_bound then
        - probability_of_transition = 0
    - If step_change_in_pu_V > upper_bound then
        - probability_of_transition = 1
    - If step_change_in_pu_V between lower_bound and upper_bound then
        - probability = line between lower_bound and upper_bound
    - Note: The stochastic behavior can be removed by making the upper_bound infinitesimally larger than the lower bound.
- The state transitions are defined by the following parameters.
    - **(I) prob_B1_trans_step_change_in_puV_LB** = 0.2
    - **(II) prob_B1_trans_step_change_in_puV_UB** = 0.4





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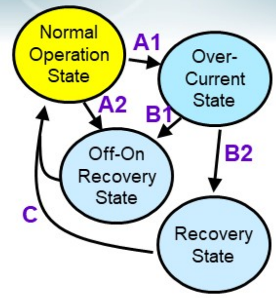
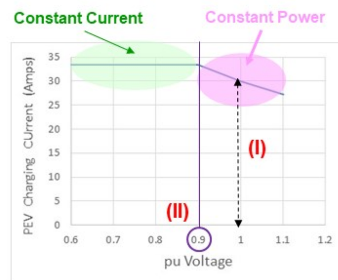
Normal Operation State

- There are two modes of operation
  - Constant Current Charging
  - Constant Power Charging
- Parameters
  - **(I) charge_current_at_nominal_voltage** = 30 Amps
    - Current PEV draws when pu Voltage = 1
  - **(II) pu_voltage_charging_mode_boundary** = 0.9
    - Above this pu Voltage the PEV charges in constant power mode
    - Below this pu Voltage the PEV charges in constant current mode





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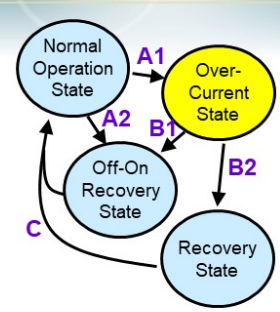
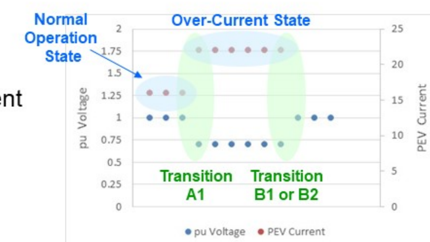
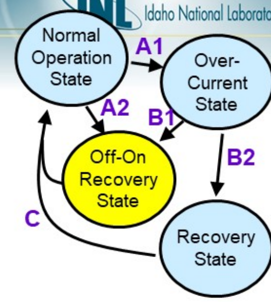
Over-Current State

- This state occurs during the voltage sag
- In this state the current the PEV is drawing from the grid increases and the PEVs tend to charge as a constant power load
- There is an upper limit to the amount of current each PEV can draw.
- Parameters
  - **OVER_CURRENT_STATE_max_PEV_current**
    - max current PEV will draw during voltage sag
- Logic
  - PEV_current = 1 * charge_current_at_nominal_voltage / puV
  - If PEV_current > OVER_CURRENT_STATE_max_PEV_current
    - PEV_current = OVER_CURRENT_STATE_max_PEV_current

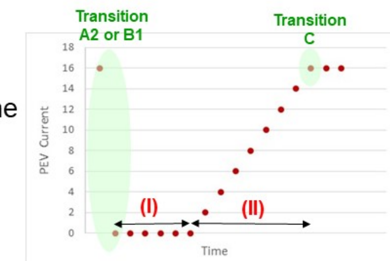




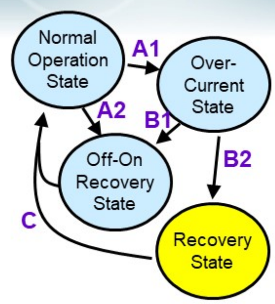
Off-On Recovery State



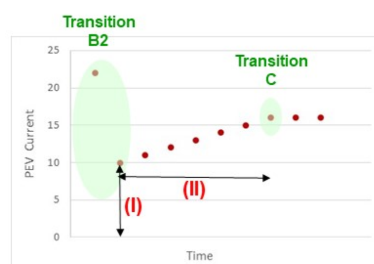
- This state models the PEV charging transition when it stops charging and then resumes charging
- The charge recovery is modeled using two line segments
  - Line segment when PEV charging is off
  - Line segment representing the recovery of PEV charging from off to the charging current in the Normal Operation State
- Parameters
  - **(I) OFF_ON_RECOVERY_STATE_off_time_sec**
    - The time the PEV remains off before the PEV begins charging.
  - **(II) OFF_ON_RECOVERY_STATE_recovery_time_sec**
    - The time required to ramp PEV charging from off to the nominal charging current



