A CORRECTIVE STRATEGY FOR VOLTAGE REGULATION IN DISTRIBUTION GRIDS WITH PLUG-IN HYBRID ELECTRIC VEHICLES

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A Corrective Strategy for Voltage Regulation in Distribution Grids

with Plug-in Hybrid Electric Vehicles

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MASTER OF SCIENCE

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ABSTRACT

The increasing integration of Plug-in Hybrid Electric Vehicles (PHEV) poses unique challenges for voltage and frequency regulation in electric distribution grids. The mobility and variability due to PHEV loads exacerbates the problem of voltage regulation in distribution grids that are characterized by high R/X ratios. Numerous studies have explored the impact of PHEV integration on distribution grids, corrective strategies have been mainly limited to designing constrained charging profiles.

This thesis examines the effect of different charging profiles and then presents a corrective strategy for voltage regulation in distribution grids without specifically constraining a user's charging profile. The proposed scheme is based on reactive power management, utilizing voltage sensitivity analysis. The compensatory scheme calculates reactive (or active when available) power injection for a bus to ensure voltage regulation at the charging bus. Simulations on the IEEE-13 bus for the scheme provides significant improvements (up to 9 %) in voltage profiles.

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I am indebted to my parents and my sister for believing in me and supporting my dreams to achieve my goals. I am blessed to have a loving and caring family.

I am lucky to have my husband, Ashu Arora, who is my greatest strength and my support whatever may come by. His endeavors and love has been the reason for my success big and small.

I would like to forward my acknowledgements to NDSU libraries and Starbucks coffee shop for providing me the decent environment to study.

DEDICATION

To my loving parents and my husband.

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LIST OF ABBREVIATIONS

PHEV…………………Plug-in Hybrid Electric Vehicle

EV…………………….Electric Vehicle

ICE……………………Internal Combustion Engine

BEV…………………..Battery Electric Vehicle

HEV………………….Hybrid Electric Vehicle

V2G…………………..Vehicle to Grid

AER………………….All-Electric Range

SOC…………………..State of Charge

CD…………………….Charge Depleting

CS……………………..Charge Sustaining

DFIG………………… Double Fed Induction Generator

EPRI............................Electric Power Research Institute

LDC.............................Load Duration Curve

DR……………………Distributed Resource

NHTS…………………National household Travel Survey

PCLP………………….PHEV Charging Load Profile

PNNL………………...Pacific Northwest National Laboratory

ORNL………………...Oak Ridge National Laboratory

NRDC………………..Natural Resources Defense Council

1. INTRODUCTION

The world we reside in is a fast paced age of development, innovation, and continuous technology advancement. Each day a new technology or a new product is introduced that would in some way make life easier and simpler. The first recorded realization of technology started when the early man invented the wheel and since then the quest to strive for betterment has been the goal of humanity. Like every other scientific field of technology the electrical industry has evolved since its inception in the industrial age. It has seen a lot of changes from that time to its today's highly futuristic version, the Smart grid. EPRI defines smart grid as one that incorporates information and communications technology into every aspect of electricity generation, delivery, and consumption in order to minimize environmental impact, enhance markets, improve reliability and service, and reduce costs and improve efficiency. Some of the features of smart grid are reliability, flexibility in network and flows, efficiency, demand side management, sustainability that are been widely experienced by consumers, operators, and utilities.

As new and advanced generation transmission and metering systems are added as a part of the smart grid, a new kind of load, "PHEV" is envisaged to be added to the electrical grid. PHEV is an acronym for Plug-in Hybrid Electric Vehicles. A PHEV is a hybrid gasoline-electric vehicle which has a huge battery pack that can be charged through the grid. As more and more PHEVs are introduced in the system they pose as an additional load to the grid. Studies and research have been progressing on how to cater to this load and if at all PHEVs can contribute in demand leveling of the grid. This research solves a similar interest. It studies the impact of penetration of plug-in hybrid electric vehicles on a distribution grid and analyzes its effect on the voltage levels at different buses. The effect of penetration is studied in increasing percentage of PHEVs. To improve the voltage deviation that is caused by the increasing sporadic PHEV load, a corrective strategy is proposed and implemented. The maximum improvement observed on the output voltage profile for local and remote compensation for various cases is 2% to 9.47%.

1.1. Electrification of Transport Industry

The ever rising demand of gasoline and increasing rate of vehicles being added to the market are certainly a well-known threat to the environment. Every now and then, innovative ideas have been adopted to decelerate the over usage of gasoline and to reduce the pollution threat to the environment. However the performance and convenience of gasoline operated vehicles is yet to be matched. A significant and evolutionary technology developed and realized in this direction is the introduction of Electric Vehicles. Electric vehicles as the name suggests are driven by electric power coming from battery packs charged from an external power source. Electric vehicles do not have an ICE (Internal Combustion Engine) or a fuel tank. Plug-in Hybrid Electric Vehicles are a step forward from the electric vehicles. PHEVs (Plug-in Hybrid Electric Vehicle) are currently the most dependable substitutes for regular gasoline cars. They are a hybrid of traditional ICE vehicle and Electric vehicle.

What makes PHEV a unique substitute, is that it shares characteristics of both kinds of vehicles. Like an electric vehicle it is free from the dependence on the fluctuating price of gasoline and has significantly low emission of greenhouse gases. In addition to this it overcomes the limitation of an electric vehicle of running out of range, since the ICE engine is available for backup in case of an emergency.

According to IEEE; A plug-in hybrid electric vehicle is defined as any hybrid electric vehicle which contains at least: (i) a battery storage system of 4 kWh or more, used to power the motion of the vehicle; (ii) a means of recharging that battery system from an external source of electricity; and (iii) and ability to drive at least 10 miles (16.1 km) in all-electric mode consuming no gasoline.

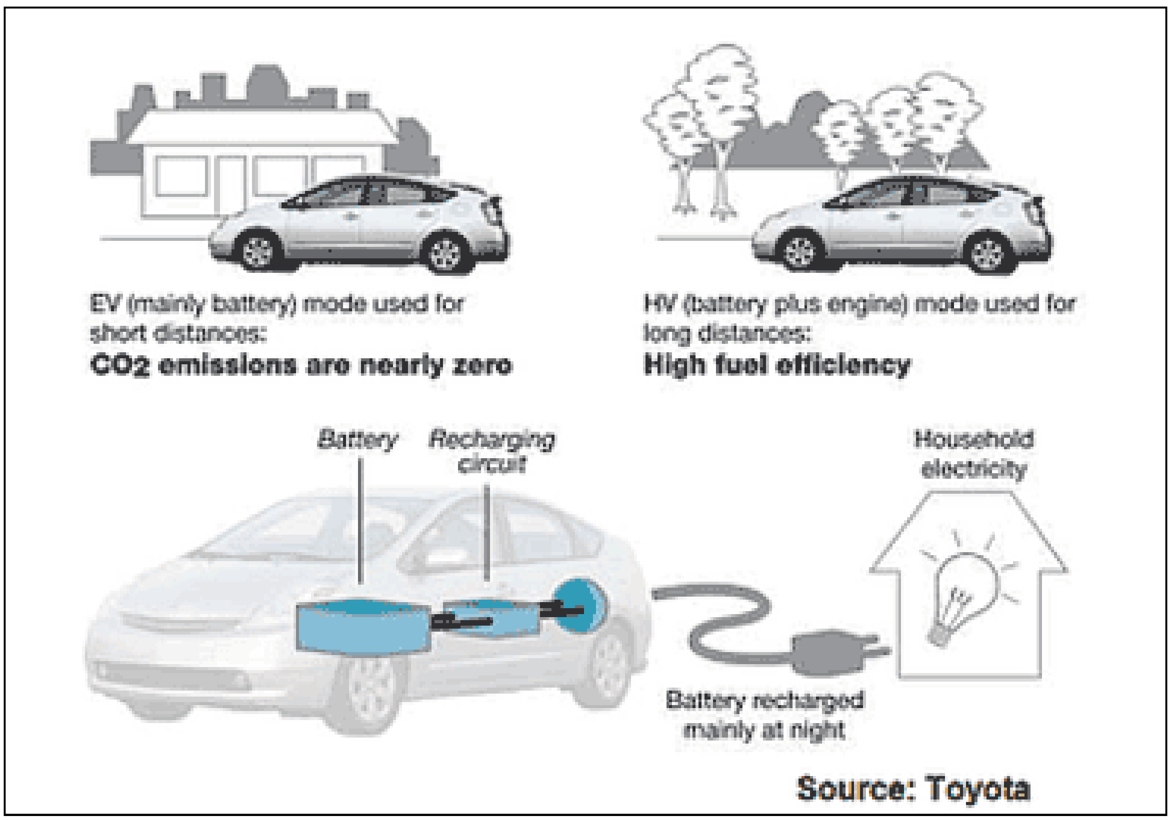


Figure 1-1. General overview of PHEV charging and benefits

1.2. Distribution Systems

The transmission system voltage is stepped-down to lower levels by distribution substation transformers. The primary distribution system is the power network between the distribution substation and the utilization transformers. The modern distribution system begins as the primary circuit leaves the sub-station and ends as the secondary service at the customers' end use. Distribution circuits serve many customers. The voltage used is appropriate for the shorter distance and varies from 2,300 to about 35,000 volts depending on utility standard practice, distance, and load to be served. The research in [1], [7], [8], [14], [15], [25] have used distribution systems as a part of their study. This research uses the distribution network to study the desired impacts and simulate the compensatory scheme.

1.3. Impacts of PHEV Integration

Research and development in this area have led countries like US, France, Germany, Korea, and UK to include Electric vehicles in their studies and planning. The US Government's commitment towards green energy has been re-iterated by the plan to have one million PHEVs on road by 2015 [49]. The research labs at University of Maryland, Argonne National labs, PNNL, and EPRI have been conducting serious research to analyze the effects of PHEV on the grid operation. The report [5] discusses the current state of US electric grid and the stages it has undergone. It analyzes the advantages and impact of electric vehicles on American utility industry. It also gives a brief idea of current operating costs and other repercussions that may arise after the integration of PHEV.

1.3.1. Highlights of the Impacts of PHEVs

- Increase in the load on distribution grid, foreseeing high PHEV penetration. The studies [5], [6], [8], [10], [21] envisage 18% - 60% increase in the load.
- The increase in load leading to higher temperatures and insulation breakdown in the power system equipment.
- Study in [7] and [18] proposes high distribution losses as a result of PHEV loading.
- Research in [10] and [18] demonstrates overload of lines as a major concern parameter due to increase of PHEV load.
- Transformer loading increasing up to 100%
- Study in [21] shows the voltage falling down to 96% of the rated value with the increase in PHEV load by 2040.

The study in [7] gives a very holistic overview of the PHEV concept. It analyzes the coordinated charging of PHEVs and the possibility of utilizing PHEVs as DRs, by injecting energy in the grid to restrict voltage drops. Quadratic and dynamic programming is used to study the charging/discharging and price tariffs. Different kinds of PHEVs are described in [9] and their impact on the grid is analyzed. The research in [30] studies the factors that account for the study of PHEV and the demand assessment for three PHEV penetration scenarios. Impacts are studied on UK grid based on the European standard. PHEV impacts on IEEE-14 bus grid are studied for uncontrolled and controlled charging of PHEV in [12]. The result of the study states that both schemes pose load on the system and the controlled scheme imposes 50% higher peak load than uncontrolled charging.

Specific and minute observations are laid out in [21]. PHEV's future in Idaho state are assessed, simulations and the study concludes that the PHEV penetration will cause an 18% increase in the distributed load on the Ada County electric grid by the year 2040. The most salient problem associated with this increase in load is the 96% drop of line voltage. Measures are suggested to cater to the load like upgrading the power system equipment and altering charging schemes.

Generic study in [13] provides a consortium of a larger research project, collects, organizes, and stores data for the PHEV studies. Results of the study are real world data that can be used to estimate the effect of PHEV penetration on utility market sales and generation capacities. On a similar subject [22] discusses the research done by various studies and summarizes their work and segregates it into different heads. Study paper [14] uses the PHEV distribution circuit impact model (PDCIM) to estimate the impact of an increasing number of PHEVs on transformers and underground cables within a medium voltage distribution system. Similar study is done in [15]; it studies the impact of charging PHEVs on a distribution transformer under different charging scenarios. Results show that PHEV penetration creates new load peaks and exceeds transformer capacity. To avoid this staggered charging or household load control options are suggested.

Research in [20] analyzes the data from NHTS for vehicles. And three charging scenarios are developed to get PHEV Charging load profiles. PCLP (PHEV charging load profiles) are added different to the domestic load profile and are developed from the NHTS data, battery info, vehicle start and arrival time, and vehicle AERs. Work done in [26] proposes minimizing power losses and voltage deviations, improvement in power quality by coordinated charging. 43 node IEEE radial bus network is used for simulation. Quadratic planning and sequential quadratic optimization is used.

1.4. Motivation

As examined in the previous researches and studies, the impacts of PHEV discussed in section 1.3, propose the remedial actions against the increasing PHEV loads. The solutions proposed for the problem of increasing PHEV load on the system are mainly:

- Addition of new transmission lines, as proposed in [21]
- Upgrading of power system equipment, proposed in [8]
- The most commonly proposed solution to the problem is coordinated charging algorithms. The studies in [6], [7], [10], [18] and [25] propose coordinated charging algorithms for PHEV load on the system.

