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# Impact of plug in electric vehicle battery charging on a distribution system based on real-time digital simulator

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# IMPACT OF PLUG IN ELECTRIC VEHICLE BATTERY CHARGING ON A DISTRIBUTION SYSTEM BASED ON REAL-TIME DIGITAL SIMULATOR

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# IMPACT OF PLUG IN ELECTRIC VEHICLE BATTERY CHARGING ON A DISTRIBUTION SYSTEM BASED ON REAL-TIME DIGITAL SIMULATOR

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# ABSTRACT

This study investigates the impact of the electric vehicles (EVs') battery charging on the distribution system in terms of maximum voltage deviation, voltage unbalance at various locations, transformers overloading, and introducing new peaks into the system.

In this research, a 12.47 kV real distribution network has been modeled using real time digital simulator, using real data from a power distributor. The study presents four different scenarios of uncoordinated EVs integration for two different charging times (evening and night) and two different charging rates (level I and level II) at different penetration levels ranging from 10% to 100%. Voltage unbalance at different locations is determined and transformer overloading is analyzed. The influence of EVs charging on the daily load curve is shown. It is noted that actual system data of voltage and current at all intellirupters of the utility distribution system were close to the data of the simulated system.

# DEDICATION

I would like to dedicate this thesis work to my beloved parents, Yousef and Ghazeel, for their love, moral support, motivation, and encouragement.

## ACKNOWLEDGEMENTS

First and foremost all praises to Allah, the Most Gracious and Most Merciful, for the strengths and his blessing in completing this thesis.

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# TABLE OF CONTENTS

CHAPTER

APPENDIX

# LIST OF TABLES

# LIST OF FIGURES

# LIST OF ABBREVIATIONS

AC, Alternating Current

ALXLP, Aluminum Cross Linked Polyethylene

BEV, Battery Electric Vehicle

CV, Conventional Vehicle

DC, Direct Current

EDV, Electric Drive Vehicle

EREV, Extended Range Electric Vehicle

EV, Electric Vehicle

HEV, Hybrid Electric Vehicle

ICE, Internal Combustion Engine

KV, Kilo Volt

KVA, Kilo Volt-Ampere

KVAR, Kilo Volt-Ampere Reactive

KW, Kilo Watt

KWH, Kilo Watt Hour

MVAR, Mega Volt-Ampere Reactive

MW, Mega Watt

NHTS, National Household Travel Survey

PEV, Plug-in Electric Vehicle

PHEV, Plug-in Hybrid Electric Vehicle

PVUR, Phase Voltage Unbalance Rate

SOC, State of Charge

# CHAPTER 1

# INTRODUCTION

## Background to the Study

Transportation and electricity generation are considered to be the contributing factors to air pollution and global warming. As a matter of fact, most of the power plants are built outside the cities; thus, conventional gasoline vehicles are considered to be the primary causes for contamination of air by smoke and harmful gases in urban areas. Conventional vehicles (CVs) add a considerable amount of air pollution every year. For instance, in the United States about 27 percent of global warming pollution are caused by gasoline vehicles, including cars, trucks, and buses [1]. Not only do conventional internal combustion engines contribute to environmental pollution but they also consume too much amount of oil. Approximately 430 million gallons of oil are used every day to fuel the conventional automobiles [2]. The bad consequences of pollution have given birth to the electrification of the transportation. Thus, the electric vehicle technology is the important promising solution to tackle this issue [3]. This solution leads automobile manufactures to shift and invest in the electric drive vehicles (EDVs) production.

In late 1800s, the first commercial electric car was launched in New York City [4]. Afterwards, the conventional and new auto manufactures entered the market of electric transportation. They invested and devoted their potentials into the technologies that would lead to producing zero or near zero emission vehicles. Currently, plug-in hybrid electric vehicles

(PHEVs) reduce CO2 emission by 25% compared to conventional vehicles [5]. Several studies [6] proved that, per mile traveled, the electricity is a cheaper source than gasoline.

Clean Edge Site [7] confirms that there will be about two millions of electric vehicles (EVs) all over the world by 2015 while the United States official domestic is planning to have one million EVs by 2015. This has been supported by the governments at all levels. Major automotive manufactures have introduced EVs into the market. Chevy Volt vehicles have been driven 187-million electric miles. Manufacturers making EVs, including Nissan, Tesla, GM, Honda, Toyota, BMW, Mercedes, etc. have introduced their PHEVs in the U.S. market. It has been predicted that 50% of new cars will be electric vehicles models by 2020 [8].

Since the market of EVs is growing rapidly, challenges due to the penetration of the EVs need to be investigated. Therefore, the penetration of plug-in electric vehicles (PEVs) into the power grid is a considered topic this time. Most of the consumers need their PEVs' batteries to be charged as soon as they get home after their working hours. However, if all batteries start charging at the same time, assuming that they are at fully discharged state, the peak demand for the electrical grid will increase, the distribution transformer would be overloaded, the power quality and the reliability of the whole system would be degraded, and the utilities' machines (e.g. three phase induction machines) as well as customers' equipment could be potentially damaged. To overcome these issues, utilities need to reinforce their generation, transmission, and distribution infrastructure. Another recommended solution is that the utilities would either apply financial incentives for off-peak charging or utilize EVs' smart charging that enables communication between utilities and vehicles to control charging pattern [9].

## Purpose of Thesis

The main purpose of this thesis is to develop a test bed on a real time digital simulator that helps the distribution utilities evaluate the impact of integrating electric vehicles in their distribution systems using eMEGASim® REAL-TIME DIGITAL SIMULATOR. This impact has been investigated in terms of voltage deviation, voltage unbalance, transformer overloading, and increase the peak load.

## Thesis Outlines

This thesis consists of six chapters and one appendix. In chapter 1, the thesis presents an overview of the plug-in electrical vehicles, their environmental benefits, and market penetration. The relevant literature reviews, including categories of electric drive vehicles, battery specifications, 2009 NHTS study, electric vehicles penetration, and impacts on the distribution system are discussed in chapter 2. Chapter 3 of this study presents a detailed 12.47 kV distribution system configuration. Chapter 4 describes the distribution system model using a real-time simulation system. Case studies and simulation results are shown and discussed in depth in chapter 5. Finally, the conclusion drawn from this work and possible future works are discussed in chapter 6.

# CHAPTER 2

# REVIEW OF LITERATURE

## Categories of Electric Drive Vehicles

The electric drive vehicles (EDVs) can be defined as vehicles that are fueled completely or partly using electricity. Generally, electric vehicle system contains a battery for energy storage, an electric motor for propulsion, a generator, a mechanical transmission and a power control system [10]. The term EDV actually includes several different vehicle technologies. The main types of electric cars available today are listed below.

### Hybrid Electric Vehicles

HEV is a type of electric vehicle which combines a gasoline engine and a battery powered electric engine. Most of the battery charges come from the gasoline engine during driving and a little from regenerative braking because the vehicles kinetic energy while breaking is captured and stored in the battery, rather than wasting it as heat and friction.  The battery in HEV increases the fuel efficiency by 25% compared to conventional automobiles. Toyota Prius is an example of hybrid vehicle that uses both gasoline and electrical engines [10].

### Battery Electric Vehicles

Battery electrical vehicle is sometimes called pure battery electrical vehicle. Unlike the hybrid, BEV has no internal combustion motor; thus, it is completely electric. It must be connected into the power grid for recharging at the end of the limited driving mileage. Since it purely relies on the electricity and accommodates the driving distance of 80 miles or more, BEV requires larger battery size and capacity (e.g., 25-35 kWh) [11]. Battery electric vehicles do not release direct harmful emission or polluting gases; however most of the power plants which generate the electricity to recharge BEVs are not renewable and produce greenhouse gasses. In late 2010 Nissan started U.S. sales of its battery electric vehicle, the LEAF [10].

### Plug-In Hybrid Electric Vehicles

A PHEV is almost similar to the current hybrid electric vehicle. Its components may include an energy storage battery, an electric drive train and a conventional internal combustion engine (ICE) for propulsion, and a power control system [10]. It has a larger battery capacity that can be recharged by connecting a plug to an external electric power source. Since the fuel is considered as a backup resource, PHEVs can be driven for long distance ranges. They first run up to 40 mph on the electricity when the state of charge is high and then they utilize the internal combustion engine for additional miles.

PHEVs and BEVs are considered similar when viewed as electrical loads on the distribution system, but certainly different in terms of their operational characteristics. PHEVs are less dependent on petroleum than HEVs [12]. Moreover, PHEVs are expected to be able to drive regular daily driving mileage depending on the electricity only.

### Extended-Range Electric Vehicles

An extended-range electric vehicle (EREV) works through a combination of a conventional internal engine, a bank of batteries, and an electric motor. In this mode, the vehicle uses a gasoline engine to charge its battery for propulsion. Unlike PHEVs, EREVs are capable of providing relatively more pure electrical driving distances in all electrical range (AER) (e.g., 40-60 miles) [13]. In addition to the high losses in the electrical system in the vehicle, the increased cost of the highly effective electric motor and batteries could be regarded as another drawback of EREV. A current example of EREV is the Chevrolet Volt.

### EVs' Battery Specifications

A battery is a device that converts stored chemical energy into electrical energy during chemical reactions when it is needed. Battery, in electric vehicle, becomes the most significant part of the vehicle structure. Therefore it is crucial to review the characteristics of the existing batteries.

### Types of Batteries

Electric vehicle batteries are entirely different from those used in electronic devices. They must have high storage capacity within limited size and weight and reasonable prices. There are different types of batteries which are used in electric vehicle. Examples of which are Sodium Sulfur (NAS), flow battery, Lithium polymer, Lithium-ion battery (Li-ion), and Nickel metal hybrid (NiMH). The last two are mostly used in all available electric vehicles because of their lightweight and the higher efficiency as well as the energy capacity. They also provide EVs with the best performance characteristics in terms of acceleration and driven distances.

## Battery Capacity

The capacity of the battery, which is the maximum amount of the stored charges that can be extracted from a fully charged battery under certain conditions, is an important element that determines the average numbers of daily driven miles in the electrical range [14]. Moreover, the battery capacity helps in the determination of the duration of the required time to recharge the battery.

According to the Electric Power Research Institute (EPRI), PHEV's battery would sufficiently supply close to 10 kWh for the average daily driven miles of 33 miles [15]. Reference [16] considered that the capacity of the PHEVs' batteries ranges form 15 to 25 kWh. In [17], the maximum storage capacity for every PHEV is 11kWh while in [18], the storage capacity for a compact PHEV-20 is 5 kWh and 14.4 kWh for a full-size SUV PHEV-40.

## State of Charge (SOC)

State of charge (SOC) can be defined as the percentage of the remaining capacity of the vehicle battery after the last trip. It is equivalent to the fuel gauge of the conventional internal combustion cars [14]. SOC can be estimated based on the number of miles driven in all electric range. SOC usually depends on some operational conditions such as temperature, chemistry limits, and the load current [8]. Reference [19] assumed that the typical state of charge of a EVs' battery is ranged between 35% and 95% of the capacity.

## Battery Lifetime

Battery lifetime is the expected period of time when the battery is capable of being recharged and retained to its full state of charge. The lifetime of the battery highly depends on some operational conditions, namely temperature, the charging and discharging cycles, and the state of charge during charging [8]. The new advanced batteries have the ability to withstand 10000 rapid charges, charging in 10 minutes efficiently [2]. The Department of Energy Freedom Car program stated that by 2010 the calendar lifetime of the EV's battery should be 15 years [20].

## Charging Levels and Locations

Charging level determines the power demand for PEVs and the required time duration for charging PEVs' batteries. Power utilities are worried about the charging power levels of the electric cars. Since there are different power system standards all over the world, various PEVs' charging levels are assumed. For example, based on Belgian power standard (230 V, 4.6 kW), [17] considered all PEVs' charging levels to be 4 kW. In North America, the PEVs' charging levels are defined by Society of Automotive Engineering (SAE). Based on the standard outlets, considering safety requirements, there are three charging levels (SAE J1772) [8],[18].

Most of electric vehicles' charging might occur at the residential level. The common site for charging EVs is the garage where the vehicle is parked overnight and it is convenient to be plugged in. It is also supposed that there are a number of public charging locations such as parking lots and shopping centers [18].

### *Level I Charger*

A level I AC charger is suitable for home. It is considered as the minimum voltage level in residential as well as commercial buildings in the United States [18]. Level I charger uses standard wall outlet of 120V/15A and the maximum power up to 1.8 kW. This kind of charger usually requires 6 to 8 hours to fully charge the EVs' battery pack. The use of level I charger demands no additional reinforcement of the existing residential infrastructure; therefore, its cost is highly effective.

### *Level II Charger*

A Level II charger for charging electric vehicle is typically used at both residential and commercial applications. It commonly utilizes 208/240VAC single phase and 30A outlet [19]. Compared to level I, level II charger can provide charging power as much as five times the power supplied by level I charger (7.2 kW). By using level II charger the EVs' battery can be charged in 2 to 3 hours depending on the battery capacity and the state of charge [21]. This leads to the conclusion that level II charger is the most preferred charging method for most of the EVs' owners. However, It is assumed that the level II charger requires additional infrastructure with safety requirements to be installed at a cost to the consumer [15]. Figure 2.1 shows two types of level I and level II chargers.

**Level (I)** **Level (II)**

Figure 2.1 Level (I) and (II) Chargers [22],[23].

### *Level III Charger and DC Fast Charger*

Level III and DC fast chargers are planned for public and commercial facilities like EVs' charging stations where the charging time is about 10- 15 minutes. The level III has rating of 208/600 VAC and maximum current of 400A (3-phase) whereas the DC fast charging charger uses 600 VDC circuit [18]. The charging power of level III AC and DC fast chargers can exceed 100 kW, which is clearly higher than those of level I and Level II [8]. Level III and DC fast chargers are still under development. All three AC charging levels and the DC fast charger are summarized in table 2.1.

Table 2.1 Summary of EVs' Charging Levels

| Level | Voltage (V) | Ampere (A) | Maximum Power (kW) | Charging Time (Hour) |
|---|---|---|---|---|
| Level I Charger | 120 | 15 | 1.8 | 6- 8 |
| Level II Charger | 208/240 | 30 | 7.2 | 2- 3 |
| Level III Charger | 208/600, 3 phase | 400 | 100 | 0.17- 0.25 |
| DC Fast Charger | 600 VDC |  | 100 | 0.17- 0.25 |

## 2009 National Household Travel Survey

Part of the PEVs' characteristics is based on the driver's behavior and the travelling habits. This section discusses the PEVs' owners driving behavior depending on 2009 National Household Travel Survey supported by U.S Department of Transportation [24]. In 2009 NHTS databases, two Microsoft Excel files are extracted: DAYV2PUB.csv and VEHV2PUB.csv.

### DAYV2PUB.csv and VEHV2PUB.csv

DAYV2PUB.csv, which refers to trips, consists of information of 1041000 person trips and each trip has 150 attributes. Those of particular concern are household ID number (HOUSEID), vehicle ID number (VEHID), type of vehicle (VEHTYPE), and travel day trip end time (ENDTIME).

VEHV2PUB.csv, which addresses vehicles, has information of 309164 vehicles and 92 attributes. Only four attributes are used here HOUSEID, VEHID, VEHTYPE, and VEHMILES. The annual mileage is obtained by dividing VEHMILES by 365.

In fact HOUSEID, VEHID, and VEHTYPE are common in the both files and should be used to join the files. Thus, a single file is created that has 163000 trips with three attributes: ENDTIME, VEHTYPE, and VEHMILES.

### PEVs' Characteristics based on 2009 NHTS

PEVs' specifications associated with the owners' behavior, including daily driven distances, vehicle arrival time, and vehicle types, are investigated based on the resulting file.

### *Daily Driven Distances*

Since the state of charge and the total required energy depend on the number of miles driven each day, based on VEHMILES attribute, the bar chart in figure 2.2 shows the percentage of vehicles on the basis of their daily miles. It is clear that the most common distance ranges between 20- 25 miles, which is daily commute distance. This figure also demonstrates that approximately 55% of the vehicles drive 30 miles or less per day.

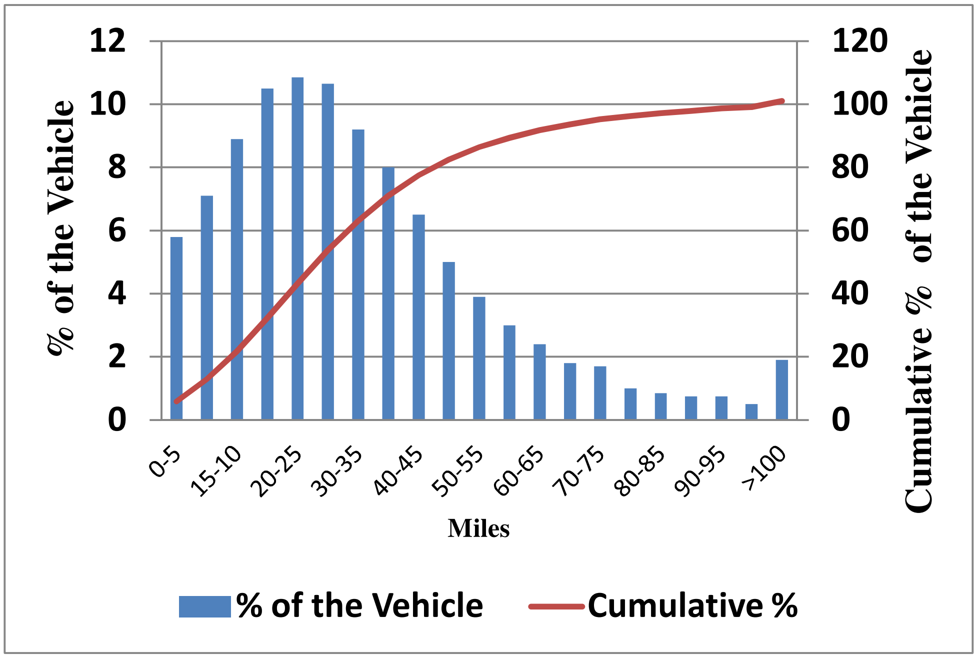


Figure 2.2 Percentage of the Vehicles Versus Daily Driven Distance

### *Vehicle Arrival Time*

To estimate the time when vehicles are plugged in, the end time that can be extracted from ENDTIME attribute is assumed to be the time at which PEVs' owners plug their vehicles after the last trip. ENDTIME attribute in the resulting file indicates that the majority of drivers arrive homes between 5:00 PM and 9:00 PM.

### *Vehicle Types*

As the PEVs' type is one of the most important factors that determine the battery size and capacity which affects the energy consumed form the power grid, VEHTYPE attribute is analyzed. Table 2.2 illustrates the types of vehicles and the percentage of each type in 2009 NHTS.

Table 2.2 Percentage of Every Types of Vehicles

| Vehicle Type | Compact Sedan | Mid-Size Sedan | Mid-Size SUV | Full-Size SUV |
|---|---|---|---|---|
| Percentage (%) | 51.5 | 10.3 | 23 | 15.2 |

### PEVs' Penetration Levels

According to Electric Power Research Institute (EPRI) in [25], The PEVs' penetration level is estimated between 2010 and 2050. As can be seen in figure 2.3 the penetration level increases up to 35%, 51%, and 62%. These would be achieved by 2020, 2030 and 2050 respectively.

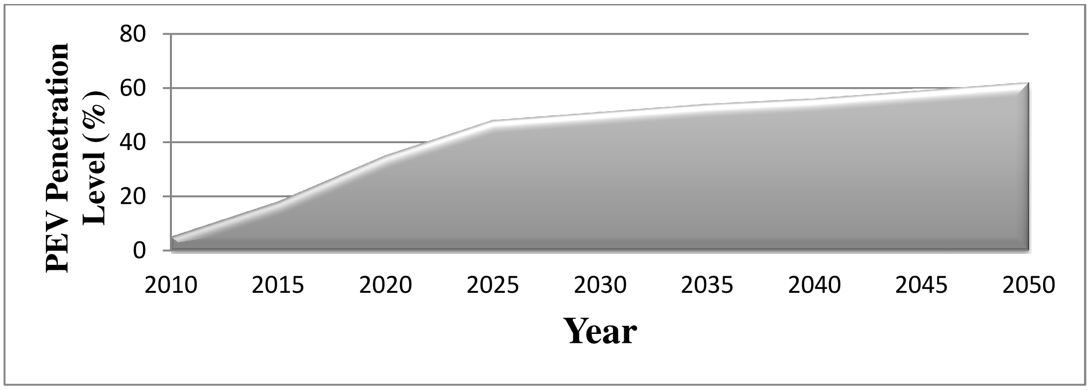


Figure 2.3 Penetration Levels of PEVs in the Distribution System

## Impact of PEVs’ Penetration on the Distribution System

Generally, widespread presence of PEVs presents a concern about their unfavorable impacts on all of the electrical power grid sectors: generation, transmission, and distribution. The distribution system is mainly affected by the penetration of the plug-in electric vehicles based on the penetration level as well as the time at which the vehicles are plugged in. Practically, increasing the number of electric cars connected to the grid might affect the distribution system performance in terms of reducing the system efficiency, reliability, power quality, and voltage regulation [26]. It also increases the voltage deviation and voltage unbalance in the system [19].

