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Power Distribution System Tools for Analyzing Impacts of Projected Electric Vehicle Load Growth Using GridLab-D

by

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A thesis submitted in partial fulfillment of the
requirements for the degree of

Master of Science
in
Electrical and Computer Engineering

Thesis Committee:
Robert Bass, Chair
Richard Campbell
John M. Acken

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Abstract

The increased penetration of Electric Vehicle (EV) will provide substantial benefits to the environment. However, each EV will present a significant additional load to electric power distribution infrastructure, especially to radial distribution feeders. The additional load may cause transformers to operate beyond their thermal limits, unacceptable voltage drops along distribution lines, and primary conductor overloads. It is now, more than ever, vital to understand the limitations of existing infrastructure in light of an accelerating push for greener alternatives with insight that stems from modeling, simulation, and proper analysis as the backbone to a well-informed response.

The objective of this work is to develop EV load growth modeling and analysis tools for distribution systems. These tools will help researchers and distribution engineers better understand the impacts EV growth will have on distribution systems. Such studies can help a utility company take appropriate action to enhance grid stability and reliability. In the following pages, three analysis tools for evaluating impacts of EV on grid infrastructure assets are presented. These tools are developed for use in the GridLAB-D modeling environment and written using Python 3.8.

The analysis tools were developed to serve unique purposes. The first tool notifies a user of voltage violations. The second tool identifies conductor overloads. The third tool alerts the user of transformer overloads. These tools have been evaluated using the IEEE

13 node test feeder coupled with typical household load profiles within GridLAB-D. Using these tools, users evaluate the impacts EV loads have on distribution systems, specifically transformer overloading, voltage violations, and the overload of conductors. These tools can help utility distribution planners prepare appropriate response for anticipated EV load growth.

Dedication

For my mom and grandma who never stopped believing in me.

Acknowledgements

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Acronyms

AAC	All Aluminum Conductor. 35, 42, 61
AC	Alternating Current. 9
ANSI	American National Standards Institute. ix, 3, 12, 31, 32, 35–37, 44–46, 52, 57, 68
AWG	American Wire Gauge. 34, 35, 42, 61
BESS	Battery Energy Storage Systems. 5
CSV	Comma Separated Values. 33, 35, 44, 48
DC	Direct Current. 9, 10
DCFC	DC Fast Charging. 10, 70
DER	Distributed Energy Resources. 5
DOE	Department of Energy. 4
EIA	Energy Information Administration. 27
EPRI	Electric Power Research Institute. 4
EV	Electric Vehicle. i, ii, xi, xii, 2–10, 12, 27, 29, 30, 34, 38–40, 42, 45, 52, 54, 55, 57, 59–61, 63, 64, 66–71
EVSE	Electric Vehicle Supply Equipment. 6, 8–10
FBS	Forward-Backwards Sweep. 5, 18

GHG	Greenhouse Gas. 1, 2
GMR	Geometric Mean Radius. 19
GS	Gauss-Seidel. 18
HELICS	Hierarchical Engine for Large-scale Infrastructure Co-Simulation. 70
HVAC	Heating, Ventilation, and Air Conditioning. 27
IEEE	Institute of Electrical and Electronics Engineers. ix, xi–xiii, 3, 7, 12, 14–18, 21, 23, 25, 27, 35, 36, 38–41, 43–47, 49, 54, 55, 59, 61, 66–68, 76
IRP	Integrated Resource Planning. 2
NEC	National Electrical Code. 3, 13, 34, 35
NR	Newton-Raphson. 5, 18
OpenDSS	Open Distribution System Simulator. 4, 5
PES	Power Engineering Software. 4
PEV	Plug-in Electric Vehicle. 29
PGE	Portland General Electric. 2, 6
PHEV	Plug-in Hybrid Electric Vehicles. 6
PNNL	Pacific Northwest National Laboratory. 4
PQ	Power Quality. 7, 8
PV	Photovoltaics. 5
RECS	Residential Energy Consumption Survey. 27, 29
SoC	State of Charge. 29
TE	Transportation Electrification. 1, 2

THD	Total Harmonics Distortion. 8, 9

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1 Introduction

1.1 Problem Statement

The transportation sector accounts for the largest share of the total Greenhouse Gas (GHG) emissions, at 28% as shown in Figure 1.1 [1]. Most of the GHG emissions from transportation come from burning fossil fuels for passenger vehicles, which accounts for 65% of the global emissions [2]. The most valuable path to reduce GHG emissions and fossil fuel dependence is Transportation Electrification (TE). However, the approach to the electrification of transportation is not without challenges. For GHG emissions reduction to succeed, most energy sources for electricity need to derive from low carbon resources, such as solar and wind power plant.

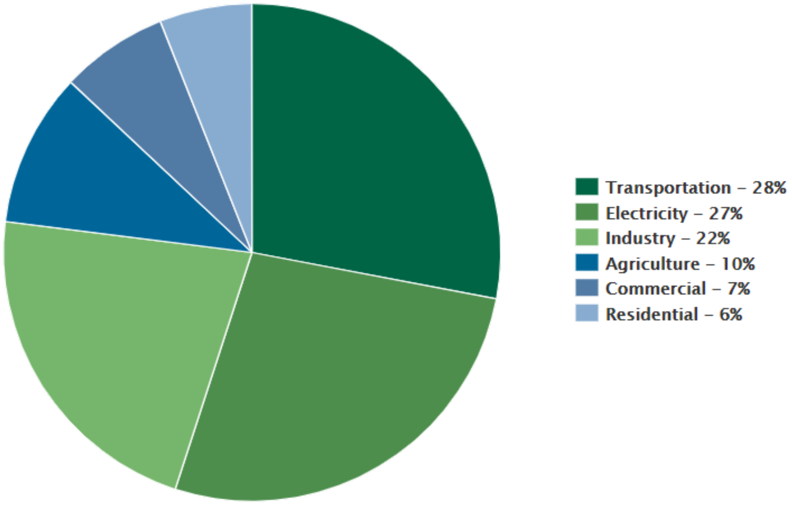


Figure 1.1: 2018 US GHG emissions by sector [1]

Utilities are planing to meet the goal of reducing GHG emissions, in part, by preparing for TE. For instance, Portland General Electric (PGE) plans to electrify at least 60% of their entire vehicle fleet by 2030 [3]. Regardless of the benefits of TE, the increased adoption of EV poses considerable concerns. High load growth due to EV penetration potentially add high power consumption and therefore high demand to the total power supplied. Considering the number of EVs anticipated to be charging during peak hours, the risk of overloading distribution transformers is exceptionally high in the summer and winter seasons due to loading from air conditioning and electric heating units, respectively. Distribution transformers need to function within their thermal limits to avoid decreasing their mean time to failure, and to maintain grid stability and reliability. Thus, transformer overloading, voltage drops along distribution lines, and primary conductor overloads must be studied and analyzed. For this research, multiple analysis tools were developed to study distribution transformers overloading, voltage violations, and overloading of primary conductors as impacted by anticipated EV loading.

1.2 Objectives of Work

As EV adoption grows, utilities need to familiarize themselves with EV load growth impacts. Generally, utilities plan for asset upgrades to compensate for future load growth by conducting Integrated Resource Planning (IRP). Utilities determine the risks associated with power demand and supply that meet future requirements and government policies. The motivation for this thesis work is to understand, analyze, and develop tools on power distribution systems that indicate voltage violations, transformer overloads, and proper conductor size. A deeper understanding of EV impacts will aid utilities in the planning process of power system distribution infrastructure upgrades by providing data imperative to scheduling these improvements.

The tools developed in this thesis, in part, address the impacts that EV load growth will have on distribution transformers. Most distribution transformers operate at high average efficiency where temperature and air quality impact transformers functionality over time. The distribution transformer tool developed in this thesis work indicates the overload time and apparent power rates compared with the Institute of Electrical and Electronics Engineers (IEEE) C57.96 standard [4]. Voltage drops along distribution lines must be within the service voltage limits, as stated by the American National Standards Institute (ANSI) C84.1 standard [5]. Therefore, the voltage drop tool was developed to indicate the voltage drop along the transmission line associated with the distribution transformers. The third and final tool is the conductors sizing tool, which was designed to show if the conductor current exceeds the primary conductor sizing established by the National Electrical Code (NEC). The tools developed for this thesis will provide asset distribution planners tools for analyzing distribution system impacts due to projected EV load growth and to position their utilities for future planning.

2 Literature Review

2.1 Power Engineering Software

Analyzing EV impact on a power distribution system requires an appropriate simulation environment. There are several Power Engineering Software (PES) available in the market that simulate smart grid technologies. Power engineers rely on PES to perform distribution system analysis. GridLAB-D and OpenDSS are examples of open-source PES. These are associated with Pacific Northwest National Laboratory (PNNL) and Electric Power Research Institute (EPRI), respectively. Utilities widely use ETAP and CYMDIST, which are commercially available. These commercial PES are usually prohibitively expensive for university research. Although the vast majority of the software capabilities are comparable, they are diverse in their features. After comparing the capabilities of GridLB-D and OpenDSS, GridLAB-D was chosen as the distribution system PES for this thesis work. In the following sections, a comparison between OpenDSS and GridLAB-D is presented.

2.1.1 GridLAB-D

GridLAB-D is a power distribution system analysis and simulation tool developed at the behest of US Department of Energy (DOE) by PNNL [6]. GridLAB-D provides several capabilities for modeling distribution systems and renewable energy, from generation to end-use models, including appliance and equipment models. Furthermore, GridLAB-D is capable of modeling Distributed Energy Resources (DER), which include Photovoltaics (PV), wind turbines, Battery Energy Storage Systems (BESS), and EVs. It also provides various modeling capabilities such as distribution power flow analysis, energy market simulation and residential load modeling [6]. GridLAB-D was used as the simulation environment for the distribution system tools for numerous reasons. Beginning with the first reason, it is open source. Besides, GridLAB-D is widely used by industry and universities. It is considered a valuable tool for modeling distribution feeders [7] [8].

2.1.2 OpenDSS

Open Distribution System Simulator (OpenDSS) is a power system simulation tool developed by Electrotek Concepts in 1997 before EPRI took over in 2014. OpenDSS supports power flow analysis, harmonic analysis, and smart grid simulation [9]. While being open-source with all distribution system simulation features, OpenDSS was not chosen for the tool validation for several reasons. OpenDSS uses a frequency-based analysis instead of time analysis, unlike the other software OpenDSS uses impedance matrix analysis and a current injection method to solve current and voltage values [9]. A non-linear system resolution algorithm in distribution system nodes such as Newton-Raphson (NR) and Forward-Backwards Sweep (FBS) method is needed to validate the nodes and loads distribution for the developed tools.

2.2 Impact of EVSE on Electric Power Distribution Infrastructure

The absence of proper planning to integrate EV load growth may lead to an additional burden on power distribution infrastructure, especially to radial distribution feeders. Furthermore, EV charging during peak hours poses several challenges for distribution systems. These challenges include power quality issues, such as voltage drop and harmonics, transformer overloading, and conductor resizing. EV is defined as a vehicle that operates on an electric motor rather than an internal combustion engine. Each EV needs Electric Vehicle Supply Equipment (EVSE), which is the equipment used for supplying EVs with electricity. As part of understanding the impact of EVSE, a literature review of EVSE charging impact on distribution infrastructure assets is presented.

2.2.1 Distribution Transformers

Distribution transformers are one of the most prolific distribution infrastructure components, connecting hundreds of thousands of residential homes to the power grid. For example, PGE, which is a midsize utility, has over 150,000 distribution transformers within its balancing area. Therefore, studying the impact of EVSE on distribution transformers is a key consideration when modeling EVSE impact. Substantial research exists concerning EVSE charging impacts on distribution transformers. Shao et al., demonstrated that Plug-in Hybrid Electric Vehicles (PHEV) charging during peak hours would overload a 25 kVA distribution transformer by 103% during winter, and 98% during summer [10]. Shao et al., speculate that if the charging scenario is uncoordinated during peak hours, distribution transformer needs to be upgraded to meet the load growth. Research by Hilshey et al., focused on the aging of a 25 kVA service transformer experimented with six EVs and while considering ambient temperature for a transformer based on IEEE standard and multiple charging scenarios [11]. It is indicated that with a high level of EV adoption, transformer aging is accelerated.

2.2.2 Power Quality

Power Quality (PQ) issues such as voltage drop and harmonic distortion within distribution feeders due to the increase of non-linear loads are of concern. EV chargers are non-linear loads, which may present a higher impact due to harmonics produced by their power electronics. Analyzing voltage drops within the feeder voltage due to increased EV load growth is essential to ensure distribution system reliability and stability because voltages must be maintained within specified tolerances in order to ensure loads can stay online. The following sections introduce the background of EV load growth impact on voltage drop and harmonic distortion.

2.2.2.1 Voltage Drop

As the load on the distribution feeder diverges, so does the voltage drop between the substation and the end-user. To maintain the end-user voltage within acceptable range, the substation voltage needs to be regulated. Therefore, analyzing the voltage drops along distribution lines is important. Significant analysis on distribution feeders has been performed concerning the impact of EV load on distribution lines. Research by Dubey and Santoso [12] analyzed the effect of EV charging on distribution voltage with a 13.8 kV distribution feeder. Results show that by installing EVSE with a single EV charging, the load leads to a voltage drop of 4.41%, as shown in Figure 2.1. Taylor et al., showed that additional EV load growth repeatedly will raise the voltage regulation in primary distribution lines [13].

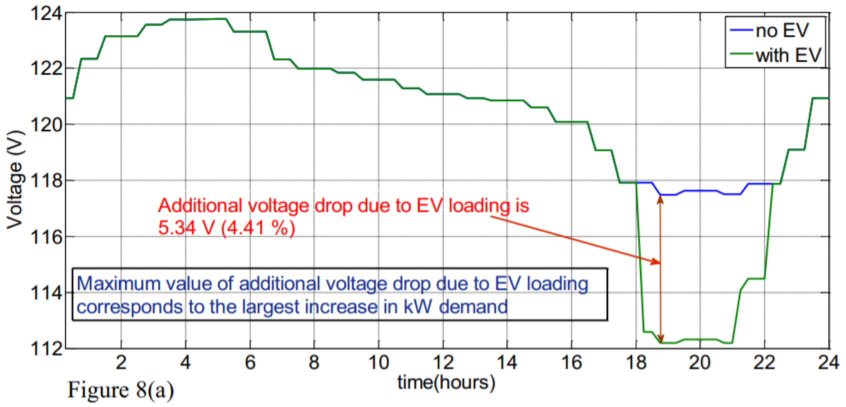


Figure 2.1: Voltage drop during EV charging in the secondary service [12].

2.2.2.2 Harmonic Distortion

Harmonic distortion is one of the most common issues of PQ. Thus, it is important to determine its impact, especially at the distribution level where EVSE are located. Several studies have been carried out to analyze the harmonic implications for EV chargers [14],[15]. Harmonic distortion is defined as the ratio of the square root of the sum of the square of harmonic magnitude to fundamental sine wave magnitude. It could be a deviation of a current or voltage waveform. Most studies focus on the harmonic current due to its potential impact on magnetic assets like distribution transformers and motors. The study by Ul-haq et al., illustrates the importance of analyzing the harmonic distortion by modeling several different EV penetration levels [14]. Results show that with light loading, the current Total Harmonics Distortion (THD) is 5.6% while the voltage remain within acceptable limits.

However, with 95% EV penetration, voltage distortion exceeds the allowable THD limit by 8%.

2.3 Electric Vehicle Service Equipment

The function of EVSE is to properly supply EV with electricity for charging of the battery. EVSE are commonly categorized into three different levels: Level 1, Level 2, and Level 3. These groupings vary by power level. Levels 1 and 2 EVSE provide Alternating Current (AC) power flow to the charger inside the vehicle. Level 3 charges the battery directly with Direct Current (DC). In the following sections, a comparison of the three charger levels is presented.

2.3.1 Level 1 and 2 Chargers

Level 1 chargers use a 120 V voltage supply connected to a 15 or 20 A receptacle with a maximum current of 12 to 16 A. These chargers generally take 8 to 12 hours to fully charge a vehicle. Therefore, EV owners with Level 1 EVSE typically charge their vehicles overnight. Level 2 chargers are the preferable chargers since they take less time to charge than Level 1 chargers. Level 2 chargers use a 208 V or 240 V input voltage with 32 to 80 A maximum current depending on the charging station design. Level 2 chargers are commonly used in residential areas and consume higher power than Level 1 chargers.

2.3.2 Level 3 Chargers

While most EV owners feel comfortable charging their vehicle at home by using either Level 1 or 2 EVSE , Level 3, known as DC Fast Charging (DCFC), is commonly used in industrial and commercial areas, as they are costly and require specific equipment. Most Level 3 chargers require a 480 V DC service. Some DCFC are capable of charging a passenger vehicle to 80% capacity in around 30 minutes.

3 Design Considerations

Design considerations are principles that provide methods to guide the development process strategy and ultimately shape the final result. Design considerations are formulated to generate focus on how the design requirements are met and, therefore, influence each tool design. In the following sections, each of the design considerations are identified and their application in the design of the *Power Distribution* tools are discussed.

Three tools were developed for this thesis work. These tools are designed for residential loads with the consideration for EV load growth impact. The *Voltage Violations* tool is designed to indicate voltage drops along the feeder line associated with distribution transformers. The *Current Violations* tool is designed to indicate over-current events along overhead lines. The *Transformer Overloading* tool is developed to indicates the percentage of transformer overloading.

3.1 Power Distribution Tools

The purpose of developing the three *Power Distribution* tools (*Voltage Violations*, *Current Violations*, and *Transformer Overloading*), is to help distribution planners analyze the impact of EV load growth. For a given distribution system study, these tools monitor the impacts of EV load growth on distribution lines and transformers.

These *Power Distribution* tools were created by following the guidance of three design considerations. The first design consideration is how to create a model to test each of the *Power Distribution* tools functionality. The second design consideration is how to provide a method for adding and distributing residential loads to each household. The third consideration is how to facilitate in the decision for the number of EV each household should be included. Using the above design considerations as guidance, the following decisions are made to facilitate the development of the three *Power Distribution* tools; the IEEE 13 node was chosen as a test feeder, 1000 households were distributed among the test feeder nodes, and each household included one EV distributed with the ability to modify the percentage of EV penetration level for any given simulation.