The various solutions proposed in the studies done on PHEV have two major disadvantages:

1. The cost involved in planning and installing new equipment in the grid has not been accounted for, which will make these propositions weak.
2. Secondly as proposed, coordinating the charging profile deeply impacts the user preference, considering the fact that user behavior is sporadic in nature and as the

sample area of impact increases it gets more difficult to control the user behavior/ preference to coordinate the charging.

1.5. Significance of the Current Research

As compared to the solutions listed in the previous section, this research presents a corrective strategy for voltage regulation in distribution grids, without specifically constraining a user's charging profile. The major benefit in the method is the freedom given to the user to charge the vehicle as per the need; hence the method is more flexible as compared to the solutions proposed otherwise. Also the additional cost incurred in adding or upgrading new equipment is considerably low and almost zero in certain cases.

This research and compensation scheme stands apart from the previous studies as it tackles the problem from a different angle however achieving the ultimate aim to provide voltage regulation at the charging bus.

1.6. Contributions of this Research

This research provides a study of PHEV impacts on the IEEE-13 bus distribution network. Bus voltage profiles for five cases in percentage increments of 0% to 100% of PHEV loading are recorded, for the network. Results show the impact on residential bus and commercial bus. Maximum Voltage deviation for these buses for different conditions/PHEV penetrations (in %) are registered. Further, local and remote compensation are suggested and implemented for individual and weighted methods. These methods involve local/remote active/reactive power injection on a bus, calculated by voltage sensitivity analysis. Maximum improvements in bus voltage for each penetration level are listed. Local and weighted compensation methods are implemented and simulations show significant improvement in the voltage profile as compared to the uncompensated case.

1.7. Simulation

The test bed used in this research is the IEEE-13 bus network. The 13 bus distribution network is modeled on OpenDSS. OpenDSS supports development of the system to analyze the various scenarios and test cases. IEEE-13 bus test feeder values are used for the base case. The IEEE-13 bus test case is adopted from OpenDSS repository. Code is developed for the various scenarios and conditions involving the PHEV penetration to perform the desired operation. The system uses a 24 hour daily load data and simulates PHEV load in order to study the effect on distribution grid. Results are obtained in form of output bus voltage. Results are processed and conditioned to obtain graphs that support the claimed improvement.

1.8. Thesis Structure

Chapter 2 discusses the basics of PHEV and its functions. The various aspects of PHEV advantages and disadvantages are highlighted. Different kinds of PHEVs are classified.

Chapter 3 primarily discusses the PHEV impacts on the grid, the concept of V2G, and the previous studies that have explained and reviewed the situation with respect to the varying scenarios and effects. It further extends to the study done in this research, on the scenarios, and what impact is observed on the network.

Chapter 4 focuses on the implementation of the interests of the current research. The test bed, various cases and the simulation software are discussed. Results of the PHEV load impacts are demonstrated and compared for various cases.

Chapter 5 suggests the corrective strategy to counterbalance the impact of the PHEV penetration. The implementation of the strategy is explained and the simulated cases are described. Results to show improvement are demonstrated.

Chapter 6 concludes the study, the contributions of the research and how they are useful in the study of PHEV and its impacts. The future research and suggestions are also listed.

2. PLUG-IN HYBRID ELECTRICAL VEHICLES

2.1. Introduction

The previous chapter describes and defines PHEVs and the various research studies that have studied the impacts of PHEV considering various quantifying parameters. In this chapter the entire PHEV system is studied and the aspects that make PHEV a sustainable choice are discussed. The various components that comprise of a complete PHEV system are laid out. The significance of PHEVs and the advantages of using PHEV are listed and compared against the conventional gasoline vehicle. The limitations of PHEV are also listed.

2.2. Electric Vehicles

Electric Vehicles (EVs) can be classified based on different criteria. The following are classified based on the basic functionality:

Battery Electric Vehicles (BEV) refers to vehicles propelled solely by electric motors. The source of power stems from the chemical energy stored in battery packs which can be recharged on the electricity grid. The future of such vehicles strongly depends on the battery developments (significantly performance and cost).

Hybrid Electric Vehicle (HEV) is a type of electric vehicle which combines a conventional ICE propulsion system with an electric propulsion system. HEVs make use of efficiency-improving technologies such as regenerative braking, which converts the vehicle's kinetic energy into electric energy to charge the battery

Plug-in Hybrid Electric Vehicles (PHEV) refers to vehicles that can use, fuel and electricity, both of them rechargeable from external sources. PHEVs can be seen as an intermediate technology between BEVs and HEVs. It can indeed be considered as either a BEV supplemented with an ICE, to increase the driving range, or as a conventional HEV where the all-electric range is extended as a result of larger battery packs that can be recharged from the grid. The IEEE (board of directors, 2007) defines a PHEV as, "any hybrid electric vehicle which contains at least: (1) a battery storage system of 4 kWh or more, used to power the motion of the vehicle; (2) a means of recharging that battery system from an external source of electricity; and (3) an ability to drive at least ten miles in all-electric mode, and consume no gasoline. These are distinguished from hybrid cars mass-marketed today, which do not use any electricity from the grid." Figure 2.1 shows the various parts of PHEV.

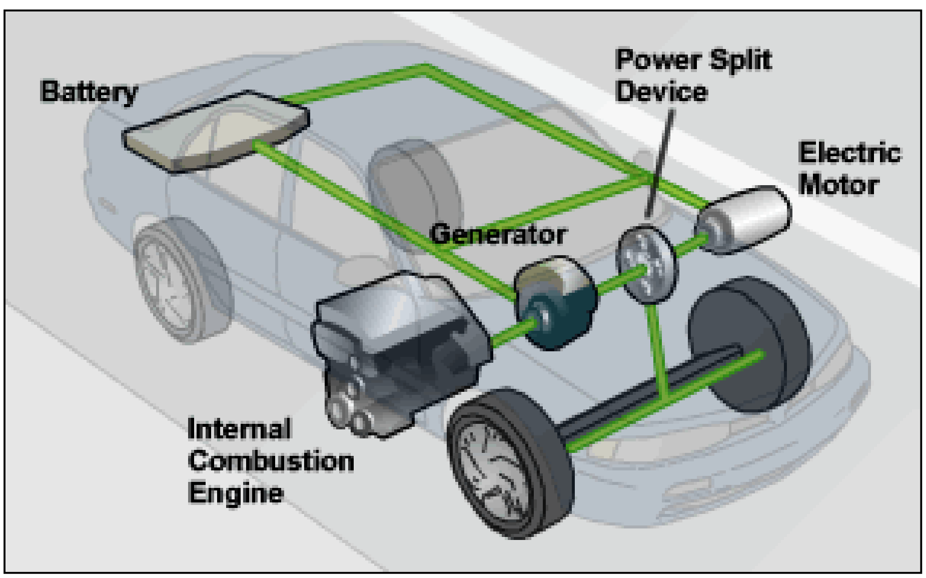


Figure 2-1. Various part/sections of a PHEV

Another aspect of classification of PHEV is by AER (All-Electric Range). All-electric range (AER) is the driving range of a vehicle using only power from its electric battery pack. For a plug-in hybrid (PHEV), it is the range of the vehicle in charge-depleting mode. The all-electric range of a particular vehicle is denoted by PHEV XX, where XX denotes the number of all-electric miles. Table 2.1 shows the PHEV savings for various AER types [2].

Table 2.1. PHEV savings for various AER types

Vehicle Class	Primary Energy Savings		Fuel Cost Savings[5]	
	PHEV 20	PHEV 60	PHEV 20	PHEV 60
Compact Sedan	42%	56%	30%	34%
Mid-Size Sedan	46%	60%	35%	39%
Mid-Size SUV	48%	62%	37%	43%
Full-Size SUV	50%	64%	40%	45%

2.3. PHEVs – Advantages and Limitations

There are many advantages of a PHEV that make it an absolute winner over a conventional gasoline vehicle. Some of these are listed below.

Advantages

1. With the rising prices of gasoline an EV can provide a fuel efficiency of up to 100mpg (Nissan Leaf- All electric and Chevy Volt – 95mpg).
2. Also for short distance travel the PHEV would not require gas (specifically depending on the AER and distance travelled). The all-electric range of the PHEV solves the purpose. An average American drives 40 miles per day

according to the NHTS report 2001. This gives a cleaner, cheaper, and a quieter car for local travel.

3. During shortage of power, the PHEV can light up a house, or a small business unit. And a fleet of PHEVs can light up small localities and micro grids.
4. PHEV emerges as a cleaner environment option for transportation. The EPRI and NRDC have approved PHEV as zero emission vehicles. Thus electrification of the transportation industry is the way to cleaner environment and reduced CO_2 and NO_x emissions. The following figure from [35] shows a comparison of a conventional gasoline vehicle, HEV, and PHEV for CO_2 and NO_x emissions.

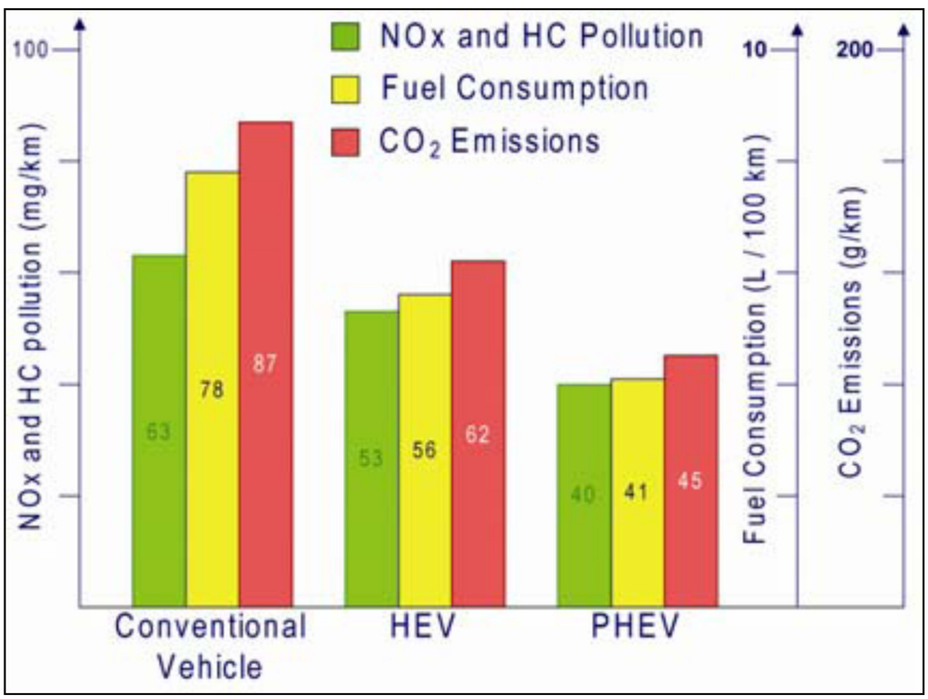


Figure 2-2. Comparison of a conventional gasoline vehicle, an HEV and PHEV for CO_2 and NO_x emissions

5. The US government offers tax rebate for owners/new buyers of PHEV. The minimum credit is \$2,500 and the credit tops out at \$7,500 to \$15,000, depending

on the weight of the vehicle and the capacity of the battery [41]. Figure 2-4 shows the most popular EVs in the US market.

6. PHEV can be utilized for load shaving and smoothening out the load profile.[2]

Limitations

1. PHEVs come with a high initial cost. Most of the PHEVs available in the market are priced high because of the sophisticated technology and high cost of the battery system. But [31] shows that the value for money on purchase and use of PHEV can be reaped in long time ownership of 120 months. The figure 2-5 depicts the savings over time.
2. The success of PHEV depends on a lot of factors that are yet being studied to be completely accountable. Efficiency of AER and battery modes of operation are some of them.
3. The research and development of efficient batteries is still underway, that can bring the price of PHEV to an affordable range.
4. The PHEV vehicle is highly bulky and offers less passenger space as compared to its ICE counterpart.
5. The impacts of PHEV charging, on the grid are still being assessed. Also the infrastructure for charging the PHEV, the connectors, meters are still limited in availability.