Recovery State

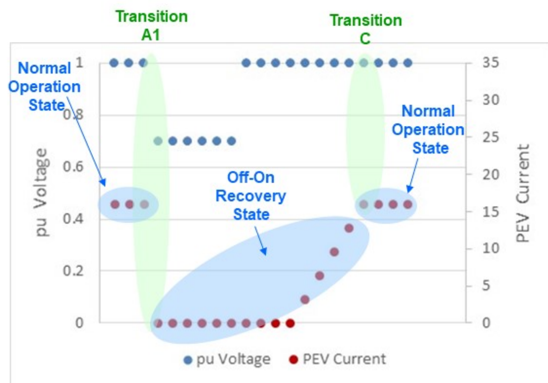


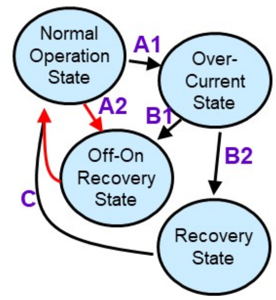
- This state models the PEV charging transition from the Over-Current State and back to the Normal Operation State.
- This transition is characterized by an abrupt drop in charging current and then a more gradual increase in charging current to the Normal Operation State charging current.
- The charge recovery is modeled using a single line segment
- Parameters
  - **(I) RECOVERY_STATE_initial_current_offset_as_percent_of_recovery_current**
    - Current as a percent of the nominal charging current
  - **(II) RECOVERY_STATE_recovery_time_sec**
    - The time required to ramp to PEV charging to the nominal charging current



State Transition Path (A2 -> C)

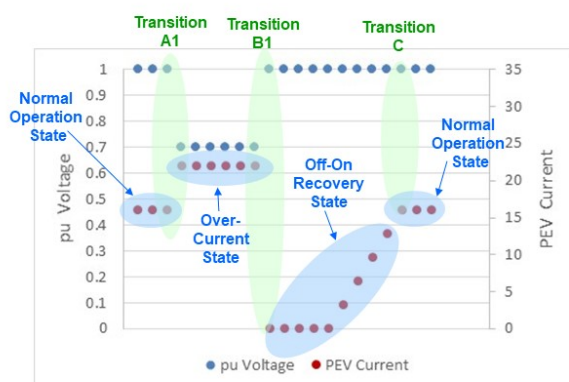
- Dominant Characteristics
  - PEV stops charging when voltage sag begins

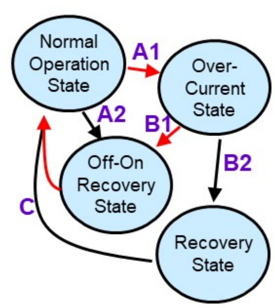




State Transition Path (A1 -> B1 -> C)

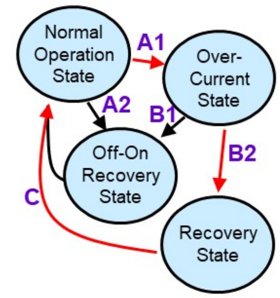
- Dominant Characteristics
  - During Voltage Sag PEV exhibits over-current charging
  - PEV stops charging when voltage recovers