3.2 Voltage Violation Tool

The *Voltage Violations* tool uses simulated voltage data to detect any voltage drop along transmission lines and alerts the user when a limit has been exceeded. The simulated voltage data input is the meter value between the service equipment and the household distribution line for a given simulation. This tool ensures that the input voltage value lies within a specific range.

In developing a tool that can identify voltage violations, two design considerations were considered. The first consideration; the nominal voltage rating and operating standard being used by utilities. The ANSI C84.1 standard for voltage violations range was found to be used by utilities [5]. The second consideration; the optimal power system type to examine.

The optimal system to be examined is a distribution system.

3.3 Current Violation Tool

The *Current Violations* tool utilizes simulated current data to detect an over-current condition along the conductors. The simulated current data input is the meter value between the service equipment and the household for a given simulation. This tool flags a current violation for overhead line conductors.

In developing a tool that can identify over-current conditions, two design considerations were considered. The considerations are as follows: which conductors are to be considered for current analysis, and the conductor sizing standard the utility employs in planning studies. The conductors considered for analysis are overhead distribution lines and the conductor sizing standard is NEC.

3.4 Transformer Overloading Tool

The *Transformer Overloading* tool indicates transformer overload conditions in distribution systems. This tool uses simulated power data between distribution lines and household loads, to alert a user when the output power exceeds the rating.

In developing a tool that can identify transformer overload conditions, two design considerations were considered. The considerations are as follows: the transformer standard used by utilities for monitoring transformer overload conditions, and the appropriate sizing typically used for distribution transformers. The transformer overloading standard used by utilities is the IEEE C57.96 to monitor each transformer overload percentage. The transformer rating for distribution are sized at 15 kVA - 35 kVA, at increments of 5 kVA.

4 Tool Development

Tool development is the process of implementing design considerations. These sections provide illustrations and detailed descriptions of the capabilities of each *Power Distribution* tools. The subsections then discuss how each design consideration is realized.

4.1 Power Distribution Tools

Three design considerations were applied during the development of *Power Distribution* tools. The first consideration is for choosing the appropriate test feeder model. The second consideration is the distribution of households along with the nodes of the test feeder model. The third consideration is adding EV loads, distributed among the households. An in-depth description of each consideration is presented in the following subsections.

4.1.1 IEEE 13 Node Test Feeder Modeling

IEEE 13 node test feeder was chosen to evaluate *Power Distribution* tools functionalities. Figure 4.1 is a one-line diagram of the IEEE 13 node test feeder selected for modeling [16]. The feeder model includes overhead and underground lines, a voltage regulator, and a substation transformer. For this thesis work, the feeder model was configured to accommodate a set of 1000 households with their respective EV loads as a means to evaluate EV load growth impact on the distribution transformers and lines. A distribution transformer was added to each node, except for nodes 650 and 634. In the IEEE 13 node test feeder, nodes 650 and 634 serve commercial loads. Figure 4.2 is the configured one line diagram of the IEEE 13 node test feeder model with a distribution transformer, a household, and an EV load connected to each node.

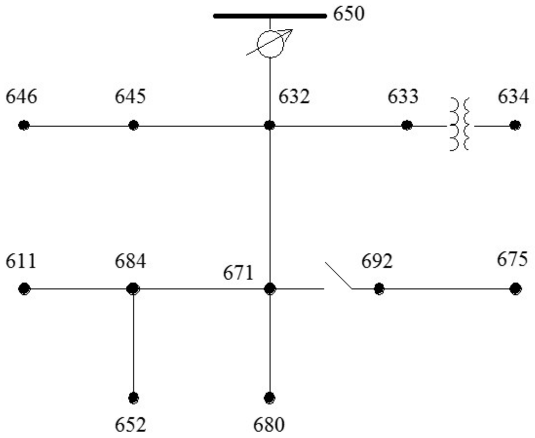


Figure 4.1: IEEE 13 nodes one line diagram [16]

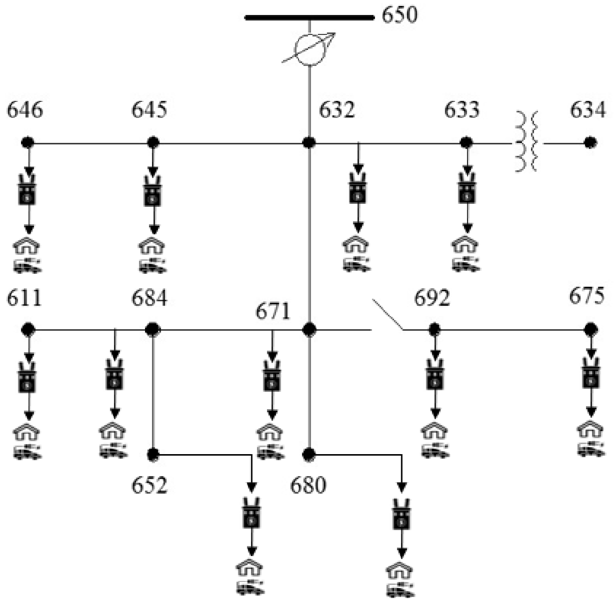


Figure 4.2: Modified IEEE 13 nodes one line diagram with EV

The method for testing *Power Distribution* tool functions was accomplished through modeling the configured IEEE 13 node test feeder in GridLAB-D [17]. GridLAB-D is a command-line program, which uses simple text files as input for specific objects, classes, and modules. The structure of creating a distribution feeder model in GridLAB-D is shown in Figure 4.3. In the next subsection, a comprehensive description of each structural element is included. It should be incorporated into the scripting code writing to model a distribution system in GridLAB-D successfully.

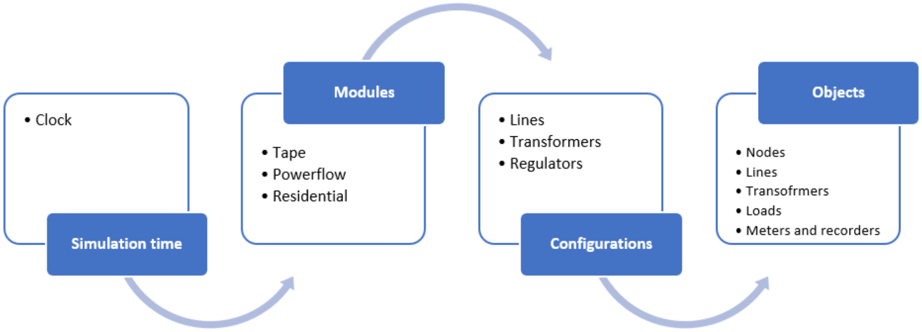


Figure 4.3: Structure of GridLAB-D distribution model

4.1.1.1 Simulation Time

In GridLAB-D, the simulation time is set by a clock that defines a timestamp and time step. The simulation time selected for the configured IEEE 13 node feeder model has a timestamp of one week, with a time step at 10 minutes:

```
clock{
        timestamp '2010-07-25 0:00:00';
        stoptime '2010-07-31 0:10:00';
        timezone PST+8PDT;
        }
```

4.1.1.2 Modules

GridLAB-D provides various types of modules to perform an analysis for a given model. The configured IEEE 13 node test feeder model used to validate *Power Distribution* tools requires three types of modules. The modules are; *tape*, *power flow*, and *residential*. The *tape* module is used to implement player and recorder objects that modify boundary conditions and identify object properties [18]. The *power flow* module is set to a specific iterative calculation method to solve power flow quantities that provide steady-state node voltage and line current. There are three power flow iterative calculation methods available in GridLAB-D: NR, FBS, and Gauss-Seidel (GS). The iterative calculation method chosen for distribution modeling is FBS. FBS was selected over NR and GS because FBS performs the calculations in an efficient and accurate manner [19]. It is important to note that the configured IEEE 13 node test feeder model is a radial system, and FBS is the preferred method for solving three-phase unbalanced systems of this system type. The *residential* module is used to provide classes for each household and simulate single-family homes. The three modules used are configured as follows:

```
module tape;
module powerflow{
        solver_method FBS;
        default_maximum_voltage_error 1e-9;
        line_limits TRUE;
};
module residential {
implicit_enduses NONE;
ANSI_voltage_check TRUE;
};
```

4.1.1.3 Configurations

Configurations are used in GridLAB-D to describe each particular object implementation. For example, each underground and overhead line, transformer, and voltage regulator is an object and requires configurations that identify and define the parameters for each object. A triplex is a type of object that sets parameters and is combined with other objects. A triplex line conductor object was used to represent conductor configurations as follows:

```
object triplex_line_conductor {
        name triplex_line_conductor_1;
        resistance 0.97;
        geometric_mean_radius 0.0111;
};
object triplex_line_configuration {
        name triplex_line_configuration_main_lines;
        conductor_1 triplex_line_conductor_1;
        conductor_2 triplex_line_conductor_1;
        conductor_N triplex_line_conductor_1;
        insulation_thickness 0.08;
        diameter 0.368;
}
```

After triplex line conductors are configured, overhead and underground line conductor configurations were listed together with the line spacing between the lines. Line spacing, Geometric Mean Radius (GMR), distance, and resistance values were used as listed in [16]. Examples of the underground and overhead line configurations are shown below:

- Overhead line conductor configuration:

```
object overhead_line_conductor:6010 {
```

```
        geometric_mean_radius 0.0313;
        resistance 0.1859;
}
object line_spacing:500601 {
        distance_AB 2.5;
        distance_AC 4.5;
        distance_BC 7.0;
        distance_BN 5.656854;
        distance_AN 4.272002;
        distance_CN 5.0;
}
object line_configuration:601 {
        conductor_A overhead_line_conductor:6010;
        conductor_B overhead_line_conductor:6010;
        conductor_C overhead_line_conductor:6010;
        conductor_N overhead_line_conductor:6020;
        spacing line_spacing:500601;
}
```

- Underground line conductor configuration:

```
object underground_line_conductor:6060 {
        outer_diameter 1.29;
        conductor_gmr 0.0171;
        conductor_diameter 0.567;
        conductor_resistance 0.41;
        neutral_gmr 0.0020800;
        neutral_resistance 14.872;
        neutral_diameter 0.0640837;
        neutral_strands 13.0;
        shield_gmr 0.0;
        shield_resistance 0.0;
```

```
}
object line_spacing:515 {
        distance_AB 0.50;
        distance_BC 0.50;
        distance_AC 1.0;
        distance_AN 0.0;
        distance_BN 0.0;
        distance_CN 0.0;
}
object line_configuration:606 {
        conductor_A underground_line_conductor:6060;
        conductor_B underground_line_conductor:6060;
        conductor_C underground_line_conductor:6060;
        spacing line_spacing:515;
}
```

Transformers are classified into two types, substation and distribution transformers. The substation transformer used in IEEE 13 node test feeder is 5000 kVA. Values used to develop substation transformer shown in Table 4.1. The configuration used to model transformers in GridLAB-D for the distribution models shown below:

Table 4.1: IEEE 13 node test feeder transformer data

	kVA	**kV- high**	**kV- low**	**R - %**	**X - %**
Substation:	5,000	115 - D	4.16 Gr. Y	1	8
XFM - 1:	500	4.16 – Gr.W	0.48 – Gr.W	1.1	2

- Substation Transformer Configuration:

```
object transformer_configuration:400 {
        connect_type WYE_WYE;
        install_type PADMOUNT;
        power_rating 500;
```

```
        primary_voltage 4160;
        secondary_voltage 480;
        resistance 0.011;
        reactance 0.02;
}
```

Distribution transformer ratings used for the distribution feeder model vary between 15 kVA and 35 kVA. An example of a 15 kVA single phase center tap transformer is shown below:

- Distribution Transformer Configuration:

```
object transformer_configuration {
        name CS15_config;
        connect_type SINGLE_PHASE_CENTER_TAPPED;
        install_type POLETOP;
        powerC_rating 15;
        primary_voltage 2401;
        secondary_voltage 120.000;
        impedance 0.006+0.0136j;
}
```

The last configuration in the GridLAB-D distribution feeder model structure is the voltage regulator, which is used to hold the system voltage at 122 V.

```
object regulator_configuration:650 {
          connect_type WYE_WYE;
          band_center 122.000;
          band_width 2.0;
          time_delay 0.0;
          dwell_time 0.0;
          raise_taps 16;
          lower_taps 16;
          current_transducer_ratio 700;
```

```
          power_transducer_ratio 20;
          compensator_r_setting_A 3.0;
          compensator_x_setting_A 9.0;
          compensator_r_setting_B 3.0;
          compensator_x_setting_B 9.0;
          compensator_r_setting_C 3.0;
          compensator_x_setting_C 9.0;
          CT_phase "ABC";
          PT_phase "ABC";
          Control MANUAL;
          control_level INDIVIDUAL;
          Type A;
          tap_pos_A 0;
          tap_pos_B 0;
          tap_pos_C 0;
          regulation 0.10;
}
object regulator:650630 {
        phases "ABCN";
        from node:650;
        to node:630;
        sense_node N671;
        configuration regulator_configuration:650;
}
```

4.1.1.4 Objects

Each object implemented in GridLAB-D is a specific instance of a class, and each class is defined as a collection of algorithms, which determines how each object should behave [20]. Objects used to develop the IEEE 13 node test feeder are as follows: nodes, lines, transformers, houses, loads, meters, and recorders. The node object is a bus of the distribution system that provides the connection point for the system voltage [20]. The voltage developed in the node object operates as a three-phase voltage connected in wye or delta connection. The triplex node object works on a split-phase level, and each triplex load phase connects through a triplex node. The triplex load is used to vary the load value with time for a given object. As shown in Figure 4.4, each distribution transformer connects to one of the triplex nodes, and then houses were connected to each transformer through a triplex meter. Triplex lines are established to connect two objects together. The triplex meter is used to provide a measurement point of power, current, and voltage for downstream connections [20]. Each triplex meter is coupled with a set of recorders. Recorders are utilized to collect and save data from meter objects associated with them.

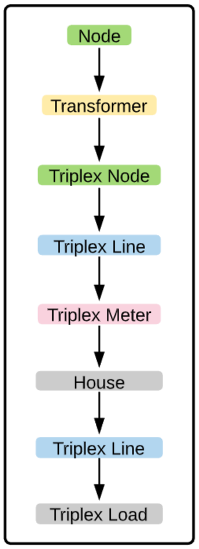


Figure 4.4: Structure of Objects developed in GridLAB-D

4.1.2 Household Load Modeling

In order to evaluate EV load growth impacts on distribution lines and transformers, a set of household loads was distributed along the IEEE 13 node test feeder. The method for the distribution of household loads applied for this dissertation was adopted from Ahourai and Alfaruque, who considered distributing 1000 houses along IEEE 13 node test feeder [21]. By using this method, three to seven houses were attached to each distribution transformer. Table 4.2 indicates the number of houses distributed for each phase of the IEEE 13 node test feeder.

Table 4.2: Total houses distributed along the IEEE 13 node test feeder model

Phases	**Numbers of Houses**
Phase A	319
Phase B	303
Phase C	378

198 distribution transformers were distributed among the IEEE 13 node test feeder. Most distribution transformers used by utilities are rated to serve between 15 to 50 kVA load. Typically, these transformers serve 5 to 15 homes. For modeling purposes, transformers were developed to serve three to seven houses and rated to serve between 15 to 35 kVA. The 15 kVA transformer was used to serve three household and the 35 kVA serves seven household. To model houses and transformers in GridLAB-D, 1000 houses were randomly distributed among the IEEE 13 node test feeder. Each single-phase center tap transformer attached to one of three, two, and single-phase nodes. The following tables illustrate how each center tap transformers connected. Tables 4.3 and 4.4 show nodes 611 and 633, a single-phase node and a three-phase node with several transformers and houses attached.

Table 4.3: Number of transformers and houses attached to node 611

IEEE 13 Nodes	Phase	Transformer Rating (kVA)	Number of Houses
Node 611	C	25	5
		15	3
		20	4
		30	6
		35	7
		25	5
		20	4
		25	5

Table 4.4: Number of transformers and houses attached to node 633

IEEE 13 Nodes	Phase	Transformer Rating (kVA)	Number of Houses
Node 633	A	25	5
		30	6
		15	3
		25	5
		35	7
		30	6
		30	6
		25	5
	B	15	3
		20	4
		15	3
		15	3
		25	5
		25	5
		20	4
		25	5
	C	20	4
		20	4
		15	3
		15	3
		25	5
		25	5
		25	5
		15	3

To evaluate the impact of EVs on lines and transformers connected with each EV and household, it is necessary to have household demand profiles. The electricity demand profiles used to model the IEEE 13 node test feeder was adopted from Muratori, who generated a modeling method that produces power consumption patterns [22]. Data for electricity demand are selected from the Residential Energy Consumption Survey (RECS) [23]. Each individual household demand profile is composed of 200 households. Each profile includes Heating, Ventilation, and Air Conditioning (HVAC) system data with 10 minutes resolution.

For modeling each household load profile in GridLAB-D, two load profile types were identified. The first type represents lower power consumption households, and the second type represents higher power consumption households. As reported by the Energy Information Administration (EIA), the average annual electricity consumption for a residential household was 10,649 kWh, which is about an average of 877 kWh per month [22]. Therefore, the average power consumption was 1.200 kW per month. As a result, the two load profile types have been chosen to be up to 3.5 kW for low power consumption and up 10 kW to represent higher power consumption. Table 4.5 shows the power consumption specification for each type. Type 1 and Type 2 were randomly distributed among 1000 houses in GridLAB-D. An example of summer and winter load profiles are presented in Figure 4.5 and Figure 4.6.