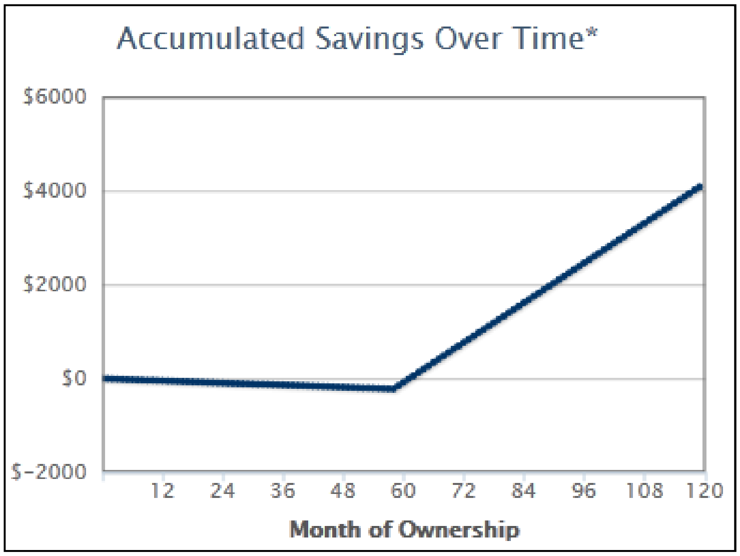


Figure 2-3. Accumulated savings over time for PHEV ownership

3. PHEV PENETRATION IN ELECTRIC GRID

As chapter 2 explains the basics of PHEV and the various forms of classification of PHEV, this chapter studies the overview of the PHEV subsystem and its components. How the various components and the entities are interconnected to the grid. It further analyzes the various operating modes of the PHEV battery and the concept of vehicle-to-grid, the viability of PHEV to supply back to the grid. After discussing the various ways of PHEV interaction with the grid the impacts of the penetration with reference to the current study are discussed.

3.1. The PHEV Subsystem

The PHEV subsystem comprises of a PHEV- the vehicle, charging circuit and the connection to the grid. It is evident that PHEV – the vehicle has two major components the electric motor and the battery as shown in Figure 2. The Figure 3.1 shows the interconnection system used for charging. The Energy Transfer System, ETS of a vehicle is comprised of the Electric Vehicle (EV) and the Electric Vehicle Supply Equipment (EVSE). The major functions performed by the ETS are, to determine when the vehicle and EVSE are ready for energy transfer, switch and convert AC electrical power to DC, and control the transfer of energy to the vehicle [2].

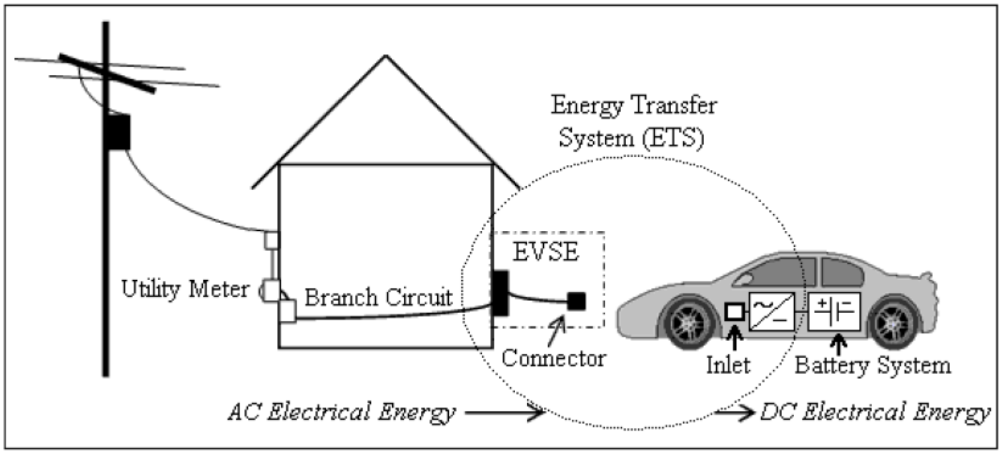
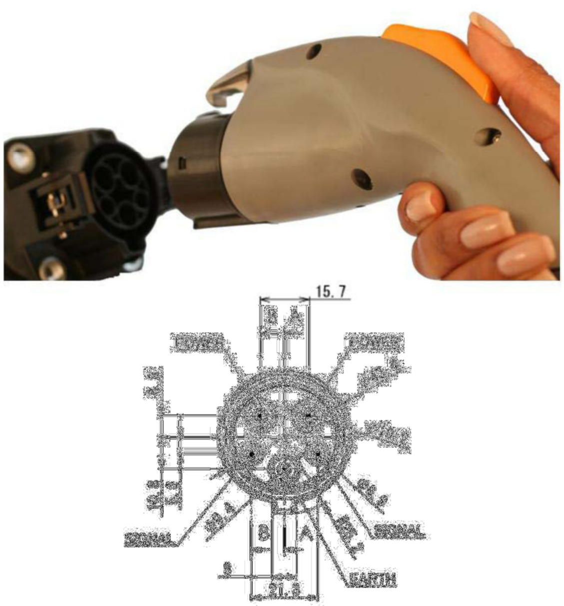


Figure 3-1. Energy Transfer system of A PHEV [2]

The SAE J1772 is a North American standard for electrical connectors for electric vehicles maintained by the Society of Automotive Engineers and has the formal title "SAE Surface Vehicle Recommended Practice J1772, SAE Electric Vehicle Conductive Charge Coupler. It covers the general physical, electrical, communication protocol, and performance requirements for the electric vehicle conductive charge system and coupler.



Preliminary Specifications		
Voltage	600 VDC	
Current, DC	200 A	
Contacts	DC Power	8.0 mm diameter
	Ground	2.8 mm diameter
	Signal	1.5 mm diameter
Cable Sizes	DC Power (2)	AWG 1/0 (50 mm^2)
	Ground (1)	AWG 6 (15 mm^2)
	Signal (4)	AWG 18 (0.75 mm^2)
Ingress Protection		IPX5
Weight Estimate, including 7.5m cable & mechanical assist		10.75 Kg (23.7 Lbs.)
Insertion / Extraction Force With Mechanical Assist		< 60 N

Figure 3-2. SAE J1772 and specifications [2], [43]

3.2. PHEV's Integration in the Electric Grid

The electrification of the transportation sector has certainly brought out benefits like reduced CO_2 and NO_x gases and freeing the customers from the dependency on petroleum and high gas prices. An important concern is that whether the grid is ready to take upon this huge load. There has been a lot of speculation on whether really the introduction of such huge numbers of PHEV is a boon to the national energy resource or will it just add itself as an enormous load that has to be fed by the already overloaded aging grid. Major studies have taken up this task to assess the impact of adding the extra load on the already aging power grid, keeping in mind the cost of infrastructure involved. As described and demonstrated further in chapter 4, the impact of increasing PHEV load on the distribution grid brings down the bus voltage bus considerably.

However the positive attribute of PHEV is that if it comes around as an additional load, it is also a resource of energy to the grid. PHEV comprises of a huge battery pack, which contributes PHEV to be used as a controllable load and a source of power that can be fed back in to the grid. The controlled charging of PHEV counts as controllable load. The charged battery pack of the PHEV can feed power back in the grid and assist in following functions [2]:

1. Load shaving
2. Load curve smoothening
3. Local back up supply in terms of crisis or if needed to draw out intermittent power from the PHEV to supply local household loads when the regular utility price for electricity consumption is high.

4. Ancillary services for voltage and frequency control.

PHEV's attributes of being a controllable load befits them to function as Distributed Resources. However V2G functionality is not implemented in this study, but the concept is highly progressive. Study in [2] provides simulation and experimental results for PHEV being used as ancillary services. Plug-in hybrid electric vehicles (PHEV) provide an opportunity for small-scale distributed storage while they are plugged-in. This feature harnessed, also provides ideal frequency regulation for short duration. Also [2] uses power system simulator model of the IEEE 14 Bus System combined with a model of PHEV charging and the controllers which facilitate vehicle-to-grid (V2G) regulation supply.

A vehicle to grid aggregator is studied in [17] makes efficient use of the distributed power of electric vehicles to produce the desired grid-scale power. This widely utilizes the principle of PHEV feeding power back to the grid. Analysis in [19] studies data from NHTS for vehicles. And three charging scenarios are developed to get PHEV Charging load profiles. PCLP (PHEV charging load profiles) is added different to the domestic load profile and are developed from the NHTS data, battery info, vehicle start and arrival time, and vehicle AERs. An advanced working strategy is yet to be developed that will be accepted globally for taking power from the PHEV.

3.3. V2G- Vehicle to Grid

V2G is defined as the system or technology that capacitates for two-way energy flow and two-way communications between an EV or PHEV and the grid; Communications may be available between the vehicle and the system operator or utility business units, or any external stakeholder. Figure 3.5a shows various components and entities involved in the process. A lot of the inspiration for the work in PHEV of this study is based on the findings and theoretical concepts of [2]. The concept of V2G is explained and implemented thoroughly in [2]. According to [2] the various entities involved in the entire process of V2G are as in the figure 3.5a shown below.

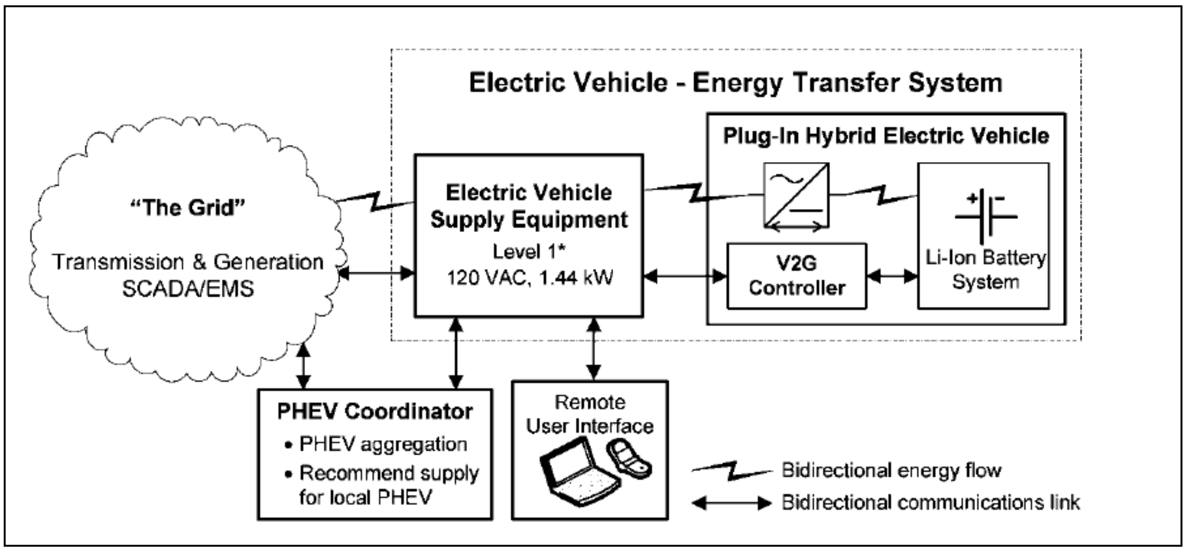


Figure 3-3. The PHEV interconnection [2]

The various entities are:

V2G Controller - the V2G controller will control battery behavior and will make the decision as to how much power and energy the battery system can provide for frequency regulation.

PHEV Coordinator - A PHEV coordinator located at a higher voltage level where reliable frequency measurements are available will be used in this study to oversee and coordinate local PHEV participating in frequency regulation through vehicle-to-grid

The grid - is the electric grid; the electric vehicle energy transfer system is discussed in section 3.1. The hierarchical overview of the entities involved is:

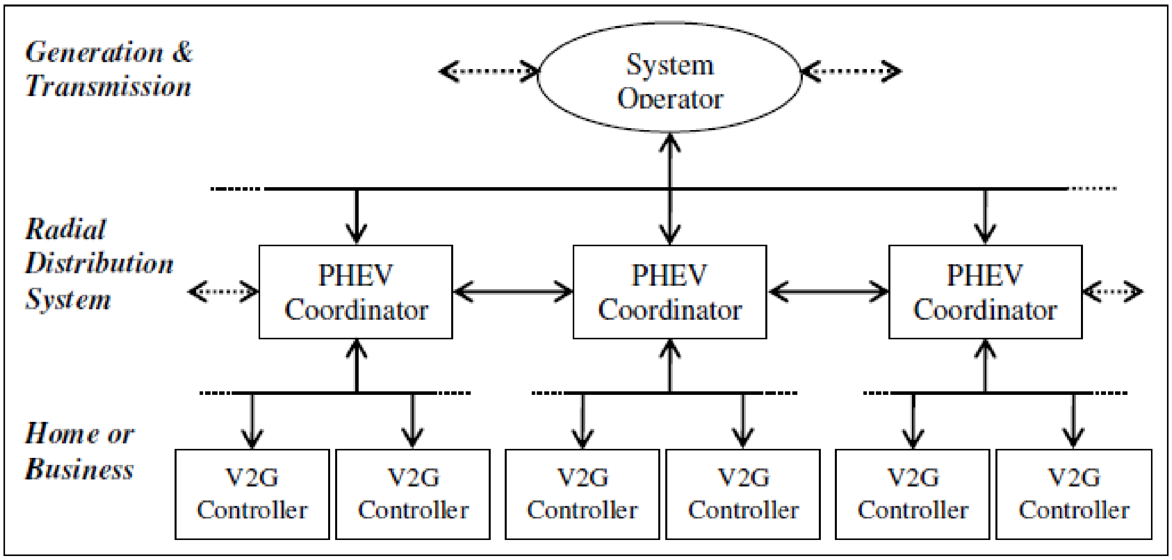


Figure 3-4. Hierarchical overview of the entities involved in PHEV interconnection [2]

The outcomes of [2] are very helpful in understanding the concept of V2G and the results provide various steps of regulation. The first step in [2] is the implementation of the V2G supply system where battery charging is modulated to provide regulation and the next part describes how PHEV contribute to primary and secondary regulation.