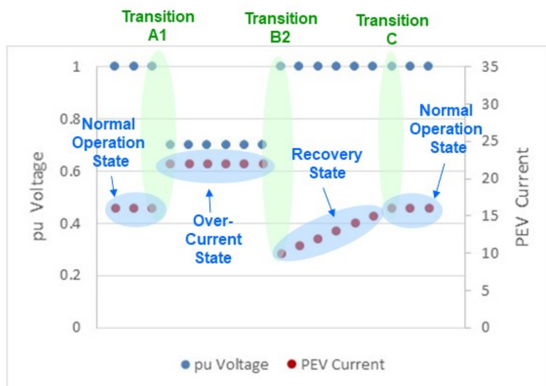




State Transition Path (A1 -> B2 -> C)

- Dominant Characteristics
  - During Voltage Sag PEV exhibits over-current charging
  - PEV transitions back to normal operation when voltage recovers





Model Parameters for 6 PEVs

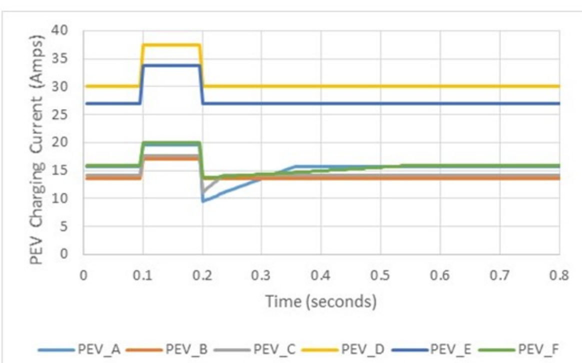
Model Parameters

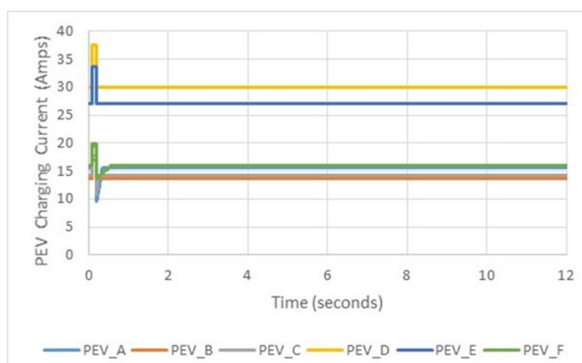
- Model parameters were calculated from lab testing of production PEVs
- Parameters calculated from 352 voltage sag tests from 6 production PEVs
- The model parameters (therefore behavior) varies widely from PEV to PEV:
  - OFF_ON_RECOVERY_STATE_recovery_time_sec:
    - max(16.24) min(0.26)
  - OVER_CURRENT_STATE_max_PEV_current
    - max(53.1) min(21.5)

Model Parameters	PEV_A	PEV_B	PEV_C	PEV_D	PEV_E	PEV_F
charge_current_at_nominal_voltage	15.65	13.6	14.15	30	27	15.9
puV_charging_mode_boundary	0.867	0.854	0.883	0.950	0.908	0.996
OFF_ON_RECOVERY_STATE_recovery_time_sec	0.5	4.44	16.24	3.9	0.263	0.57
OFF_ON_RECOVERY_STATE_off_time_sec	0.5	7.59	7.89	1.69	0.3	0.75
RECOVERY_STATE_recovery_time_sec	* 0.152	0.001	0.035	0.001	0.001	0.35
RECOVERY_STATE_initial_current_offset_as_percent_of_recovery_current	* 61%	100%	79%	100%	100%	86%
OVER_CURRENT_STATE_max_PEV_current	36.1	21.5	35	38.3	53.1	25.2
prob_A1_trans_step_change_in_puV_LB	0.05	0.05	0.05	0.05	0.05	0.05
prob_A1_trans_step_change_in_puV_UB	0.10	0.10	0.10	0.10	0.10	0.1
prob_A2_trans_step_change_in_puV_LB	0.81	0.25	0.65	0.58	0.63	0.33
prob_A2_trans_step_change_in_puV_UB	0.90	0.33	0.75	0.67	0.75	0.42
prob_B1_trans_step_change_in_puV_LB	0.77	0.23	0.58	0.33	0.50	0.25
prob_B1_trans_step_change_in_puV_UB	0.85	0.31	0.67	0.42	0.62	0.36
	* Parameter is a linear function of sag depth. Average value used.					