Table 4.5: Power consumption specification

Types	Power Consumption (kW)
Type 1	1 - 3.5
Type 2	3.6 - 10

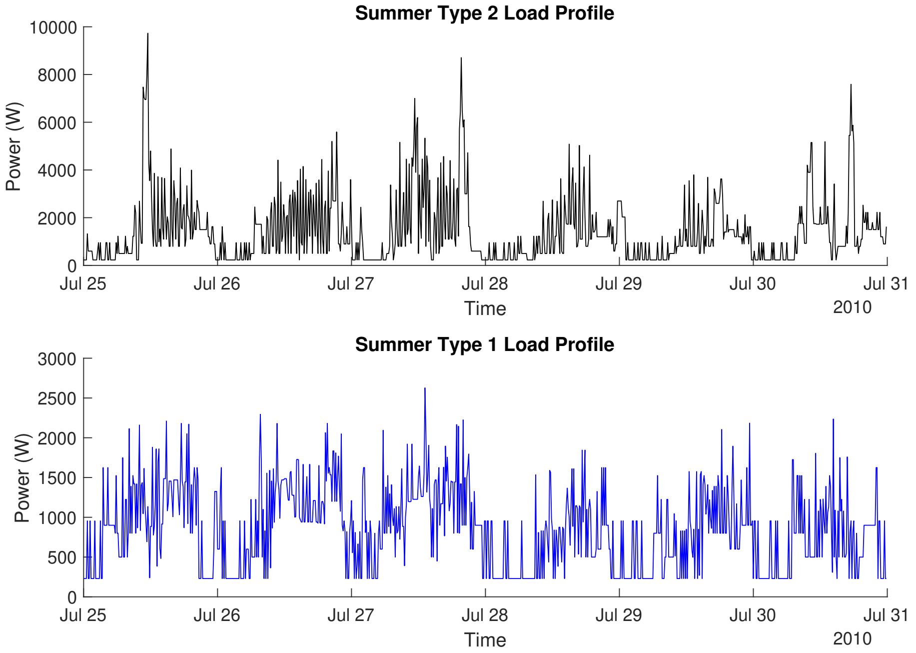


Figure 4.5: Type 1 and Type 2 summer load profiles

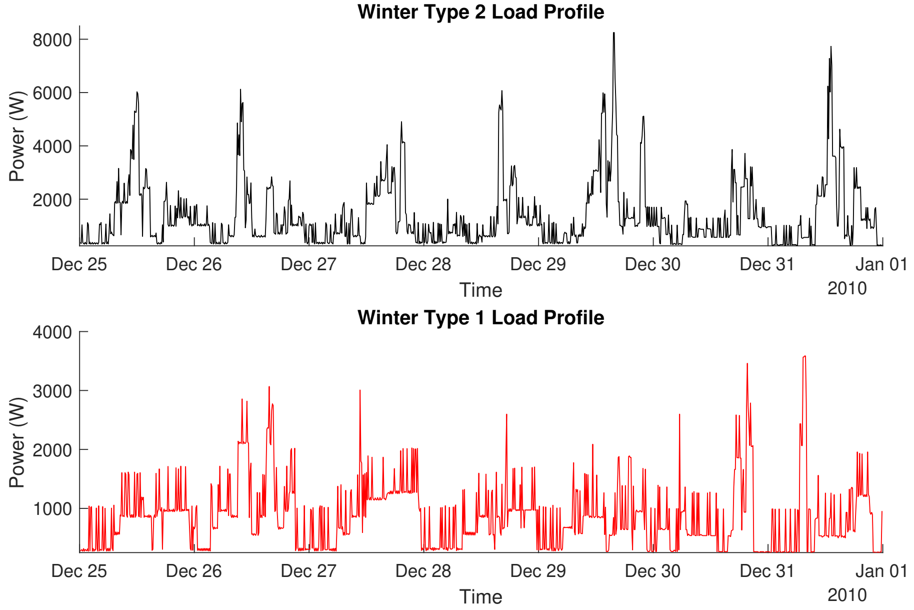


Figure 4.6: Type 1 and Type 2 winter load profiles

4.1.3 Household EV Modeling

To accurately analyze EV impacts on distribution transformers and lines, EV load profile data are used to characterize the load. All EV load profile data used in this work, acquired from RECS, are randomly distributed among 1000 houses [23]. These profiles have been generated using the modeling method proposed by Muratori et al., who considered generating 348 Plug-in Electric Vehicle (PEV) charging profiles for in-home charging [24]. Two assumptions were made while developing these load profiles. The first assumption is the EV were at 60% of State of Charge (SoC) for 200 mile range and 40% of SoC for 40 mile range. The second assumption is the in-home charging station is a Level 2 charging station with a maximum power of 6600 W. An illustration of winter and summer EV load profiles are shown in Figures 4.7 and 4.8.

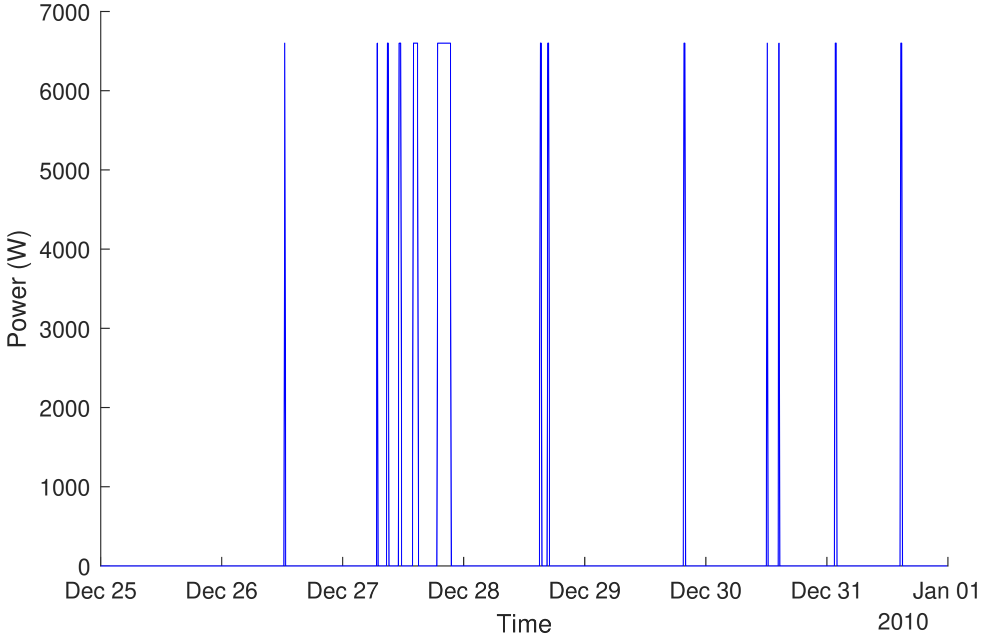


Figure 4.7: Winter EV load profile

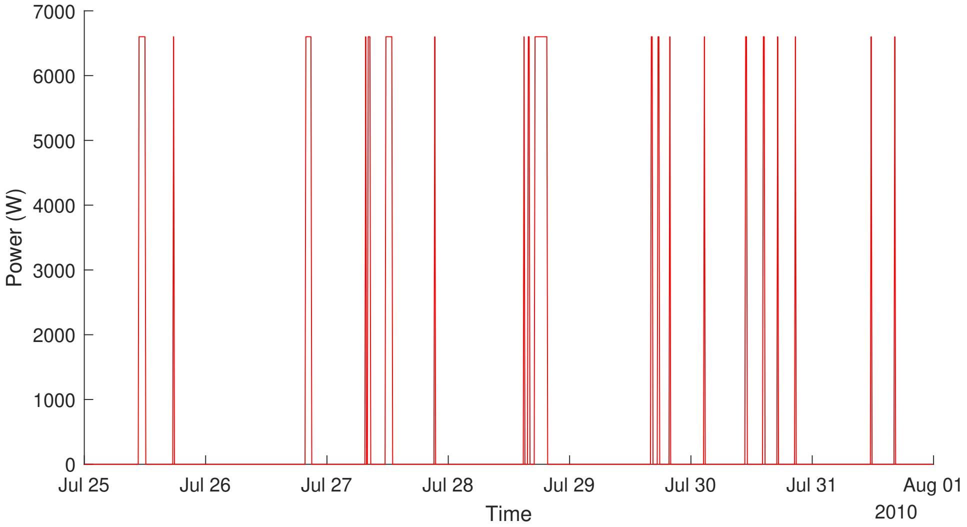


Figure 4.8: Summer EV load profile

For modeling EV impacts in GridLAB-D, five different penetration rates of EV were considered. Table 4.6 shows each penetration level and the number of EV added. Additionally, an assumption is made that each household has one EV.

Table 4.6: EV penetration level with number of EV added to each house

EV Penetration %	**Number of EV**
20%	200
40%	400
60%	600
80%	800
100%	1000

4.2 Voltage Violations Tool

The *Voltage Violations* tool detects voltage drops along distribution lines and alerts the user if the voltage value exceeds the specified range allowed by the ANSI C84.1 standard [5]. The input file of this tool is a CSV file that is comprised of simulated voltage data. The tool identifies the voltage drop location, then the relevant data are logged, flagged, and displayed to the user when the voltage is out of that range. Figure 4.9 is an illustration of the flow chart the *Voltage Violations* tool process.

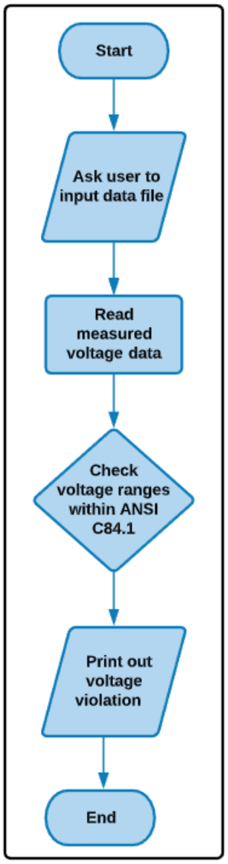


Figure 4.9: Voltage violations tool flow chart

4.2.1 ANSI C84.1 Standard

The biggest challenge in distribution system design is to regulate the voltage under widely varying load conditions. Therefore, voltage regulators are used to hold the system voltage within a specific voltage range. Standards are used to establish the particular allowed range of service voltage. The ANSI C84.1 standard is widely used by utilities to specify voltage regulation. This standard establishes the nominal voltage rating and the operating tolerances for 60 Hz [5]. Two ranges were designed for establishing a service voltage range. Range A provides the expected voltage tolerance of service voltage. The allowable range is +5% to -5% for systems operating at 600 V and below [5]. For a given distribution system study, the nominal voltage is 120 V, which means that no more than 6 V voltage drop is allowed. Range B provides voltage tolerances for above and below rang A limits.

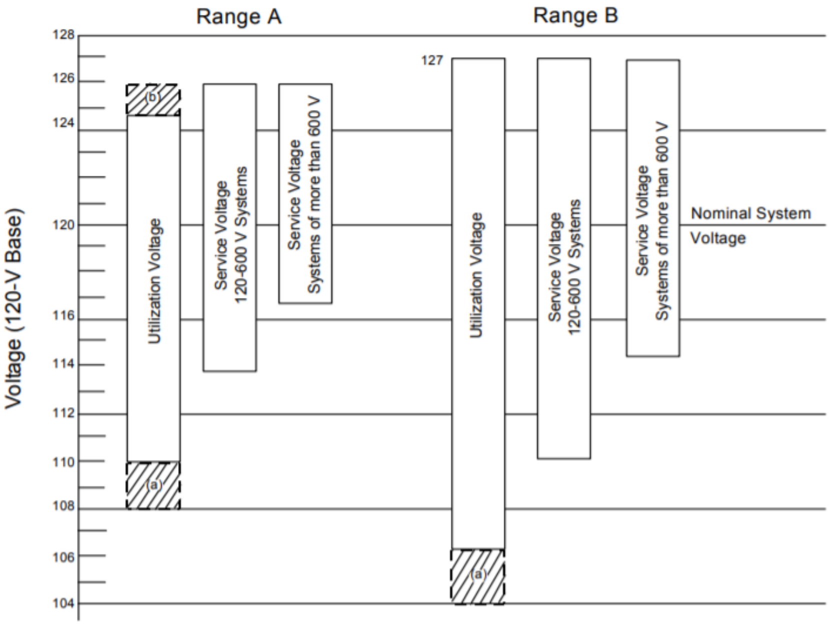


Figure 4.10: ANSI C84.1 Voltage Ranges [5]

For *Voltage Violation* tool, Range A was used to establish the voltage range from 114 V to 126 V of the nominal 120 V. The voltage ranges for range A and B is shown in Figure 4.10.

4.3 Current Violations Tool

The *Current Violations* tool detects over-current along overhead lines and alerts the user if the current value exceeds the rated ampacity value. This tool input is a CSV file, which contains the simulated current data. The tool inspects the data for current violations then identifies the location. The tool logs the relevant data for each of the current violation events and displays it to the user. Figure 4.11 is a visual representation of the evaluation process the *Current Violations* tool performs on the input data.

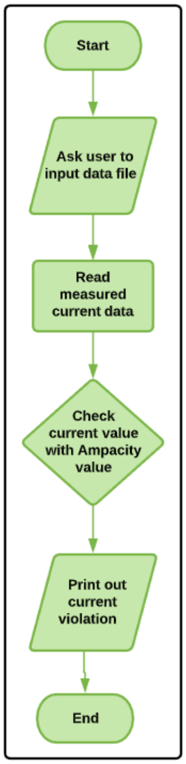


Figure 4.11: Current violations tool flow chart

4.3.1 Overhead Distribution Lines

Overhead distribution lines are used to transmit electrical energy across long and short distances and comprise sets of conductors that allow current to flow. In distribution system planning, EV load growth impacts are essential to analyze because appropriately-sized conductors must be chosen based on projected demands making the system suitable for future load growth. Selecting the appropriate type and size of conductors is based on many factors, like ambient temperature and insulation type. A series of standards provide the minimum size requirements for conductors in order to prevent overheating, which leads to severe damage and power loss. In most cases, overheating occurs when an over-current condition exists. An over-current condition occurs when the current value exceeds the conductor rated ampacity value for an extended period. Ampacity is the maximum current that can be carried continuously by the conductor without exceeding the temperature rating.

4.3.2 NEC Standard

Distribution planning engineers select the size of a conductor partially based on operating temperature and ambient temperature. The temperature value ratings associated with conductor sizing are largely based on codes and standards. The NEC is the most widely used set of codes utilities follow for electric standards and safety requirements. The *Current Violations* tool employs NEC codes for overhead conductors and, therefore, the American Wire Gauge (AWG) standard measurement is used. The conductors chosen to represent the overhead distribution lines configured in the distribution system model are 1/0 AWG

All Aluminum Conductor (AAC). The *Current Violations* tool assesses whether the current exceeds the ampacity rating for 1/0 AWG AAC as specified by the NEC standard. A 1/0 AWG conductor was chosen for testing, tool can be configure to analyze conductors sizing from 1/0 to 4/0 AWG AAC. The NEC establishes the code of possible ampacity rating that can be used for conductor sizing [25].

4.4 Transformer Overloading Tool

The *Transformer Overloading* tool indicates distribution transformer overload condition and alerts the user with the specific period of time for each overload. This tool input file is a CSV file, which includes simulated power data. The tool identifies an overload condition, then the relevant data are recorded, flagged, and displayed to the user when the output power exceeds the rating. This tool checks the power rating and identifies overloading condition time compared to the ANSI C57.96 and IEEE C57.96 standards. Figure 4.12 is an illustration of the flow chart the *Transformer Overloading* tool process.

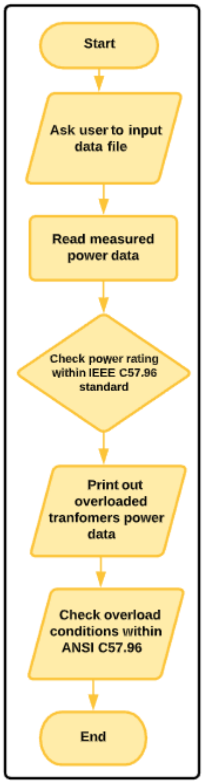


Figure 4.12: Transformer overloading tool flow chart

4.4.1 IEEE / ANSI C57.96 Standard

Overloading distribution transformers is a prolific concern for utilities. The transformer overloading condition depends highly on the state of the internal insulation materials, which are impacted by the hottest spot temperature. Continuously overloading distribution transformers may reduce the service life of a transformer. Therefore, a standard for transformer life expectancy and overloading conditions are essential. The IEEE C57.96 establishes a guide for loading dry-type distribution and power transformers [4]. Transformer rated output is the load value delivered continuously at the rated secondary voltage without exceeding the temperature rise value under usual conditions. Rated values for distribution transformers refer to the nameplate ratings [4]. The standard establishes that the transformer can deliver service by less or more rated output, depending upon operating conditions.

Transformer rated output range is used to check overloading events. For a given distribution transformer rated at 15 kVA, for instance, the tool checks if the simulation rated power is above or below 15 kVA and records an event. After the event is recorded, this tool checks the overloading condition established by the ANSI C57.96 standard. For short-term overload conditions of low voltage dry-type distribution transformers, the ANSI C57.96 standard specifies that a distribution transformer can deliver 200% nameplate load for up to one-half hour, 150% load for up to one hour, and 125% load for up to four hours without damaging transformers.

5 Tool Validation

Tool validation is the process of ensuring that all tool design considerations are satisfied. The tool validation process is essential for showing that each *Power Distribution* tool is performing as intended. The input-output diagrams for each *Power Distribution* tool are presented in the following sections. Each subsection then provides illustrations for each case, demonstrating how validation is applied to each tool function.

5.1 Power Distribution Tools

Power Distribution tools were developed to analyze the impacts of EV load growth on power distribution infrastructure assets. These tools are designed to detect, locate, and report voltage drops in distribution lines, current violations along overhead conductors, and transformer overloads. The IEEE 13 node test feeder is used to validate the function and viability for each *Power Distribution* tool. Two validation cases were developed during the verification process for each of the *Power Distribution* tools. These cases examine how each *Power Distribution* tool performs under test. First, the *Base* case is established. This is done by running simulations using the IEEE 13 node test feeder model in GridLAB-D without EV loads included and recording the baseline electrical data. The second case is the *EV* case, which is produced by running simulations using the IEEE 13 node test feeder model in GridLAB-D including EV load growth and recording the electrical data. The *Base* case provides the means by which to compare simulation data that include EV load growth. This comparison provides the data on impacts EV load growth has on the system.