A similar study is provided by [4]. It discusses the vehicle fleet to grid interaction model, the PHEV charging algorithms, communication networks over the grid for data exchange, data encryption of grid networks and simulation of various scenarios of PHEV fleet. Study in [6] uses a national energy modeling system (NEMS), software package to predict the growth of power generation plants for high PHEV penetrations. For deregulation various charging strategies for PHEV are analyzed to study the impacts. An integration scheme is presented in [10] for PHEV in power network, modeled as energy hub, PHEV manager, PHEV assumption of SOC 20-80%, Changes of hub loads, line flows, converter utilization degrees, and prices paid by PHEVs are studied and ramifications are analyzed

This chapter has touched base on how a PHEV interacts with the grid. The main focus of this study is the impacts of PHEVs on the grid. To analyze the nature of changes and deviations that will occur when significant number of fleet of vehicles are introduced to the system. The lists of studies mentioned in section 1.3 have similar interest of findings; however the study of impacts varies on what parameters have been selected to measure or quantify the impacts. This study performs numerical simulations and quantifies the impacts by analyzing the voltage deviation on the bus.

4. PHEV LOAD AND CHARGING SCHEMES

This chapter describes how the objectives of the research studies are established. The simulation test bed used the input data collection and processing of the data to study the results. Also, the various kinds of load profiles are demonstrated and the PHEV charging profiles are listed. The software tools used for writing the code, the assumptions of the study are listed and how the various features are implemented for the study are explained in detail.

4.1. Simulation Introduction

The study uses the IEEE-13 bus distribution network. IEEE-13 bus network is modeled on OpenDSS. OpenDSS is a comprehensive electrical power system simulation tool for electric utility power distribution systems. It supports a wide variety of simulation options and analyses commonly performed on electric utility power distribution systems. Many of the IEEE Test Feeders have been implemented in OpenDSS. The model for IEEE-13 test feeder used in the research study has been adopted from OpenDSS repository and has been modified for various test cases used in the research. OpenDSS has functions and facilities to develop complex electrical systems and analyze the various conditions. The basic code function has been listed in Appendix A.1. The code function listed in A.1 is just one test case scenario for PHEV penetration, it has to be noted that for each case, and every penetration level function is changed. All of the test case code functions are not listed in A.1. This research and study findings are based on the IEEE-13 bus network. IEEE-13 node test feeder data is listed in Appendix

A.3. The document is the source of data for the study of the base system. The IEEE Node Test Feeder is shown in Figure 4.1. There are nine load buses in the network.

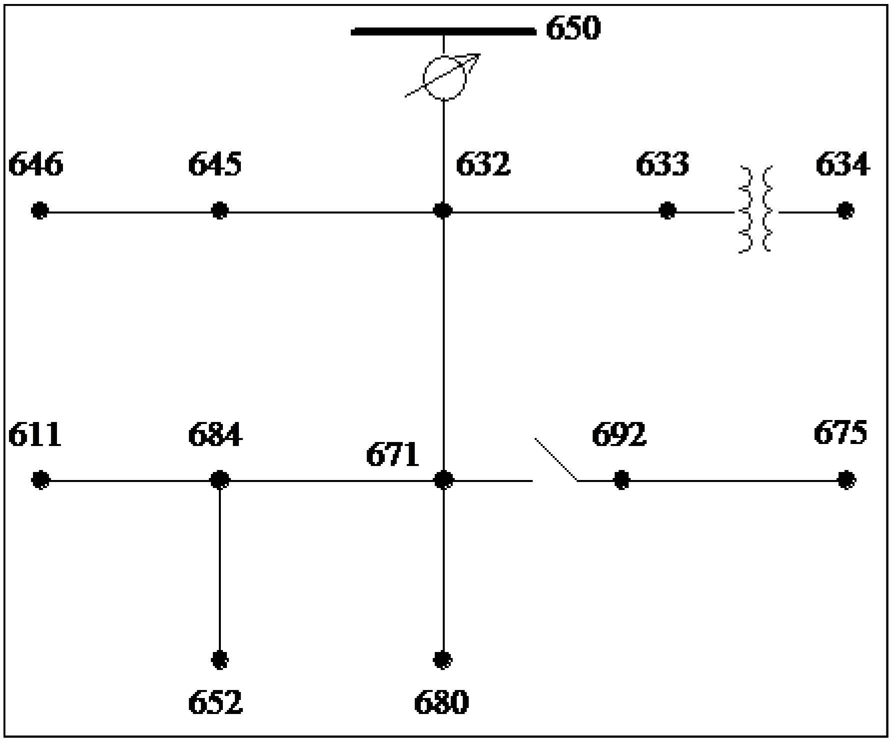


Figure 4-1. IEEE-13 Node Test Feeder (details Appendix C)

4.2. Assumptions for Simulation

The following assumptions have been used to simulate the PHEV load, the load profiles and charging behavior:

1. The buses in IEEE-13 bus network have been segregated into residential and commercial buses. It has been assumed that 60% of the load is residential, and industrial/commercial loads contribute 40% as per [48]. The buses 634, 645, 675, 611, and 652 are designated as residential load buses. And 671, 646, 692, and 670 are industrial/commercial load buses.

2. The 24 hour load profiles for residential and commercial load profiles have been adopted form [46] and [47], they are described in detail in section 4.3.
3. PHEV load has been simulated based on [2]. According to [2] the basic charging power of PHEV is considered to be 1kW. Each PHEV is equivalent to 1 kW of electrical load seen by the load bus. Hence the total number of PHEVs can be calculated from the total kW of the bus. And once the total number of PHEVs is obtained, the specific percentage of PHEV can be calculated for each case.
4. Another assumption is that the bus 675 has been chosen as the target bus for all the studies, since the bus is located farthest from the source bus and also it is highly sensitive to the load changes as per Appendix A.2.
5. The assumptions made for the simulation of charging profiles has been discussed in detail in section 4.6.

4.3. Regular/Base Load (non PHEV) on the Network

The table 4.2 is the spot load values obtained from IEEE 13 test feeder document, Appendix A.3. However this system study uses 24 hour load profiles for the residential and commercial/ industrial loads. The residential and commercial load profiles were obtained from [46] and [47]. The load profiles are for an average day in a distribution system. The method to subject variable load on the network is explained in section 4.3. The standard 24 hour load profiles is subjected to the load values of the IEEE-13 bus test feeder and 24 hour load profile for each bus on the network is developed. After analyzing the load profiles used in various studies and research, for simplicity the hourly load profile has been selected. The 24 hour load profile for the residential load is shown in figure 4.1 and the industrial/commercial load profiles are shown in figure 4.2.

Table 4.1. Spot load values (details in Appendix A.3)

Node	Load	Ph-1	Ph-1	Ph-2	Ph-2	Ph-3	Ph-3
	Model	kW	kVAr	kW	kVAr	kW	kVAr
634	Y-PQ	160	110	120	90	120	90
645	Y-PQ	0	0	170	125	0	0
646	D-Z	0	0	230	132	0	0
652	Y-Z	128	86	0	0	0	0
671	D-PQ	385	220	385	220	385	220
675	Y-PQ	485	190	68	60	290	212
692	D-I	0	0	0	0	170	151
611	Y-I	0	0	0	0	170	80
	TOTAL	1158	606	973	627	1135	753

As very distinctly visible from the load profiles, the residential load has its peak during the latter half of the day and the commercial/industrial load have a constant load during the middle hours of the day time.

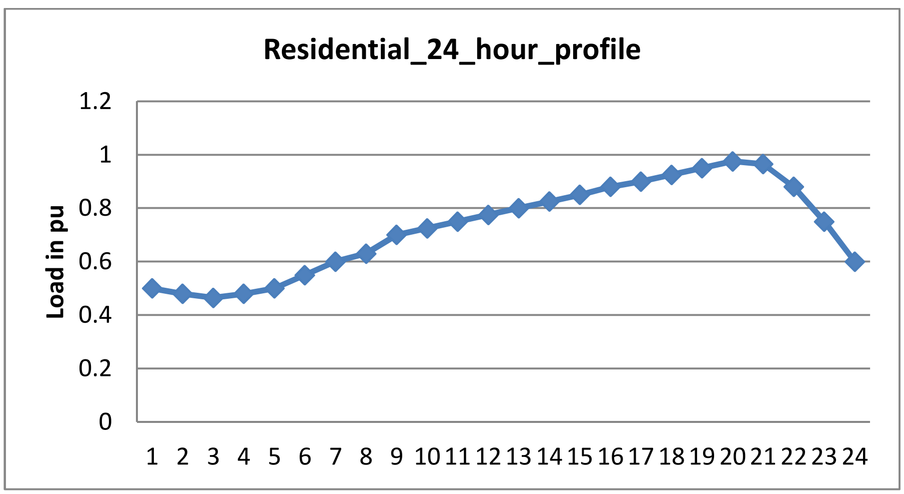


Figure 4-2. 24 hour Residential Load profile

These load profiles have been used in the basic normal loading cases of the simulation. At certain places in the document they are also referred to as the base load or non-PHEV load profile of the system. Section 4.5 explains how these profiles have been applied to the network.

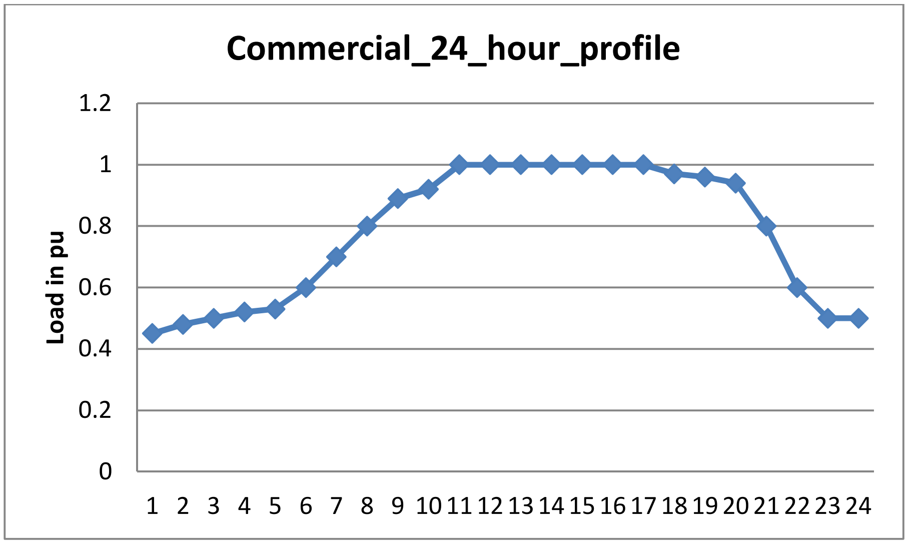


Figure 4-3. 24 hour Commercial Load Profile

4.4. Variable Load in the Network in OpenDSS

The initial development of IEEE test feeder in OpenDSS uses the spot loads. However this study requires the 24 hour load profiles to be subjected on the system. Hence the variable loads are added by taking help from the Open DSS Manual [37]. OpenDSS provides an option to use the "loadshape" object and define the multipliers for the load. The following example shows how a loadshape is used in the code.

new loadshape.resi 24 1.0 mult=[0.5 0.525 0.55 0.575 0.6 0.625 0.65 0.675 0.7 0.725 0.75 0.775 0.8 0.825 0.85 0.875 0.9 0.925 0.95 0.975 0.8 0.7 0.6 0.5]

The factors in the square bracket are called multipliers and name of the loadshape is "resi".

When defining the load on the bus, the name of the loadshape ("resi" in this case) has been defined in the "daily" object for that particular load. The similar feature is used when the various charging schemes are applied to the network.

4.5. PHEV Load

For the study and assessment of effect of PHEV, PHEV load is applied on the network in addition to the normal or the non PHEV Load. There are different ways of defining PHEV loads in the system for study. This study uses the same method to apply PHEV load as done in [2]. In [2] the basic charging power of PHEV is considered to be 1kW. Each PHEV is equivalent to 1 kW of electrical load seen by the load bus. Also the average residential load per household is assumed to be 1 kW for simplicity of calculation and simulation. For simulation it is assumed that each household owns one PHEV and similarly for commercial load unit, each unit is assumed to own one PHEV (the assumption being that one household or one commercial facility has a 1 kW total load.). Thus the PHEV load would be one PHEV per 1kW. This assumption is useful when subjecting PHEV load penetration in percentage. For example if the total load on the bus is 500kW, then the 100% PHEV penetration on the bus would be 500 PHEVs i.e 500kW added load in addition to the base load of 500kW. Similarly, the cases for 25%, 50% and 100% PHEV penetration can been calculated. PHEV Penetration has been explained in detail in section 4.6.