Model Performance: Voltage Sag to 0.8 pu (192 Volts)

- Voltage Sag
  - At 0.1 seconds voltage drops from 240 V to 192 V
  - At 0.2 seconds voltage recovers to 240 V
- No PEVs stop charging





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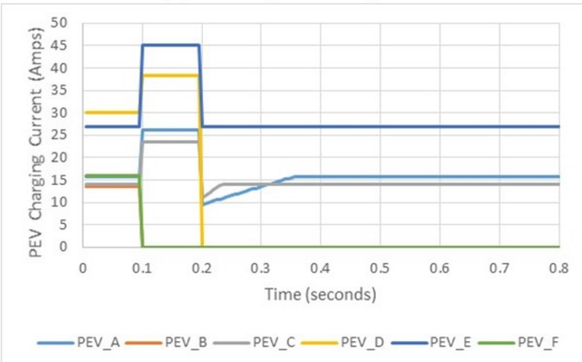
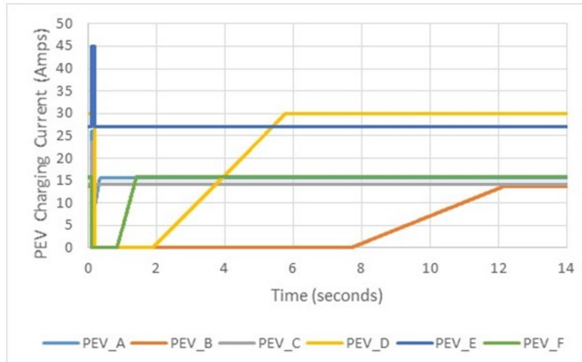
Model Performance: Voltage Sag to 0.6 pu (144 Volts)

- Voltage Sag
  - At 0.1 seconds voltage drops from 240 V to 144 V
  - At 0.2 seconds voltage recovers to 240 V
- PEVs that stop charging:
  - PEV_B, PEV_D, PEV_F

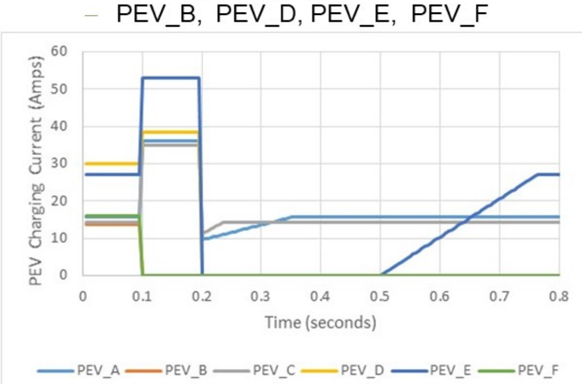


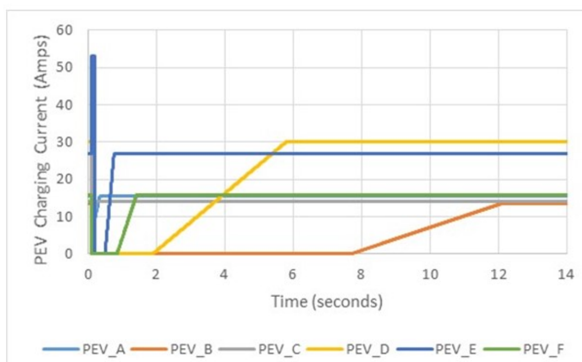


Idaho National Laboratory

Model Performance: Voltage Sag to 0.4 pu (96 Volts)

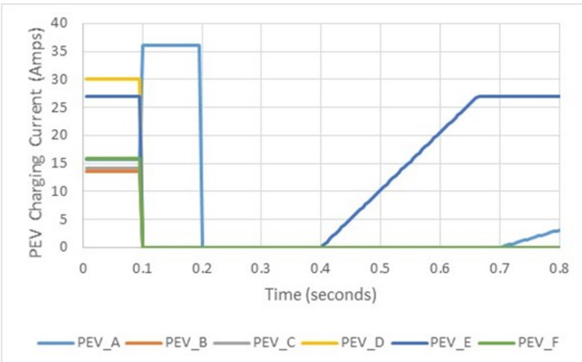
- Voltage Sag
  - At 0.1 seconds voltage drops from 240 V to 96 V
  - At 0.2 seconds voltage recovers to 240 V
- PEVs that stop charging:
  - PEV_B, PEV_D, PEV_E, PEV_F