5.1.1 IEEE 13 Node Test Feeder

In order to verify the functionalities for each of *Power Distribution* tools, the IEEE 13 node test feeder was first modeled and configured in GridLAB-D with transformers supplying households [17]. Therefore, the *Base* case represents the simulated voltage, current, and power data for each set of households configured to transformers in the IEEE 13 node test feeder model. A diagram illustrating the input and output data for the IEEE 13 node test feeder model is shown in Figure 5.1. The input is a collection of power consumption load profiles that are distributed among 1000 houses. The output data generated from the simulation, is meter data for each transformer at every node in the model.

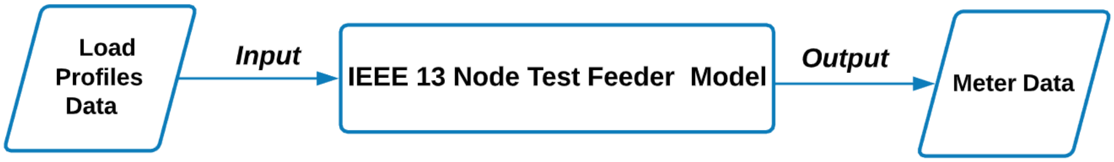


Figure 5.1: Input-output diagram of IEEE 13 node test feeder model

5.1.2 Base Case

The IEEE 13 node test feeder model contains 11 residential nodes. In order to achieve a granular understanding of the *Base* case, this discussion examines node 675. Node 675 is a three-phase node, in which each phase supports seven transformers, each connected to several houses each. The *Base* case is utilized to examine the test feeder model performance in the absence of EV loads. A demonstration of the *Base* case output simulated using winter weather data is presented in Figures 5.2 - 5.4. The output data illustrated in these three figures establish the baseline electrical data for three of the seven transformers at node 675 and their associated number of houses connected on phase A. The transformer meters record current, apparent power, and voltage data, respectively, during the *Base* case simulation.

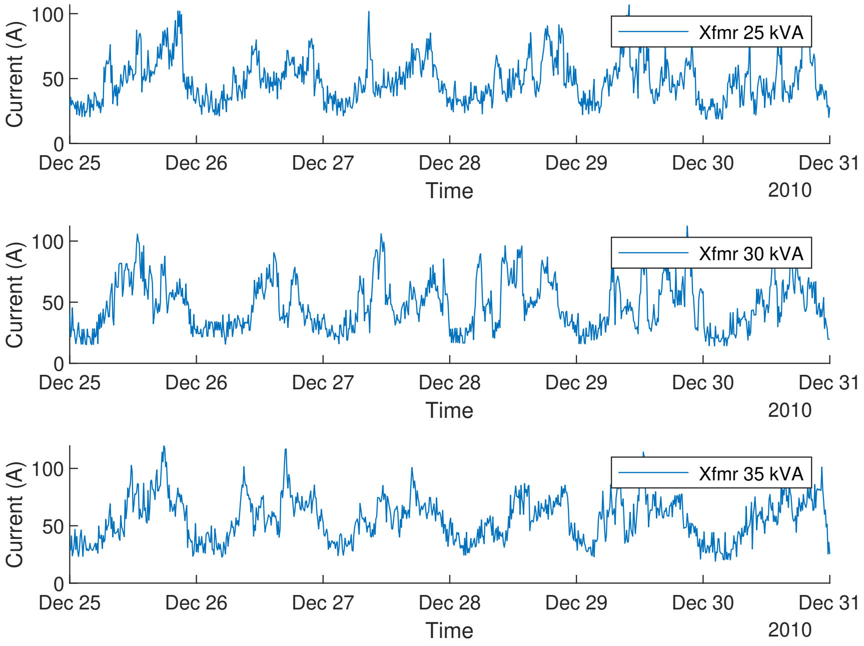


Figure 5.2: Base case simulated current data on three transformers connect to Node 675 of the IEEE 13 node test feeder model (Winter)

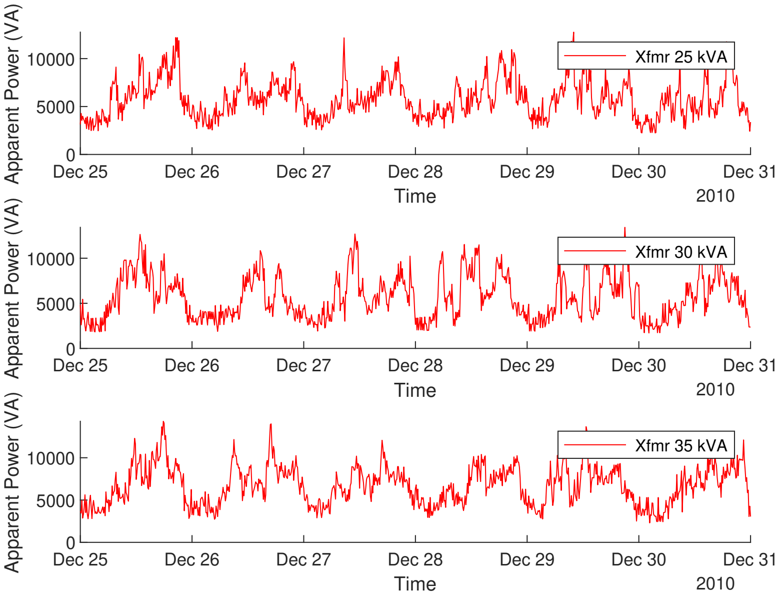


Figure 5.3: Base case simulated Apparent Power data on three transformers connect to Node 675 of the IEEE 13 node test feeder model (Winter)

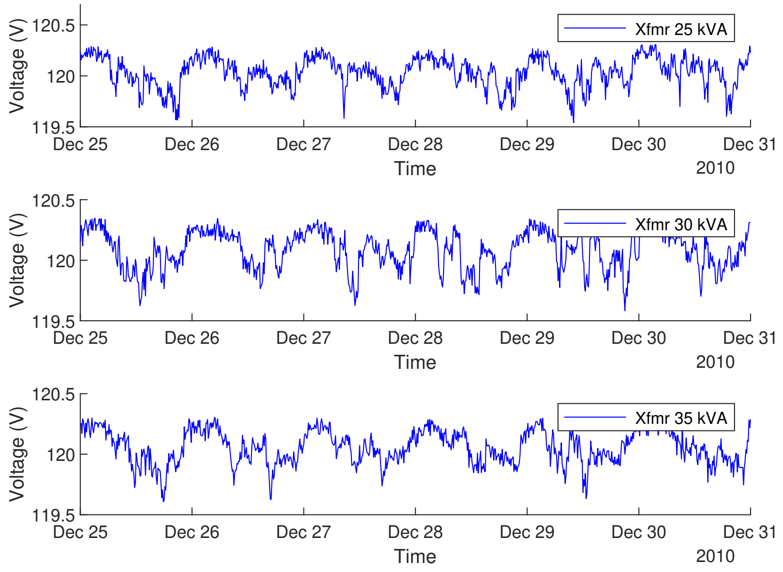


Figure 5.4: Base case simulated Voltage data on three transformers connect to Node 675 of the IEEE 13 node test feeder model (Winter)

Base case simulated current, apparent power, and voltage represent the baseline electrical data. Simulated data provide three sets of transformer data: the current values associated with conductors connected between transformer and household, apparent power values of distribution transformers, and voltage over distribution lines. Simulated base case data show no overload conditions. Therefore, current values are within the ampacity capacity, the power through distribution transformers is within the rated values, and service voltages are with allowable range.

5.1.3 EV Case

The *EV* case is developed to analyze the impact of EV load growth on power distribution infrastructures assets, including overhead lines and distribution transformers. Similar to the *Base* case, data collected include current, apparent power, and voltage. EV loads were added with varying penetration levels. For validation purposes, 100% EV penetration level was added to node 675 phase A. For transformers specific to Figures 5.5-5.7, five houses were connected to the 25 kVA transformer, six houses were connected to the 30 kVA transformer, and seven houses were connected to the 35 kVA transformer. Therefore, each household corresponds to five, six, and seven EV loads. The collected simulated data show the impact of adding EV loads on the conductors. Figure 5.5 shows when the current value exceeds the rated ampacity. Rated ampacity is 214 A for 1/0 AWG of AAC. Figure 5.6 shows transformer overloading conditions. No voltage violation were detected when EV loads are attached on node 675.

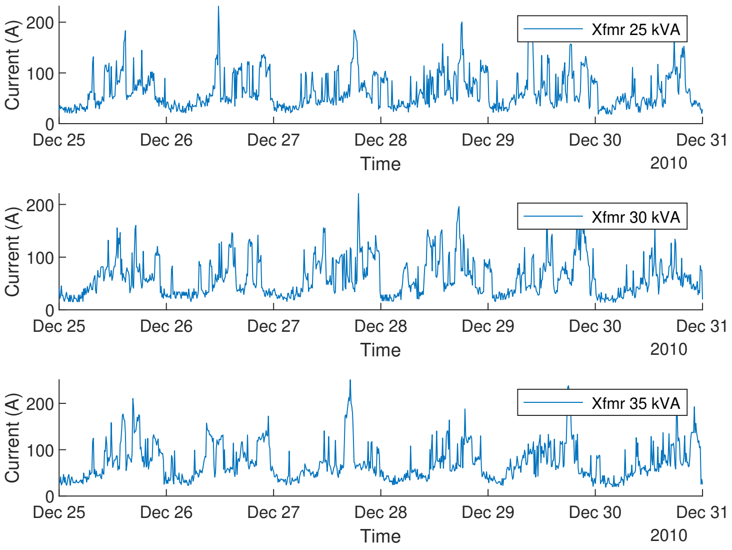


Figure 5.5: EV case simulated current data on three transformers connect to Node 675 of the IEEE 13 node test feeder model (Winter)

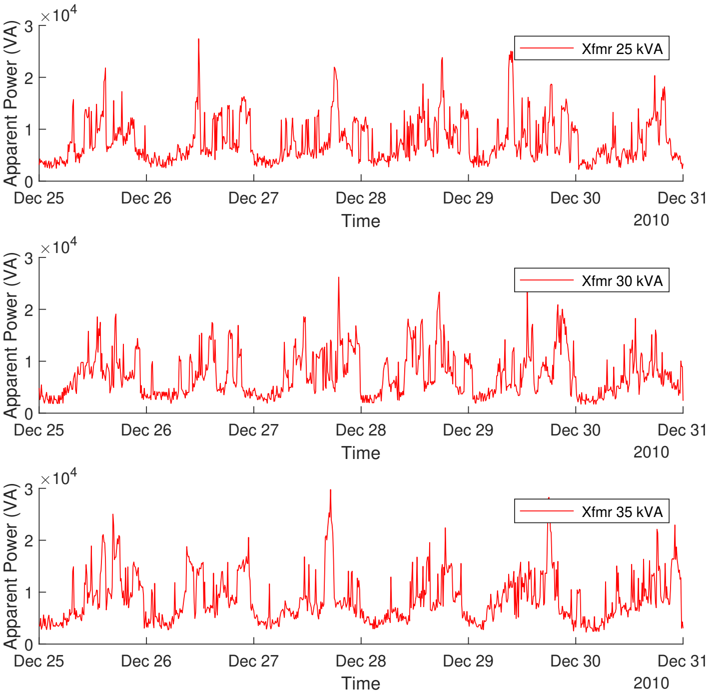


Figure 5.6: EV case simulated Apparent Power data on three transformers connect to Node 675 of the IEEE 13 node test feeder model (Winter)

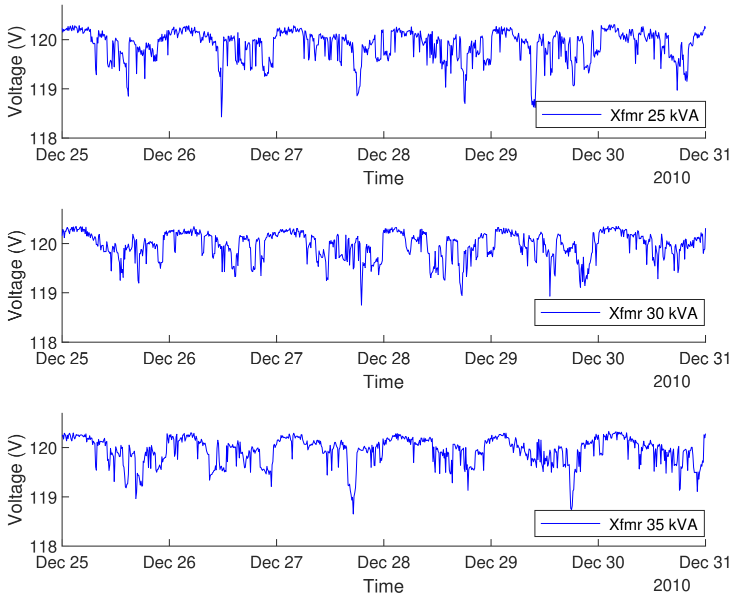


Figure 5.7: EV case simulated Voltage data on three transformers connect to Node 675 of the IEEE 13 node test feeder model (Winter)

5.2 Voltage Violations Tool

The *Voltage Violations* tool detects voltage violations within the distribution network. This tool alerts the user if the measured voltage values lie outside of the voltage range established by ANSI C84.1 standard. The acceptable voltage range is +/- 5% of the system nominal voltage. The *Voltage Violations* tool receives input data in a CSV file containing the simulated voltage measurements. Figure 5.8 demonstrate input-output diagram of *Voltage Violations* tool. When the tool detects voltages out of the acceptable range, the tool output notifies the user of those unacceptable voltages.

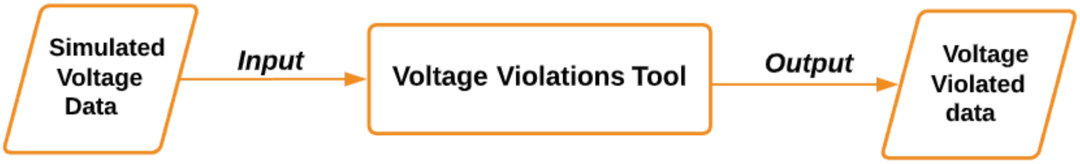


Figure 5.8: Input-output diagram of Voltage Violation tool

In order to check the *Voltage Violations* tool function, it is necessary to applied the function to the IEEE 13 node test feeder model. To accomplish this, Node 611 is chosen to run the simulation. Node 611 is a single-phase node that has eight distribution transformer attached to several houses. Figures 5.9 and 5.10 show the *Base* case of the measured voltage along the distributions lines. Voltages are within the acceptable range of ANSI C84.1 standard. The *Base* case will be compared with the voltage violation events when EV loads are added to the model.

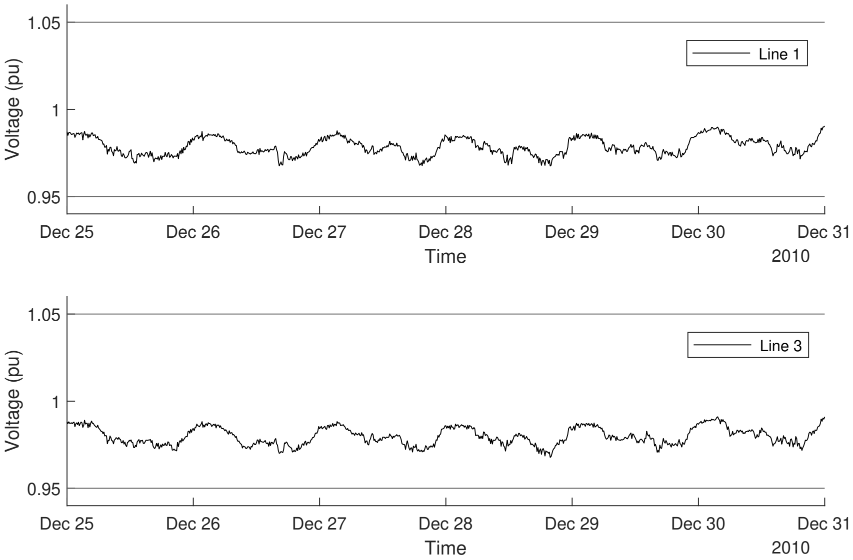


Figure 5.9: Base case measured voltage of lines 1 and 3 of IEEE 13 node test feeder model

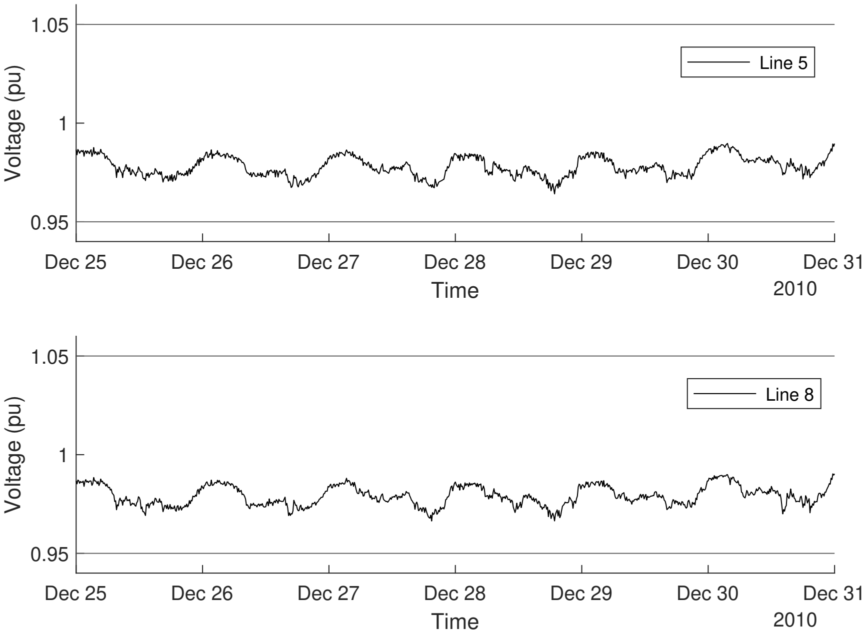


Figure 5.10: Base case measured voltage of lines 5 and 8 of IEEE 13 node test feeder model

The output of voltage violation events generated from the simulation is shown in Table 5.1. The four events recorded occurred for 20 minutes each. Figures 5.11 and 5.12 represent the recorded measured voltage data, which show the voltage drop events. The two horizontal lines at the top and bottom of each plot represent the minimum and maximum allowable voltage as per ANSI C84.1 standards.