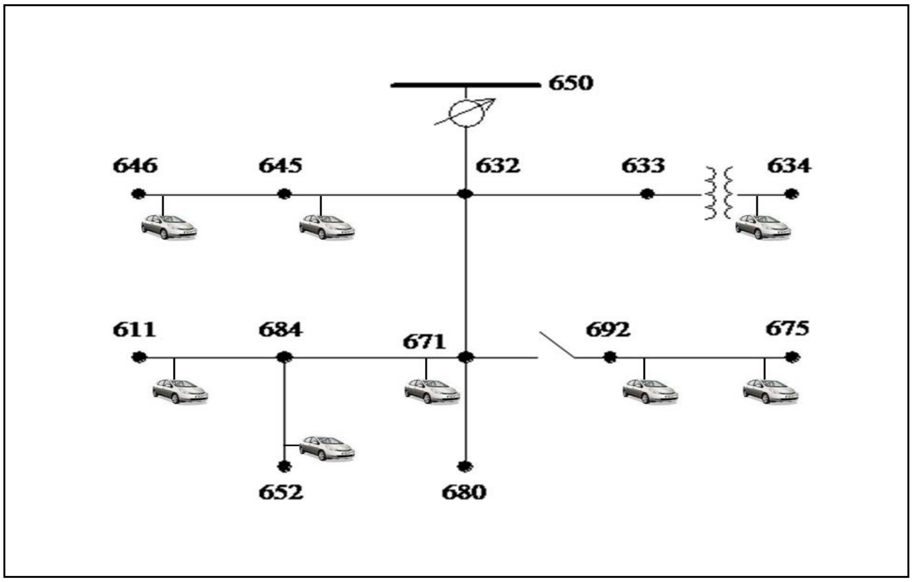


Figure 4-4. IEEE-13 bus system with PHEV load

4.6. Charging Schemes

The PHEV load is applied to the bus/grid when they are plugged in for charging. The charging profiles are the profile of how the PHEV load is applied to the bus over a period of 24 hours. When only a small of PHEVs are plugged in the system for charging it would not create an effect that requires attention or study. But when we see the electrification of the transportation industry, a huge number of PHEVs on a bus are expected, which contributes to be a substantial amount of load.

The two types of charging schemes studied in this research for PHEV are Uncoordinated charging scheme and Coordinated charging scheme.

4.6.1. Uncoordinated Charging Scheme

As the name suggests in this case there is no strategy or planning involved while applying the PHEV load to the grid. There is no V2G Controller or PHEV coordinator involved in the system [2] that monitors the demand or follow a scheme for PHEV charging. The vehicle owners do not have the incentive or the essential information to schedule the charging of the batteries to optimize the grid utilization. In this case the PHEV are randomly subjected to bus. In this study the uncoordinated charging is simulated by using a random function to generate an uneven profile ranging from zero to maximum PHEV penetration. It is considered that the entire PHEV load is applied to the bus irrespective of the condition of grid load. Figure 4.4 shows the uncoordinated PHEV charging profile.

4.6.2. Coordinated Charging

This method of applying PHEV load to the grid is a strategized and pre-researched technique of applying PHEV load. A coordinated charging scheme is influenced by various factors. These factors are clearly identified in [6]. According to [6] the two basic mechanisms that govern PHEV charging profiles are time sensitivity of electricity prices and embedded controllers in the electric chargers. Charging scheme by electricity pricing determines the system load and indicates how and when the end users should schedule to utilize the energy. This cost estimation and pricing schemes like analyzed in [10] and [24] can be highly mathematical and complex.

Typical charging schemes are listed below:

i. Uniform Charging – Where the load is distributed equally over the period of 24 hours.
ii. Home Based Charging – Charging scheduled at home.

iii. Off Peak Charge – This charging profile is uniformly distributed in the off peak time, late night, and early morning time of the day.

iv. V2G Charging – In the V2G concept the battery of the PHEV is utilized as a storage device for powering back the grid in case needed and scheduled. Instead of valley filling the V2G facilitates the PHEV to inject power in the grid during peak hours.

The PHEV charging schemes used in this study are the home based charging and off peak charging. For coordinated charging two charging profiles are used the Residential charging profiles, where the PHEVs are charged when the vehicles are parked at home during late evenings till early mornings. The charge profiles significantly include and follow the fact that the PHEV requires eight hours to completely charge [2]. Figure 4.6 shows the PHEV residential charging profile.

The second kind of charging profiles used in this research is the PHEV Commercial charging profile. This scheme utilizes the time duration while the users are at work and the PHEVs can be charged in the parking lots. This charging profile will use the eight hours of the day time. The PHEV commercial charging profile is shown in figure 4.7.

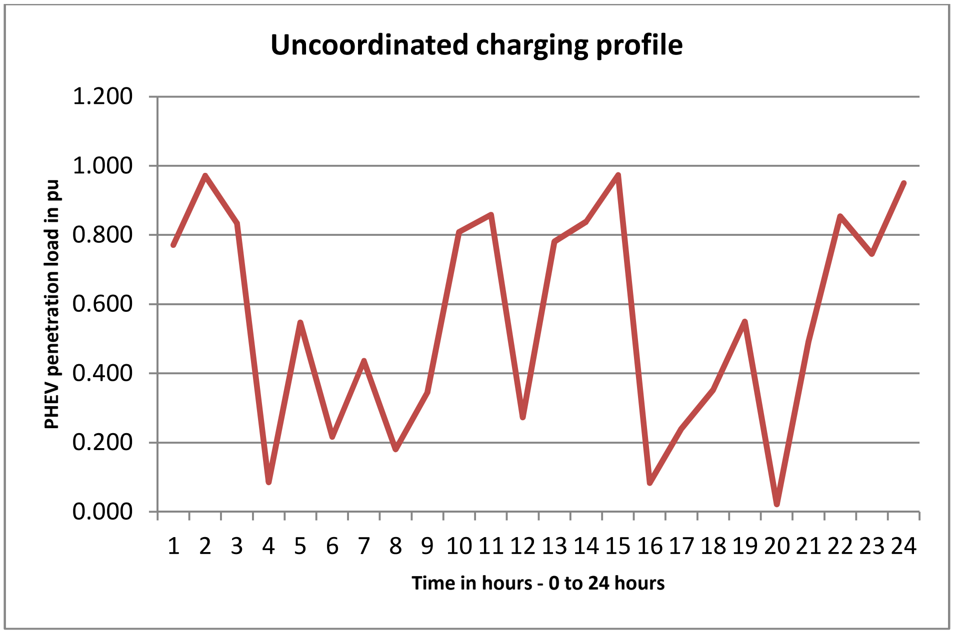


Figure 4-5. PHEV Uncoordinated Charging

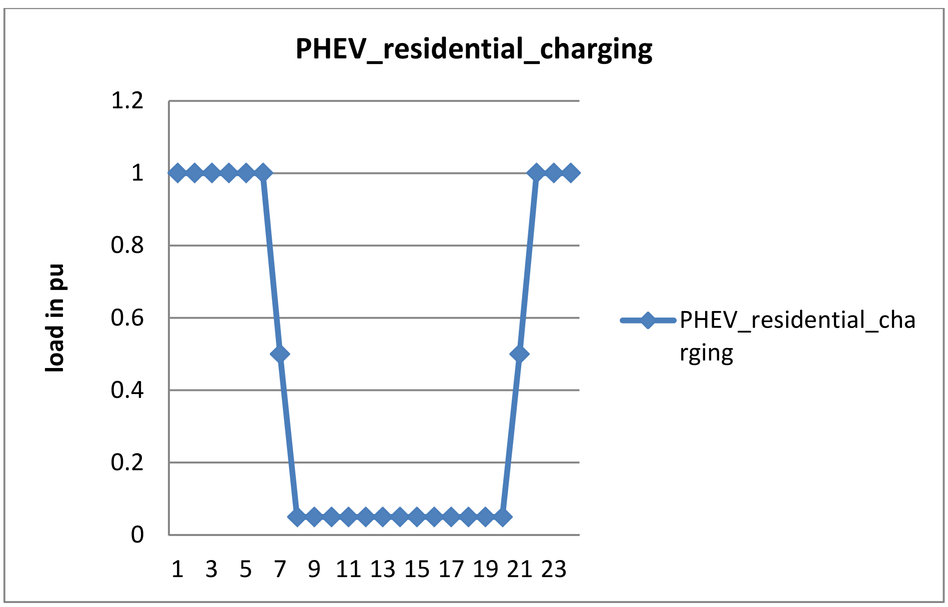


Figure 4-6. PHEV Residential profile

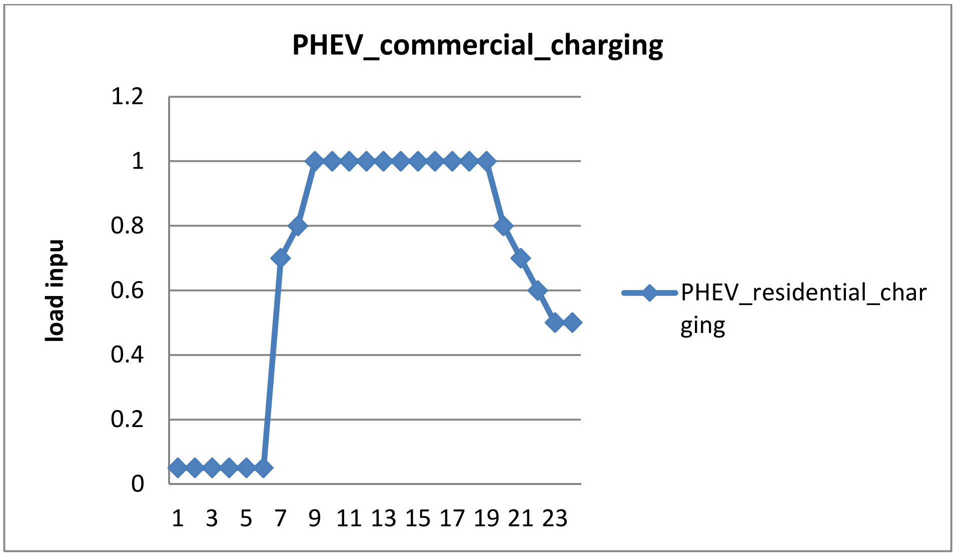


Figure 4-7. PHEV Commercial profile

4.7. PHEV Penetration in the Grid

The study of PHEV impacts on the bus is studied in different increments of PHEV load. The PHEV load is applied in percentage increments 0%, 25%, 50%, and 100%. The percentage of PHEVs is based on the total number of PHEVs calculated. Also the standard base case (non PHEV) is also available where the regular non PHEV load is on the system. Studying the effect of PHEV load in increments helps to break down the analysis and helps to understand the severity of the scenario. Each penetration level of the PHEV load is one particular scenario and increment of percentage depicts the increment on the load at the bus. Each bus on the IEEE-13 bus network has been pre designated to be residential or commercial. Figure 4.8 shows the PHEV penetration levels – as load for bus 671, Commercial bus. Figure 4.9 shows the PHEV penetration loading profiles for bus 675, Residential bus.

For each kind of bus residential and commercial there is PHEV charging profile available as shown in figure 4.6 and 4.7 and described in section 4.5.2. It is to be noted that the PHEV penetration load is the additional load. The residential and the commercial buses already use the normal load profiles from figure 4.2 and 4.3 and the added PHEV load for each case of penetration as follows:

i. Normal Load – no PHEVs
ii. Normal Load + 10% PHEV load
iii. Normal Load + 30% PHEV load
iv. Normal Load + 60% PHEV load
v. Normal Load + 100% PHEV load

Figure 4.8 and 4.9 show the increments on load profile on bus 671 and bus 675 respectively. The PHEV increments are in percentage. The various 24 hour load curves are for five penetrations of PHEV.