Additional demands due to unmanaged PEVs charging either increase peak demand or introduce a new peak load of the system. In both cases, additional investments on distribution infrastructure are necessary [19].

Uncontrolled loads resulted from PEVs can have a negative impact on the service transformers. It could increase the transformer losses and the thermal loading, which leads to insulation breakdown; consequently, the lifespan of the transformer is reduced [6],[19].

Power electronics (e.g., dc/dc, dc/ac converters, etc.) used in PEVs’ chargers produce harmonic distortion in both voltage and current waves. This could harmfully influence the quality of the utility distribution system [6].

## Voltage Deviation and Voltage Unbalance

One of the power quality problems at the distribution level is voltage unbalance. It means that the magnitudes of line or phase voltages are different. It includes unequal voltage magnitudes at the system frequency, unequal harmonic distortion levels, and phase angle deviation. Voltage unbalance usually occurs in rural areas where the distribution lines are too long. It is mainly caused by uneven distribution of single phase loads over the three phase system. Uncoordinated charging of electric vehicles could significantly increase the voltage unbalance of the distribution system [27].

The voltage unbalance has negative impacts on the power system and its equipment. The power system will have heating effects and more losses in case of unbalanced conditions. Moreover, under unbalanced conditions, the induction machines' losses and the temperature will be increased which result in reduced efficiency and decreased life of the machines.

National Electrical Manufacture Association (NEMA) defines the voltage unbalance in percent as the ratio of maximum voltage deviation from the average line voltage to the average line voltage (%LVUR). The same definition is used by IEEE and the only difference is that the IEEE uses the phase voltage rather than the line voltage [27] , so the phase voltage unbalance rate (PVUR) is given by

$$\%\,\text{PVUR} = \frac{\text{Maximum voltage deviation from the average phase voltage}}{\text{Average phase voltage}} \times 100.$$

NEMA recommends that the maximum voltage unbalance of the electrical supply system must be restricted to 3%. According to the standers of "NEMA Motors and Generators" and International Electrotechnical Commission (IEC), the permissible maximum voltage unbalance for the induction motors is one percent [27].

# CHAPTER 3

# DISTRIBUTION SYSTEM CONFIGURATION

## Description of the System Under Study

Generally, a distribution system can be defined as all distribution infrastructures located beyond distribution substations [28]. In view of this, the system used in this study is a 12.47 kV radial distribution system, representing a typical residential network, receiving power from a substation that steps down the voltage from 161 to 12.47 kV. The one-line diagram of this distribution system is shown in figure 3.1.

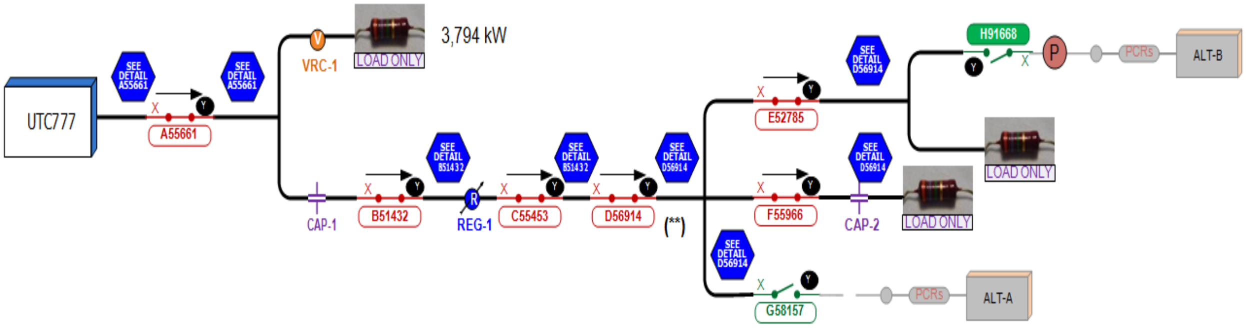


Figure 3.1 One Line Diagram of the Distribution System

In this study, the distribution system under consideration includes the system up to the intellirupter (intelligent circuit breaker) number C55453. The system is divided into three sections A, B, and C as labeled in figure 3.2. Each section consists of several laterals that have many distribution transformers of different sizes.

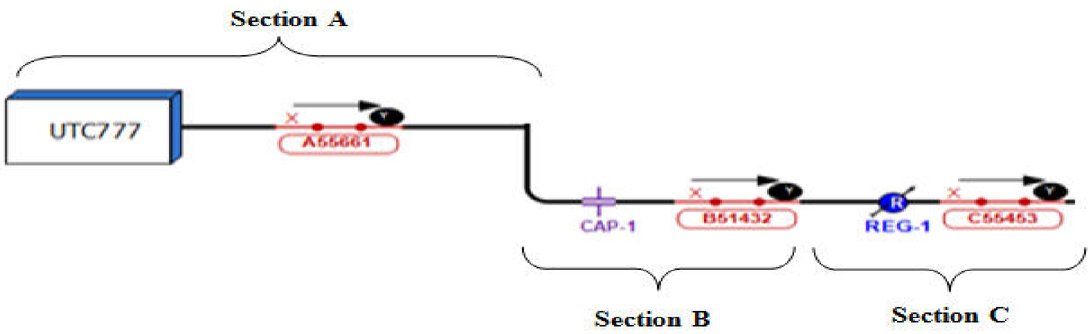


Figure 3.2 One Line Diagram of the Studied Distribution System's Sections

System Data Analysis

The studied distribution system consists of residential metered and primary metered customers. The distribution network under the study has three intellirupters that lie along the main feeder from substation UTC777 to the intellirupter number C55453. Different distribution transformers, distribution cables as well as a variety of customers' loads are scattered throughout the main feeder and its laterals. The data of the service transformers, overhead lines and underground cables, and the connected consumers will be analyzed in the following sections.

## Distribution Transformers

Near every consumer a distribution transformer that takes the primary voltage (either 12.47 kV for a three phase circuit or 7.2 kV for a single phase) and steps it down to a secondary voltage circuit, usually 480, 240, and 120 V. In the system under the study, there are 61 service transformers, three of which are three phase, distributed over the three sections. 10 transformers in section A while 34 in section B and 17 transformers in section C. Most of the single phase transformers are on phase A as 37 transformers connected to A-phase. In the modeled system, depending on the load sizes and types, the service transformers' sizes typically range from 15 to

100 kVA for single phase and up to 500 kVA in case of three phase. Table 3.1 lists the ratings of the distribution transformers utilized in the modeled system. These data were provided by the power distributer.

Table 3.1 Distribution Transformers Ratings

| Transformer Rating (kVA) | Positive and Zero Sequence Impedances (%Z1 & %Z0) | X/R Ratio | Full Load Current at 7.2 kV | Full Load Current at 240 V |
|---|---|---|---|---|
| 15 | 2.5 | 4 | 2.08A | 62.50 A |
| 25 | 4.5 | 4 | 3.47 A | 104.17 A |
| 37 | 4.5 | 4 | 5.14 A | 154.17 A |
| 50 | 4.5 | 4 | 6.94 A | 208.34 A |
| 75 | 3.0 | 4 | 10.42 A | 312.50 A |
| 100 | 4.5 | 4 | 13.89 A | 416.67 A |
| 15 (3-phase) | 4.5 | 4 | | |
| 225 (3-phase) | 4.5 | 4 | | |
| 500 (3-phase) | 3.94 | 10 | | |

### Overhead Lines and Underground Distribution Cables

The main feeder is completely overhead line whereas the connected several branch lines are comprised of both overhead lines and underground cables. The studied distribution network has a variety of sizes and types of conductors. Most of the overhead lines, which made of Aluminum, have conductors' sizes ranging from 1033 Aluminum to 4/0 AL. The underground cable is represented by 1/0 AlXLP conductor (Cross-Linked Polyethylene XLP). The power distributor provides the positive and zero sequences for resistances, inductances and capacitances of all overhead and underground conductors as shown in table 3.2.

Table 3.2 Resistances, Inductances and Capacitances of Overhead Lines and Underground Cables

| conductor Size | Positive sequence and zero sequence resistances, inductances and capacitances | | | | | |
|---|---|---|---|---|---|---|
| | R1 (Ω /km) | R0 (Ω /km) | L1 (H/km) | L0 (H/km) | C1 (uF/km) | C0 (uF/km) |
| 1033 Aerial | 0.0583005 | 0.4045275 | 0.0010064 | 0.0032491 | 0.01177871 | 0.00549267 |
| 1033 AL | 0.0590551 | 0.3733595 | 0.0010143 | 0.0034145 | 0.01173521 | 0.00510642 |
| 1/0 AL | 0.5501968 | 0.8959974 | 0.0012500 | 0.0034918 | 0.00944732 | 0.00492896 |
| 4/0 AL | 0.2748031 | 0.6207349 | 0.0011796 | 0.0034222 | 0.01004757 | 0.00508642 |
| 2 AL | 0.993 | 0.993 | 0.0023559 | 0.0023559 | 0.00702669 | 0.00702669 |
| 6 CU (1-Phase) | 1.471 | 1.471 | 0.0021395 | 0.0021395 | 0.00653862 | 0.00653862 |
| 6 CU (2-Phase) | 1.355 | 1.689 | 0.0014928 | 0.0035305 | 0.00771370 | 0.00444307 |
| 1/0 AlXLP | 0.56 | 0.9614 | 0.0006493 | 0.0006925 | 0.06885428 | 0.02658488 |

## Load Profile

The load profile, provided by the power distributor, covers 24 hours on a fifteen-minute time basis. These load profiles, obtained at the substation UTC777, include all household metered customers and primary metered customers connected to the grid. However, only the residential metered customers are considered in the studied distribution system. The total active and reactive power that are supplied by the substation are shown in figures 3.3 and 3.4, respectively.

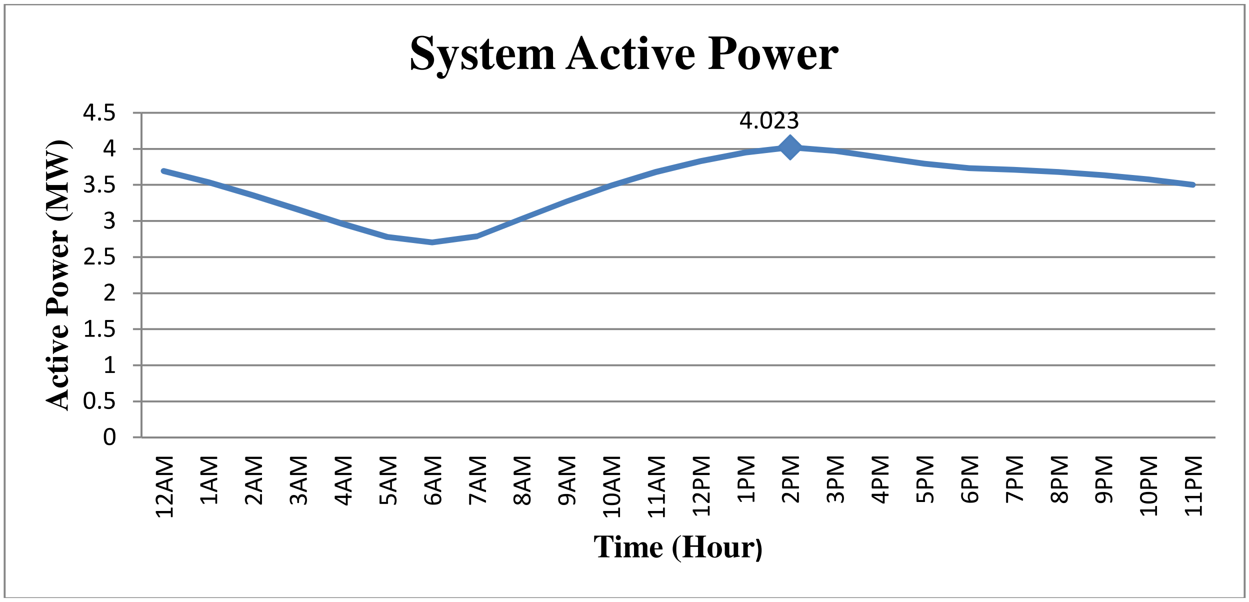


Figure 3.3 Total Active Power of the System

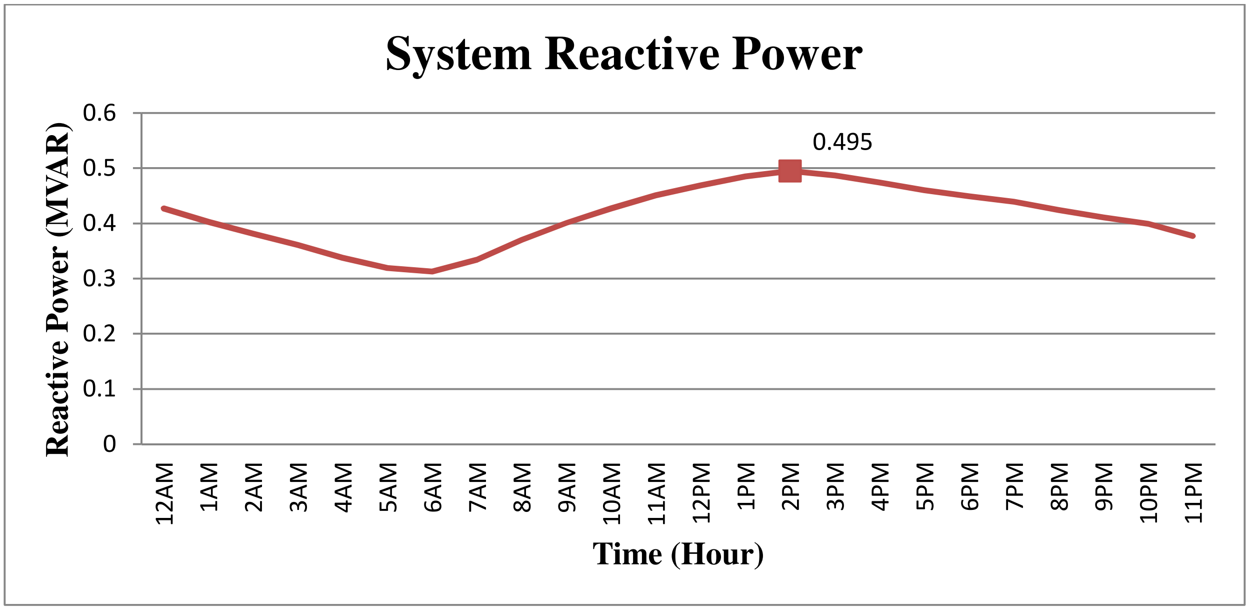


Figure 3.4 Total Reactive Power of the System

Since the electric utility usually charges consumers for the energy usage (Watt Hours), it has only meters that measure the consumed energy by each residential metered customer.

Therefore, the active power (Watts) for each single consumer is obtained from the available energy data while the reactive power for each end user is estimated and calculated by knowing the total active and reactive power of the entire system and having the active power being consumed by each customer.

From the all data provided by the power utility, and for the purpose of this study, the active and reactive power are determined at two specific times: one in the evening (at 6:00 PM) and the other at night (at 10:00 PM). The real and reactive power as well as the number of customers connected to all distribution transformers in all of the three sections are shown in tables 3.3, 3.4, and 3.5.

Table 3.3 Real and Reactive Power Demands for All Distribution Transformers in Section A

| Transformer Labeling | Transformer kVA Rating | No. of customers connected | Evening (6:00PM) | | Night (10:00PM) | |
|---|---|---|---|---|---|---|
| | | | Real power (kW) | Reactive power (kVAR) | Real power (kW) | Reactive power (kVAR) |
| OW5567 | 37 | 1 | 11.588 | 1.124 | 0.692 | 0.059 |
| OW5568 | 25 | 2 | 0.284 | 0.027 | 1.316 | 0.112 |
| OW5739 | 37 | 2 | 2.228 | 0.216 | 4 | 0.340 |
| OW5741 | 37 | 3 | 4.348 | 0.422 | 7.572 | 0.644 |
| OW5P024 | 37 | 1 | 2.068 | 0.201 | 2.176 | 0.185 |
| OW5P025 | 37 | 3 | 5.304 | 0.515 | 8.736 | 0.743 |
| OW5P026 | 50 | 3 | 3.476 | 0.337 | 1.308 | 0.111 |
| OW5P165 | 225 | 1 | 0.325 | 0.032 | 0.156 | 0.013 |
| OW5P232 | 500 | 1 | 0.184 | 0.018 | 0.132 | 0.011 |
| OW5006 | 50 | 1 | 0.72 | 0.069 | 0.72 | 0.061 |

Table 3.4 Real and Reactive Power Demands for All Distribution Transformers in Section B

| Transformer labeling | Transformer kVA rating | No. of customers connected | Evening (6:00PM) | | Night (10:00PM) | |
|---|---|---|---|---|---|---|
| | | | Real power (kW) | Reactive power (kVAR) | Real power (kW) | Reactive power (kVAR) |
| OW5880 | 37 | 2 | 1.892 | 0.184 | 2.484 | 0.211 |
| OW5882 | 25 | 1 | 0.604 | 0.059 | 0.688 | 0.059 |
| OW5883 | 25 | 2 | 1.576 | 0.153 | 1.728 | 0.147 |
| OW5884 | 37 | 1 | 1.94 | 0.188 | 1.568 | 0.133 |
| OW5913 | 25 | 1 | 0.708 | 0.069 | 0.504 | 0.043 |
| OW5915 | 50 | 2 | 1.208 | 0.117 | 1.756 | 0.149 |
| OW5917 | 37 | 2 | 3.224 | 0.313 | 1.168 | 0.099 |
| OW5925 | 37 | 2 | 6.564 | 0.637 | 8.608 | 0.733 |
| OW5800 | 15 | 1 | 0.072 | 0.007 | 0.028 | 0.002 |
| OW51142 | 25 | 2 | 5.932 | 0.576 | 6.444 | 0.548 |
| OW5P109 | 100 | 18 | 19.712 | 1.912 | 49.232 | 4.189 |
| OW5P110 | 100 | 18 | 25.044 | 2.429 | 39.564 | 3.367 |
| OW5P111 | 100 | 18 | 26.888 | 2.609 | 36.84 | 3.135 |
| OW5P112 | 100 | 18 | 20.244 | 1.964 | 22.824 | 1.942 |
| OW5P244 | 75 | 2 | 0.756 | 0.073 | 1.62 | 0.138 |
| OW5666 | 37 | 9 | 9.676 | 0.939 | 12.98 | 1.105 |
| OW5656 | 25 | 4 | 6.508 | 0.631 | 3.568 | 0.304 |
| OW5657 | 25 | 1 | 0.452 | 0.044 | 0.544 | 0.046 |
| OW5658 | 25 | 7 | 8.928 | 0.866 | 11.316 | 0.963 |
| OW5562 | 37 | 8 | 10.844 | 1.052 | 5.176 | 0.441 |
| OW51325 | 15 | 1 | 0.252 | 0.024 | 0.244 | 0.021 |
| OW5932 | 50 | 2 | 1.208 | 0.117 | 1.756 | 0.149 |
| OW5502 | 50 | 3 | 1.094 | 0.106 | 0.986 | 0.084 |
| OW5556 | 15 | 1 | 0.072 | 0.007 | 0.028 | 0.002 |
| OW5557 | 25 | 4 | 5.932 | 0.576 | 6.444 | 0.548 |
| OW5558 | 25 | 1 | 0.284 | 0.028 | 1.316 | 0.112 |
| OW5P018 | 75 | 1 | 1.304 | 0.127 | 4.896 | 0.417 |
| OW51593 | 50 | 2 | 1.208 | 0.117 | 1.756 | 0.149 |
| OW5683 | 37 | 1 | 10.844 | 1.052 | 5.176 | 0.441 |
| OW5835 | 37 | 9 | 11.588 | 1.124 | 0.692 | 0.059 |
| OW5838 | 37 | 3 | 9.676 | 0.939 | 12.98 | 1.105 |
| OW51657 | 25 | 7 | 6.508 | 0.631 | 3.568 | 0.304 |
| OW5839 | 50 | 3 | 3.476 | 0.337 | 1.308 | 0.111 |
| OW5840 | 25 | 2 | 0.452 | 0.044 | 0.544 | 0.046 |

Table 3.5 Real and Reactive Power Demands for All Distribution Transformers in Section C

| Transformer labeling | Transformer kVA rating | No. of customers connected | Evening (6:00PM) | | Night (10:00PM) | |
|---|---|---|---|---|---|---|
| | | | Real power (kW) | Reactive power (kVAR) | Real power (kW) | Reactive Power (kVAR) |
| OW5147 | 50 | 2 | 3.66 | 0.702 | 3.324 | 0.598 |
| OW515X2 | 50 | 7 | 10.844 | 2.079 | 3.156 | 0.568 |
| OW5154 | 50 | 9 | 14.1 | 2.704 | 18.3 | 3.294 |
| OW5177 | 50 | 7 | 14.884 | 2.855 | 9.008 | 1.621 |
| OW52679 | 25 | 2 | 4.96 | 0.951 | 3.576 | 0.644 |
| OW5550 | 50 | 7 | 10.844 | 2.079 | 3.156 | 0.568 |
| OW5553 | 37 | 5 | 3.484 | 0.668 | 4.7 | 0.846 |
| OW5548 | 25 | 6 | 14.064 | 2.697 | 2.564 | 0.461 |
| OW5549 | 37 | 6 | 5.724 | 1.098 | 13.46 | 2.423 |
| OW52068 | 25 | 3 | 2.604 | 0.499 | 5.104 | 0.919 |
| OW51483 | 37 | 2 | 2.6 | 0.499 | 2.972 | 0.535 |
| OW5187X2 | 50 | 7 | 10.844 | 2.079 | 3.156 | 0.568 |
| OW51327 | 25 | 2 | 4.96 | 0.951 | 3.576 | 0.644 |
| OW51328 | 15 | 1 | 1.016 | 0.195 | 0.864 | 0.156 |
| OW5232 | 50 | 11 | 18.656 | 3.578 | 10.1 | 1.818 |
| OW5622 | 50 | 9 | 18.388 | 3.527 | 8.736 | 1.572 |
| OW5545 | 75 | 7 | 12.64 | 2.424 | 15.056 | 2.709 |

## Number and Representation of Customers

As shown in the above three tables, the system has a total of 270 customers. Only three of them take their power directly from three-phase transformers. Most of the connected consumers are on B-phase as approximately 46 percent of consumers receive their daily usage of electricity from service transformers connected to phase-B. Further, 110 out of 270 consumers are connected to phase-A while 34 end-users are on phase-C.