Table 5.1: Voltage violation events

Time	Line #	Voltage (pu)
12/28/2010 19:10	Line 1 of Node 611	0.944
12/28/2010 19:30		0.947
12/28/2010 19:10	Line 3 of Node 611	0.944
12/28/2010 19:30	Line 5 of Node 611	0.947
12/28/2010 19:10	Line 8 of Node 611	0.944
12/28/2010 19:30		0.947

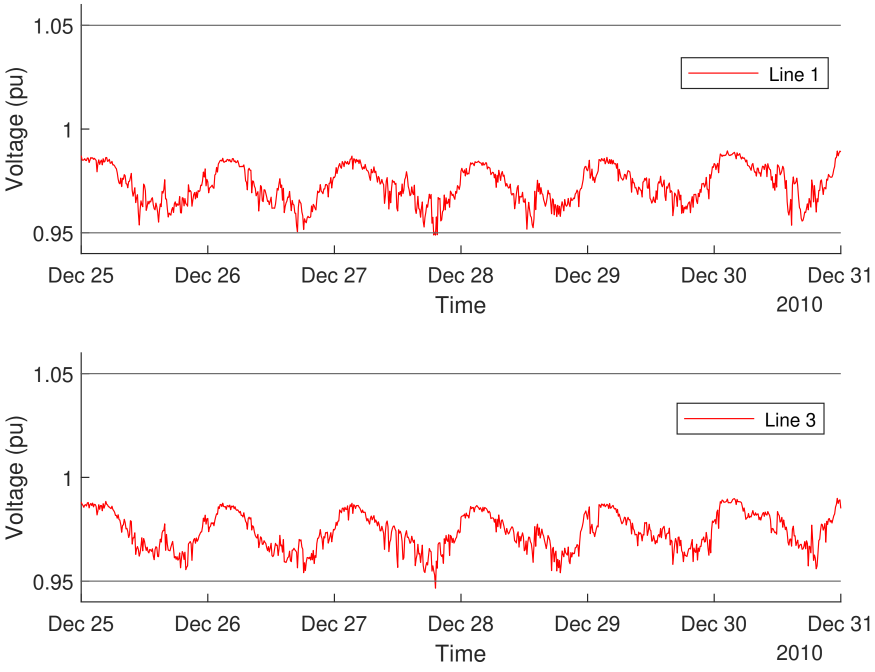


Figure 5.11: EV case measured voltage of lines 1 and 3 of IEEE 13 node test feeder model

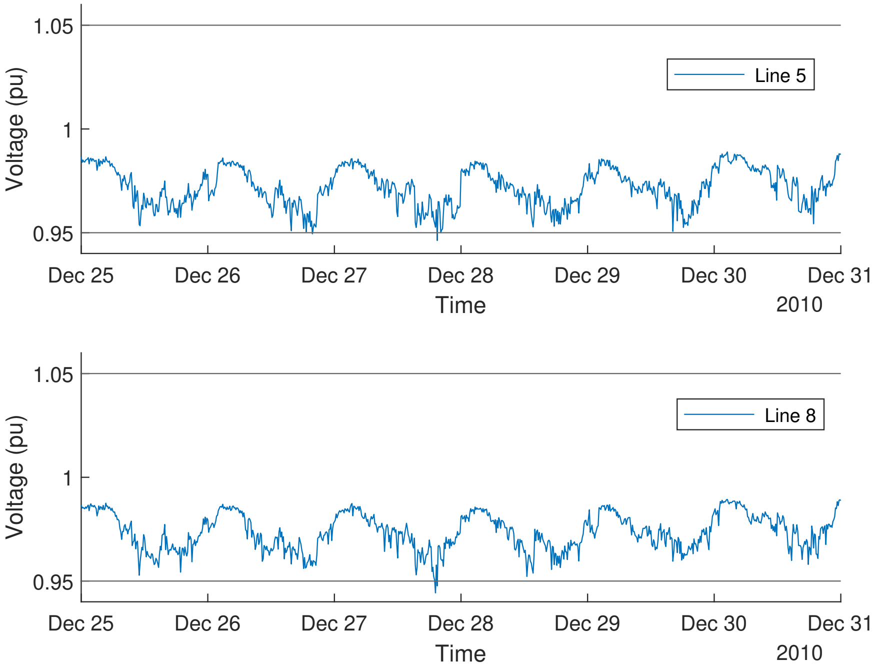


Figure 5.12: EV case measured voltage of lines 5 and 8 of IEEE 13 node test feeder model

5.3 Current Violations Tool

The *Current Violation* tool detects over-current events associated with overhead conductors. When the current value exceeded the ampacity value, the event is recorded. The *Current Violation* tool receives input in the form of a CSV file that included simulated current data. The output generated by the tool is data of current values that have exceeded the ampacity rating. Figure 5.13 shows the input-output diagram of *Current Violation* tool, illustrating the flow of data going into and out of the tool.

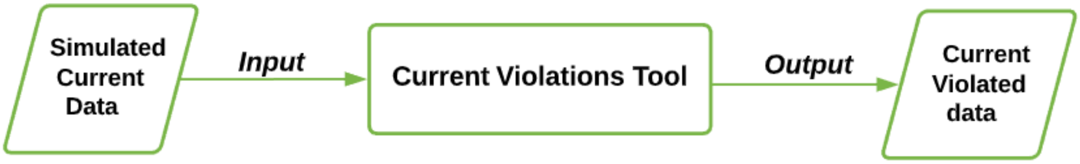


Figure 5.13: Input-output diagram of Current Violation tool

To demonstrate this tool functionality, simulated current data were recorded for node 611, including eight distribution transformers attached to houses. Overhead lines were examined to check the current violation events. Tables 5.2 and 5.3 are a demonstration of over-current events results examined with the rated ampacity of 214 A. Figures 5.14 and 5.15 represent the *Base* and *EV* cases for the simulated current data of lines five, six, seven and eight of node 611.

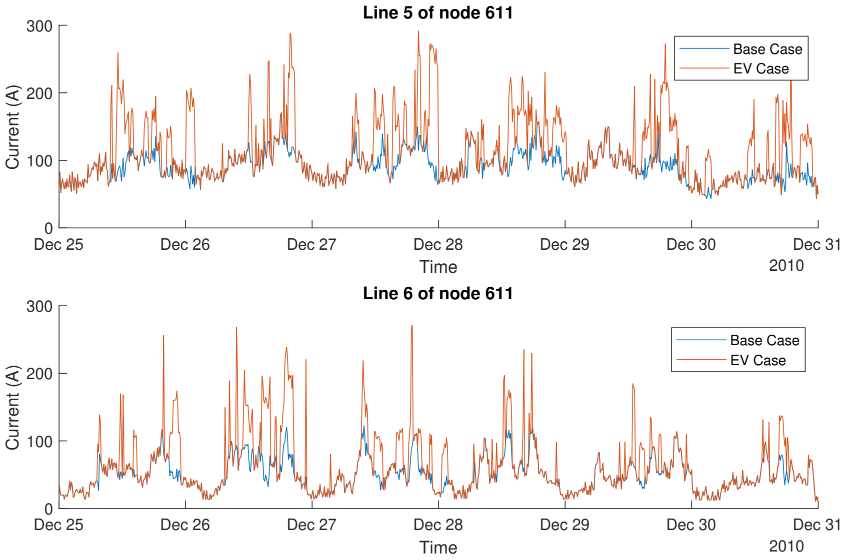


Figure 5.14: EV case measured current of lines 5 and 6 of IEEE 13 node test feeder model

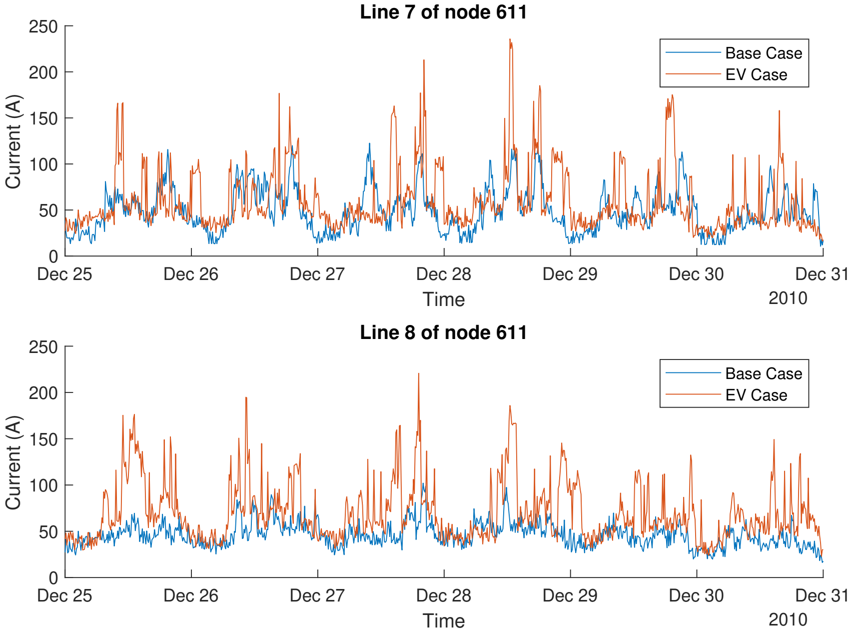


Figure 5.15: EV case measured current of lines 7 and 8 of IEEE 13 node test feeder model

Table 5.2: Line 5 current violation events

Time	**Line**	**Current Violation (A)**
12/25/2010 11:10	Line 5 of Node 611	259
12/25/2010 12:10		220
12/26/2010 12:10		227
12/26/2010 15:40		245
12/26/2010 15:50		248
12/26/2010 18:40		242
12/26/2010 19:30		230
12/26/2010 19:40		222
12/26/2010 19:50		288
12/26/2010 20:00		284
12/26/2010 20:10		237
12/26/2010 20:20		238
12/26/2010 20:30		235
12/26/2010 20:40		229
12/27/2010 19:30		234
12/27/2010 20:10		291
12/27/2010 20:20		255
12/27/2010 20:30		255
12/27/2010 22:20		273
12/27/2010 22:30		264
12/27/2010 22:40		271
12/27/2010 22:50		270
12/27/2010 23:00		264
12/27/2010 23:10		254
12/27/2010 23:20		243
12/27/2010 23:30		266
12/27/2010 23:40		244
12/27/2010 23:50		238
12/28/2010 13:40		223
12/28/2010 15:50		224
12/28/2010 16:00		219
12/28/2010 20:10		230
12/29/2010 16:10		227
12/29/2010 17:00		220
12/29/2010 18:40		216
12/29/2010 19:00		272
12/29/2010 19:20		216
12/30/2010 18:50		270

Table 5.3: Lines 6,7 and 8 current violation events

Time	Line	Current Violation (A)
12/25/10 19:50	Line 6 of Node 611	257
12/26/10 9:40		268
12/26/10 18:50		216
12/26/10 19:00		230
12/26/10 19:10		239
12/26/10 19:20		224
12/26/10 22:50		220
12/27/10 9:40		219
12/27/10 18:50		265
12/27/10 19:00		271
12/28/10 16:10		235
12/28/10 17:40		230
12/28/10 12:30	Line 7 of Node 611	236
12/28/10 12:40		225
12/28/10 12:50		232
12/28/10 13:00		224
12/27/10 19:10	Line 8 of Node 611	221

5.4 Transformer Overloading Tool

The *Transformer Overloading* tool indicates overload condition in distribution transformers when the measured value exceeds the transformer power rating. An event is recorded when the power is exceeded, then the exceeded values are compared to ANSI C57.96 standard. Figure 5.16 shows an input-output diagram. To test the transformer overloading tool, a 100% EV penetration level was added to node 611. Two overloading events were recorded from a total of eight transformers. In a 15 kVA distribution transformer, an overload event occurred for ten and 15 minutes, and of a 20 kVA transformer, an overload condition occurred for half an hour. The output of overloaded transformers events generated from the simulation of Node 611 is shown in Table 5.3.

Figure 5.16: Input-output diagram of Transformer Overloading tool

Table 5.4: Overloaded transformers events

Time	Transformer Rating (kVA)	Measured power (kVA)	Duration (min)
12/26/2010 20:30	15	18.9	15
12/26/2010 19:40		19.3	
12/28/2010 19:40		18.7	10
12/30/2010 19:40		15.7	10
12/25/2010 19:00	20	22.7	30

Figure 5.17 show transformer overloading events. The blue curve represents the measured power of 100% EV penetration. The grey lines at 20 kVA and 15 kVA are transformer rated power.

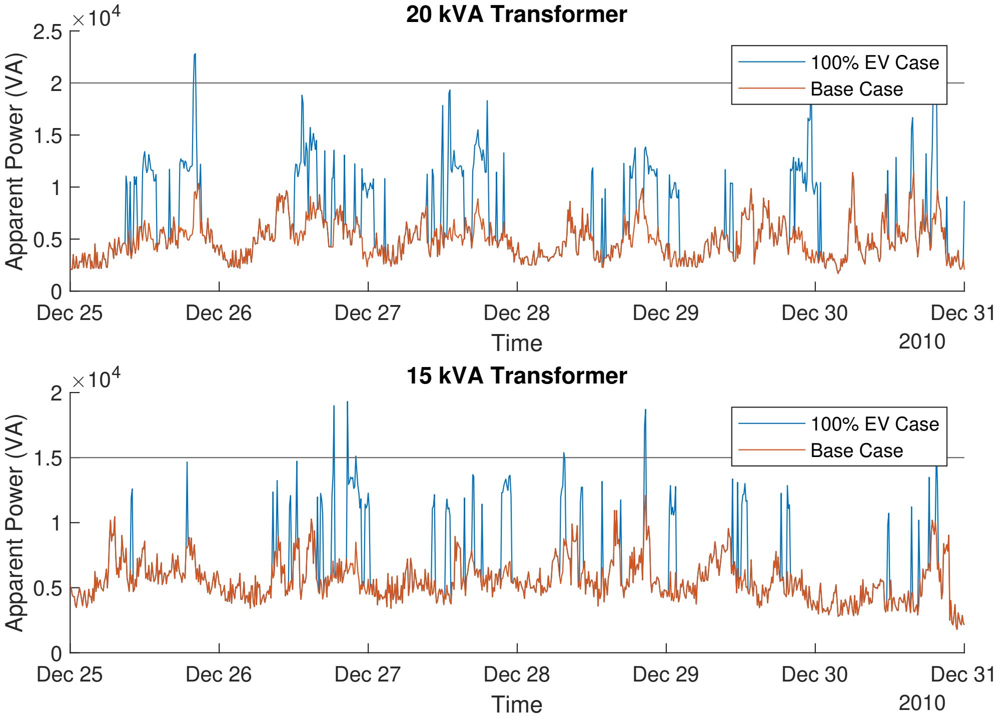


Figure 5.17: 20 and 15 kVA transformers overloading events

6 Discussion

This work aims to develop EV load growth modeling and analysis tools for distribution systems. Three *Power Distribution* tools were developed. Each examines the impacts of EV load growth on power distribution infrastructure assets by three distinct methods. The *Power Distribution* tools indicate voltage drops along distribution lines, reveal current violations along conductors, and detect distribution transformer overloading. The following sections discuss the detailed analysis of the performance and utility for each of the *Power Distribution* tools. With the support of visual aids, the objective of this discussion of analysis is to provide a clear understanding of the proficiency of each of the *Power Distribution* tools in detecting over-current, voltage drops, and transformer overloading events.

The discussion of analysis derives from two simulation test cases, which examine distribution transformers and lines of the IEEE 13 node test feeder model as developed in GridLAB-D. The simulation test cases are *Summer EV Test* case and *Winter EV Test* case. These cases consider single-phase, two-phase, and three-phase nodes of the IEEE 13 node test feeder model.

6.1 Summer EV Test Case

The *Summer EV Test* case uses summer load profiles that replicate a typical energy consumption profile for the mid-western United States and run for a period of one week. The

Summer EV Test case was developed to analyze the impact of EV load growth and to provide tool evaluation comparison with typical summer energy use. Two test analysis conditions were considered in developing a study for examining voltage violation and current violation events. The two test analysis conditions considered are a penetration level of EV ranging from 20% to 100% through a step of 20% and the examination of single-phase and two-phase nodes. The case study results are discussed in the following sections for several nodes of the IEEE 13 node test feeder model. Illustrations of the results are provided to support the major points of analysis.

6.1.1 Voltage Violations Tool

For the *Summer EV Test* case, node 652 was arbitrarily selected from the IEEE 13 node test feeder model to examine the *Voltage Violation* tool results. In this section, the test results are obtained from simulating varying EV penetrations applied to the IEEE 13 node test feeder model. Node 652 is a single-phase node where eight distribution transformers were connected. For this analysis, the EV loads were added at 20 - 100% penetration, incremented by 20% for each simulation.

The *Voltage Violation* tool was applied to the IEEE 13 node test feeder model simulation output data. The base case with no EV load added is shown in Figure 6.1. The results show at 20% EV penetration no voltage violation are detected by the *Voltage Violation* tool. However, at 40% EV penetration the tool detects two violations, as shown in Figure 6.2.