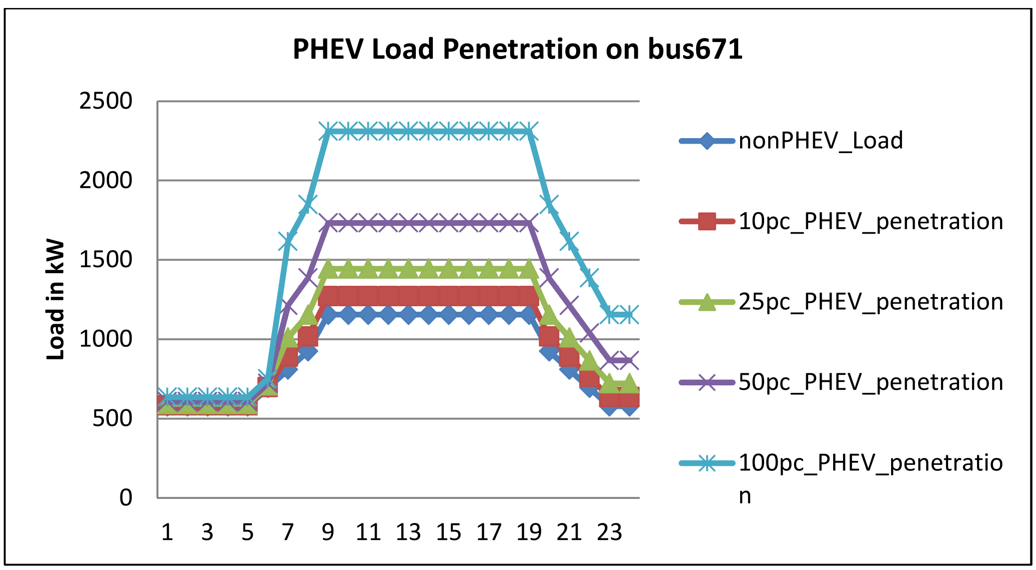


Figure 4-8. PHEV load penetration load profiles Commercial bus

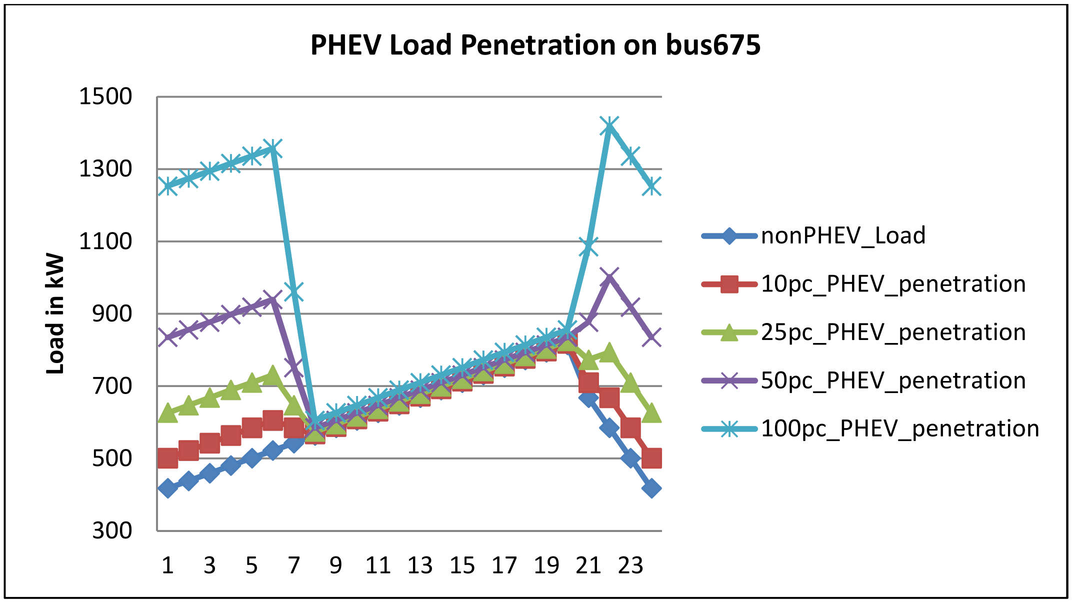


Figure 4-9. PHEV load penetration load profiles Residential bus

4.8. Simulation

Code functions for each of the five scenarios listed in section 4.6 are written. And simulations are run for each case separately. The output bus voltage is recorded for each bus hourly for the 24 hour period. The "monitor" object from OpenDSS is used to collect the output bus voltage for each hour. The result of each monitor object is recorded as a csv file. The csv files are then processed to analyze the results.

The output of OpenDSS monitor object is monitored for voltage deviation for the increasing load on the bus for increasing PHEV load in each penetration scenario. The voltage deviations for the 24 hour period and maximum voltage deviations are monitored for analysis.

4.9. Results

The lists of results in this chapter include the following:

i. Voltage deviations shown for the PHEV load for each penetration scenario

ii. Uncoordinated PHEV charging – resulting voltage profile on the bus 675 residential and bus 671 commercial bus. Maximum voltage deviation on each penetration scenario

iii. Coordinated PHEV charging – resulting voltage profile on the bus 675 residential and bus 671 commercial. Maximum voltage deviation on each penetration scenario

4.9.1. Maximum Voltage Deviation for the PHEV Load for each Penetration scenario

i. Voltage v/s Load - 10 percent PHEV Loading

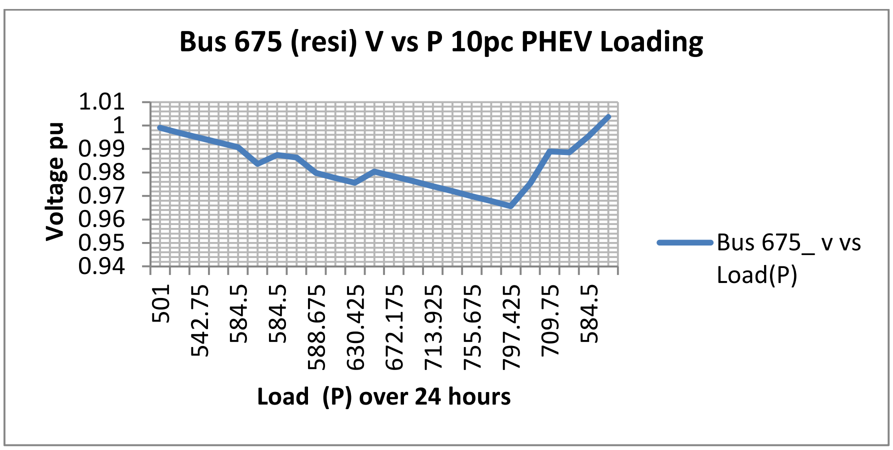


Figure 4-10. Bus 675 voltage v/s Load curve – 10% PHEV Load

ii. Voltage v/s Load - 25 percent PHEV loading

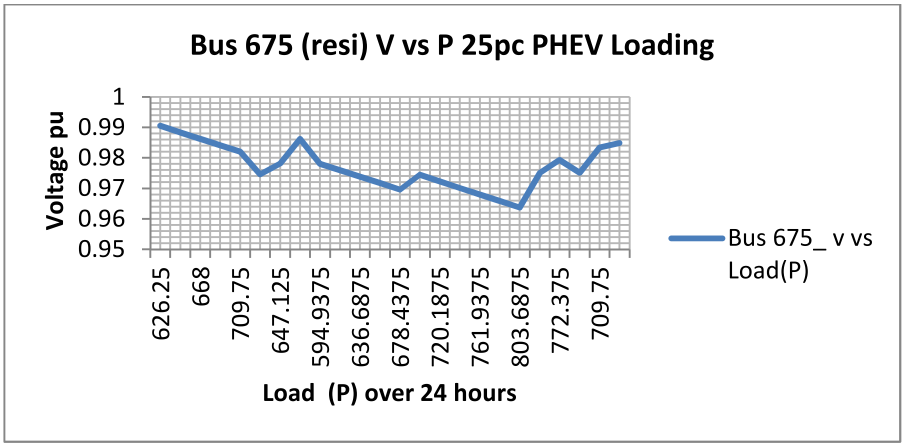


Figure 4-11. Bus 675 voltage v/s Load curve – 25% PHEV Load

iii. Voltage v/s Load - 50 percent PHEV loading

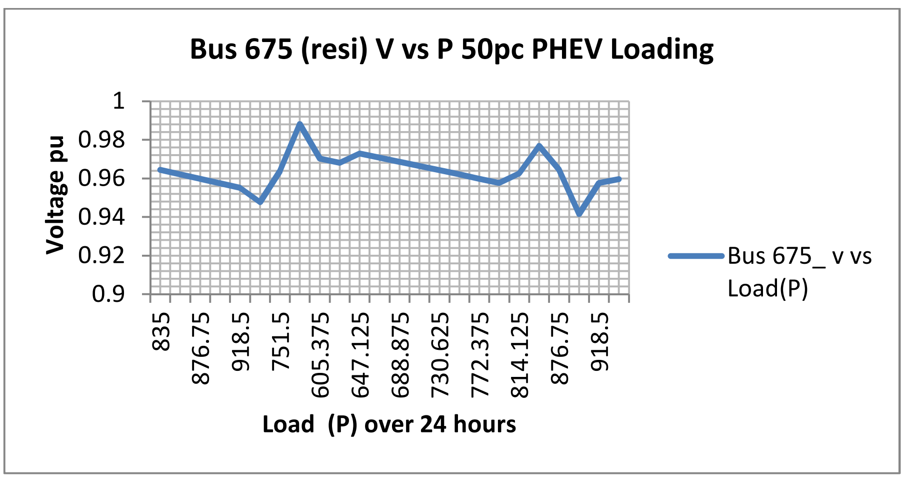


Figure 4-12. Bus 675 voltage v/s Load curve – 50% PHEV Load

iv. Voltage v/s Load - 100 percent PHEV loading

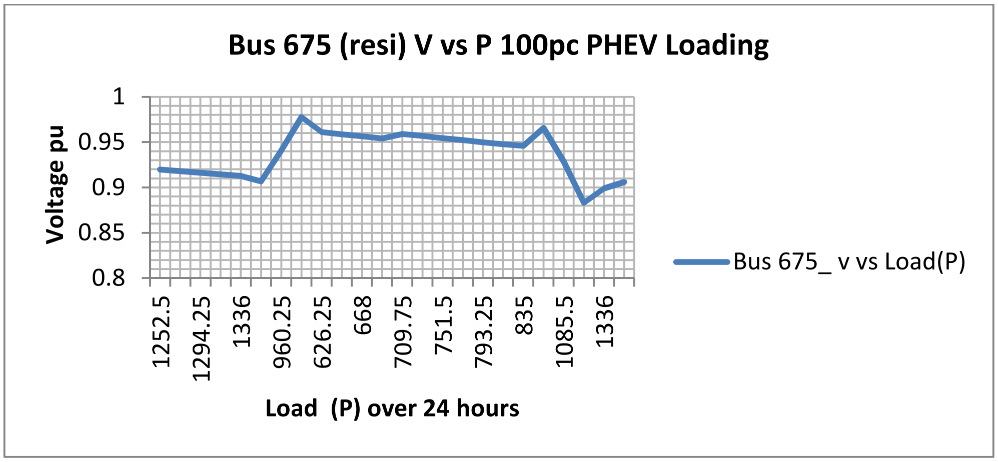


Figure 4-13. Bus 675 voltage v/s Load curve – 100% PHEV Load

4.9.2. Uncoordinated Charging PHEV Load – Output Voltage Profiles

The uncoordinated charging profiles mentioned in 4.5.1 when applied for various PHEV penetration level gives the following voltage results.

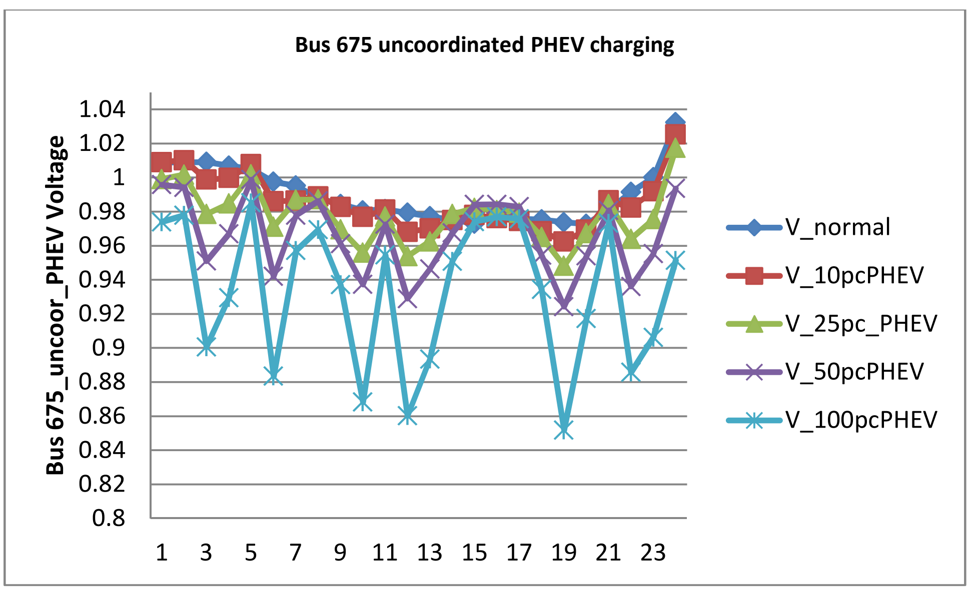


Figure 4-14. Voltage Profile Bus 675 Residential Bus – PHEV Penetration– 0% to 100%- Uncoordinated charging

4.9.3. Maximum Voltage Deviation for Bus 675

The table 4-1 shows the maximum – highest and second highest percentage deviation in the voltage in percentage, compared on a same operation hour, in different loading conditions for bus 675.

Table 4.2. Maximum voltage deviation (in %) on bus 675 in different loading conditions

Bus 675	**10pc PHEV Load**	**25pc PHEV Load**	**50pc PHEV Load**	**100pc PHEV Load**
Highest	1.16	4.67	5.76	12.53
2nd highest	1.14	3.94	5.59	12.1

4.9.4. Coordinated PHEV Charging – Output Voltage Profiles

i. Residential Bus 611 is subjected to loading conditions. The plot below shows the voltage deviation at the bus over a 24 hour period when Load is increased from 10 % to 100 % PHEV load. Highest voltage pu is 1.03 and lowest is 0.88.