# CHAPTER 4

# REAL TIME SIMULATION IMPLEMENTATION

## Real Time Simulation Overview

Over the last two decades, thanks to the powerful and affordable computers, simulation software has got a rapid evolution from the slowly analog simulators to the highly sophisticated digital simulators. These digital simulators not only solve complex problems in less time but they also become widely available at a decreasing cost for every user. Nowadays, digital simulation technologies have been used extensively in a variety of engineering fields; for instance, the real-time simulation can be used for many applications like planning and design of electrical system, aircraft design and simulation, and industrial motor drive design [29], [30].

The real-time simulation can be defined as a virtual model of an actual physical system that runs at the same rate as actual time [31]. The most important advantage of the real-time digital simulation is that it enables testing the simulated devices beyond their limits without the danger involved in testing real devices in the real world. The applications of real-time simulation can be divided into three categories: [29]

- Rapid control prototyping (RCP)
- Hardware-in-the-loop (HIL)
- Pure simulation (PS)

In RCP applications, the controller prototype is implemented using a real-time simulator and connected to a physical system by input and output ports. The virtual controller model is more flexible, faster and easier to debug. In HIL applications, the actual controller is connected to a simulated virtual plant. One of the features of HIL is that it provides more repeatable results and testing conditions that could be dangerous in the real environment [30].

## RT-LAB for Real Time Simulation

The RT-LAB™ software is modern design software that enables engineers and scientists to rapidly and easily converting Simulink™ dynamic models to real-time models with hardware-in-the-loop in less time. It is flexible enough to be applied to the most complex simulation and control problem, either for real-time hardware-in-the-loop applications or for speeding up model execution, control and test [32].

The real-time simulation is performed in a predetermined time interval (e.g., 1ms, 5ms or 20ms). During this time step, the processor must receive and read input data from other systems such as sensors and compute all necessary calculations like control algorithms. After completing the computations, the simulator writes all outputs. This predefined time step is normally known as fixed- step simulation as shown in figure 4.1.

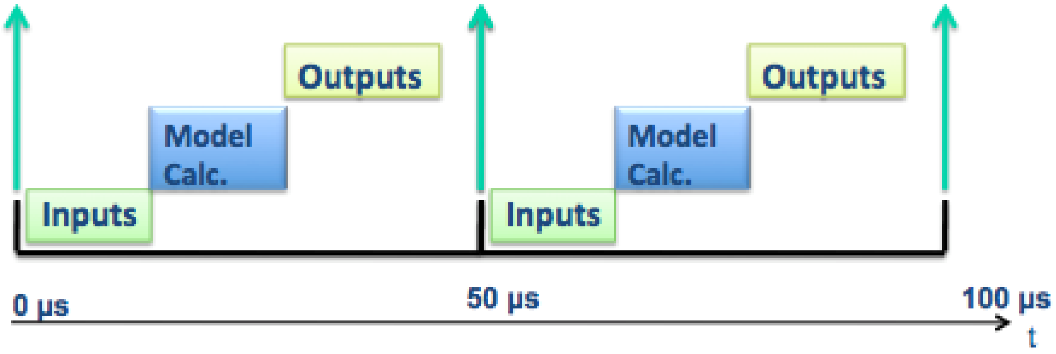


Figure 4.1 Fixed Time-Step Simulation

“Overrun” phenomenon occurs when the predetermined time step is very short and not enough for the simulator to perform inputs, model computation, and outputs. To overcome this state, the fixed time-step should be increased; however, the accuracy of the results decreases as the predefined time-step increases.

To ensure a high speed real-time simulation with the improved accuracy of the results for the complicated power systems, the RT-LAB distributed processing software, in addition to the already existing SimPowerSystems blockset, comes with special Simulink-based modeling toolboxes such as ARTEMiS and RT-Events [32].

### ARTEMiS Blockset

ARTEMiS is an add-on toolbox for SimPowerSystems developed by Opal-RT. ARTEMiS solvers are built to enhance the accuracy of power system simulation over a larger time-step. Therefore, users can get the required accuracy with less powerful and lower-cost systems to give the performance needed for high-fidelity real-time simulation. Unlike SimPowerSystems blockset, ARTEMIS was designed intentionally to support real-time implementations of power systems simulations. Moreover, ARTEMiS solvers are stable as they have essential immunity to numerical oscillations caused by network switching or inductive circuit opening [33].

### Modeling Concepts

The RT-LAB™ utilizes Matlab/Simulink™ to define models and corresponding parameters which will be executed by the real-time multi-processing system [34]. After implementing the system model using Matlab/Simulink™, a user must follow more several steps for the system to be realized in real-time with Opal-RT's software and hardware. First, regroup into different subsystems. Second, add the OpComm block(s). Third, maximize parallel execution and state variable. Forth, set the real-time parameters.

According to the fundamental principles of RT-LAB software, the original model, built using Simulink™, must be separated into several subsystems based on the state of every subsystem. There is always one and only one master subsystem inside every real-time simulated model. It contains the important computational elements of the model such as the mathematical operations, the I/O blocks, and the signal generators. For every simulated model, there can be zero or several slave subsystems. The slave subsystem is only needed when the computational elements are required to be distributed across multiple nodes. Third, all user interface blocks such as scopes, displays, switches, and controls must be placed in a console subsystem. Note that there can be only one console subsystem per model. The console runs on the host computer asynchronously from the other subsystems to show the results of the real-time simulation. It is important to notice that no mathematical components can be found in the top-level of the model. According to the Opal-RT naming convention, a prefix of "SM_" indicates a master subsystem while "SS_" is a prefix that indicates a slave subsystem. A console subsystem's name starts with "SC_". As shown in figure 4.2, both master and slave subsystems are located at different CPUs of the target computer. In contrast, the console subsystem runs and stays at the user workstation and communicates with the target computer through a TCP/IP protocol [32].

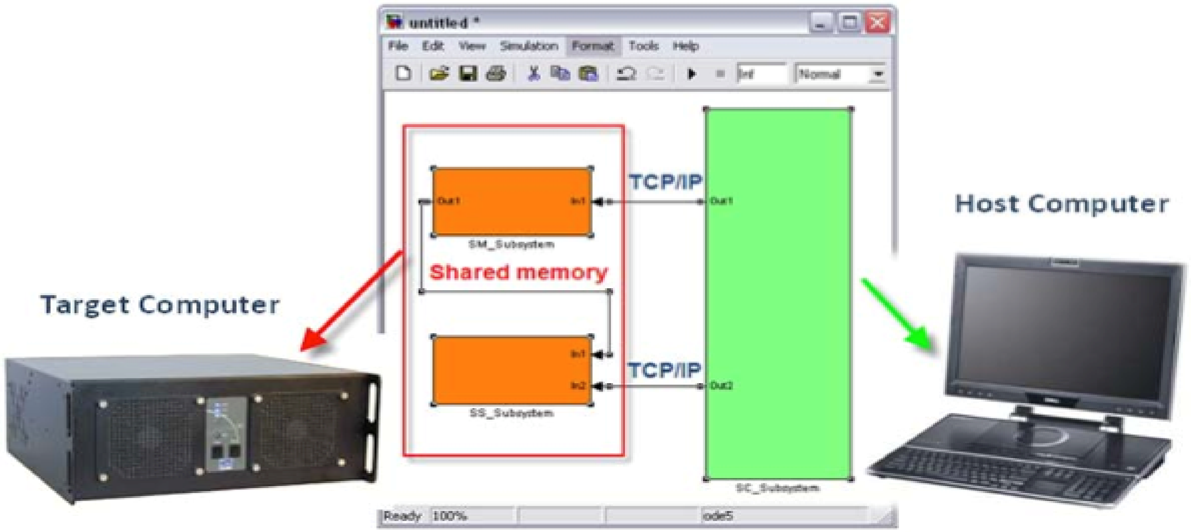


Figure 4.2 Different Types of RT-LAB Subsystems

The "OpComm" communication block must be inserted into the subsystems of the model. RT-LAB uses "OpComm" to enable and save communication setup information between any two subsystems. According to the recommended OPAL-RT rules, all inputs to top-level subsystems must first go through an "OpComm" block before any operations can be done in the signal. Generally, only one "OpComm" block can be used regardless of the number of inputs in one subsystem and must be inserted after creating and naming the subsystems [32].

## Hardware and Software Details Used for this Study

In this study, OP5600 digital simulator is used to demonstrate the real-time performance of the distribution grid under the effect of electrical vehicles charging. It is built using cost-effective, high availability commercial-off-the-shelf (COTS) components that includes advanced monitoring capabilities and scalable input/output and processor power.

The eMEGASim® simulator contains a powerful real-time target computer equipped 12 3.3-GHz processor cores with Red Hat Linux real-time operating system. It features two userprogrammable FPGA-based I/O management options available, powered by the Xilinx Spartan-3 or more powerful Virtex-6 FPGA processor. Available expansion slots accommodate up to 8 signal conditioning and analog /digital converters modules with 16 or 32 channels each for a total of fast 128 analog or 256 discrete or a mix of analog and digital signals [35].

It appears as a single target that can be networked into a multiple-target PC cluster or for complex applications capable of implementing large models with more than 3000 input and output channels and a time step below 25 micros. It also offers versatile monitoring on the front panel through RJ45 to mini-BNC connectors such as DB37 input and output connections on the back panel [35]. The front and back views of the OP5600 real-time digital simulator is shown in figure 4.3.

Back View Front View

Figure 4.3 OP5600 Real-Time Simulation Target Overview

The components of the power system used to simulate the distribution network come from SimPowerSystem blockset. The Real-Time Solvers for electromechanical system simulation come from the ARTEMiS blockset that are also targeted to the OP5600 digital simulator.

## Model Construction

The distribution system shown in figure 3.2 is modeled firstly using Matlab/Simulink™. Then, by following the steps mentioned in the previous section, this distribution model has been modified to be realized in the RT-LAB environment.

The three sections of the distribution network A, B, and C are divided into nine subsystems. In addition to the source and console subsystems, section B is broken down into four subsections and section C is split into two subsections. Figure 4.4 shows the Simulink model of the distribution system used in this study. The detailed view layouts of the all subsystems are shown in appendix A.

Due to the higher complexity of detailed model of each subsystem that leads to excessive overruns in real time simulation which increases the computation time considerably, RT-LAB software utilizes a number of decoupling tools from ARTEMiS block library to overcome this issue. These tools divide big matrices into multiple small state-space matrices which lead to quick and easier computation so the subsystems can then be processed in parallel using RT-LAB simulators [36]. In this thesis, since all distribution lines are less than 500 meters, the "StubLine" block from the ARTEMiS toolbox is used as a connection between subsystems.

It is known that the real-time simulation must run in the fixed-step mode. Further, the sampling time of real-time simulation is 50 us in this study.

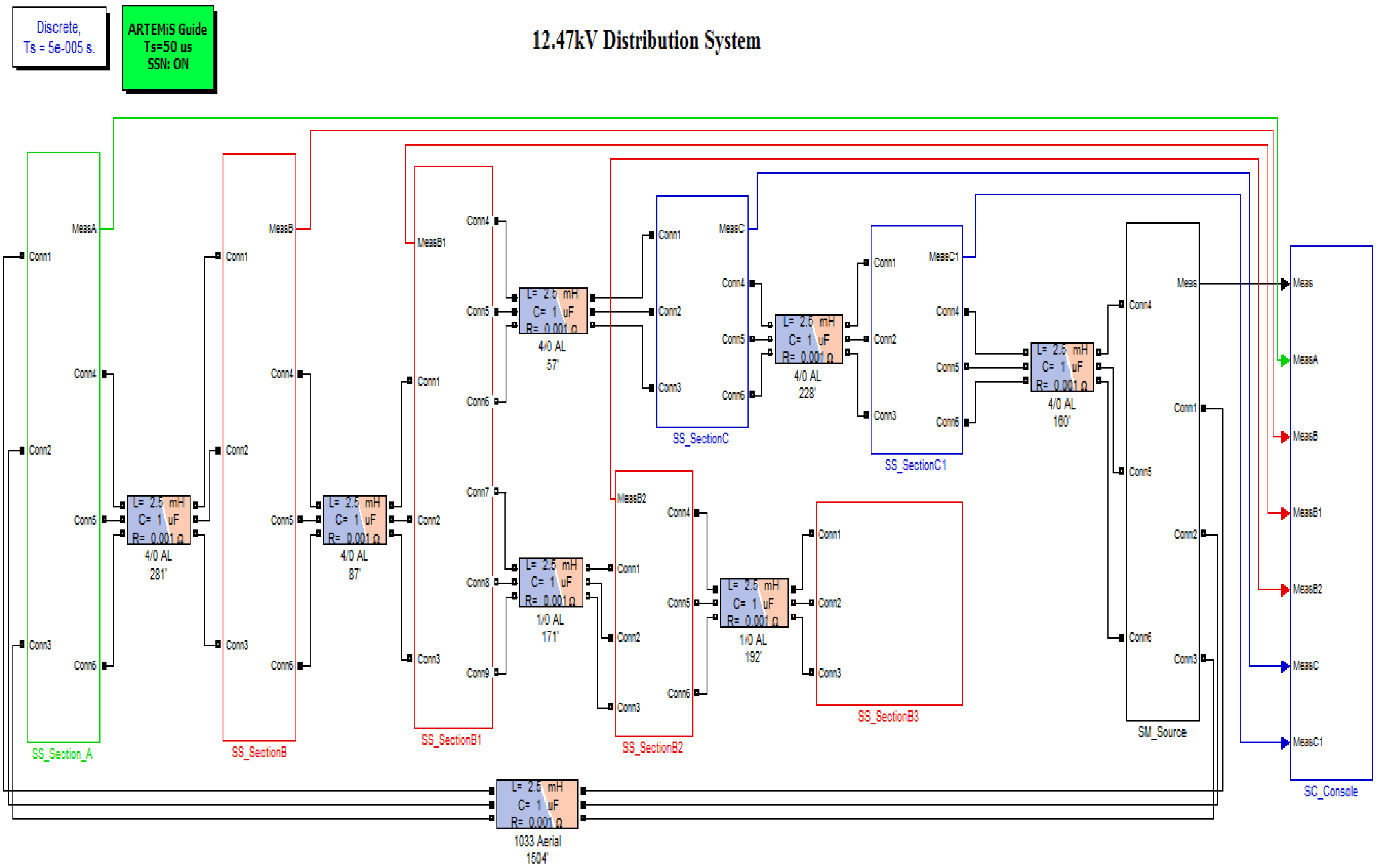


Figure 4.4 Simulink Implementation of the Distribution Network

# CHATPER 5

# CASE STUDY AND SIMULATION RESULTS

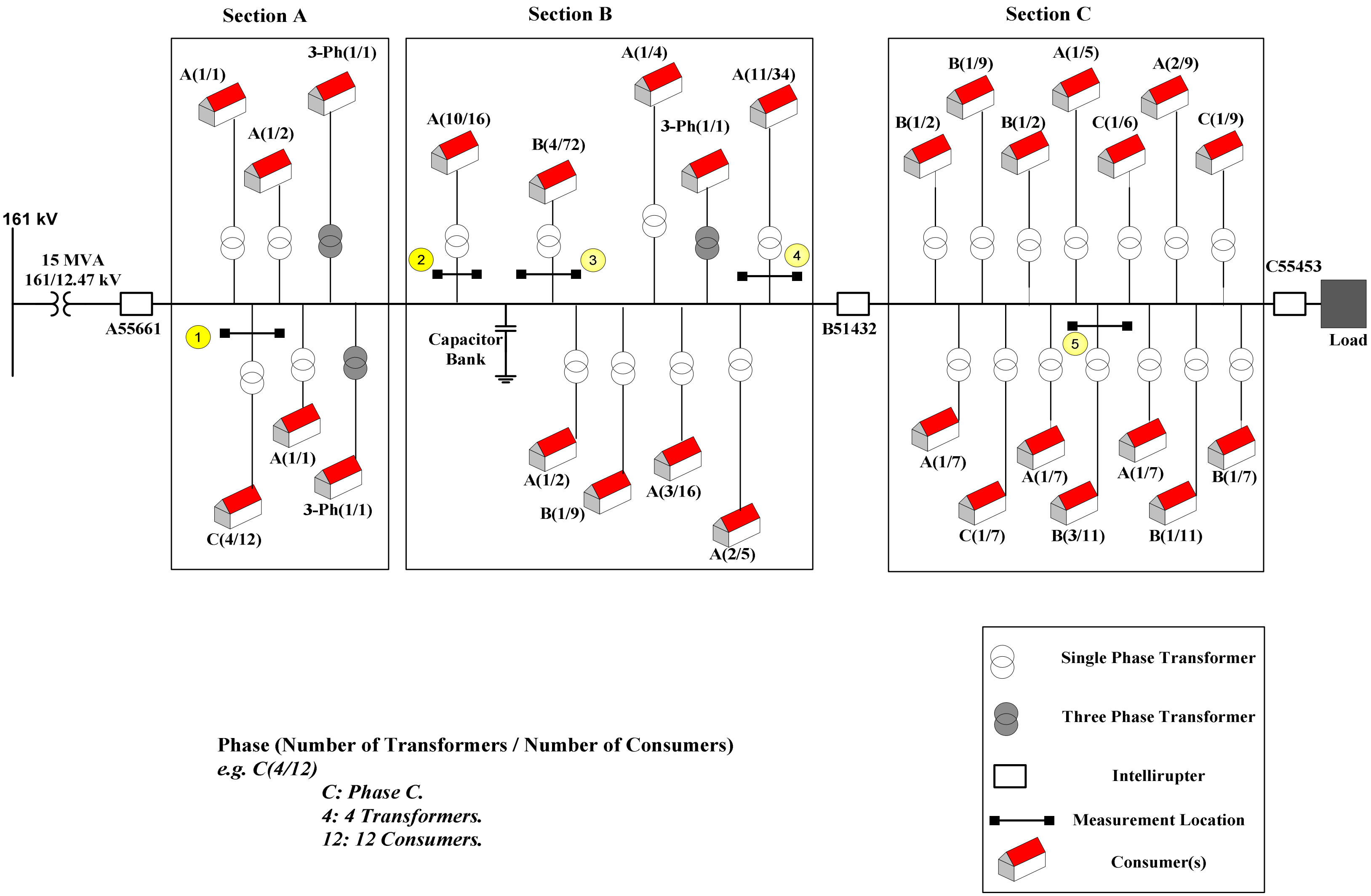
This section represents the impacts of unmanaged PEVs' charging on voltage deviation at load points, voltage unbalance, transformer overloading, and the impact on load curve such as increasing peak demand or introducing a new peak.