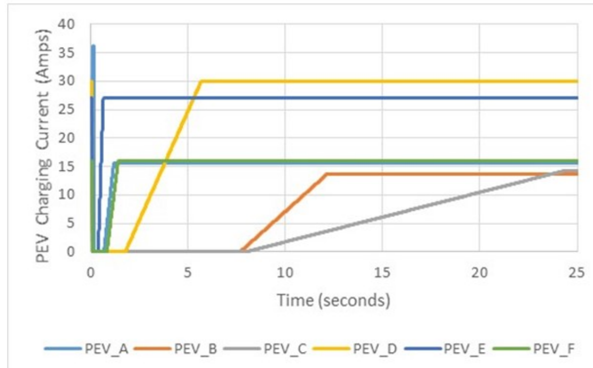




Model Performance: Voltage Sag to 0.2 pu (48 Volts)

- Voltage Sag
  - At 0.1 seconds voltage drops from 240 V to 48 V
  - At 0.2 seconds voltage recovers to 240 V
- All PEVs stop charging





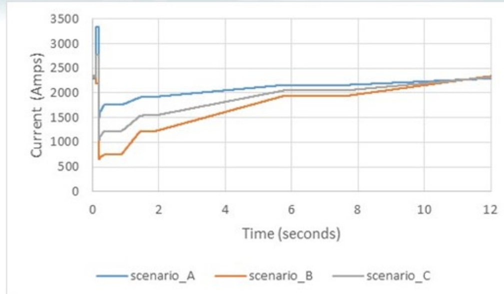
Scenario Examples

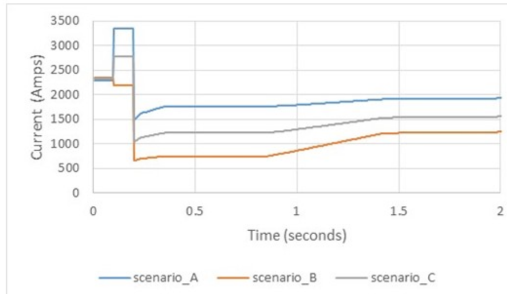
Scenario Examples

- Three hypothetical scenarios
  - Each scenario contains 120 PEVs
  - Each scenario has different combination of PEV type
- Voltage Sag to 0.6 pu
  - At 0.1 seconds voltage drops from 240 V to 144 V
  - At 0.2 seconds voltage recovers to 240 V
- Collective response depends on number and types of PEVs modeled
- Type of PEVs modeled is very important in scenario selection

Number of PEVs in Scenario

	Scenario A	Scenario B	Scenario C
PEV_A	30	10	20
PEV_B	10	30	20
PEV_C	30	10	20
PEV_D	10	30	20
PEV_E	30	10	20
PEV_F	10	30	20





Appendix B – Development of Plug-in Electric Vehicle Models

This appendix describes the process of defining an accurate representation of actual PEV behavior. We initially evaluated the prescriptive behavior described in Society of Automotive Engineers' standard SAE J2894/1-2019, but questions arose regarding whether PEVs actually behaved in that manner and how manufacturers interpreted the standard. This appendix describes laboratory tests of PEVs conducted by Idaho National Laboratory (INL). Results from these tests were used to develop models for six different types of PEVs. These models were implemented in Caldera (see Appendix A), and integrated with GridLAB-D to conduct our distribution feeder simulations (see Section 3).

B.1 PEV Testing

Between 2014 and 2017, INL conducted charging testing of eight PEV makes/models to characterize PEVs loads on the grid when charging using alternating current Level 2 PEVs (i.e., 240 volts [V] alternating current). In its Electric Vehicle Infrastructure Laboratory, INL designed and conducted up to five categories of tests per PEV model to understand various aspects of charging system operation under a wide range of operating conditions. This testing was accomplished using a grid simulator that altered the voltage provided to the PEVs. Table B-1 lists the tests conducted for the eight PEV makes/models.