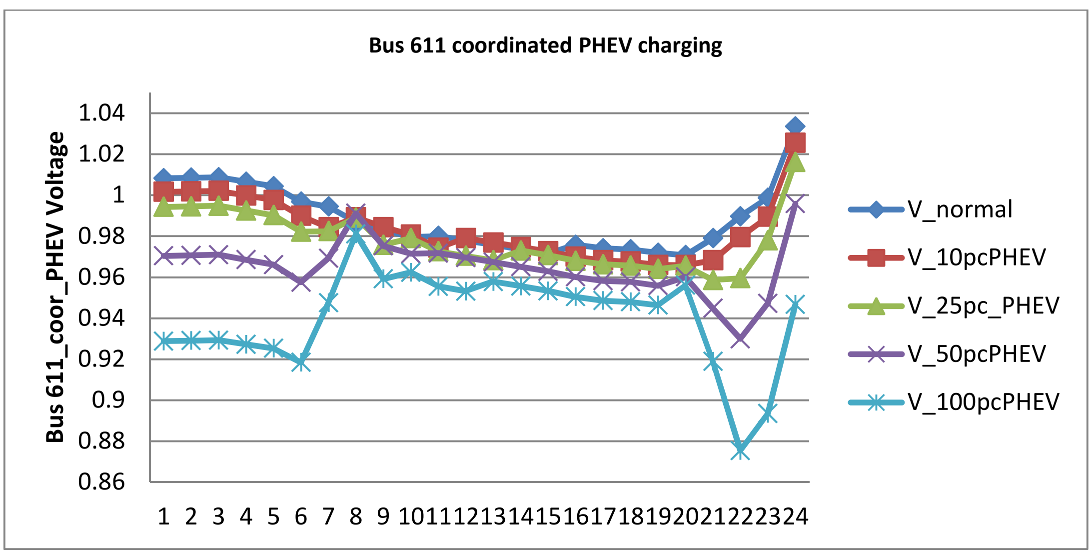


Figure 4-15. Residential bus 611 voltage output profiles for different PHEV penetration

ii. Residential bus 675 voltage results on five different loading conditions. More sensitive results are obtained. Highest voltage pu observed is 1.03 and lowest is 0.87.

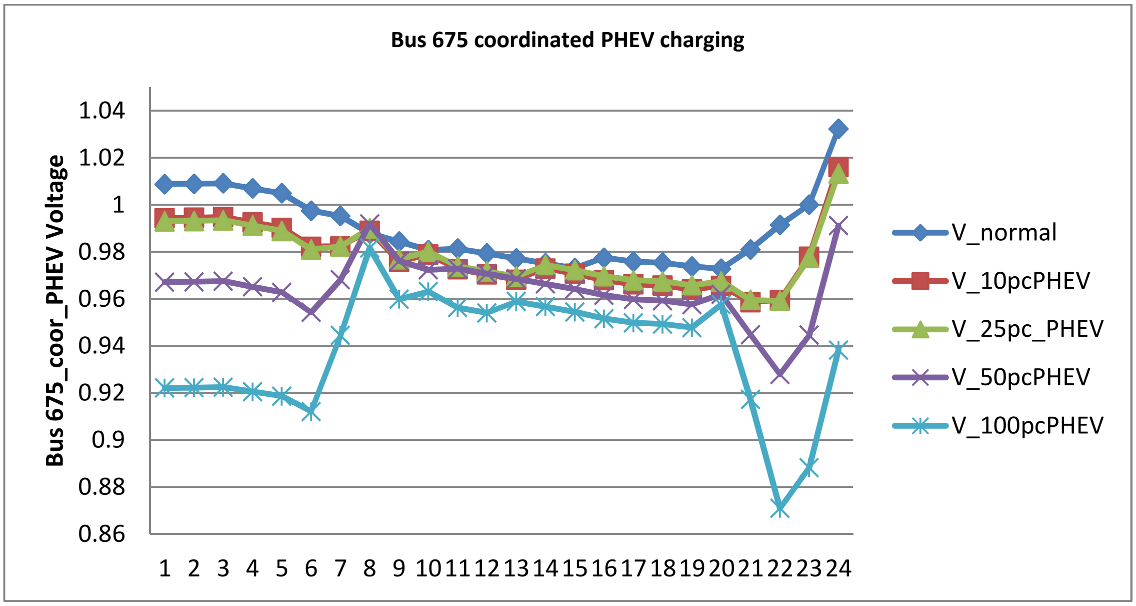


Figure 4-16. Residential bus 675 voltage output profiles for different PHEV penetration

iii. Commercial bus 611 voltage results - The commercial bus 671 follows a different regular load profile/pattern as discussed in section 4.2 and 4.4. Also the PHEV charging profiles assumed for a commercial bus are different from a residential bus. However due to the bus's indigenous property of being lightly loaded a non-significant deviation has been observed.

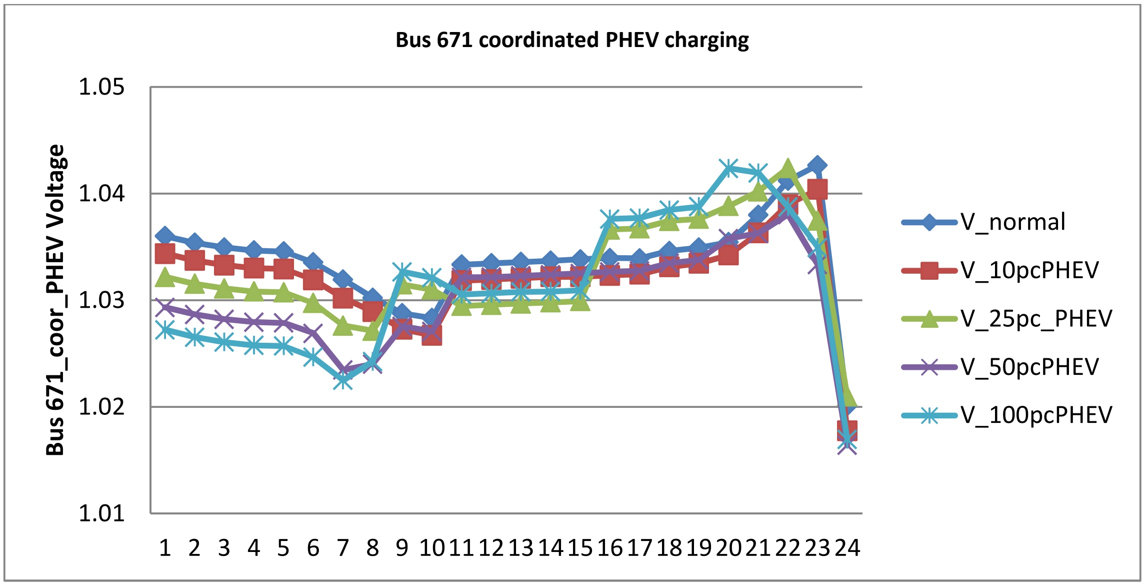


Figure 4-17. Commercial bus 671 voltage output profiles for different PHEV penetration

4.9.5. Maximum Voltage Deviations for bus 675 in different conditions (in %)

This table shows the maximum/ highest and second highest percentage deviation in the voltage, compared on a same operation hour.

Table 4.3. Maximum voltage deviation (in %) on bus 675 in different loading conditions for coordinated charging – PHEV penetration

Bus 675	**10pc PHEV Load**	**25pc PHEV Load**	**50pc PHEV Load**	**100pc PHEV Load**
Highest	3.19	3.2	6.3	11.4
2nd highest	2.2	2.2	5.5	9.4

4.10. Conclusion

This chapter provides a description of how the regular and PHEV loads are used in the system and how they are applied to the network. Different kinds of charging profiles for PHEV for each case- residential and commercial are explained and quantified. The impacts of PHEV charging load on residential and commercial buses are compiled and results are compared for each case of PHEV penetration. Along with graphical analysis of the resultant voltage profiles, the chapter provides the comparison of maximum voltage deviation on each PHEV penetration scenario as compared to the normal case at the same hour of operation.

The uncoordinated charging of PHEV when applied gives a maximum deviation of 12.53%. The coordinated charging provides a slightly better result in the worst case scenario 11.4 %. This is still a high deviation as compared to the normal operating voltage level. Hence it is observed that the coordinated charging cannot alone provide the desired voltage regulation needed for the stable system operation.

5. CORRECTIVE STRATEGY

The previous chapter quantifies the effect of PHEV loads on the distribution network. The effect is monitored on the bus voltage. The maximum voltage deviation of 12.53% is observed on bus 675 after the PHEV loads are added in an uncoordinated pattern. And 11.4% (in the worst loading case) drop in bus voltage is observed on bus 675 when coordinated charging profiles of PHEV are subjected to the bus. Which proves that coordinating the charging profiles, might not be the best solution to overcome the problem of PHEV loading. The corrective strategy proposed to improve the voltage regulation on the bus, is based on the technique proposed in [1] and [3]. In [1] a voltage sensitivity analysis based scheme is proposed to achieve voltage regulation at a target bus in a micro grid. A similar strategy is used in this study to compensate for the effect of increasing load on the bus; dispatchable local power source is used to inject power to the bus. Since the charging profiles/ load profiles of the PHEVs are known, the duration and periods for when to inject the source is predetermined.

5.1. Introduction

The corrective strategy proposed in the study is inspired by [1] which proposes the voltage sensitivity based scheme to achieve voltage regulation on the bus. The method in [1] and [2] uses the DFIG active power signal to adjust the reactive power. Also, the use of voltage sensitivity factors lead to a desirable power factor in the constant power factor mode. This research study however, focuses only on the voltage sensitivity and voltage regulation on the bus which is governed by the changes in PHEV load.

5.1.1. Compensation/Corrective Strategy

The compensation/corrective strategy proposes a local dispatchable power source that injects pre-computed active/reactive power to the local target bus. The whole idea of injecting power is based on the fact that the bus voltage is sensitive to the incremental load on the bus as shown in section 4.8.1. The increments of load in this case are the PHEV load. The target bus is chosen based on voltage sensitivity. In this case bus 675 is chosen, since it is highly sensitive to load changes and it is placed far from the source bus. Hence, it is an ideal choice to monitor the impacts of the varying PHEV load.

Two different methods are discussed and then adopted as compensation strategies. One method is the individual compensation method, where the bus active/reactive power injections are calculated based on the sensitivity of the bus to its own changing loads. The other method is the weighted compensation method, where the injections are calculated based on the sensitivity of the bus to the loads of the other buses in the network. Both of these methods are local.

As used in [1] the power flow and Jacobian equations for the network are:

$$\begin{cases} Pk = \sum_{n=1}^{N} |Vk| \cdot |Vn| \cdot |Ykn| \cdot \cos(\theta n + \delta n - \delta k) \\ Qk = \sum_{n=1}^{N} |Vk| \cdot |Vn| \cdot |Ykn| \cdot \sin(\theta kn + \delta n - \delta k) \end{cases} \tag{5.1}$$

$$\begin{vmatrix} \Delta P \\ \\ \Delta Q \end{vmatrix} = \begin{vmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial P}{\partial V} \end{vmatrix} \cdot \begin{vmatrix} \Delta \delta \\ \\ \Delta V \end{vmatrix} \tag{5.2}$$

The Jacobian in 5.2 is processed to obtain the deviations in voltage as achieved by equation 5.1. The sensitivities $S\delta p$ and Svp are, respectively, bus angle and bus voltage sensitivity to the active/reactive power (load in this particular study) of the bus. Similarly $S\delta q$ and Svq are bus angle and bus voltage sensitivity, respectively, to the reactive power of the bus.

$$\begin{vmatrix} \Delta\delta \\ \Delta V \end{vmatrix} = \begin{vmatrix} [S\delta p] & [S\delta q] \\ [Svp] & [Svq] \end{vmatrix} . \begin{vmatrix} \Delta P \\ \Delta Q \end{vmatrix} \tag{5.3}$$

From equation 5.3 the following can be derived

$$\Delta V = Svp.\Delta P + Svq.\Delta Q \tag{5.4}$$

Equation 5.4 can be customized for a particular case of a bus. If “w” is the reference bus and “v” is the target bus then equation 5.4 can be re-written to give the voltage deviations on “v” with the active and reactive power deviations at “w”.

$$\Delta Vv = Svp_{vw}.\Delta Pw + Svq_{vw}.\Delta Qw \tag{5.5}$$

Svp_{vw} and Svq_{vw} are the voltage sensitivity of the voltage at bus “v”, due the active and reactive load changes occurring on bus “w”. ΔPw and ΔQw are the actual active and reactive load changes. ΔVv is the resultant voltage deviation on bus “v”.

The remaining sections in this chapter explain how these equations are conditioned to establish the results for individual and weighted compensations.

5.2. Local Individual Injection

For the local individual compensation method, it is assumed that the target bus "w" is sensitive its load flow changes occurring on same bus (bus w). As discussed in section 4.8.1 with the PHEV loads increasing on the bus, the voltage deviates and they have been demonstrated in in 4.8.1. This section describes how these deviations are quantified to obtain the necessary active/reactive power injections on the bus.