## Assumptions for Investigating PEVs' Charging Impact

Based on the associated report, 2009 NHTS, most of the drivers arrive homes between 5 PM and 9 PM. Thus, evening at 6 PM as well as night at 10 PM are chosen to be the best times for the vehicles' owners to start charging their cars' batteries.

In this thesis, level I and level II are used to demonstrate the impact of PEVs' charging on the distribution system. Assuming energy conversion efficiency of 88% and based on the ratings of PEVs' charging levels in table 2.1, the maximum available output power form level I and level II chargers are 1.548 kW and 6.336 kW, respectively. Depending on the penetration level, the charger's load is added to the existing load of the customer.

Various locations, where there are more than ten connected consumers, have been chosen properly to measure the three phase voltages and currents. These five locations are labeled as shown in figure 5.1.



**Phase (Number of Transformers / Number of Consumers)**

***e.g. C(4/12)***

***C: Phase C.***

***4: 4 Transformers.***

***12: 12 Consumers.***

Figure 5.1 Simplified Diagram of the Distribution System with the Locations of Measurement

Distribution System Model without PEVs' Penetration

The model of the distribution system is analyzed without PEVs' loads in the evening and at night to check the validity of the system. The actual voltages and currents, measured in the field, that are provided by the power distributor are compared with the resulted voltages and currents of the simulated system. Table 5.1 shows the actual and the simulation results of phase to ground voltages and phase currents in the evening (6 PM) at intellirupters A55661, B51432, and C55453.

Table 5.1 Comparison between Actual and Simulated Voltages and Currents at Intellirupters in the Evening

| In the Evening | | Phase to Ground Voltages (V) | | | Phase Currents (A) | | |
|---|---|---|---|---|---|---|---|
| | | $V_a$ | $V_b$ | $V_c$ | $I_a$ | $I_b$ | $I_c$ |
| At A55661 | Actual Values | 7138 | 7115 | 7091 | 185 | 179 | 172 |
| | Simulation Results | 7139 | 7117 | 7108 | 184 | 172 | 170 |
| At B51432 | Actual Values | 7122 | 7095 | 7086 | 52 | 67 | 47 |
| | Simulation Results | 7122 | 7083 | 7084 | 52.21 | 75.1 | 49.59 |
| At C55453 | Actual Values | 7109 | 7082 | 7082 | 46 | 61 | 39 |
| | Simulation Results | 7107 | 7074 | 7071 | 58.06 | 61.65 | 59.63 |

Table 5.2 shows the actual and the simulation results of phase to ground voltages and phase currents at night (10 PM) at intellirupters A55661, B51432, and C55453.

Table 5.2 Comparison between Actual and Simulated Voltages and Currents at Intellirupters at Night

| At Night | | Phase to Ground Voltages (V) | | | Phase Currents (A) | | |
|---|---|---|---|---|---|---|---|
| | | $V_a$ | $V_b$ | $V_c$ | $I_a$ | $I_b$ | $I_c$ |
| At A55661 | Actual Values | 7118 | 7100 | 7074 | 178 | 172 | 164 |
| | Simulation Results | 7120 | 7138 | 7133 | 177 | 163 | 154 |
| At B51432 | Actual Values | 7099 | 7083 | 7071 | 56 | 74 | 49 |
| | Simulation Results | 7114 | 7102 | 7084 | 54.4 | 67.1 | 49.59 |
| At C55453 | Actual Values | 7086 | 7064 | 7065 | 50 | 66 | 40 |
| | Simulation Results | 7099 | 6989 | 7072 | 59 | 62 | 60 |

### Distribution System Model with PEVs' Penetration

Four case studies are conducted to investigate the impact of PEVs' loads on the distribution residential network. The first scenario is charging PEVs' batteries using level I chargers in the evening. Second, the vehicles' batteries are charged also in the evening using level II chargers. Third, at night, level I chargers are used to charge the electric vehicles. The last scenario, level II chargers are used to charge PEVs' batteries at night.

In the aforementioned scenarios, the penetration levels are considered from 10% to 100% PEVs' penetration in step of 10%. As discussed in chapter 3, the number of single-phase customers is 267; 110 customers are on phase A, 123 residents are on phase B, and 34 customers are on phase C. In each penetration level, the PEVs' loads are added precisely to the selected customers based on load and the size of the service transformers.

### Case I: Level I Chargers in the Evening

In this case, different penetration levels of PEVs' charging using level I chargers in the evening are investigated in terms of voltage deviation, voltage unbalance and the peak load. Tables 5.3 and 5.4 show the calculated maximum voltage deviation and voltage unbalance, respectively, for the different penetration levels of charging PEVs' batteries for level I chargers at 6 PM.

Table 5.3 Maximum Voltage Deviation (in Volt) at Different Locations for Level I in the Evening in the 12.47 kV Distribution System

| Penetration Level | A55661 | B51432 | C55453 | Location 1 | Location 2 | Location 3 | Location 4 | Location 5 |
|---|---|---|---|---|---|---|---|---|
| NO PEVs | 8.54 | 55.46 | 54.33 | 36.68 | 44.13 | 47.86 | 56.91 | 54.62 |
| 10% | 8.91 | 56.30 | 55.11 | 37.31 | 44.85 | 48.61 | 57.76 | 55.42 |
| 20% | 9.25 | 56.96 | 55.80 | 37.84 | 45.44 | 49.21 | 58.44 | 56.09 |
| 30% | 9.45 | 57.62 | 56.43 | 38.29 | 46.01 | 49.80 | 59.12 | 56.72 |
| 40% | 9.73 | 58.26 | 56.98 | 38.75 | 46.55 | 50.35 | 59.79 | 57.29 |
| 50% | 10.13 | 59.06 | 57.74 | 39.35 | 47.22 | 51.06 | 60.60 | 58.06 |
| 60% | 10.44 | 59.87 | 58.50 | 39.91 | 47.86 | 51.74 | 61.43 | 58.84 |
| 70% | 10.61 | 60.60 | 59.14 | 40.32 | 48.38 | 52.32 | 62.19 | 59.51 |
| 80% | 11.02 | 61.77 | 60.25 | 41.12 | 49.29 | 53.30 | 63.37 | 60.63 |
| 90% | 11.41 | 62.74 | 61.20 | 41.76 | 50.03 | 54.11 | 64.37 | 61.59 |
| 100% | 11.69 | 63.56 | 61.95 | 42.29 | 50.65 | 54.79 | 65.20 | 62.37 |

Table 5.4 % Voltage Unbalance at Different Locations for Level I in the Evening in the 12.47 kV Distribution System

| Penetration Level | A55661 | B51432 | C55453 | Location 1 | Location 2 | Location 3 | Location 4 | Location 5 |
|---|---|---|---|---|---|---|---|---|
| NO PEVs | 0.120 | 0.785 | 0.770 | 0.516 | 0.622 | 0.675 | 0.805 | 0.774 |
| 10% | 0.125 | 0.797 | 0.782 | 0.525 | 0.632 | 0.686 | 0.818 | 0.785 |
| 20% | 0.130 | 0.806 | 0.791 | 0.533 | 0.641 | 0.695 | 0.827 | 0.795 |
| 30% | 0.133 | 0.816 | 0.801 | 0.539 | 0.649 | 0.703 | 0.837 | 0.804 |
| 40% | 0.136 | 0.825 | 0.808 | 0.546 | 0.657 | 0.711 | 0.847 | 0.812 |
| 50% | 0.142 | 0.837 | 0.819 | 0.554 | 0.666 | 0.721 | 0.858 | 0.824 |
| 60% | 0.147 | 0.848 | 0.830 | 0.562 | 0.675 | 0.731 | 0.870 | 0.835 |
| 70% | 0.149 | 0.859 | 0.840 | 0.568 | 0.683 | 0.739 | 0.881 | 0.844 |
| 80% | 0.155 | 0.875 | 0.856 | 0.580 | 0.696 | 0.753 | 0.898 | 0.861 |
| 90% | 0.160 | 0.889 | 0.869 | 0.589 | 0.706 | 0.765 | 0.912 | 0.874 |
| 100% | 0.164 | 0.901 | 0.880 | 0.596 | 0.715 | 0.775 | 0.924 | 0.886 |

For the penetration levels of PEVs' level I chargers in the evening, it is clear from the above tables that the increase in maximum voltage deviation (V) form the beginning of the simulated system (Intellirupter A55661) to the end of the simulated system (Intellirupter C55453) is 46.2 V for 10% penetration level and 50.26 V in case of 100% penetration level of PEVs. On the other hand, the increase in %voltage unbalance from the intellirupter A55661 to the intellirupter C55453 ranges from 0.657 V to 0.716 V for the 10% and 100 % penetration levels, respectively. Figures 5.2 and 5.3 demonstrate the maximum voltage deviation and voltage unbalance for using level I chargers in the evening.

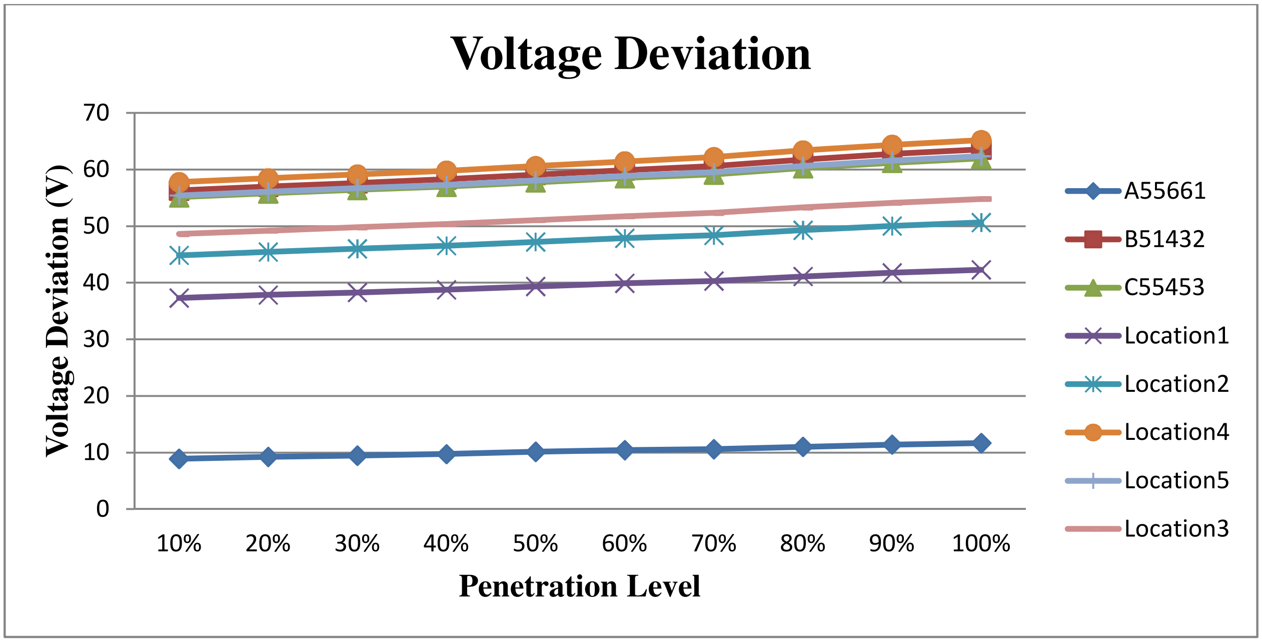


Figure 5.2 Impacts of PEVs Charging on the Voltage Deviation for Level I Charger in the Evening

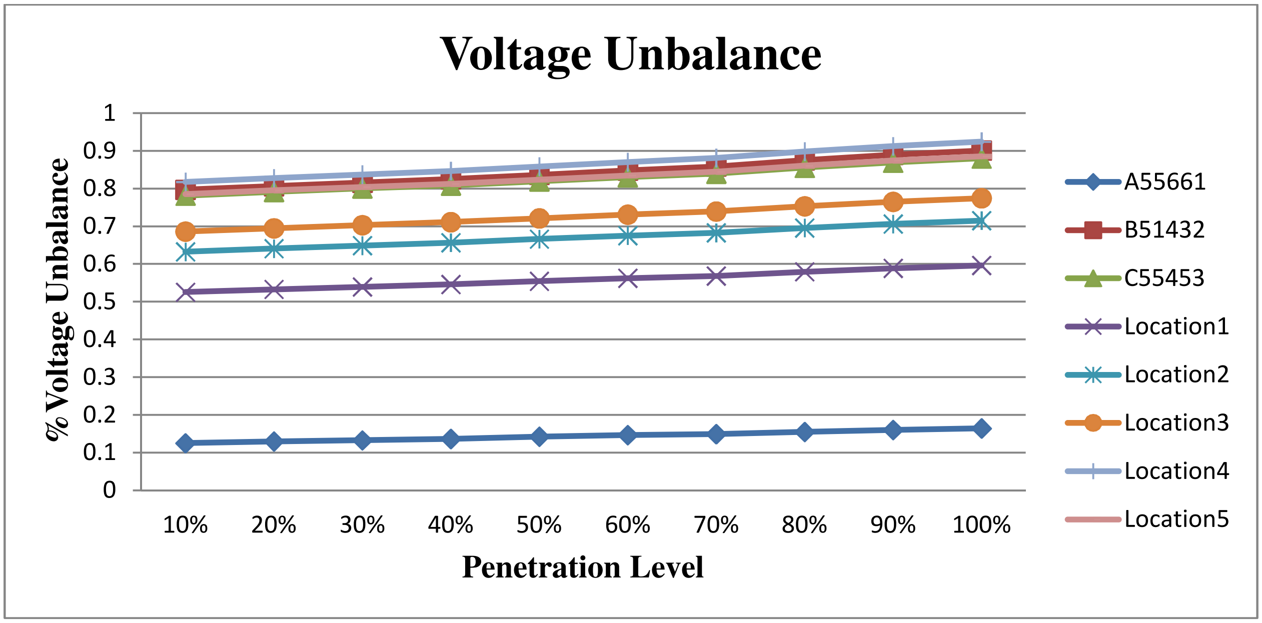


Figure 5.3 Impacts of PEVs Charging on the Voltage Unbalance for Level I Charger in the Evening

Figure 5.4 presents the impact of PEVs' level I chargers on the peak load. The peak load is shifting from 2:30 PM to 6 PM when consumers plug-in their vehicles in the evening. For 100% penetration level, the peak load increases to 4.162 MW at 6 PM compared to 4.023 MW at the daily peak hour at 2:30 PM.

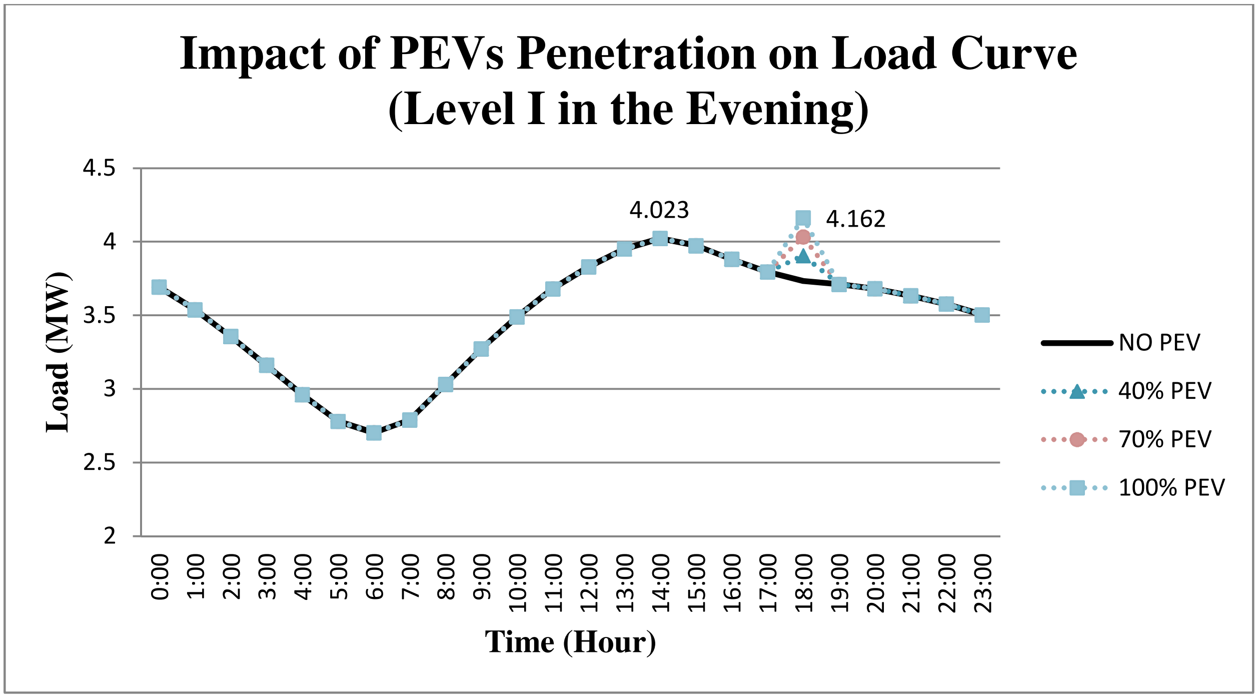


Figure 5.4 Impacts of PEVs Charging on the Peak Load for Level I Charger in the Evening

### Case II: Level II Chargers in the Evening

In this case, different penetration levels of PEVs' charging using level II chargers in the evening are investigated in terms of voltage deviation, voltage unbalance, the peak load, and transformers overloading. Tables 5.5 and 5.6 show the calculated maximum voltage deviation and voltage unbalance, respectively, for the different penetration levels of charging PEVs' batteries for level II chargers at 6 PM.

Table 5.5 Maximum Voltage Deviation (in Volt) at Different Locations for Level II in the Evening in the 12.47 kV Distribution System

| Penetration Level | A55661 | B51432 | C55453 | Location 1 | Location 2 | Location 3 | Location 4 | Location 5 |
|---|---|---|---|---|---|---|---|---|
| NO PEVs | 8.54 | 55.46 | 54.33 | 36.68 | 44.13 | 47.86 | 56.91 | 54.62 |
| 10% | 10.01 | 58.83 | 57.46 | 39.19 | 47.04 | 50.89 | 60.34 | 57.82 |
| 20% | 11.39 | 61.50 | 60.24 | 41.34 | 49.42 | 53.30 | 63.08 | 60.52 |
| 30% | 12.09 | 64.05 | 62.70 | 43.07 | 51.60 | 55.58 | 65.71 | 63.00 |
| 40% | 13.46 | 66.94 | 65.18 | 45.24 | 54.08 | 58.12 | 68.70 | 65.56 |
| 50% | 14.82 | 69.94 | 68.05 | 47.39 | 56.57 | 60.74 | 71.74 | 68.47 |
| 60% | 16.26 | 73.46 | 71.36 | 49.92 | 59.40 | 63.75 | 75.33 | 71.85 |
| 70% | 16.91 | 76.38 | 73.93 | 51.56 | 61.48 | 66.08 | 78.35 | 74.52 |
| 80% | 18.29 | 80.73 | 78.08 | 54.53 | 64.87 | 69.74 | 82.80 | 78.74 |
| 90% | 19.67 | 84.44 | 81.67 | 56.93 | 67.66 | 72.80 | 86.59 | 82.37 |
| 100% | 20.68 | 87.56 | 84.57 | 58.95 | 70.04 | 75.42 | 89.77 | 85.37 |

Table 5.6 % Voltage Unbalance at Different Locations for Level II in the Evening in the 12.47 kV Distribution System

| Penetration Level | A55661 | B51432 | C55453 | Location 1 | Location 2 | Location 3 | Location 4 | Location 5 |
|---|---|---|---|---|---|---|---|---|
| NO PEVs | 0.120 | 0.785 | 0.770 | 0.516 | 0.622 | 0.675 | 0.805 | 0.774 |
| 10% | 0.140 | 0.833 | 0.815 | 0.552 | 0.664 | 0.719 | 0.855 | 0.820 |
| 20% | 0.160 | 0.872 | 0.855 | 0.583 | 0.698 | 0.753 | 0.894 | 0.859 |
| 30% | 0.170 | 0.908 | 0.891 | 0.607 | 0.729 | 0.786 | 0.932 | 0.895 |
| 40% | 0.189 | 0.950 | 0.927 | 0.638 | 0.764 | 0.823 | 0.975 | 0.932 |
| 50% | 0.208 | 0.993 | 0.969 | 0.669 | 0.800 | 0.860 | 0.997 | 0.974 |
| 60% | 0.229 | 1.044 | 1.016 | 0.705 | 0.840 | 0.903 | 1.071 | 1.023 |
| 70% | 0.238 | 1.086 | 1.054 | 0.729 | 0.870 | 0.937 | 1.114 | 1.062 |
| 80% | 0.258 | 1.149 | 1.114 | 0.771 | 0.919 | 0.990 | 1.179 | 1.123 |
| 90% | 0.277 | 1.203 | 1.166 | 0.806 | 0.959 | 1.034 | 1.233 | 1.175 |
| 100% | 0.291 | 1.248 | 1.208 | 0.835 | 0.993 | 1.071 | 1.279 | 1.219 |

For the penetration levels of PEVs' level II chargers in the evening, it is clear from the above tables that the increase in maximum voltage deviation (V) form the beginning of the simulated system (Intellirupter A55661) to the end of simulated system (Intellirupter C55453) is 47.45 V for 10% penetration level and 63.89 V in case of 100% penetration level of PEVs. On the other hand, the increase in %voltage unbalance from the intellirupter A55661 to the intellirupter C55453 ranges from 0.675 V to 0.917 V for the 10% and 100 % penetration levels, respectively. Figures 5.5 and 5.6 demonstrate the maximum voltage deviation and voltage unbalance for using level II chargers in the evening.