Voltage deviation tests allowed INL to characterize PEV charging behavior in the presence of under-voltage transients, also referred to as voltage sags or dips. These tests were modeled after procedures that Southern California Edison developed to study air conditioner stalling effects (Lesieutre et al., 2010). Five distinct under-voltage transient tests were conducted on six makes/models to understand the response of the PEV in a variety of under-voltage transient conditions. Data were recorded using a high-fidelity data acquisition system, sampling analog signals at 500 kilohertz (kHz), filtered, and decimated, resulting in waveforms with a sampling rate of 50 kHz.

PEVs were exposed to voltage sags of different durations and depths. Voltage scan tests were also conducted that measured each type of PEV's response when varying voltage from 240 V to 60 V over a 5-minute period. These tests identified power and current set points, indicating periods when the PEVs operate in constant-power and constant-current modes.

Table B-1 – INL PEV charging tests conducted between 2014 and 2017

	2012 Nissan LEAF	2012 Chevy Volt	2013 Ford Fusion Energi	2014 BMW i3	2015 Merc. Benz B Class	2015 Nissan LEAF	2015 Kia Soul EV	2016 Chevy Volt
Control Pilot Tests								
Control Pilot Transition Test	X	X	X	X	X	X	X	X
Control Pilot Charge Start/End Test	X	X	X	X	X	X	X	X
Control Pilot Ramping Test			X				X	X
Control Pilot Soft Start Test			X				X	X
Voltage Deviation Tests								
Voltage Scan Test	X	X	X			X	X	X
Long Notch Voltage Transient	X	X	X			X	X	X
Delayed Voltage Recovery Transient	X	X	X			X	X	X
Circuit Breaker Clearing Transient	X	X	X			X	X	X
Momentary Outage Test	X	X	X			X	X	X
Frequency Deviation Tests								
Frequency Scan Test	X	X	X			X	X	X
Frequency Transient Test			X				X	X
Voltage Distortion Tests								
Individual Harmonic Test			X				X	X
Harmonic Profile Test			X				X	X
Interrupt Charging Tests								
PEV Timeout Test							X	X
Stop/Resume Charging Test	X	X	X	X	X	X	X	X
Other Tests								
Power Limit Test	X	X	X	X		X	X	X
In-rush Current Test	X	X	X		X	X	X	X
Complete Charge	X		X	X		X	X	X

B.2 EVSE Behavior Observed during Voltage Sags

Testing showed that the six types of PEVs on which voltage deviation tests were performed exhibited three predominant responses to voltage sags. In the first predominant response, the PEV stopped drawing current (i.e., stopped charging) at the beginning of the voltage sag and then returned to normal operation following the end of the voltage sag. In the second predominant response, the PEV increased current during the voltage sag to maintain power. Once voltage recovered, the PEV stopped drawing current momentarily and then returned to its normal operating state. This momentary cessation varied by PEV; the shortest time was 0.30 seconds, and the longest was 7.59 seconds. In the third predominant response, the PEV increased current during the voltage sag to maintain power and then transitioned to normal operation when voltage recovered. The transition was a linear response back to the nominal current once the voltage recovered, with the recovery time varying from 0.26 seconds to 16.24 seconds.

All six PEVs exhibited all three responses in varying degrees. The specific response (i.e., first, second, or third) varied for different PEVs for different voltage sag depths and durations. Furthermore, the PEVs showed heightened responses (e.g., greater current draw or longer duration with zero current draw) with increasing duration and depth of voltage sag.

B.3 Modeling of PEV Behavior during Voltage Sags

Based on the behavior observed during testing, INL developed an Alternating Current Level 2 charging model and derived model parameters from test data for each of the six PEVs. The model focused on responses to voltage sags that lasted up to 0.200 seconds. Prominent characteristics of the model and the model parameters for each PEV are found in Appendix A. These models were added to the charging model library in INL’s Caldera simulation platform. These and other high-fidelity charging models in Caldera allow researchers to study the impact of PEV charging on the electricity grid and to develop and verify control strategies that mitigate negative impacts and increase resiliency (Pennington 2020).

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