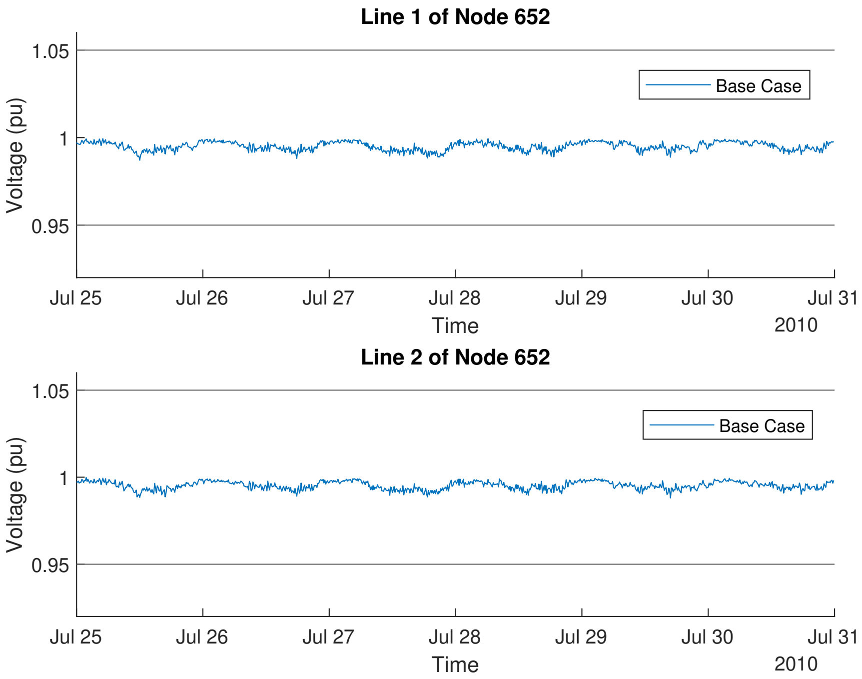


Figure 6.1: Base case of Lines 1 and 2 of Node 652 with no EV loads

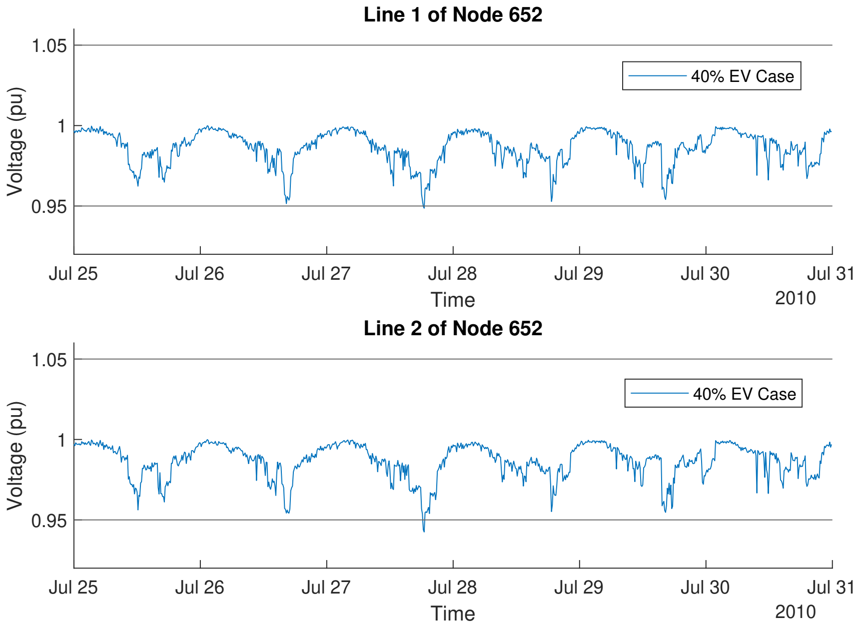
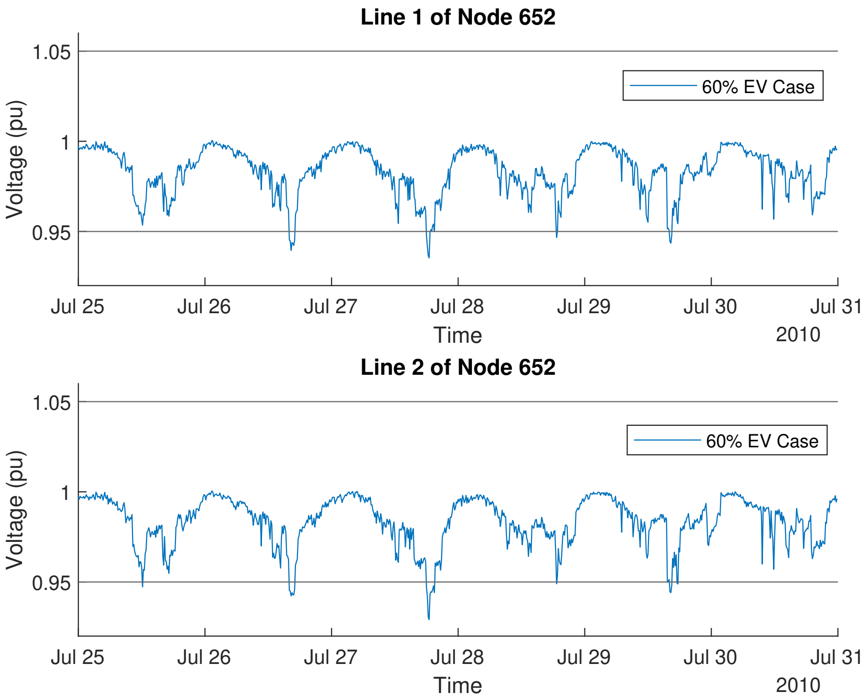


Figure 6.2: Voltage violation detected in lines 1 and 2 of Node 652 with 40% EV

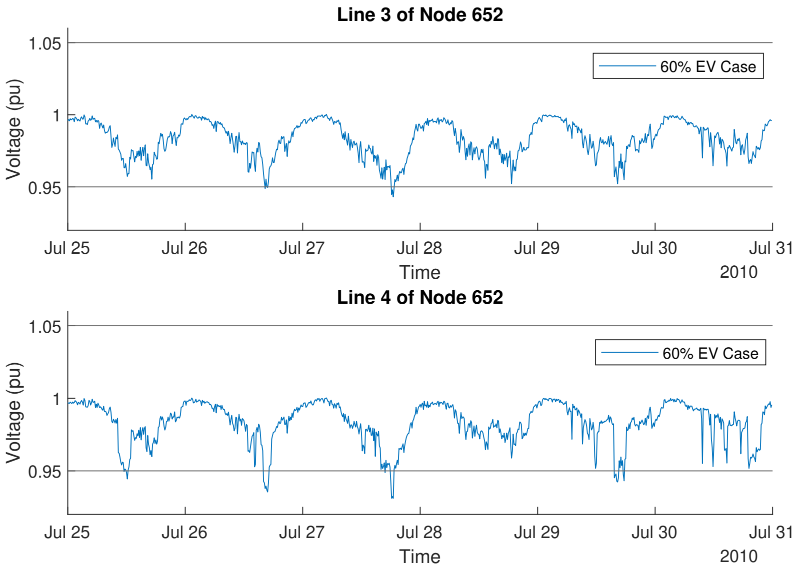
The lines depicted in the plots shown in Figure 6.2, Line 1 and Line 2, serve seven households each. EV loads were randomly distributed among the households. The blue curve represents load including aggregated EV penetration at 40%. The grey lines at 0.95 and 1.05 are the voltage thresholds for detecting voltage violation events. Between July 27 and July 28, the *Voltage Violation* tool detects one voltage violation for both lines occurring ten minutes apart. These results reveal that with only 40% EV load penetration, the service lines exceed the threshold provided by ANSI standards during the detected voltage violations.

As the percentage of EV penetration level increases, the *Voltage Violation* tool detects an increasing number of voltage violations, given all other parameters stay the same. At node 652 and with just 60% EV penetration, four out of eight service lines experienced voltage violation events during this simulation, which means service voltage violation occur on 50% of lines. Figures 6.3 and 6.4 show voltage violations on Lines 1 - 4 that occurred with 60% EV penetration.


Line 1 of Node 652

Line 2 of Node 652

Figure 6.3: Voltage violation detected in lines 1 and 2 of Node 652 with 60% EV


Line 3 of Node 652

Line 4 of Node 652

Figure 6.4: Voltage violation detected in lines 3 and 4 of Node 652 with 60% EV

In order to better represent the *Voltage Violation* tool detected events, a histograms plot is created for the voltage violation events at node 652. Figure 6.5 shows the histograms of the voltage drop events associated with node 652. From these histogram, it is obvious that when the EV penetration increases, the occurrence and duration of voltage violation increase.

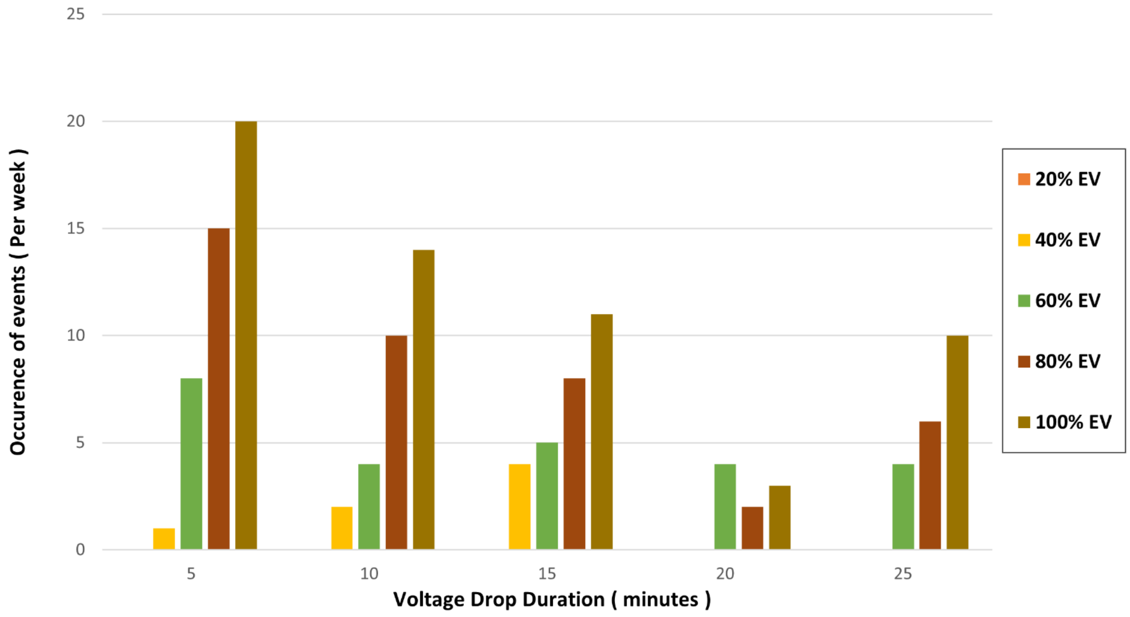


Figure 6.5: Voltage violation events histogram at Node 652

The *Voltage Violation* tool results along with simulation data reveal that as EV penetration levels increase, voltage violation events increase on the IEEE 13 node test feeder model as illustrated using node 652 for this test case. Figures 6.6 and 6.7 represent Line 1 voltage violation events, in which 20% - 100% EV penetration are examined. The occurrence of voltage drops outside the acceptable range poses a significant risk to distribution infrastructure assets, possibly leading to premature equipment failure. Thus, evaluation of the impacts due to projected EV load growth is essential to evaluate, and the *Voltage Violation* tool is a simple means to analyze and detect voltage violation events.

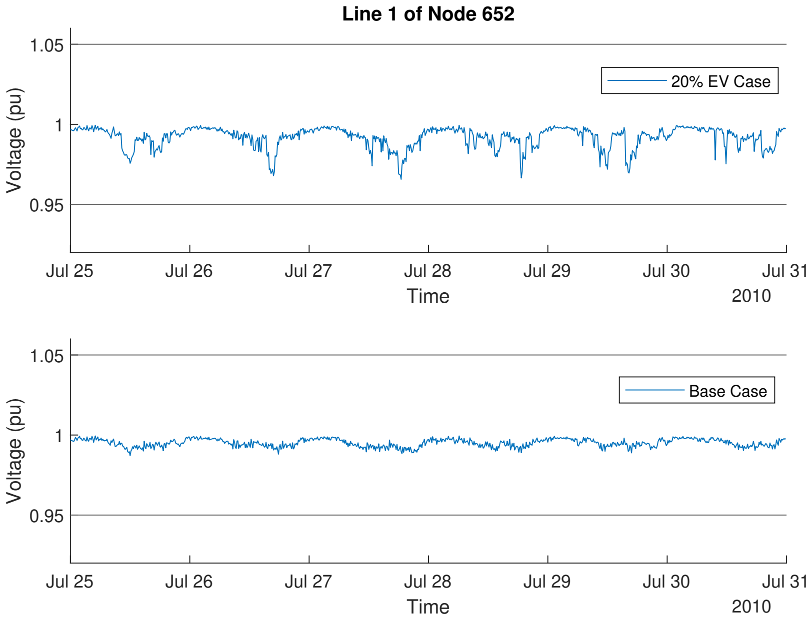


Figure 6.6: 20% EV with no voltage violation compared with base case with no EV in line 1 of Node 652

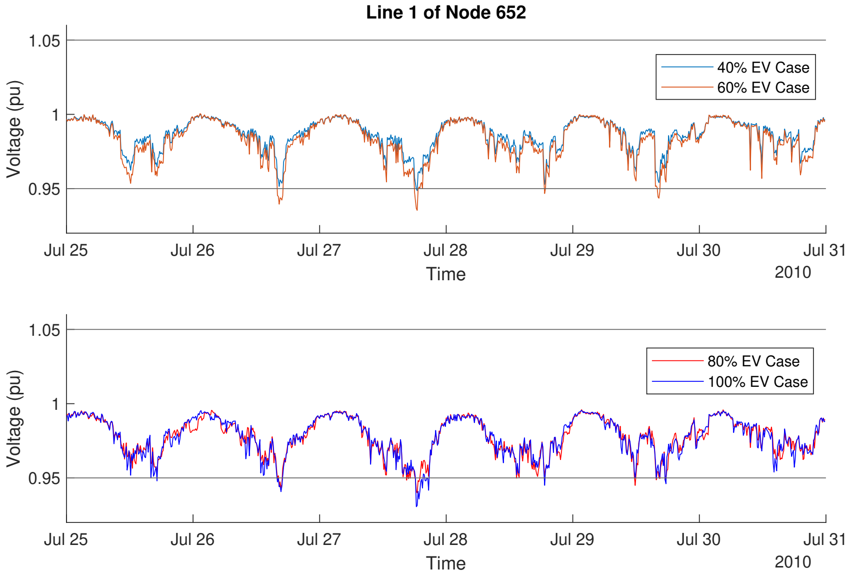


Figure 6.7: Voltage violations detected in line 1 of Node 652 with 40% - 100% EV

6.1.2 Current Violations Tool

Node 646 was chosen from the IEEE 13 node test feeder model to test *Current Violation* tool results. Test results are gathered from simulating different EV penetration levels applied to the IEEE 13 node test feeder. Node 646 is a two-phase node. In each phase, eight distribution transformers are connected with 34 households distributed along phase B and 43 households distributed along phase C. The test case examines only phase B. For analysis purposes, 20% - 100% penetrations of EV loads were again examined.

The *Current Violation* tool was applied to the IEEE 13 node test feeder model simulation output data. The results of node 646 phase B show at 20% EV penetration no current violation events are detected by the *Current Violation* tool. But, at 40% EV penetration multiple events are detected. Figures 6.5 and 6.6 depict the recorded current violation events. The grey line in the Figures represents the rated conductor ampacity value, for reference to the IEEE 13 node test feeder model simulation output data. The rated ampacity capacity value is 214 A, which is the ampacity of 1/0 AWG AAC. Between July 27 to July 29, several events are detected by the *Current Violation* tool. Line 1, which serves five houses, has the highest number of current violation events: five EV loads were attached to the five households. As shown in Figures 6.8 and 6.9, fewer current violation events were detected on Line 5 and Line 6.