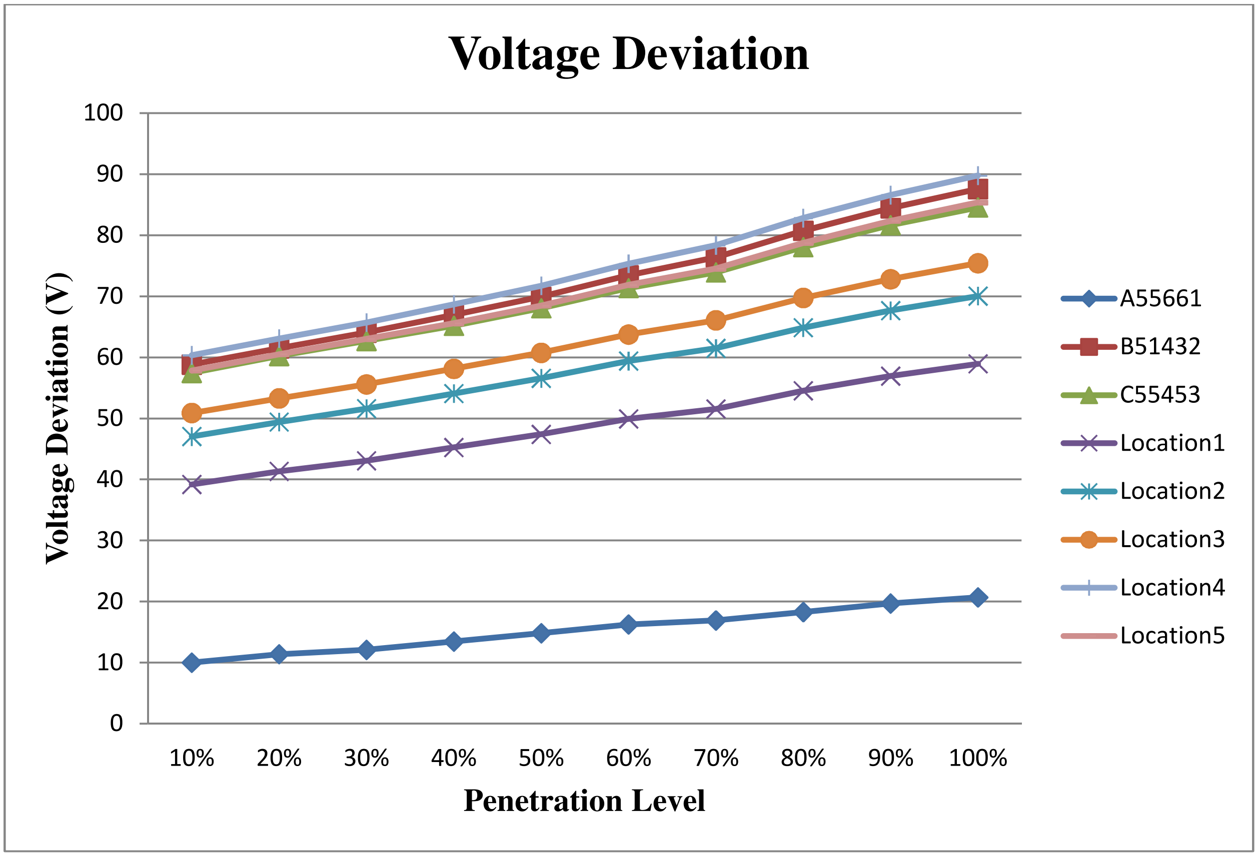


Figure 5.5 Impacts of PEVs Charging on the Voltage Deviation for Level II Charger in the Evening

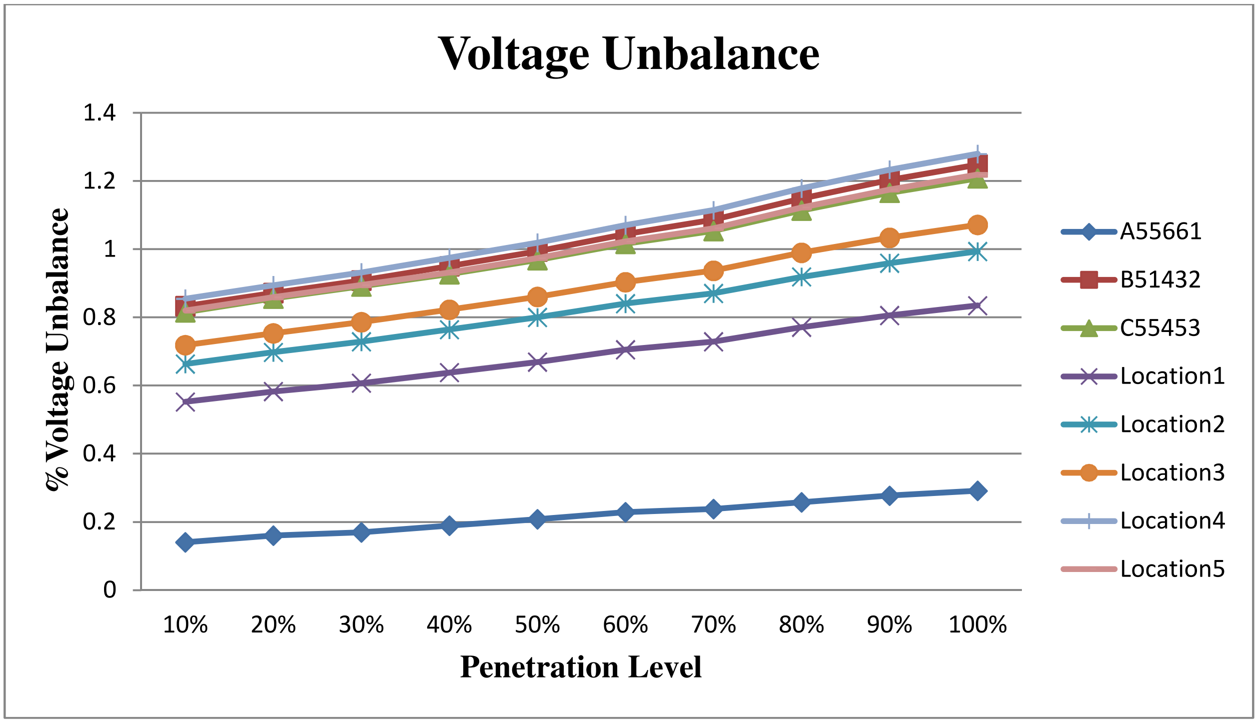


Figure 5.6 Impacts of PEVs Charging on the Voltage Unbalance for Level II Charger in the Evening

Figure 5.7 presents the impact of PEVs' level II chargers on the peak load. The peak load is shifting from 2:30 PM to 6 PM when consumers plug-in their vehicles in the evening. For 100% penetration level, the peak load increases to 5.445 MW at 6 PM compared to 4.023 MW at the daily peak hour at 2:30 PM.

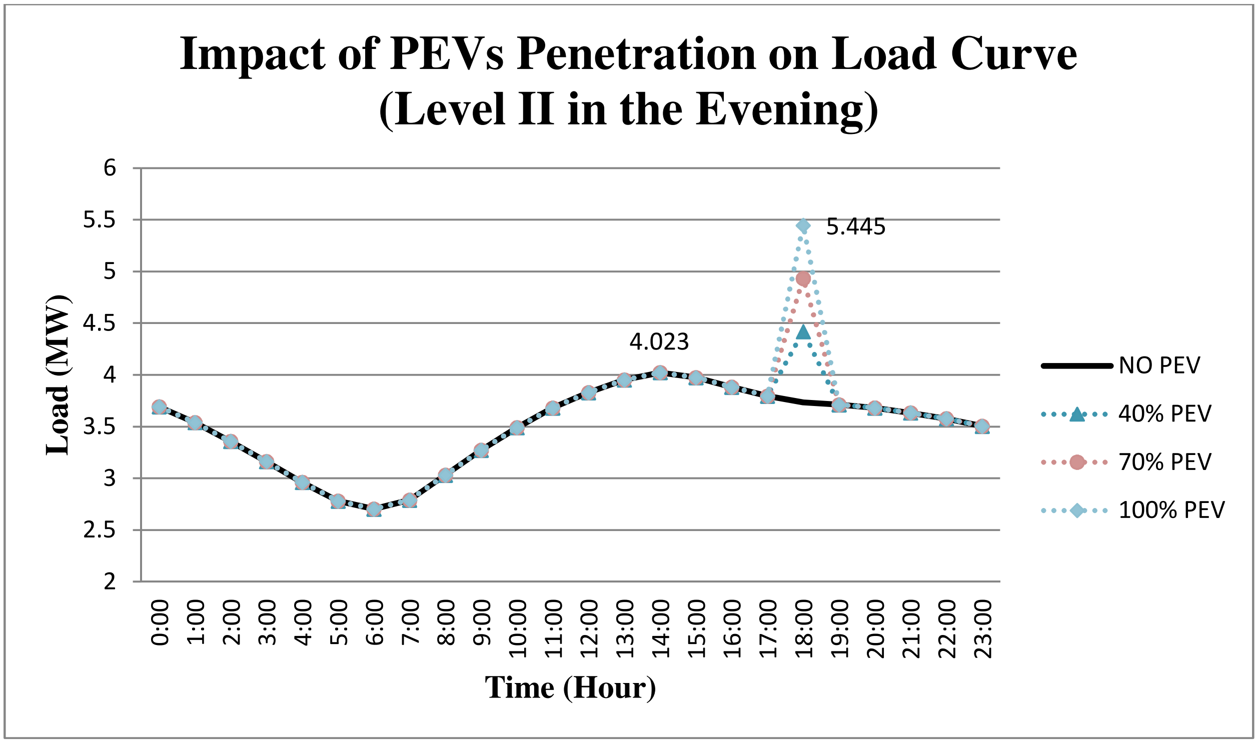


Figure 5.7 Impacts of PEVs Charging on the Peak Load for Level II Charger in the Evening

As shown in table 5.7, charging PEVs' using level II chargers in the evening causes a localized overload on the distribution transformers. It has been noticed that as the number of connected costumers increases the service transformers are highly susceptible to be overloaded. Each transformer in table 5.7 has at least 7 customers. Most of the transformers are overloaded or close to be overloaded by the penetration level of 70% or more. Further, at 100% PEVs' penetration, most of the transformers carry as much as twice of their rated load.

Table 5.7 Rated and Measured Currents for Service Transformers for Level II Charger in the Evening

| Phase | Transformer Labeling | Transformer kVA Rating | Rated Current At 240V (Amps) | Measured Current At 10% PEV penetration | Measured Current At 40% PEV penetration | Measured Current At 70% PEV penetration | Measured Current At 100% PEV penetration |
|---|---|---|---|---|---|---|---|
| A | OW5658 | 25 | 104.17 | 37.38 | 41.25 | 90.08 | 222.04 |
| | OW5562 | 37 | 154.17 | 45.40 | 51.14 | 124.46 | 256.43 |
| | OW5835 | 37 | 154.17 | 48.51 | 56.34 | 127.57 | 285.93 |
| | OW51657 | 25 | 104.17 | 27.25 | 38.53 | 79.69 | 211.94 |
| | OW515X2 | 50 | 208.34 | 72.11 | 98.37 | 151.04 | 230.15 |
| | OW5550 | 50 | 208.34 | 75.02 | 107.41 | 163.78 | 244.05 |
| | OW5187X2 | 50 | 208.34 | 92.56 | 92.56 | 198.01 | 258.92 |
| B | OW5P109 | 100 | 416.67 | 135.17 | 293.44 | 425.41 | 557.39 |
| | OW5P110 | 100 | 416.67 | 157.48 | 289.33 | 447.66 | 579.64 |
| | OW5P111 | 100 | 416.67 | 165.19 | 297.03 | 455.36 | 587.33 |
| | OW5P112 | 100 | 416.67 | 137.40 | 295.66 | 427.63 | 559.61 |
| | OW5666 | 37 | 154.17 | 40.51 | 119.58 | 172.36 | 277.94 |
| | OW5154 | 50 | 208.34 | 85.89 | 112.12 | 191.08 | 296.56 |
| | OW5232 | 50 | 208.34 | 105.20 | 131.38 | 210.26 | 368.44 |
| | OW5545 | 75 | 312.50 | 79.71 | 132.25 | 211.31 | 237.68 |
| C | OW5177 | 50 | 208.34 | 89.22 | 141.72 | 194.38 | 247.10 |
| | OW5622 | 50 | 208.34 | 104.06 | 182.81 | 261.83 | 314.56 |

### Case III: Level I Chargers at Night

In this case, different penetration levels of PEVs' charging using level I chargers at night are investigated in terms of voltage deviation, voltage unbalance and the peak load. Tables 5.8 and 5.9 show the calculated maximum voltage deviation and voltage unbalance, respectively, for the different penetration levels of charging PEVs' batteries for level I chargers at 10 PM.

Table 5.8 Maximum Voltage Deviation (in Volt) at Different Locations for Level I at Night in the 12.47 kV Distribution System

| Penetration Level | A55661 | B51432 | C55453 | Location 1 | Location 2 | Location 3 | Location 4 | Location 5 |
|---|---|---|---|---|---|---|---|---|
| NO PEVs | 7.66 | 47.34 | 45.75 | 30.86 | 37.34 | 40.57 | 48.74 | 46.02 |
| 10% | 8.04 | 48.21 | 46.56 | 31.51 | 38.09 | 41.35 | 49.63 | 46.84 |
| 20% | 8.39 | 48.88 | 47.26 | 32.05 | 38.69 | 41.96 | 50.32 | 47.53 |
| 30% | 8.57 | 49.53 | 47.89 | 32.49 | 39.25 | 42.54 | 50.99 | 48.16 |
| 40% | 8.92 | 50.26 | 48.51 | 33.04 | 39.87 | 43.18 | 51.74 | 48.80 |
| 50% | 9.27 | 51.01 | 49.24 | 33.58 | 40.50 | 43.84 | 52.51 | 49.54 |
| 60% | 9.64 | 51.90 | 50.08 | 34.22 | 41.21 | 44.60 | 53.42 | 50.39 |
| 70% | 9.81 | 52.66 | 50.75 | 34.65 | 41.75 | 45.20 | 54.20 | 51.09 |
| 80% | 10.18 | 53.79 | 51.82 | 35.42 | 42.63 | 46.15 | 55.35 | 52.18 |
| 90% | 10.54 | 54.76 | 52.76 | 36.04 | 43.35 | 46.95 | 56.34 | 53.13 |
| 100% | 10.82 | 55.59 | 53.53 | 36.58 | 43.98 | 47.64 | 57.18 | 53.92 |

Table 5.9 % Voltage Unbalance at Different Locations for Level I at Night in the 12.47 kV Distribution System

| Penetration Level | A55661 | B51432 | C55453 | Location 1 | Location 2 | Location 3 | Location 4 | Location 5 |
|---|---|---|---|---|---|---|---|---|
| NO PEVs | 0.107 | 0.670 | 0.649 | 0.435 | 0.526 | 0.573 | 0.690 | 0.652 |
| 10% | 0.113 | 0.682 | 0.660 | 0.444 | 0.537 | 0.584 | 0.702 | 0.664 |
| 20% | 0.118 | 0.692 | 0.670 | 0.451 | 0.546 | 0.592 | 0.712 | 0.674 |
| 30% | 0.120 | 0.701 | 0.679 | 0.458 | 0.554 | 0.601 | 0.722 | 0.683 |
| 40% | 0.125 | 0.712 | 0.688 | 0.465 | 0.562 | 0.610 | 0.733 | 0.692 |
| 50% | 0.130 | 0.723 | 0.699 | 0.473 | 0.571 | 0.619 | 0.744 | 0.703 |
| 60% | 0.135 | 0.735 | 0.711 | 0.482 | 0.581 | 0.630 | 0.757 | 0.715 |
| 70% | 0.138 | 0.746 | 0.720 | 0.488 | 0.589 | 0.639 | 0.768 | 0.725 |
| 80% | 0.143 | 0.762 | 0.736 | 0.499 | 0.602 | 0.652 | 0.784 | 0.741 |
| 90% | 0.148 | 0.776 | 0.749 | 0.508 | 0.612 | 0.664 | 0.799 | 0.754 |
| 100% | 0.152 | 0.788 | 0.760 | 0.516 | 0.621 | 0.673 | 0.811 | 0.766 |

For the penetration levels of PEVs' level I chargers at night, it is clear from the above tables that the increase in maximum voltage deviation (V) form the beginning of the simulated system (Intellirupter A55661) to the end of the simulated system (Intellirupter C55453) is 38.52 V for 10% penetration level and 42.71 V in case of 100% penetration level of PEVs. On the other hand, the increase in %voltage unbalance from the intellirupter A55661 to the intellirupter C55453 ranges from 0.547 V to 0.608 V for the 10% and 100 % penetration levels, respectively. Figures 5.8 and 5.9 demonstrate the maximum voltage deviation and voltage unbalance for using level I chargers at night.

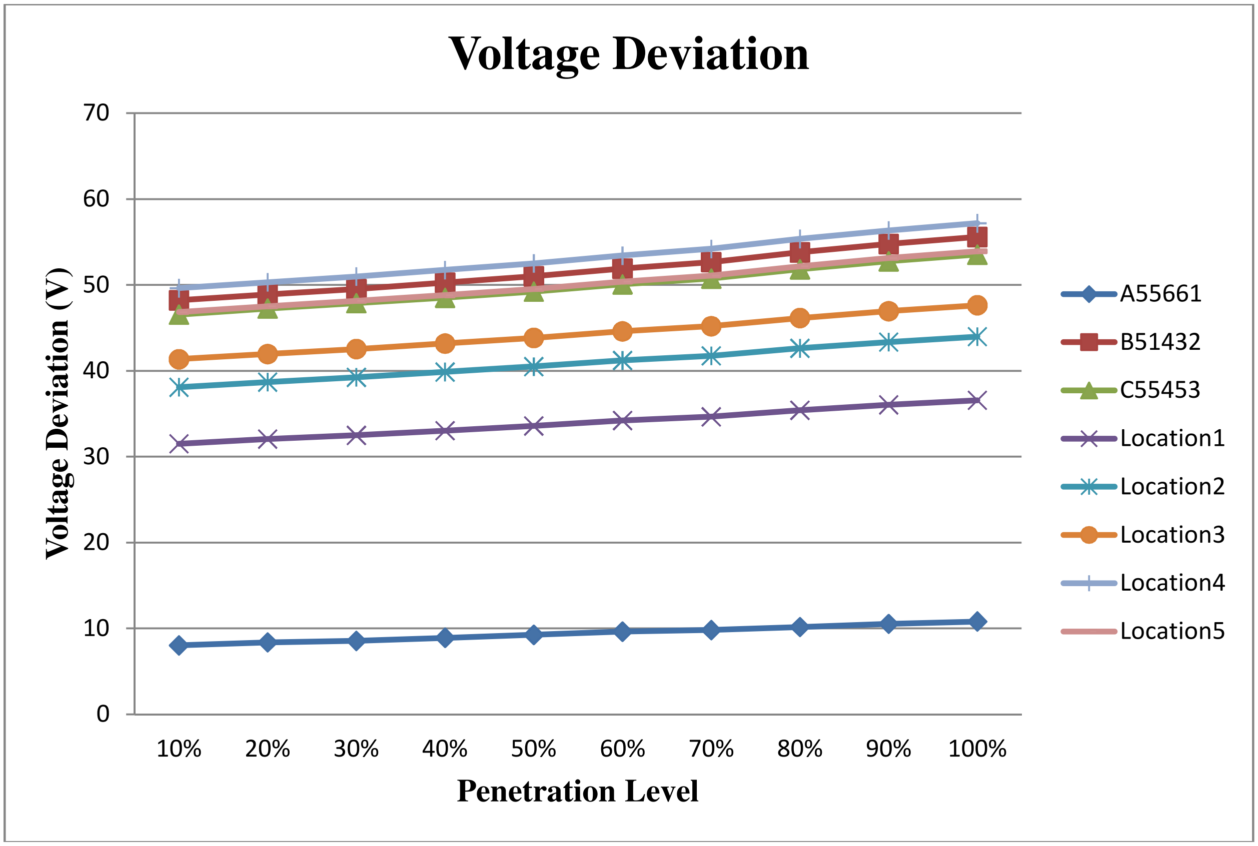


Figure 5.8 Impacts of PEVs Charging on the Voltage Deviation for Level I Charger at Night

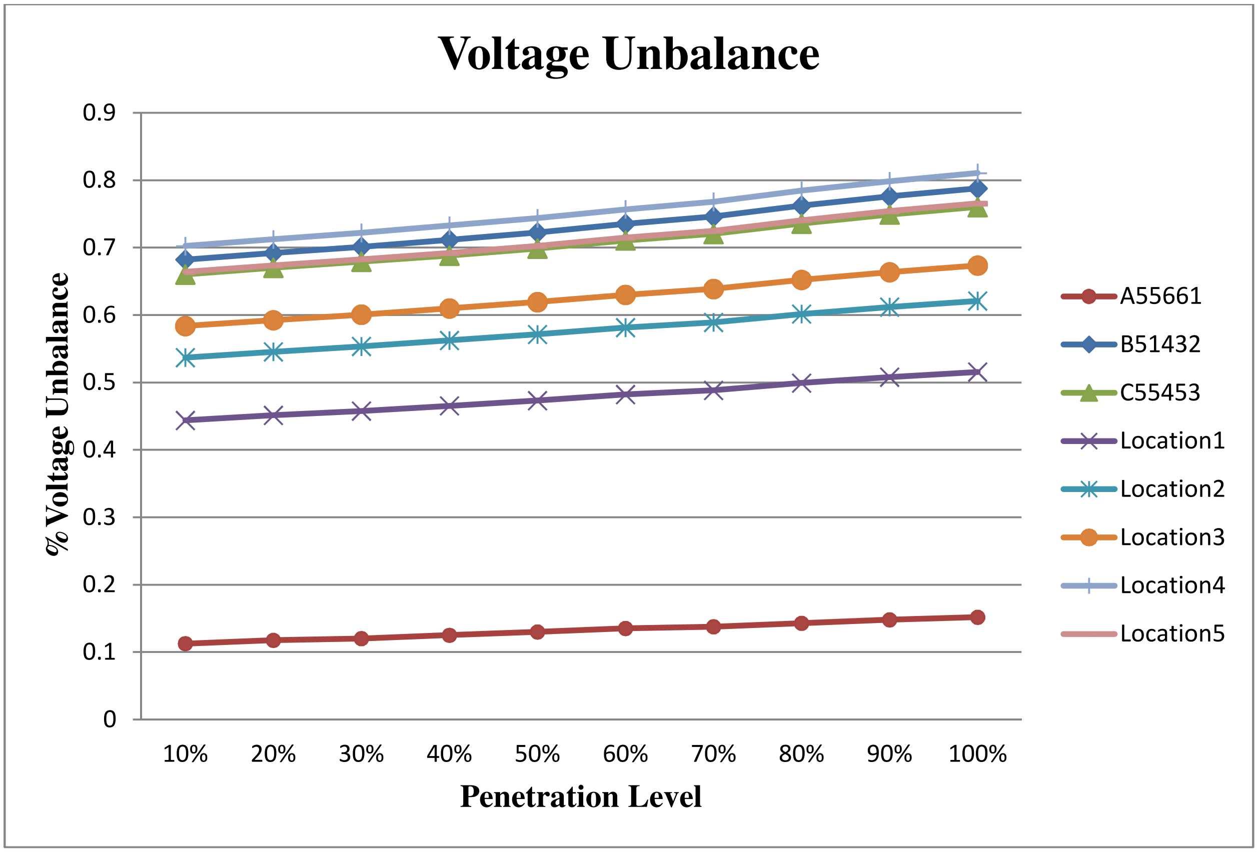


Figure 5.9 Impacts of PEVs Charging on the Voltage Unbalance for Level I Charger at Night

Figure 5.10 presents the impact of PEVs' level I chargers on the peak load. The peak load is shifting from 2:30 PM to 10 PM when consumers plug-in their vehicles at night. For 100% penetration level, the peak load increases to 4.005 MW at 10 PM compared to 4.023 MW at the daily peak hour at 2:30 PM.

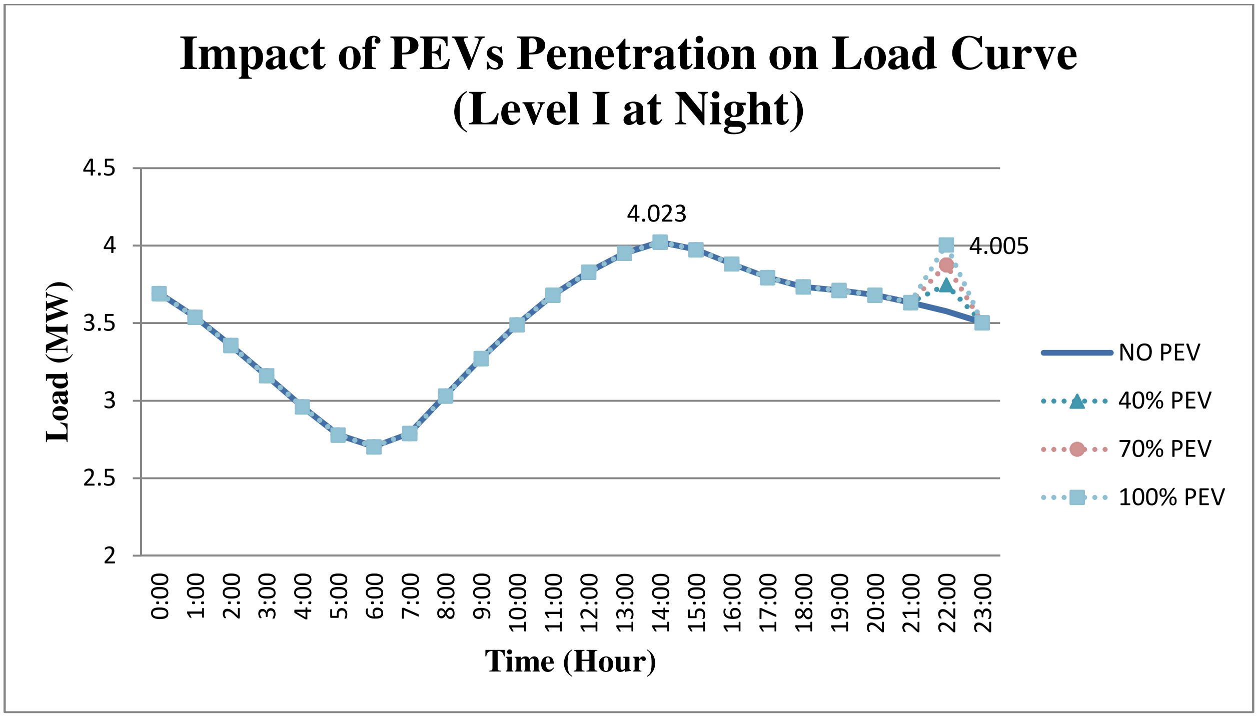


Figure 5.10 Impacts of PEVs Charging on the Peak Load for Level I Charger at Night

### Case IV: Level II Chargers at Night

In this case, different penetration levels of PEVs' charging using level II at night are investigated in terms of voltage deviation, voltage unbalance, the peak load, and transformers overloading. Tables 5.10 and 5.11 show the calculated maximum voltage deviation and voltage unbalance, respectively, for the different penetration levels of charging PEVs' batteries for level II chargers at 10 PM.

Table 5.10 Maximum Voltage Deviation (in Volt) at Different Locations for Level II at Night in the 12.47 kV Distribution System

| Penetration Level | A55661 | B51432 | C55453 | Location 1 | Location 2 | Location 3 | Location 4 | Location 5 |
|---|---|---|---|---|---|---|---|---|
| NO PEVs | 7.66 | 47.34 | 45.75 | 30.86 | 37.34 | 40.57 | 48.74 | 46.02 |
| 10% | 9.17 | 50.80 | 48.98 | 33.45 | 40.34 | 43.69 | 52.27 | 49.32 |
| 20% | 10.55 | 53.51 | 51.79 | 35.62 | 42.74 | 46.13 | 55.04 | 52.05 |
| 30% | 11.26 | 56.09 | 54.30 | 37.38 | 44.96 | 48.44 | 57.71 | 54.57 |
| 40% | 12.63 | 59.03 | 56.82 | 39.58 | 47.47 | 51.03 | 60.74 | 57.18 |
| 50% | 13.99 | 62.08 | 59.75 | 41.77 | 50.01 | 53.69 | 63.83 | 60.14 |
| 60% | 15.44 | 65.67 | 63.14 | 44.35 | 52.90 | 56.77 | 67.51 | 63.60 |
| 70% | 16.10 | 68.66 | 65.78 | 46.04 | 55.04 | 59.16 | 70.60 | 66.34 |
| 80% | 17.50 | 73.10 | 70.01 | 49.06 | 58.49 | 62.90 | 75.13 | 70.64 |
| 90% | 18.88 | 76.87 | 73.67 | 51.51 | 61.34 | 66.01 | 78.98 | 74.35 |
| 100% | 19.89 | 80.05 | 76.62 | 53.56 | 63.76 | 68.68 | 82.21 | 77.39 |

Table 5.11 % Voltage Unbalance at Different Locations for Level II at Night in the 12.47 kV Distribution System

| Penetration Level | A55661 | B51432 | C55453 | Location 1 | Location 2 | Location 3 | Location 4 | Location 5 |
|---|---|---|---|---|---|---|---|---|
| NO PEVs | 0.107 | 0.670 | 0.649 | 0.435 | 0.526 | 0.573 | 0.690 | 0.652 |
| 10% | 0.129 | 0.719 | 0.695 | 0.471 | 0.569 | 0.617 | 0.740 | 0.699 |
| 20% | 0.148 | 0.758 | 0.735 | 0.502 | 0.603 | 0.652 | 0.780 | 0.739 |
| 30% | 0.158 | 0.795 | 0.771 | 0.527 | 0.635 | 0.685 | 0.818 | 0.775 |
| 40% | 0.177 | 0.838 | 0.808 | 0.558 | 0.671 | 0.722 | 0.862 | 0.813 |
| 50% | 0.197 | 0.882 | 0.850 | 0.590 | 0.707 | 0.760 | 0.907 | 0.855 |
| 60% | 0.217 | 0.933 | 0.899 | 0.627 | 0.748 | 0.804 | 0.959 | 0.905 |
| 70% | 0.227 | 0.976 | 0.937 | 0.651 | 0.779 | 0.839 | 1.004 | 0.945 |
| 80% | 0.246 | 1.040 | 0.998 | 0.694 | 0.829 | 0.892 | 1.069 | 1.007 |
| 90% | 0.266 | 1.095 | 1.051 | 0.729 | 0.869 | 0.937 | 1.125 | 1.061 |
| 100% | 0.280 | 1.141 | 1.094 | 0.758 | 0.904 | 0.976 | 1.172 | 1.105 |

For the penetration levels of PEVs' level II chargers at night, it is clear from the above tables that the increase in maximum voltage deviation (V) form the beginning of the simulated system (Intellirupter A55661) to the end of the simulated system (Intellirupter C55453) is 39.81 V for 10% penetration level and 56.73 V in case of 100% penetration level of PEVs. On the other hand, the increase in %voltage unbalance from the intellirupter A55661 to the intellirupter C55453 ranges from 0.566 V to 0.814 V for the 10% and 100 % penetration levels, respectively. Figures 5.11 and 5.12 demonstrate the maximum voltage deviation and voltage unbalance for using level II chargers at night.

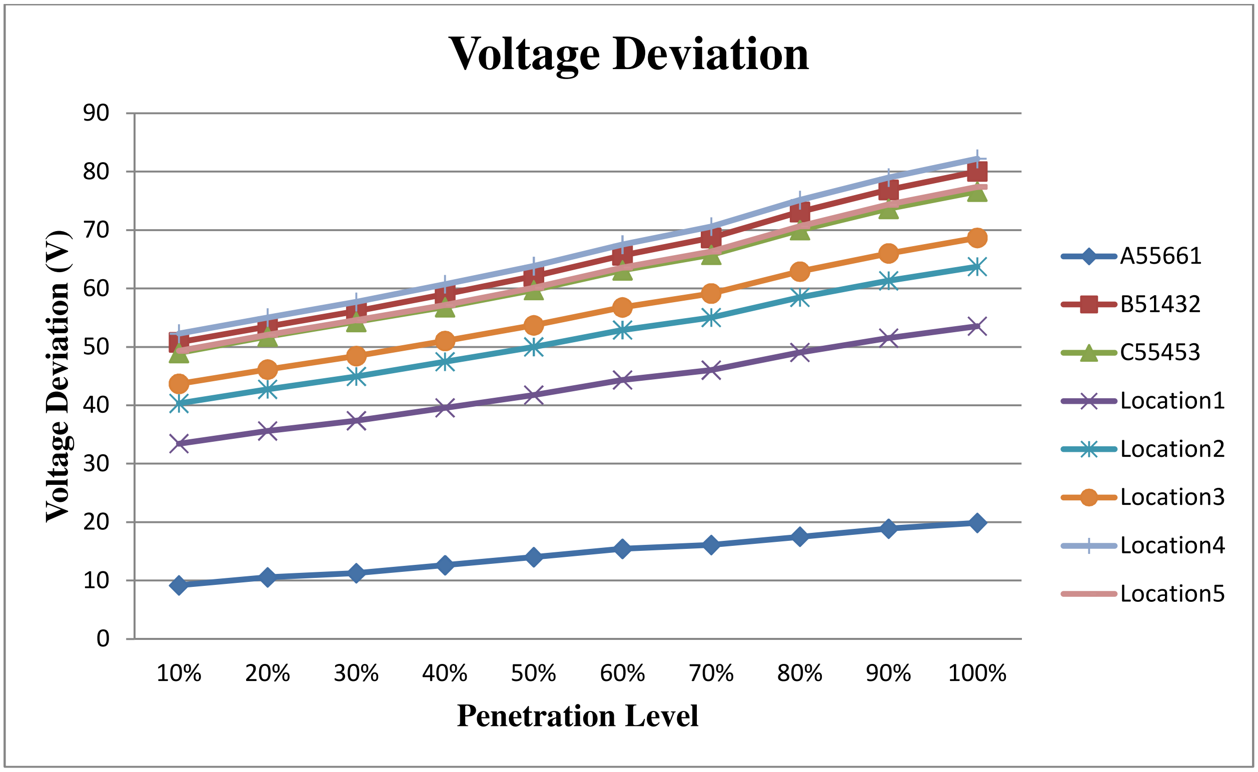


Figure 5.11 Impacts of PEVs Charging on the Voltage Deviation for Level II Charger at Night

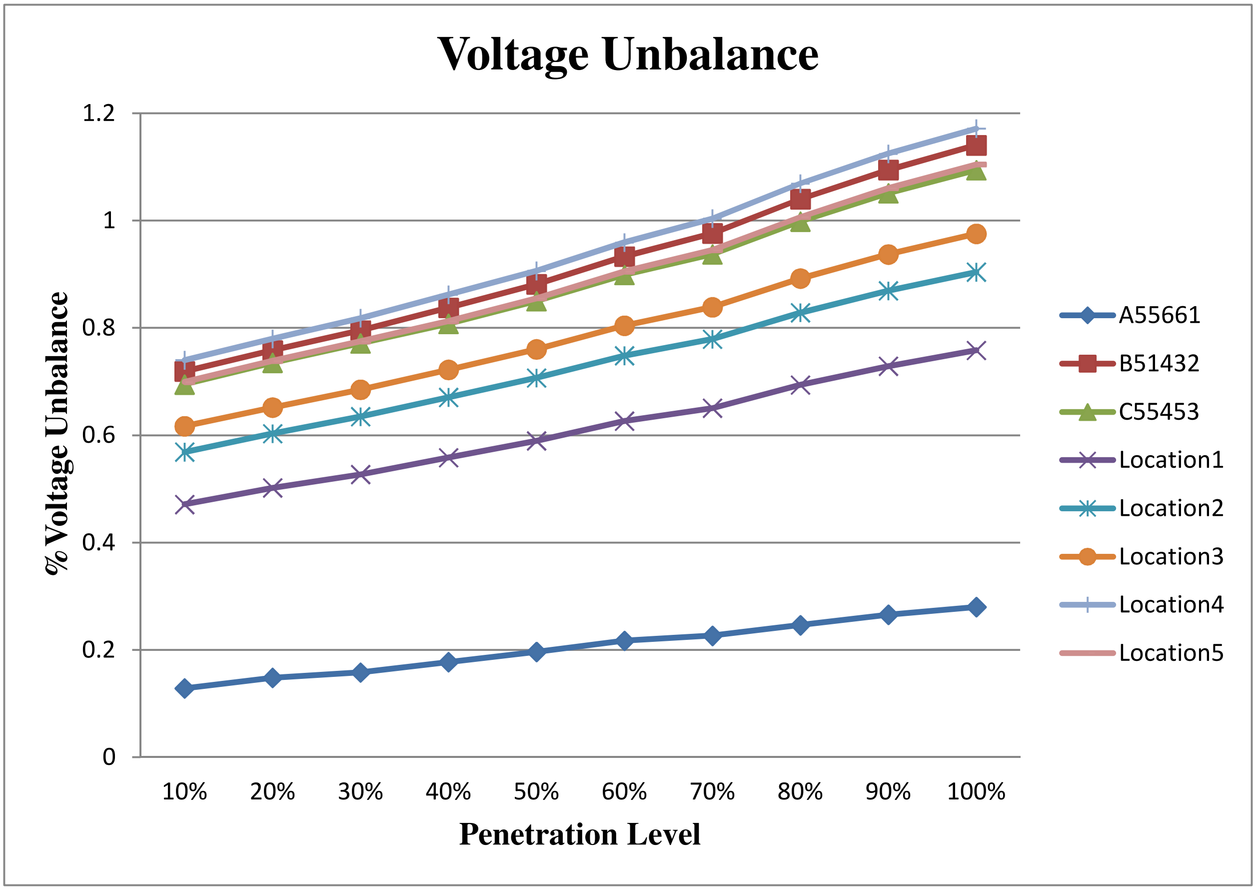


Figure 5.12 Impacts of PEVs Charging on the Voltage Unbalance for Level II Charger at Night

Figure 5.13 presents the impact of PEVs' level II chargers on the peak load. The peak load is shifting from 2:30 PM to 10 PM when consumers plug-in their vehicles at night. For 100% penetration level, the peak load increases to 5.288 MW at 10 PM compared to 4.023 MW at the daily peak hour at 2:30 PM.