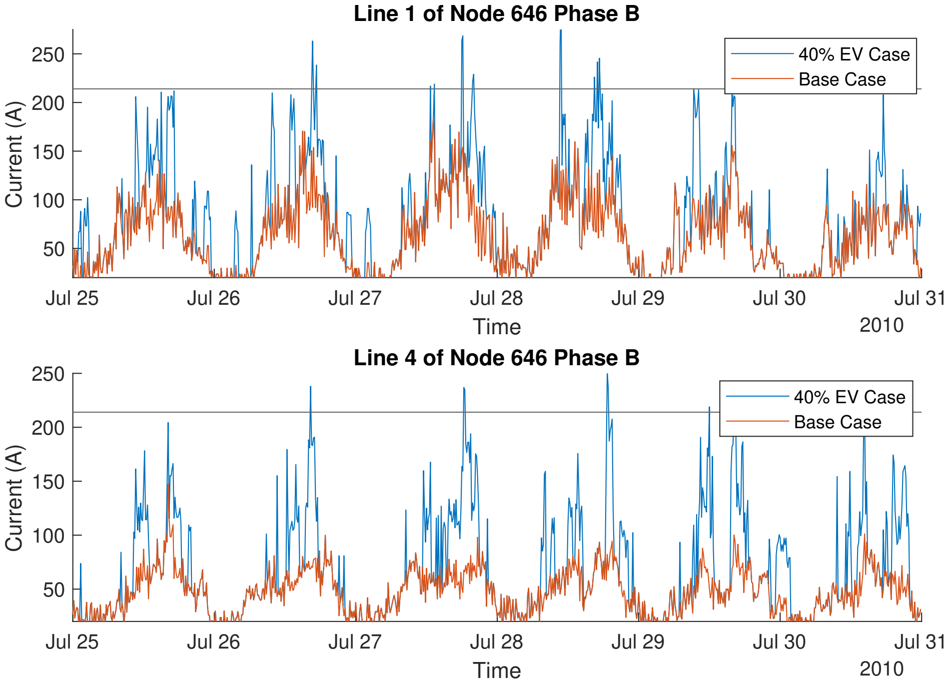


Figure 6.8: Current violations detected in lines 1 and 4 of Node 646 with 40% EV

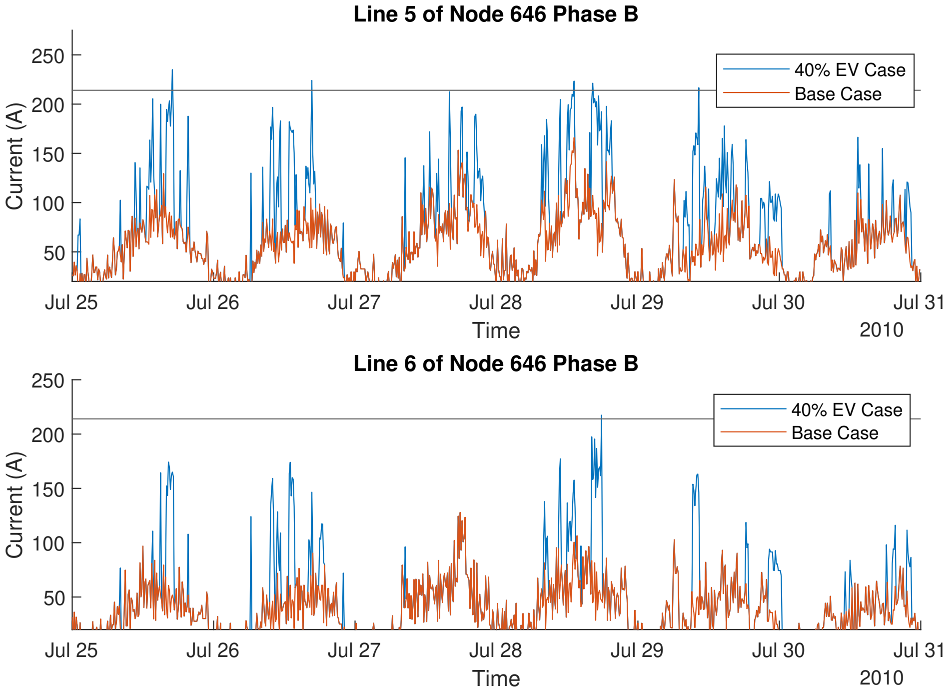


Figure 6.9: Current violations detected in lines 5 and 6 of Node 646 with 40% EV

As the penetration of EV level increases, more current violation events are recorded by the *Current Violation* tool. At 60% EV penetration, several events are detected. Figures 6.10 and 6.11 show the current violation events for four lines. These results illustrate that at 60% EV penetration, most of the lines have current violations. These occur for about 20 minutes maximum. As a result, appropriate action could be recommended to resize conductors to avoid overheating conditions, which may exist due to the anticipated load growth.

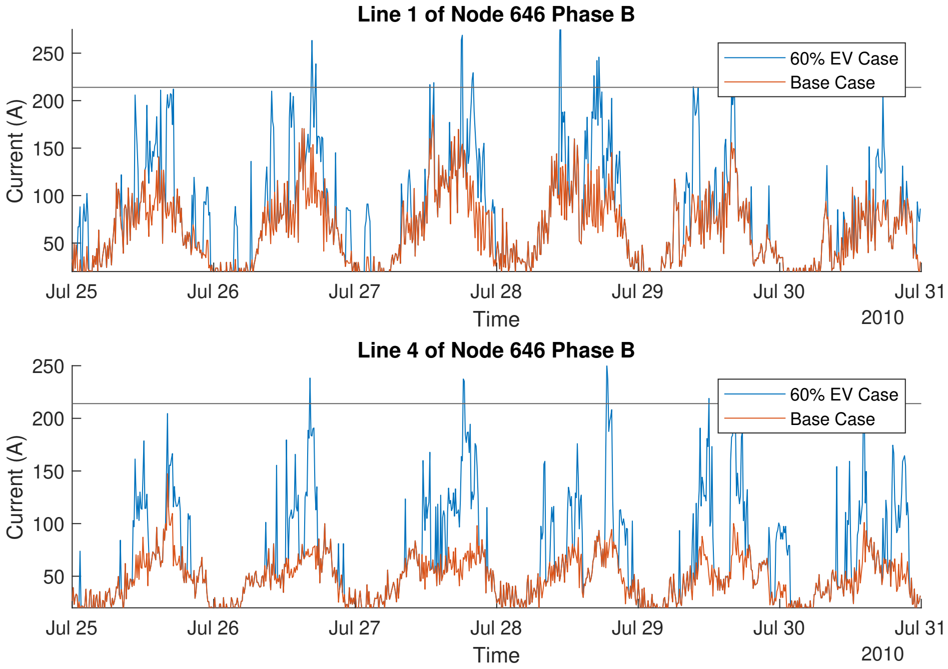


Figure 6.10: Current violations detected in lines 1 and 4 of Node 646 with 60% EV

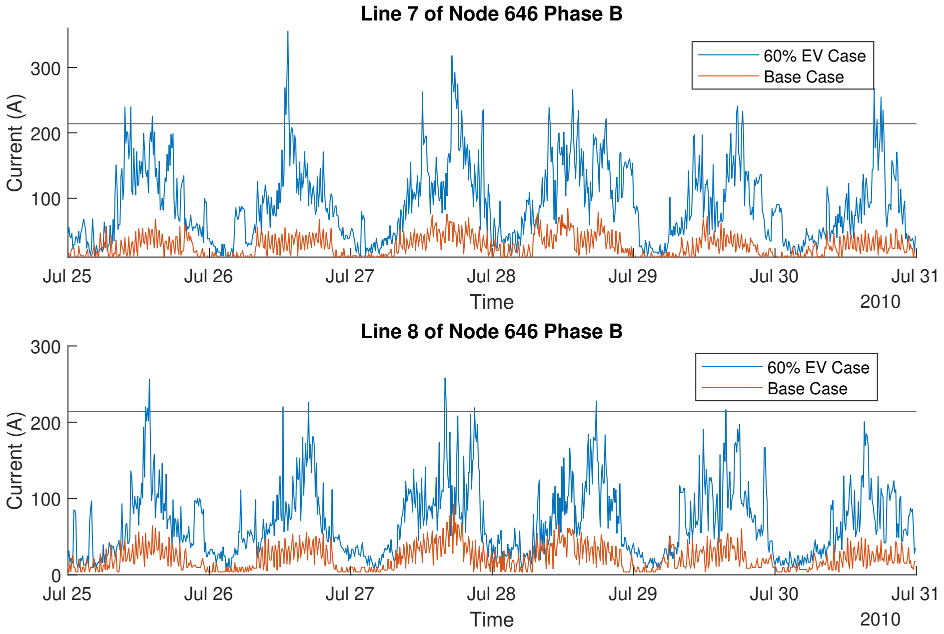


Figure 6.11: Current violations detected in lines 7 and 8 of Node 646 with 60% EV

Furthermore, at node 646 phase B with 80% EV penetration, six out of eight lines were found to have current violations. About 75% of the total lines are experiencing current violations issue. Figures 6.12 - 6.14 show these events within the affected lines. From the simulated results, Line 8 experienced the lonest duration of current violation events, for about 30 minutes. The maximum simulated current value was 296 A, which is about 138% of the ampacity capacity value.

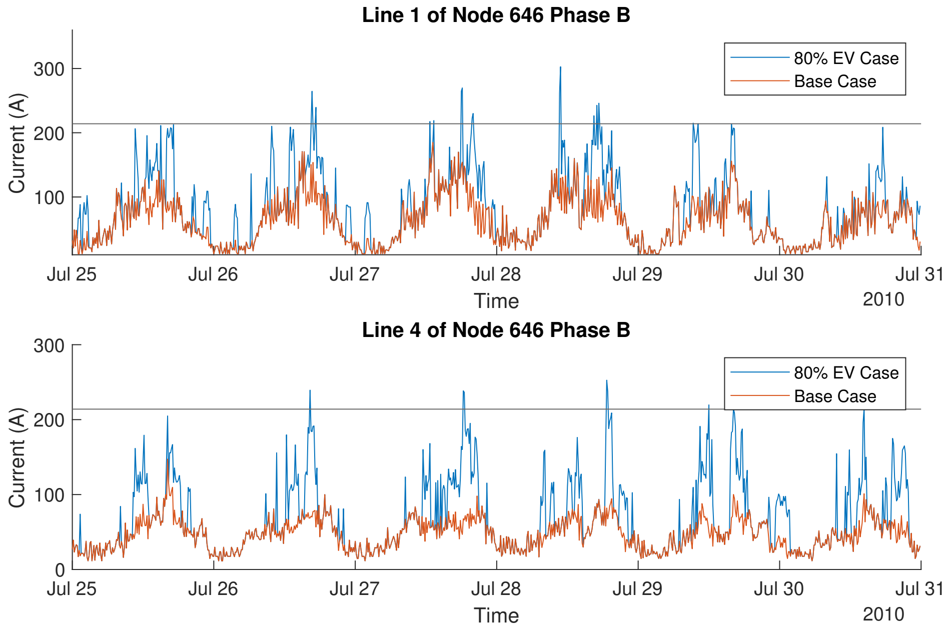


Figure 6.12: Current violations detected in lines 1 and 4 of Node 646 with 80% EV

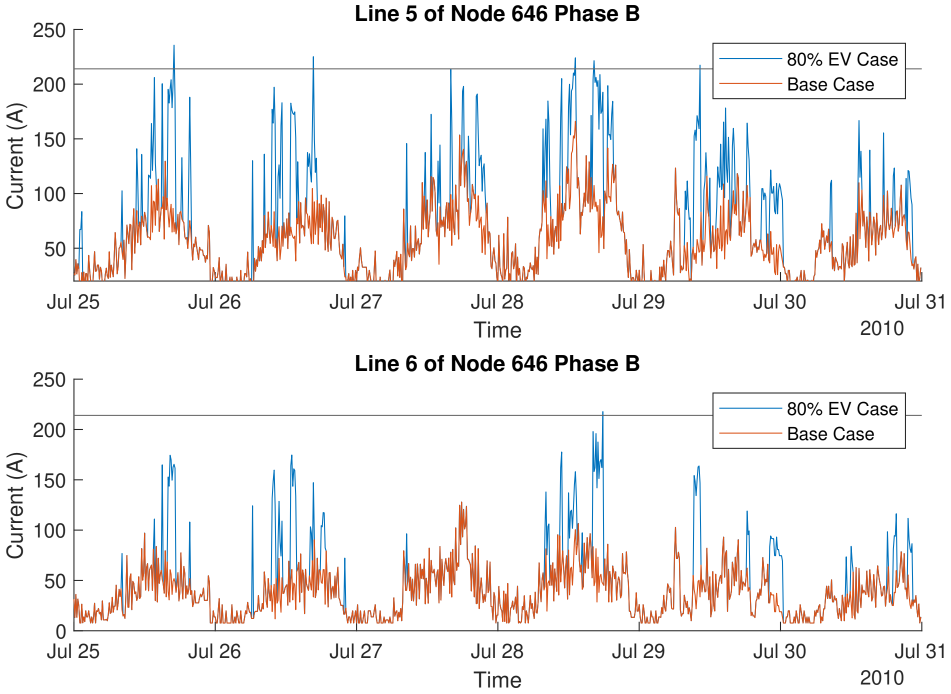


Figure 6.13: Current violations detected in lines 5 and 6 of Node 646 with 80% EV

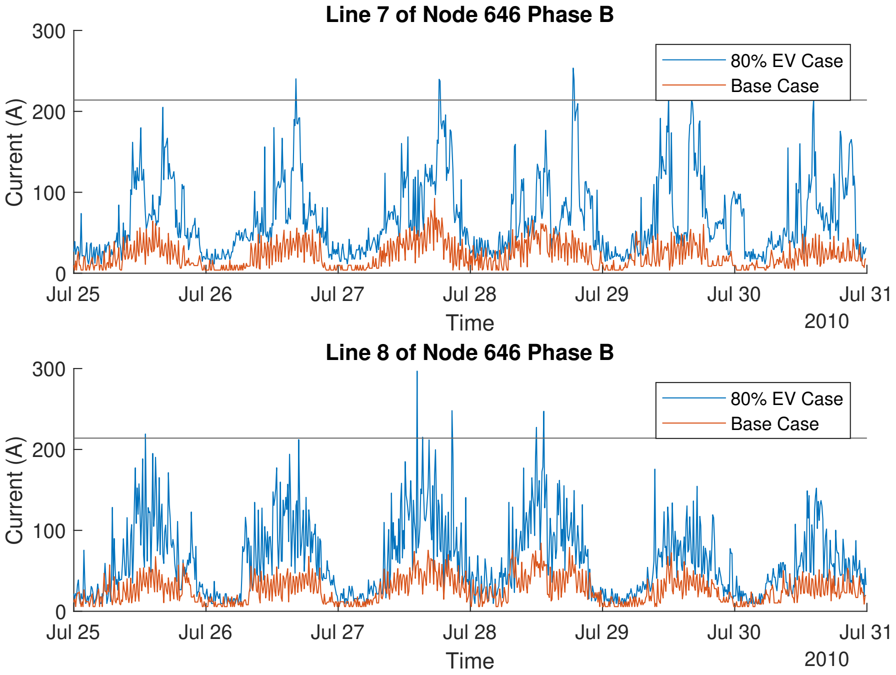


Figure 6.14: Current violations detected in lines 7 and 8 of Node 646 with 80% EV

The *Current Violation* tool results with the simulation test cases showed that as EV penetration level increases, so do the number and duration of current violation events at the distribution overhead lines examined on the IEEE 13 node test feeder as presented using node 646. The occurrence of current violations on the overhead conductors poses a major issue in distribution system infrastructure assets. To maintain grid reliability and customer safety, the current should be at or below the rated conductor ampacity. When the conductor current exceeds the ampacity value, the conductor will overheat, leading to decrease asset lifetime, power loss, and excessive voltage drops. Consequently, evaluating the impact of projected EV load growth is essential for preparing distribution system to provide service to EV owners. The *Current Violation* tool is a simple means to analyze and detect current violations events using simulation data.

6.2 Winter EV Test Case

The *Winter EV Test* case uses the winter load profiles. These represent typical energy consumption for the mid-western United States and run for a period of one week. The *Winter EV Test* case was considered to analyze the impact of EV load growth and to present tool evaluation comparison with winter energy use. While developing the *Winter EV Test* case, three conditions were considered. First, a test case was developed for examining transformer overloading events. Second, penetration levels of EV ranging from 20% to 100% were examined. Test cases focused on three-phase nodes of the IEEE 13 node test feeder model. In the following sections, an illustration of the test results are demonstrated to support the major of the analysis.

6.2.1 Transformer Overloading Tool

For the *Winter EV Test* case, node 692 was chosen from the IEEE 13 node test feeder model to test the *Transformer Overloading* tool. Node 692 is a three-phase node. Seven distribution transformers are attached to each phase. Distribution transformers are rated between 15 - 35 kVA, at increments of 5 kVA. For this case analysis, EV loads were added gradually by 20% for each simulation test.

The *Transformer Overloading* tool was applied to the IEEE 13 node test feeder model. This test case applied to phase A,B and C of node 692. Phase A of node 692 is connected to seven transformers and serve total of 38 household.

At 20% EV penetration, results showed no transformer overloading events. However, at 40% the *Transformer Overloading* tool detected events occurred for 30 minutes and an hour. Additional events were examined at 60% EV penetration. Four distribution transformers were overloaded for two hours, six overloading events were detected for an hour, and 16 transformer overloading events were detected for 30 minutes. In summary, higher EV penetration leads to a greater number of duration overloading events. To better identify distribution transformer overloading events, histograms are examined. Figure 6.15 represent histograms plot of node 692 A. These histograms highlight the duration of transformer overloading events and the occurrence for each duration. Histograms presented in Figure 6.15 show the duration of 30 minutes to four hours events. However, 30 minutes overloading events are not of concern, due to the short period of these events. Events were examined to the reference of ANSI and IEEE standard [4]. Therefore, one-half hour events can deliver 200% load of the nameplate rate without damaging the transformer.

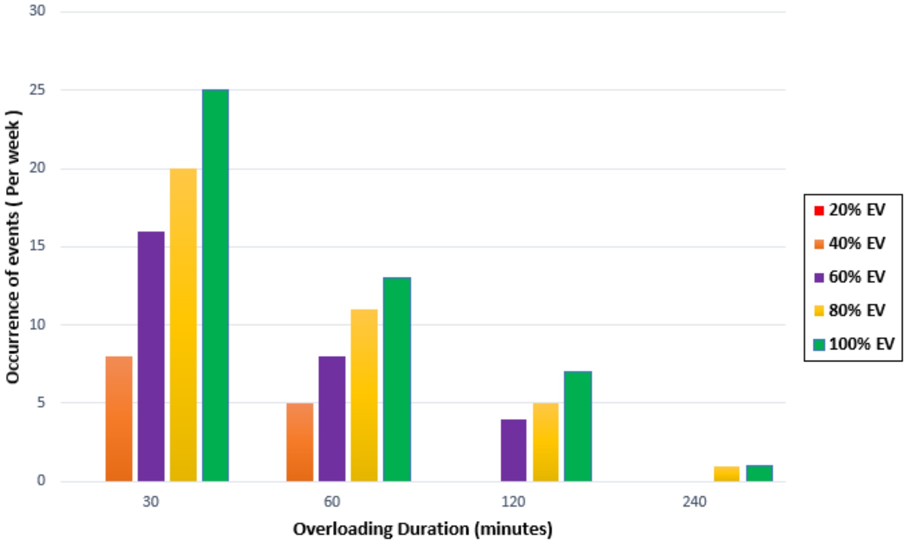


Figure 6.15: Transformer overloading events histograms at Node 692 phase A

The same testing procedures applied to phase A of node 692 are used to phase B, and C. A total of 114 households are attached to node 692, in which 38, 35 and 41 houses are connected to phase A, B, and C, respectively. Histograms of transformer overloading events of phase B and C show that with large EV penetrations have more overloading events and for longer duration, as shown in Figures 6.16 and 6.17. Test results lead to the conclusion that the impact of EV load growth on distribution transformer overloading events gradually increase as the EV penetration increases.