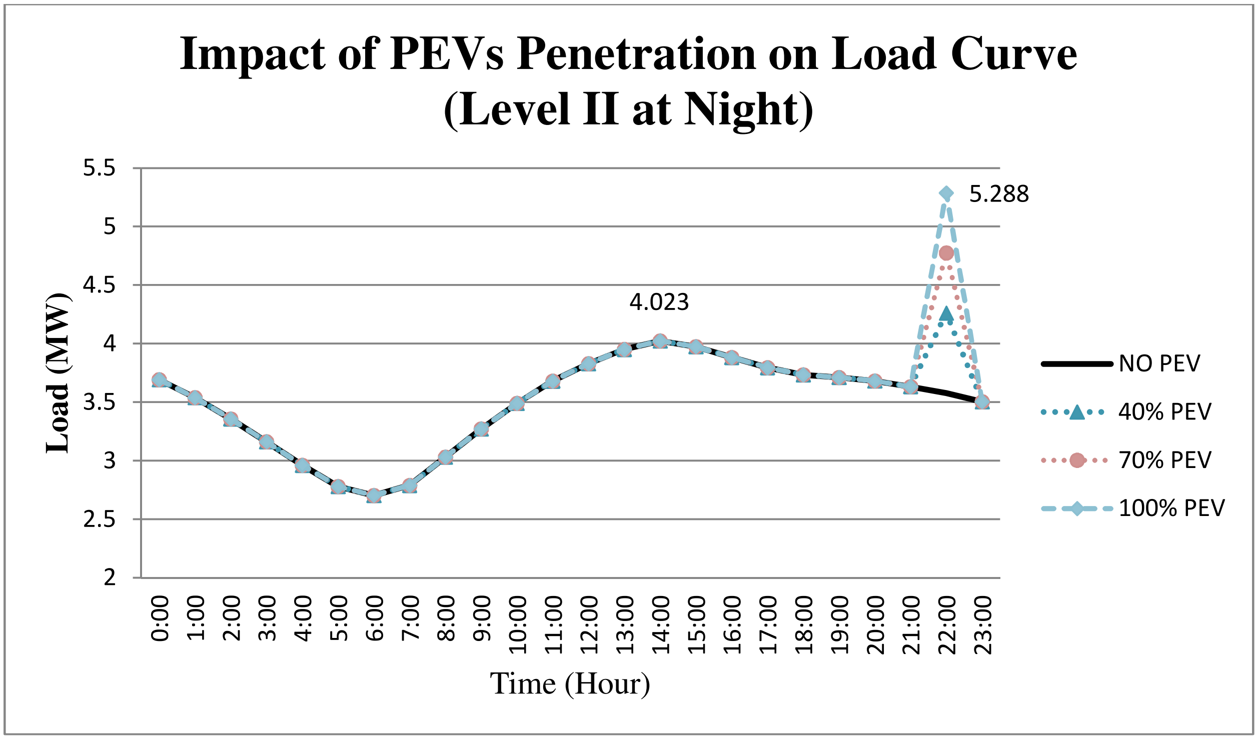


Figure 5.13 Impacts of PEVs Charging on the Peak Load for Level II Charger at Night

As shown in table 5.12, charging PEVs' using level II chargers at night causes a localized overload on the distribution transformers. It has been noticed that as the number of connected costumers increases the service transformers are highly susceptible to be overloaded. Each transformer in table 5.12 has at least 7 customers. Most of the transformers are overloaded or close to be overloaded by the penetration level of 70% or more. Further, at 100% PEVs' penetration, most of the transformers carry as much as twice of their rated load.

Table 5.12 Rated and Measured Currents for Service Transformers for Level II Charger at Night

| Phase | Transformer Labeling | Transformer kVA Rating | Rated Current At 240V (Amps) | Measured Current At 10% PEV penetration | Measured Current At 40% PEV penetration | Measured Current At 70% PEV penetration | Measured Current At 100% PEV penetration |
|---|---|---|---|---|---|---|---|
| A | OW5658 | 25 | 104.17 | 47.32 | 55.52 | 100.03 | 231.98 |
| | OW5562 | 37 | 154.17 | 21.65 | 30.14 | 100.78 | 232.77 |
| | OW5835 | 37 | 154.17 | 12.89 | 29.28 | 82.08 | 240.48 |
| | OW51657 | 25 | 104.17 | 14.92 | 41.29 | 94.08 | 199.67 |
| | OW515X2 | 50 | 208.34 | 39.62 | 65.99 | 118.77 | 197.96 |
| | OW5550 | 50 | 208.34 | 45.02 | 77.10 | 125.78 | 201.48 |
| | OW5187X2 | 50 | 208.34 | 42.50 | 45.99 | 122.01 | 218.81 |
| B | OW5P109 | 100 | 416.67 | 258.52 | 416.70 | 548.61 | 680.56 |
| | OW5P110 | 100 | 416.67 | 218.10 | 349.93 | 508.24 | 640.20 |
| | OW5P111 | 100 | 416.67 | 206.71 | 338.55 | 496.87 | 628.84 |
| | OW5P112 | 100 | 416.67 | 148.12 | 306.41 | 438.37 | 570.36 |
| | OW5666 | 37 | 154.17 | 54.28 | 133.36 | 186.14 | 291.72 |
| | OW5154 | 50 | 208.34 | 103.56 | 129.78 | 208.70 | 314.15 |
| | OW5232 | 50 | 208.34 | 68.90 | 95.19 | 174.25 | 332.57 |
| | OW5545 | 75 | 312.50 | 89.85 | 142.38 | 221.42 | 247.79 |
| C | OW5177 | 50 | 208.34 | 64.29 | 116.93 | 169.67 | 222.44 |
| | OW5622 | 50 | 208.34 | 63.14 | 142.15 | 221.30 | 274.08 |

Finally, these results are close to what were obtained in [37] for voltage unbalance and transformers overloading. The author in [37] used the same distribution system data for the Matlab/Simulink™ model and got similar conclusion. For instance, most of the service transformers in [37] were overloaded during the 60% penetration level while in this study, these transformers are overloaded by 70% of PEVs' penetration level. Additionally, voltage unbalance reached 1% at the penetration level of 70% in [37] whereas in this thesis the voltage unbalance is 1% or more during 60% penetration level for evening charging and during 70% of PEVs' charging at night. These slight differences might be attributed to the different times chosen for plugging electric vehicles. Moreover, the "StubLine" block used in this study between subsystems could be considered as another reason for these differences.

# CHAPTER 6

# CONCLUSION

Large-scale proliferation of plug-in electric vehicles in distribution systems will undoubtedly influence the design and the operation of the distribution network. The increased adoption of electric vehicles has a huge impact on some specifications of the distribution system such as voltage quality at load points and the load curve.

In this thesis, a comprehensive analysis of the electric drives' charging impact on the distribution systems is investigated. This study obtains PEVs' specifications from real data from the available travelling reports (NHTS 2009). These data are used to estimate the characteristics of PEVs utilized in this study. A 12.47 kV residential distribution system has been modeled in RT-LAB environment. This thesis focuses on the impact of PEVs' charging on different terms of the distribution system including maximum voltage deviation, voltage unbalance, transformers overloading, and the daily load shape. It has been observed that the increased PEVs' penetration levels can dramatically affect the daily load profile, service transformers as well as the voltage quality.

Utilities should be able to handle the loads that are associated with EVs batteries' charging. Moreover, coordinated or "smart" charging is very essential to mitigate the disastrous consequences of EVs' penetration on the electrical grids. This controlled charging is an open research area which is currently under study.

Finally,the test bed that has been modeled using real time digital simulator can be used to perform various studies on the distribution system such voltage reduction techniques.

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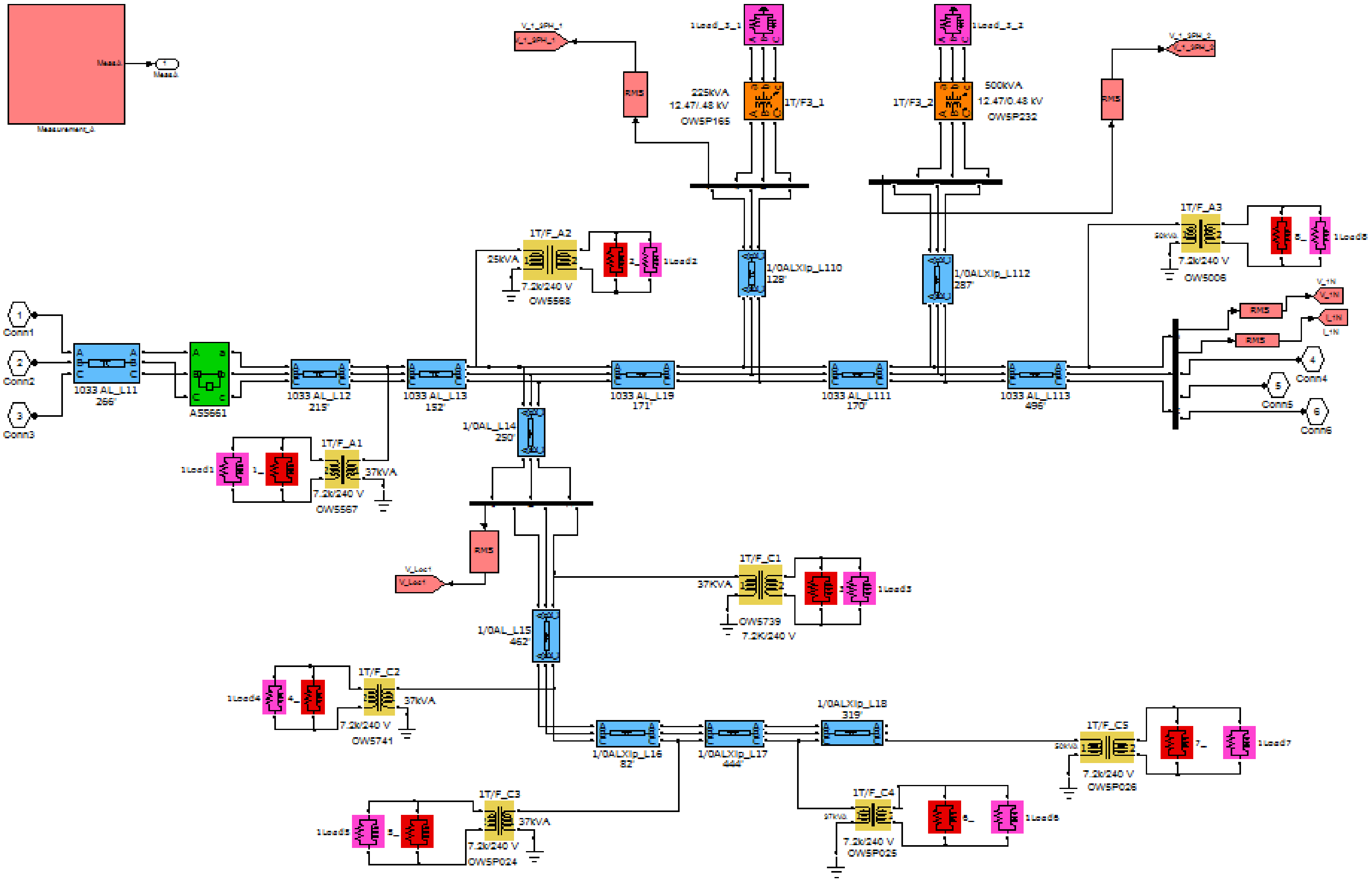
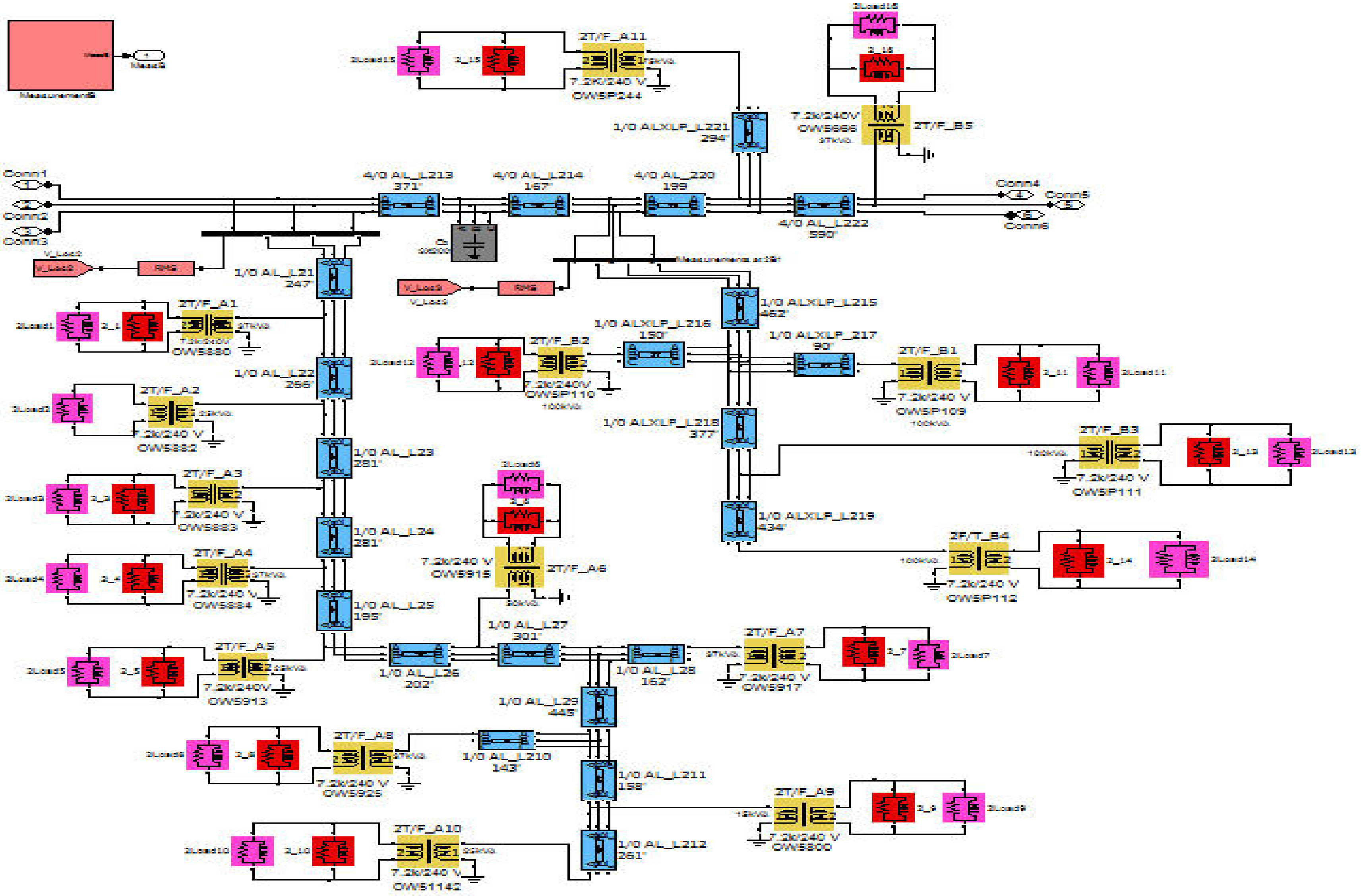
# APPENDIX A

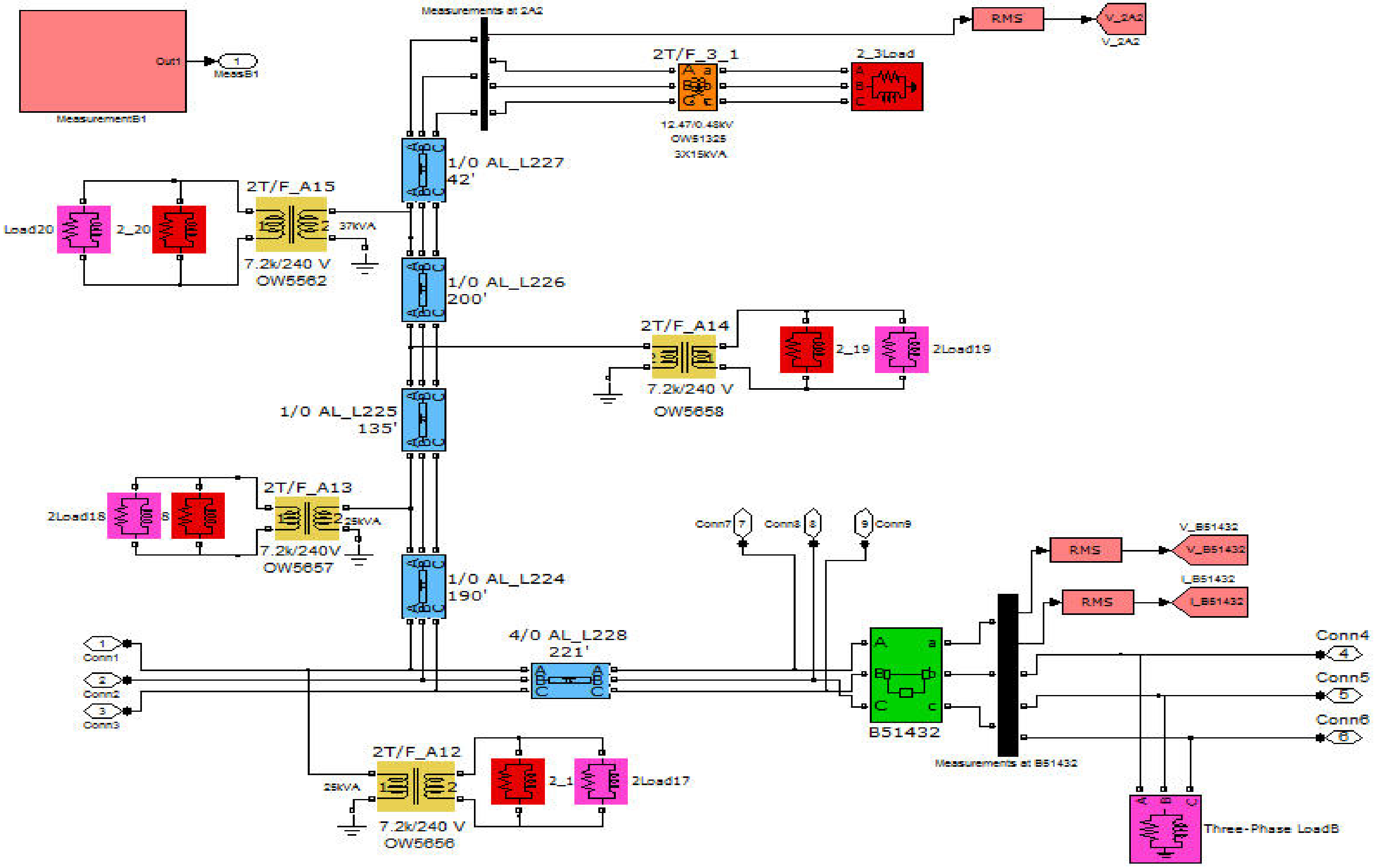
# DETAILED VIEW LAYOUTS OF THE MODEL’S SUBSYSTEMS



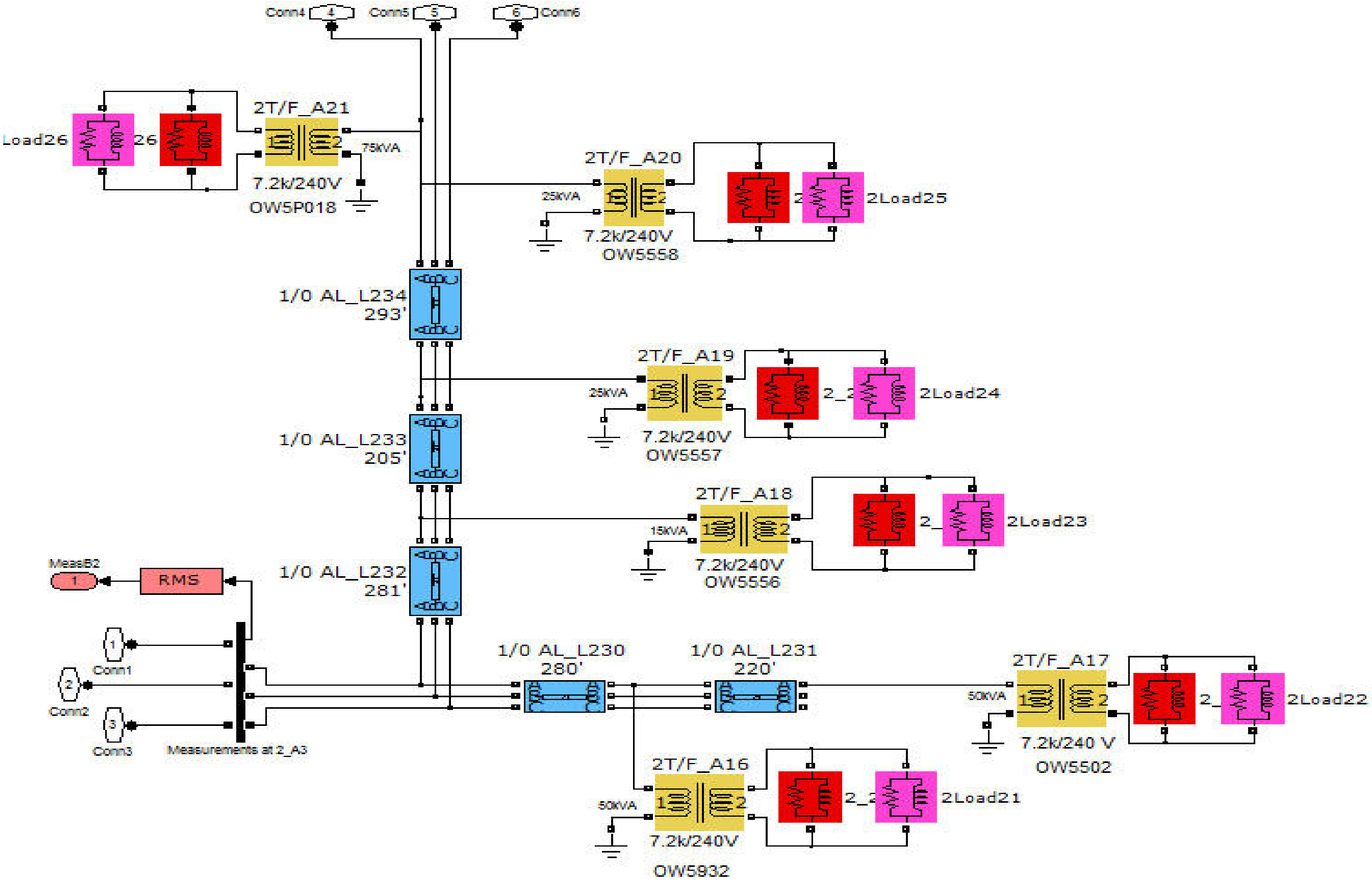
Distribution system layout of subsystem section A