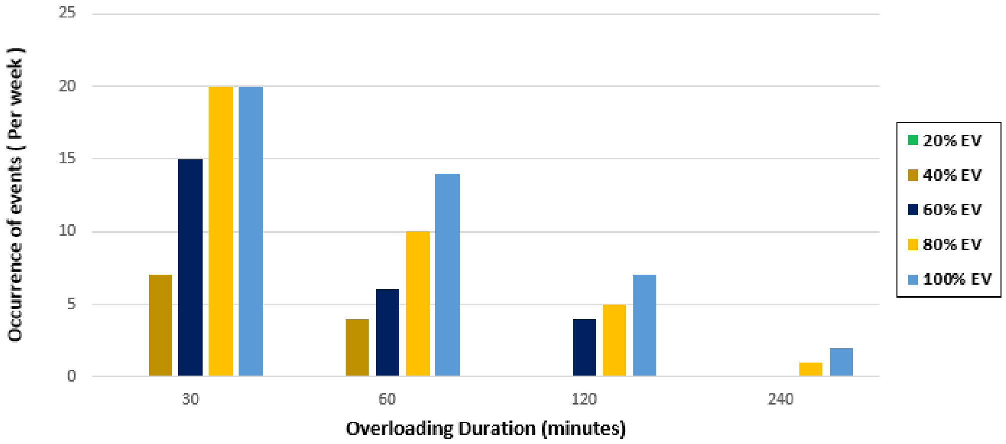


Figure 6.16: Transformer overloading events histograms at Node 692 phase B

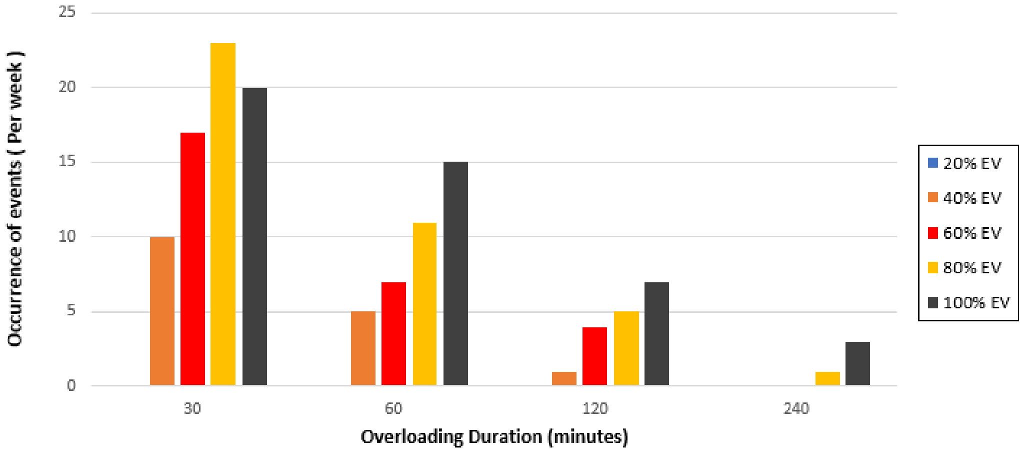


Figure 6.17: Transformer overloading events histograms at Node 692 phase C

7 Conclusion

This thesis motivation was to develop tools for analyzing the impacts of projected EV load growth. A suite of tools was successfully developed to model the impact of EV loads on power distribution infrastructure assets. These tools indicate voltage violations within a distribution network, detect over-current violation events associated with overhead conductors, and reveal distribution transformer overload events. These tools were developed for use in GridLAB-D and written using Python 3.8. Such tools can be used to help utility distribution planners prepare appropriate responses for the anticipated EV load growth.

When EV load growth increases, power distribution lines and transformers are impacted. The tools developed for this thesis showed evidence that at only 40% - 60% penetration, distribution transformers become overloaded, distribution lines experience voltage violation events, and conductors exceed the rated ampacity. Thus, planner engineers can use these tools to study and analyze EV load growth impact and then take appropriate actions.

Several opportunities for future improvement are possible to enhance analyzing EV load growth impact on power distribution infrastructure assets. One possible improvement is to use Hierarchical Engine for Large-scale Infrastructure Co-Simulation (HELICS) to enable bringing together multiple existing software tools. For example, one could develop distribution feeder in GridLAB-D and then integrated with Python or a C++ compiler to control the tool during simulation. Another possible opportunity is to simulate DCFC. This improvement would help utilities to examine the commercial side of their assets particularly high-power EV chargers. A final improvement opportunity would be developing a tool that examines the impact of the harmonic distortion in the conductors. However, GridLAB-D may not be the optimal platform for such analysis.

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Appendix A: Tables

A.1 Transformers and houses distributed along IEEE 13 node test feeder

A.1.1 Single phase node

IEEE 13 Nodes	Phase	Transformer Rating (kVA)	Number of Houses
Node 652	A	35	7
		35	7
		30	6
		35	7
		30	6
		20	4
		35	7
		15	3

IEEE 13 Nodes	Phase	Transformer Rating (kVA)	Number of Houses
Node 645	B	15	5
		25	3
		25	4
		15	6
		15	7
		25	5
		20	4
		35	5
	C	30	6
		25	5
		25	5
		35	7
		15	3
		35	7
		20	4
		30	6

A.1.2 Two phase nodes

IEEE 13 Nodes	Phase	Transformer Rating (kVA)	Number of Houses
Node 684	A	30	6
		35	7
		30	6
		35	7
		20	4
		15	3
		35	7
		30	6
	C	15	3
		35	7
		15	3
		25	5
		15	3
		15	3
		20	4

IEEE 13 Nodes	Phase	Transformer Rating (kVA)	Number of Houses
Node 646	B	25	5
		15	3
		20	4
		30	6
		30	6
		20	4
		15	3
		15	3
	C	20	4
		35	7
		30	6
		15	3
		30	6
		35	7
		25	5
		25	5

A.1.3 Three phase nodes

IEEE 13 Nodes	Phase	Transformer Rating (kVA)	Number of Houses
Node 632	A	20	4
		35	7
		15	3
		20	4
		30	6
		25	5
		35	7
		20	4
	B	25	5
		35	7
		25	5
		35	7
		25	5
		35	7
		20	4
		35	7
	C	25	5
		30	6
		15	3
		25	5
		20	4
		35	7
		30	6
		30	6

IEEE 13 Nodes	Phase	Transformer Rating (kVA)	Number of Houses
Node 692	A	15	3
		30	6
		25	5
		30	6
		35	7
		25	5
		30	6
	B	25	5
		15	3
		30	6
		30	6
		15	3
		30	6
		30	6
	C	20	4
		25	5
		35	7
		35	7
		35	7
		35	7
		20	4

IEEE 13 Nodes	Phase	Transformer Rating (kVA)	Number of Houses
Node 675	A	25	5
		25	5
		30	6
		30	6
		15	3
		35	7
		25	5
	B	25	5
		25	5
		30	6
		25	5
		30	6
		30	6
		30	6
	C	35	7
		15	3
		20	4
		30	6
		20	4
		15	3
		30	6

IEEE 13 Nodes	Phase	Transformer Rating (kVA)	Number of Houses
Node 671	A	20	4
		35	7
		15	3
		25	5
		35	7
		20	4
		20	4
	B	25	5
		20	4
		30	6
		35	7
		35	7
		20	4
		20	4
		25	5
	C	30	6
		25	5
		15	3
		30	6
		35	7
		25	5
		35	7

IEEE 13 Nodes	Phase	Transformer Rating (kVA)	Number of Houses
Node 680	A	35	7
		15	3
		30	6
		15	3
		30	6
		30	6
		20	4
	B	30	6
		15	3
		30	6
		30	6
		20	4
		20	4
		30	6
		30	6
	C	30	6
		35	7
		20	4
		25	5
		30	6
		20	4
		20	4

A.2 Python Code

A.2.1 Voltage Violation Tool

```
## This code is for checking Voltage Violations with ANSI C84.1
   standard:
## [114V] ---- [120V] ---- [126V] +/-5%
## Ask the user which standard?
## Input file >> CSV of Timestamp and Simulated measured voltage
## Output >> Voltage Violations Events, If no Voltage Violations
   detected, No # WARNING:
import pandas as pd
import numpy as np
def ansic84():
   '''
      handles ansic84
   '''
   ideal = minLimit = maxLimit = 120
   maxLimit += ideal * 0.05
   minLimit -= ideal * 0.05
   dev = {}
   f = input("enter file name: ")
   try:
```

```
    csv =
        pd.read_csv(f,skiprows=range(0,7),error_bad_lines=False)
    csv.rename({'#
        timestamp':'timestamp'},axis='columns',inplace=True)
    # change values
    for i in csv.columns[1:]:
        csv[i] = csv[i].str.replace('d','j')
        csv[i] = csv[i].apply(lambda x:np.complex(x).real)
        csv[i] = pd.to_numeric(csv[i])
        dev[i+'_min'] = csv[csv[i]<=minLimit] # check for values
            below minLimit
        dev[i+'_max'] = csv[csv[i]>=maxLimit] # check for values
            above maxLimit
        if dev[i+'_min'].empty:
            dev[i+'_min'] = 'NO WARNING'
        if dev[i+'_max'].empty:
            dev[i+'_max'] = 'NO WARNING'
        # print( dev[i+'_max'])
    for k,v in dev.items():
        print(f'{"-"*20}{k}{"-"*20}')
        print(v)
    print(f"ideal: {ideal} ; max: {maxLimit} ; min: {minLimit}")
except Exception as e:
```

```
      print(e)
      print("-"*5+">Error occured\nexiting...")
      exit()
   return
def main():
   stds = {1:'ANSIC84'}
   funcs = {'ANSIC84':ansic84}
   print("enter your desired standard:")
   std = int(input("[1] - ANSI C84\n[2] - XX\n"))
   if not std in stds:
      print("-"*5+">Not a supported standard\nexiting...")
      exit()
   print(f"you entered {std} : {stds[std]}")
   '''
      call ansi
   '''
   std = stds[std]
   funcs[std]()
if __name__=="__main__":
   main()
   exit()
```

A.2.2 Current Violation Tool

```python
## This code is for checking Current Violations of Overhead conductors
## Input Files : >> CSV of Timestamp and Simulated measured current
## Output >> Current Violations Events, Current exceeded amapcity rating and % of Violations

'''
   *** THIS FILE NEEDS TO BE IN A DIRECTORY WITH ONLY THE FILES TO BE PARSED ***
'''
import pandas as pd
import numpy as np
import os

DIR = '.' # directory where csv files are stored
VALUE = # value to check against for values greater than
output_file = 'output.csv'
outs = {}
files = os.listdir(DIR)
files = filter(lambda x: x.endswith('.csv'),files)
def convert_complex(c):
```

```
    x = c.real
    y = c.imag
    return np.sqrt(x*x+y*y)
def fun(value):
    percentage = (value/VALUE) *100
    return f'{round(percentage,3)}%'


for f in files:
    try:
        csv = pd.read_csv(f,skiprows=range(0,7))
        csv.set_index(csv.columns[0],inplace=True)
        for col_name in csv.columns[1:]:
            col = csv[col_name].str.replace('d','j').str.replace('
                ','').apply(lambda x:
                np.complex(x)).rename('complex')
            converted = col.apply(lambda x:
                convert_complex(x)).rename('converted')
            percentage = converted.apply(lambda x:
                fun(x)).rename('percentages')
            df = pd.concat([col,converted,percentage],axis=1)
            df = df[df['converted'] >= VALUE]
            outs[col_name] = df
    except Exception as e:
```

```
      print(e)

with open(output_file,'w') as f:

   for k,v in outs.items():

      f.write(f"{'-'*20} {k} {'-'*20}\n")

      f.write(v.to_csv())
```

A.2.3 Transformer Overloading Tool

```
'''
## This code is for checking Overloading transfomers conditions
## Input Files : >> CSV of Timestamp and Simulated measured Power
## Output >> Overloaded Transformers depend on % of Overloaded
   condition provided with the duration of Overloading
'''
import pandas as pd
import argparse
import time
import numpy as np
import os
def get_power_rates(cols):
   power_rates = []
   # compare against the given Y value
   for i in cols:
      power_rates.append(float(input(f"enter {i} Power Rate: ")))
   return power_rates
def get_file_names():
   files = []
   for c in cols:
      files.append(input(f"enter name of output file for {c}: "))
```

```
    return files
def query_csv():
    vals = []
    for y,c in zip(power_rates,cols):
        vals.append(csv.query(f"`{c}` >= {y}"))
    return vals
def first_version():
    '''
    first verison just writes the query results to their respective files
    '''
    for v,f,c in zip(query_results,output_files,cols):
        v[["# timestamp",f"{c}"]].to_csv(f"{f}",index=False)
    return
def query(df, col, t_delta, ep, pr,step):
    sz = csv.shape[0]
    res = []
    result = []
    df = csv[['# timestamp',col,'timestamp']] # change from csv to df
    i = 0
    steps = pd.Timedelta(step,unit='m')
    if i<sz:
```

```
        prev = df.loc[0]
    while i < sz:
        cur = df.loc[i]
        if cur['timestamp'] == (prev['timestamp'] + steps) and
            (abs(cur[col] - pr) <= ep) and (abs(prev[col] - pr) <=
            ep):
            res.append(prev)
            if t_delta/step == len(res):
                res.append(cur)
                result.append(res)
                res = []
        else:
            res = []
        prev = cur
        i += 1
    return result
def open_file(FILE):
    csv = pd.read_csv(FILE)
    cols = csv.columns[1:]
    csv['timestamp'] = pd.to_datetime(csv['# timestamp']) #
        convert normal timestamp format to datetime timestamp
    csv['timestamp'].apply(lambda x: time.mktime(x.timetuple())) #
        converts datetime timestamp to unix timestamp
```

```
    return (csv,cols)
def second_version(csv):
    '''
    200% ----------------- 30 minutes
    150% ----------------- 1 hour
    125% ----------------- 4 hours
    others ----------------- remaining
    second version checks for time constraints before writing the
        query results to their respective files
    '''
    specs = {} # these specs define the previously stated rules
    # query for the 1.25 === %125
    # there will be only 1 column (besides timestamps) & 1
        power_rate for the column
    pr = power_rates[0]
    col = cols[0]
    # ------------- 200% -------------
    x = 2 * pr
    # 10% of x
    ep = 0.1 * x
    print(f"{50*'-'} calculating 200% {50*'-'}")
    res = query(csv,col,30 ,ep,x, 10) # 30 minutes and 10 minutes
        step ( in case that changes in the future)
```

```
if len(res) > 0:
   res = sum(res,[])
   df = pd.DataFrame(res)
   print(df)
   specs[f"#{50*'-'} {FILE}--(200%) {50*'-'}"] = df
# ------------- 150% -------------
x = 1.5 * pr
# 10% of x
ep = 0.1 * x
print(f"{50*'-'} calculating 150% {50*'-'}")
res = query(csv,col,60 ,ep,x, 10) # 60 minutes and 10 minutes
   step ( in case that changes in the future)
if len(res) > 0:
   res = sum(res,[])
   df = pd.DataFrame(res)
   print(df)
   specs[f"#{50*'-'} {FILE}--(150%) {50*'-'}"] = df
# ------------- 125% -------------
x = 1.25 * pr
# 10% of x
ep = 0.1 * x
print(f"{50*'-'} calculating 125% {50*'-'}")
```

```
    res = query(csv,col,240 ,ep,x, 10) # 240 minutes and 10
        minutes step ( in case that changes in the future)
    if len(res) > 0:
        res = sum(res,[])
        df = pd.DataFrame(res)
        print(df)
        specs[f"#{50*'-'} {FILE}--(125%) {50*'-'}"] = df
    return specs
def write_output(fname,output):
    if os.path.exists(fname):
        os.remove(fname)
    for DICT in output:
        if DICT:
            for k,v in DICT.items():
                with open(fname,'a+') as f:
                    f.write(k+'\n')
                del v['timestamp']
                v.to_csv(fname,mode='a',index=False)
    return


parser = argparse.ArgumentParser(description='.')
parser.add_argument('-f', type=str, help='input file
    name',default='')
```

```
parser.add_argument('-d', type=str, help='input dir
   name',default='')
parser.add_argument('-m', type=int, help='mode of operation (0:
   old version; 1: percentage mode)', default=1)
args = parser.parse_args()
FILE = args.f # grab file name
mode = args.m # grab the mode (version of file)
DIR = args.d # grab dir
if FILE == '' and DIR=='':
   parser.print_help()
   exit(0)

if mode == 0:
   if FILE == '':
      parser.print_help()
      exit(0)
   (csv,cols) = open_file(f'{FILE}')
   power_rates = get_power_rates(cols) # get power rates
   query_results = query_csv()
   output_files = get_file_names()
   # change columns to floats
   for i in cols:
      csv[f"{i}"] = csv[f"{i}"].astype(float)
```

```python
    first_version()
elif mode == 1:
    output = []
    if DIR == '':
        parser.print_help()
        exit(0)
    # read all files in the given directory
    if DIR[-1] != '/':
        DIR += '/'
    for FILE in os.listdir(DIR):
        print(f"{'*'*50} {FILE} {'*'*50}")
        (csv,cols) = open_file(f'{DIR}{FILE}')
        power_rates = get_power_rates(cols) # get power rates
        res = second_version(csv)
        output.append(res)
    write_output('output.csv',output)
    # second_version()
```

A.3 IEEE 13 Node Test Feeder Model in GridLAB-D

A.3.1 Input Data Files

Season	**Load profile**
Summer	Households
	Households + EV
Winter	Households
	Households + EV

A.3.2 Glm Files

Summer Cases	
Cases	**Cases information**
Summer Base Case	Base case GridLab-D model configuration with no EV
20% EV Case	EV case with 200 EVs
40% EV Case	EV case with 400 EVs
60% EV Case	EV case with 600 EVs
80% EV Case	EV case with 800 EVs
100% EV Case	EV case with 1000 EVs

Winter Cases	
Cases	**Cases information**
Winter Base Case	Base case GridLab-D model configuration with no EV
20% EV Case	EV case with 200 EVs
40% EV Case	EV case with 400 EVs
60% EV Case	EV case with 600 EVs
80% EV Case	EV case with 800 EVs
100% EV Case	EV case with 1000 EVs