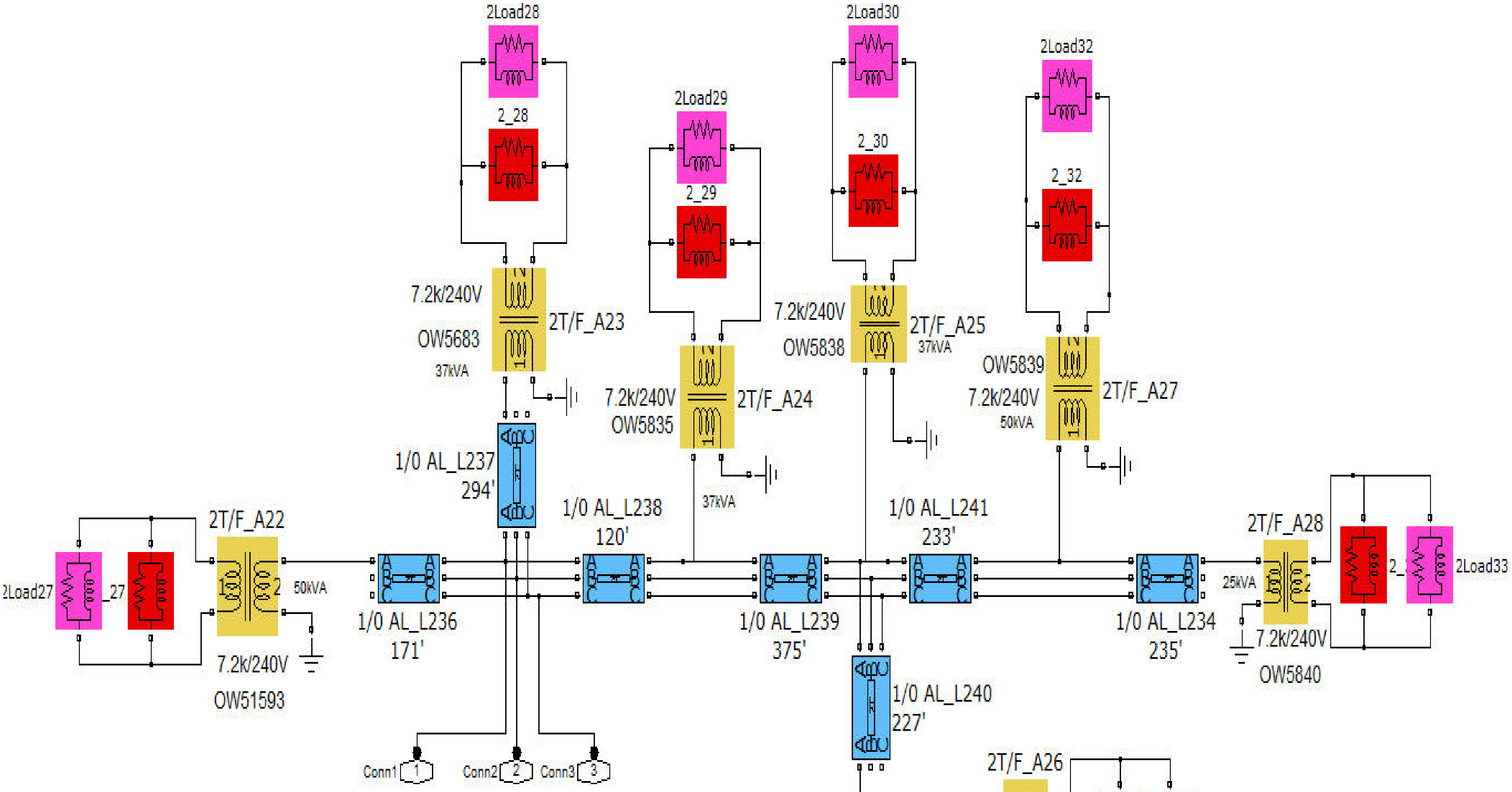
Distribution system layout of subsystem section B



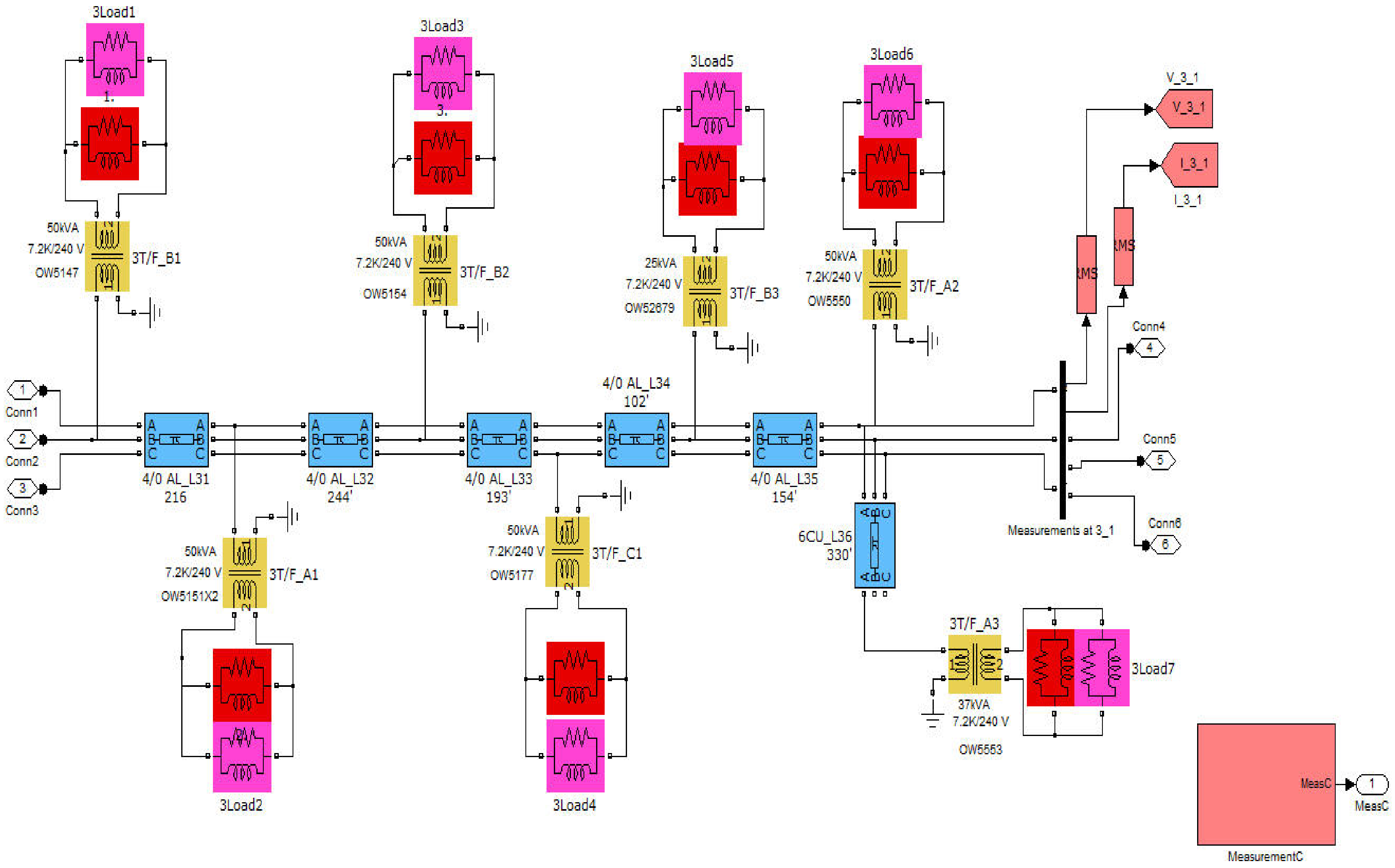
Distribution system layout of subsystem section B1



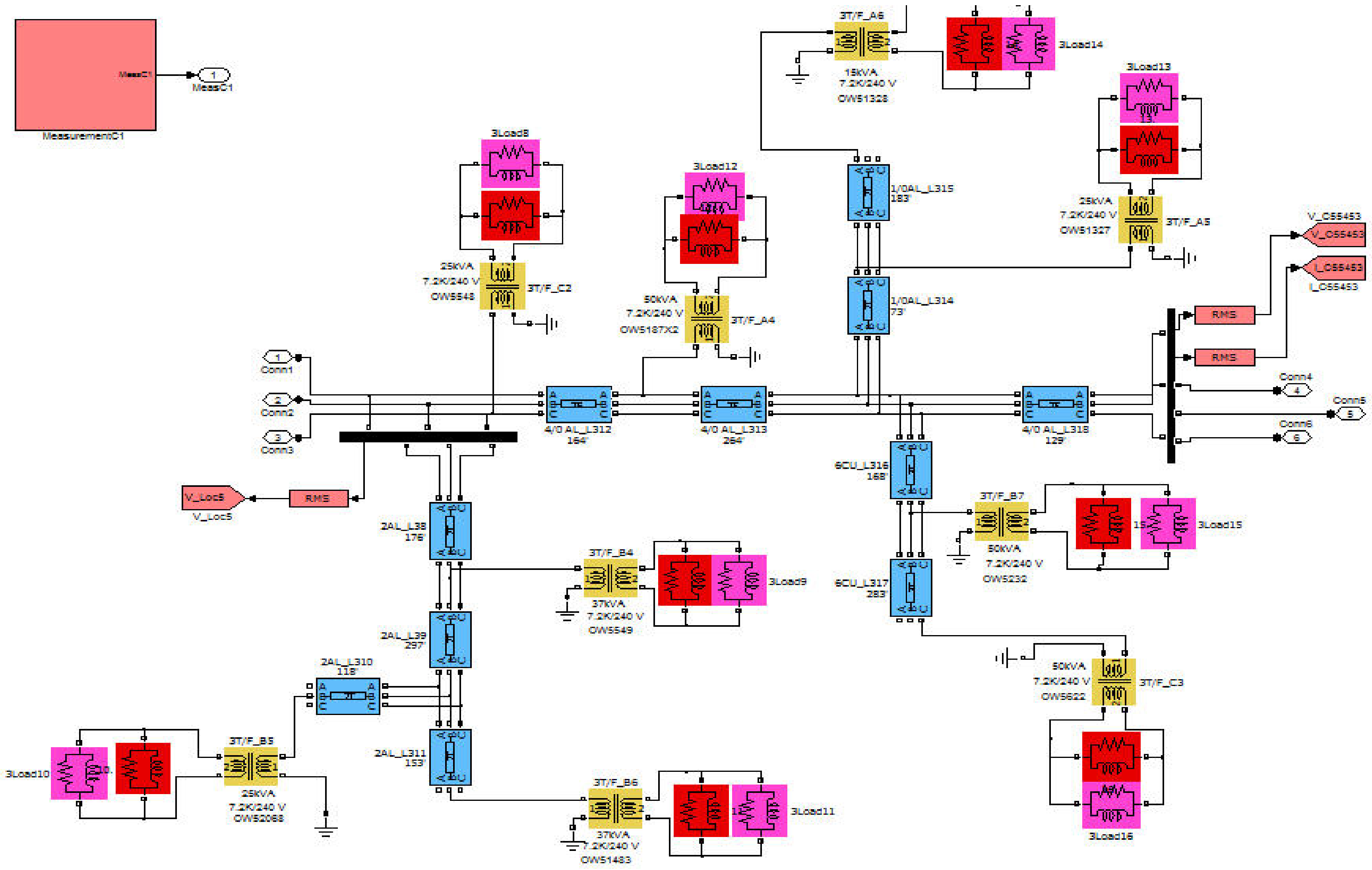
Distribution system layout of subsystem section B2



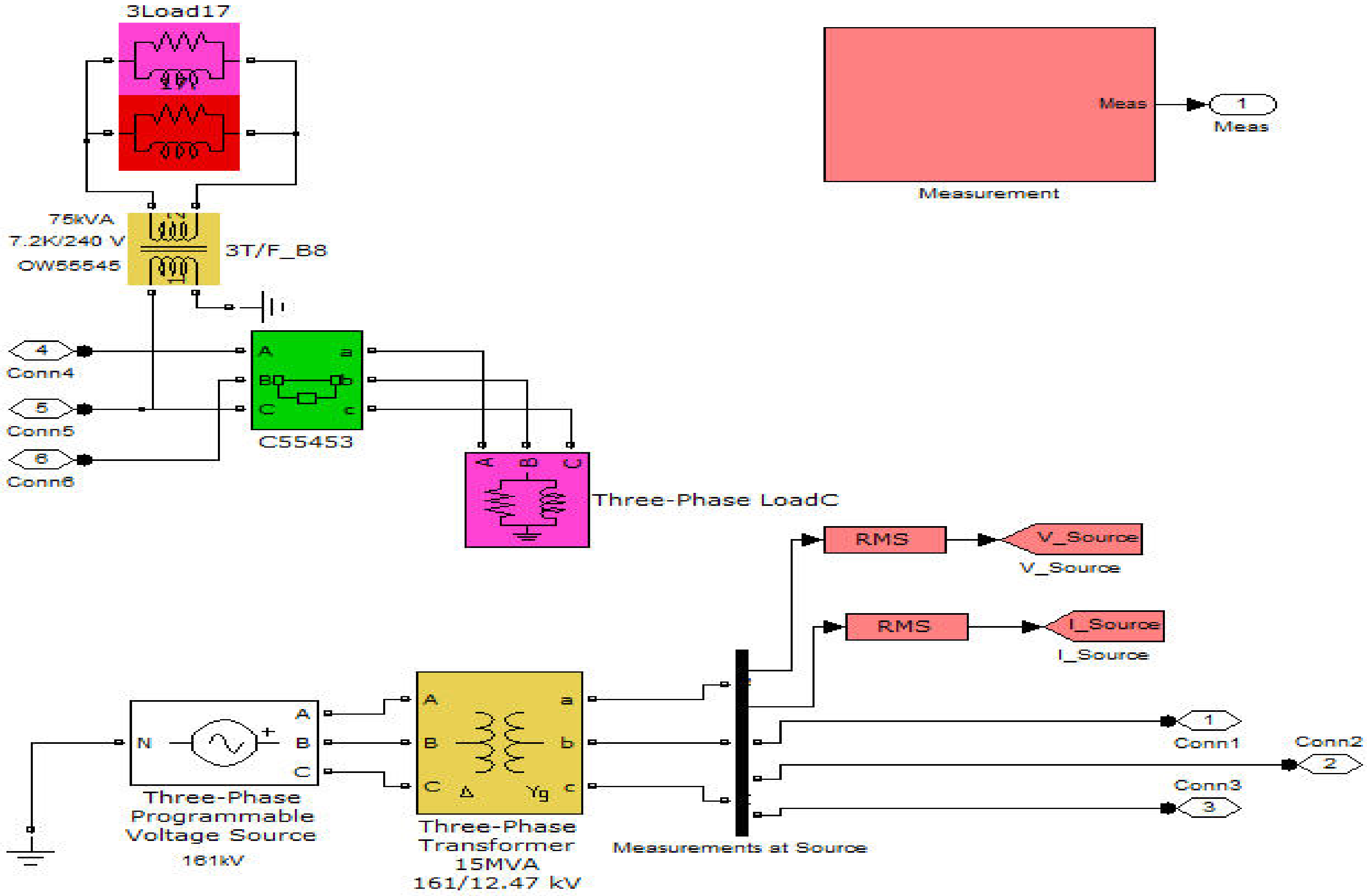
Distribution system layout of subsystem section B3



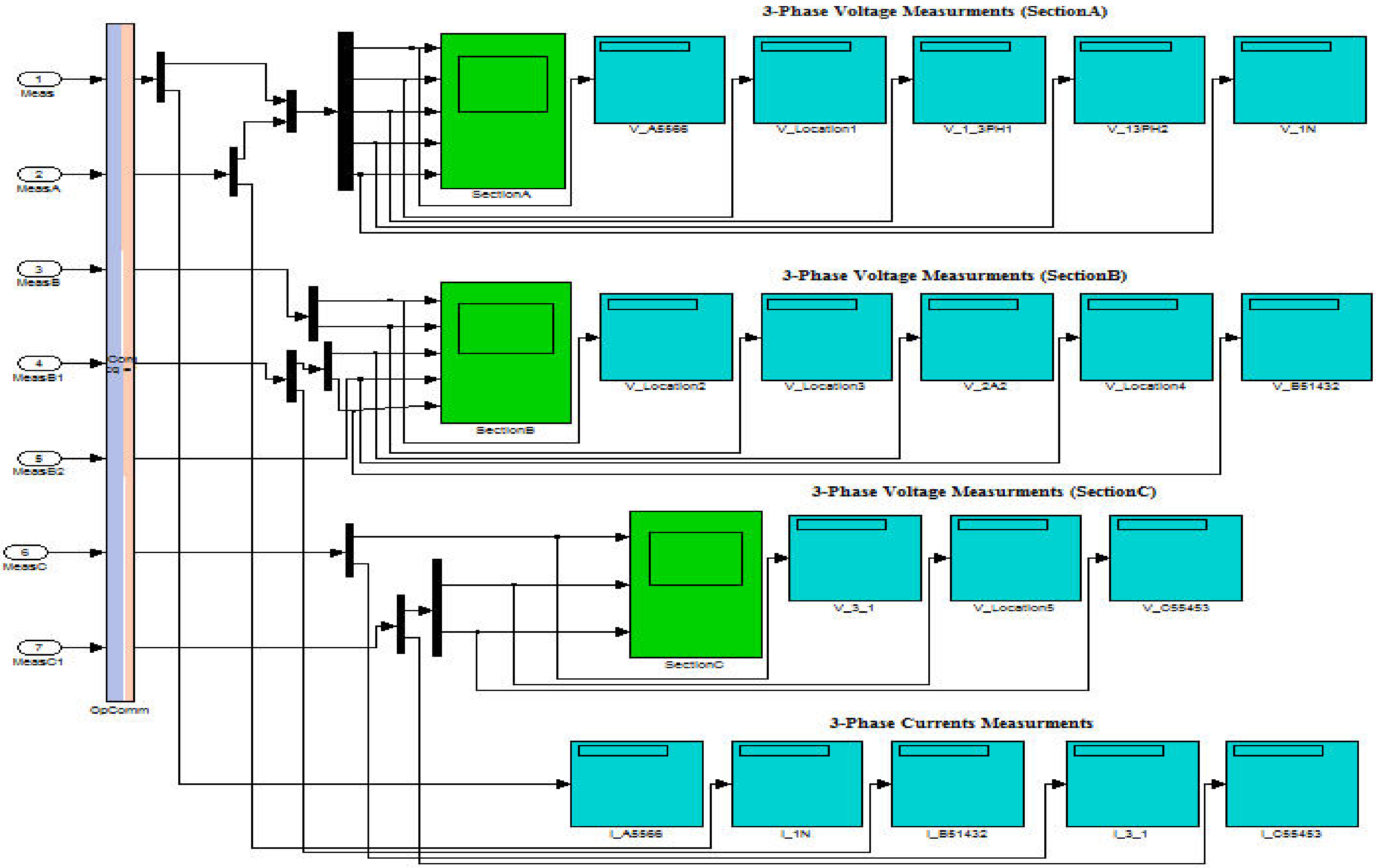
Distribution system layout of subsystem section C



Distribution system layout of subsystem section C1



Distribution system layout of subsystem Source section



Distribution system layout of subsystem Console section

# VITA

Abdulelah Alharbi was born in Buraydah, Saudi Arabia. In July 2009 he completed his Bachelor of Science Degree in Electrical Engineering from Qassim University. In 2010 he joined the Department of Electrical Engineering at Qassim University as a teaching assistant which enables him to pursue his higher studies in the Electrical Engineering field. Abdulelah started the MS Electrical Engineering program at the University of Tennessee at Chattanooga in Spring 2012. He graduated with a Master of Science degree in Electrical Engineering in December 2013.