5.2.1. Description and Calculations

The local individual compensation evaluates the correction for the target bus looking at the bus voltage sensitivities due to the load flows on the current or same bus. The target bus is "w" and hence the equation 5.5 is now

$$\Delta Vw = Svp_{ww}.\Delta PwSvq_{ww}.\Delta Qw \tag{5.6}$$

The values of voltage sensitivities are obtained from [1] Appendix A.2. To simplify equation 5.6 further, in an ideal voltage regulation case, the voltage deviation is equated to zero. Equation 5.6 can be simplified for ideal case to:

$$\frac{\Delta Qw}{\Delta Pw} = \frac{Q-Qo}{P-Po} = -\frac{Svp_{ww}}{Svq_{v\backslash ww}} \tag{5.7}$$

Equation 5.7 simplified to be

$$Qw = -\frac{Svp_{ww}}{Svq_{ww}}(Pw - Po) + Qo \tag{5.8}$$

In equation 5.8 the voltage sensitivities, Svp_{ww} and Svq_{ww} are obtained from Appendix A.2. The sensitivity matrix is used from [1] is an 11X11 matrix. The Sij is the sensitivity picked from the matrix, where i and j are row and column of the sensitivity matrix. For the individual correction the target bus is the also the reference bus. The set points for the equation 5.8, Qo=0 and Po is the average active power at the bus. The average power at the bus is calculated as the average power over a period of 24 hours.

The reactive power injections for bus 675, residential bus are calculated based on equation 5.8 for each penetration level of PHEV. For each bus the sensitivities Svp_{ww} and Svq_{ww} are picked. And the average power Po is calculated from the 24-hour load value. And Q injections are calculated for each instance of the 24 hour load.

Once the active/reactive power injections are calculated, they are injected into the bus and the power flow is run in OpenDSS to generate the voltage profiles at the bus for each penetration level. The next section shows the results of injecting these into the system.

5.2.2. Results – Voltage Profiles

The results show a comparison between the regular voltage output profiles at bus 675 versus the improved voltage profile after the corrective reactive compensation is applied. The results are recorded and compared for each PHEV penetration level for the graphs with compensation and without compensation.

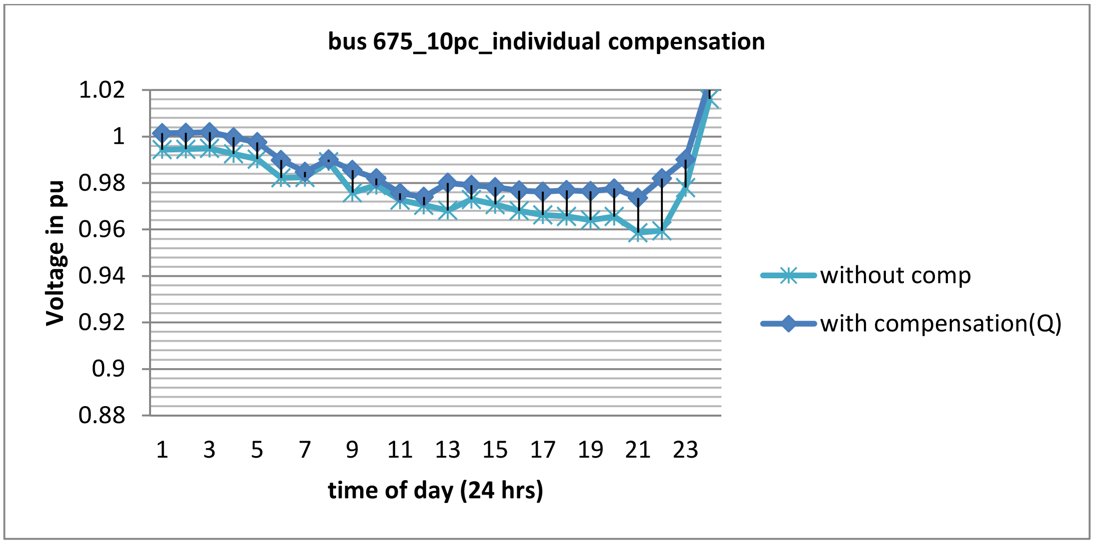


Figure 5-1. Bus675 10% PHEV penetration- uncompensated voltage v/s compensated voltage profile

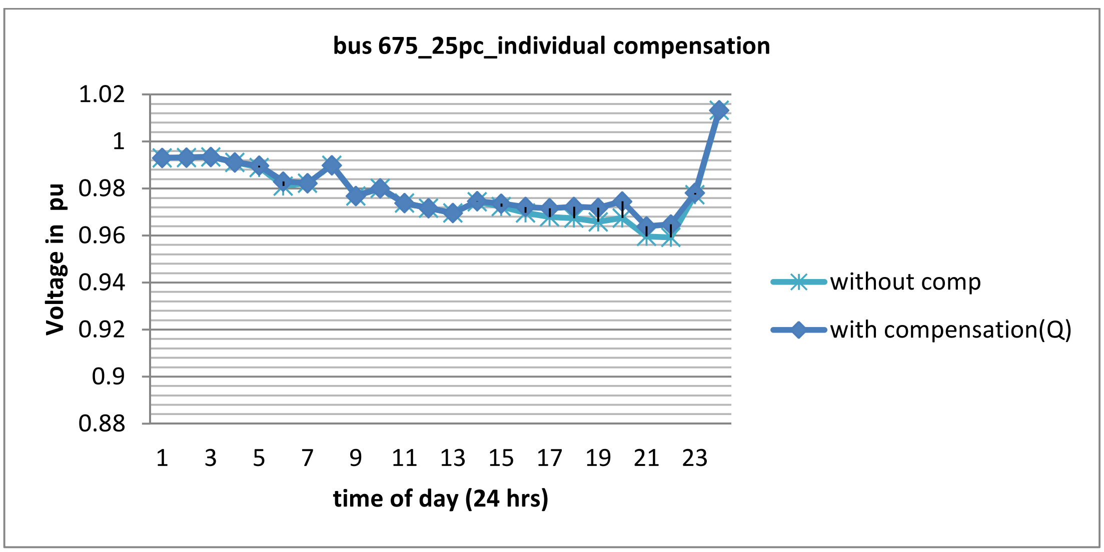


Figure 5-2. Bus675 25% PHEV penetration- uncompensated voltage profile v/s compensated voltage profile

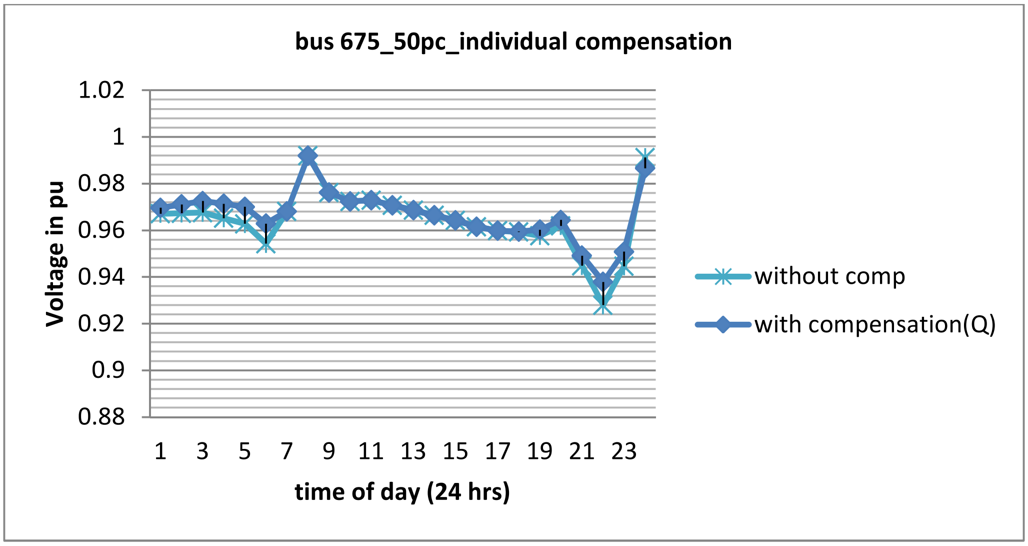


Figure 5-3. Bus675 50% PHEV penetration- uncompensated voltage profile v/s compensated voltage profile

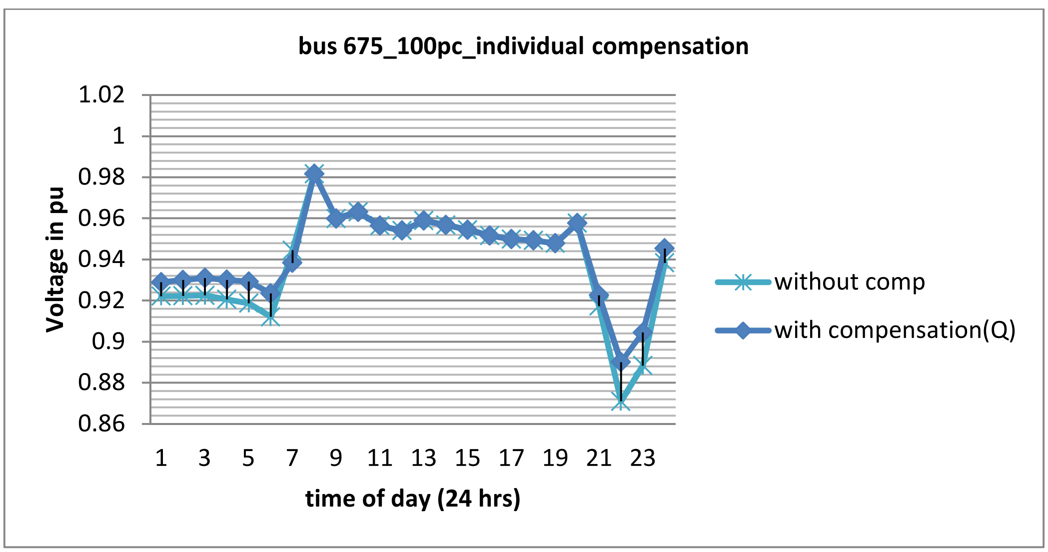


Figure 5-4. Bus675 100% PHEV penetration- uncompensated voltage profile v/s compensated voltage profile

5.2.3. Maximum Improvement

Table 5.2.3 shows the maximum improvement recorded after the compensation is applied on the bus for a particular PHEV penetration case. The compensation for each

PHEV penetration level is calculated by taking the difference of compensated voltage and uncompensated voltage at every instance of the hour for each PHEV penetration level. The maximum for each case is recorded in the table.

Table 5.1. Maximum improvement

bus675	**Maximum improvement**
10% PHEV	1.86%
25% PHEV	0.74%
50% PHEV	1.07%
100% PHEV	2.19%

5.3. Local Weighted Compensation

Section 5.2 discusses the implementation and calculation of the individual compensation for the bus. This section describes the weighted compensation. In the weighted compensation the target bus is viewing at the load flow changes at multiple reference buses. The power injections at the target bus are calculated based on the sensitivities of the various reference load buses on the target bus.

5.3.1. Description and Calculations

For weighted compensation the equation 5.6 used for the individual compensation is conditioned further. The aim is to include the effect of the rest of the load buses in the network. The effect is seen by the target bus. The sensitivity of the target bus with reference to the other load buses is also included in the equation 5.6. The objective of voltage regulation can be met by choosing the weighted least square method. According to 5.6 we have $\Delta Vw = Svp_{ww}.\Delta PwSvq_{ww}.\Delta Qw$. Hence by weighted least square method and minimizing voltage deviation on the bus, $\sum_{i=1}^{n} we_i|\Delta Vw|^2 = 0$ we have,

$$\sum_{i=1}^{n} we_i|Svp_{iw} + k.Svq_{iw}|^2 = 0 \tag{5.9}$$

$$k = \frac{\Delta Qw}{\Delta Pw} \tag{5.10}$$

In equation 5.9, n=11 for the 11 load buses and "w" is the target bus. And the equation is expanded for bus 675 and the quadratic is solved for a value of k. The "we_i" is the weight or importance of the bus, each of the buses. For simplicity of calculation the weightage for all the buses is considered to be the same. Therefore we_i=1. Hence the equation 5.9 reduces to equation 5.11.

$$\sum_{i=1}^{n}(Sp_{iw} + k.Sq_{iw})^2 = 0 \tag{5.11}$$

The summation runs for 11 load buses. The equation 5.11 is expanded for the eleven load buses to a quadratic of thirty three coefficients

$S^2p_{1w} + k^2.S^2q_{1w} + \ 2.Sp_{1w}.k.q_{1w}$

$S^2p_{2w} + k^2.S^2q_{2w} + \ 2.Sp_{2w}.k.q_{2w}$

.

.

.

$$S^2p_{11w} + k^2.S^2q_{11w} + \ 2.Sp_{11w}.k.q_{11w} = 0 \tag{5.12}$$

Solving the quadratic equation 5.12 for 'k' which can be substituted in 5.10 and the active and reactive power injections can be calculated as described for the local individual compensation.

Next section lists the results of bus voltage profile after the weighted compensation is added and the comparison is made to an uncompensated bus voltage profile. The results are divided in two parts (i) the active and reactive power injections are made to the local bus 675 and (ii) the reactive power injection made to the local bus 675.

5.3.2. Results (Active and Reactive power injection)

The results show a comparison between the regular voltage output profiles at bus 675 versus the improved voltage profile after the corrective active/reactive compensation is applied. . The results are recorded and compared for each PHEV penetration level for the graphs with compensation and without compensation.

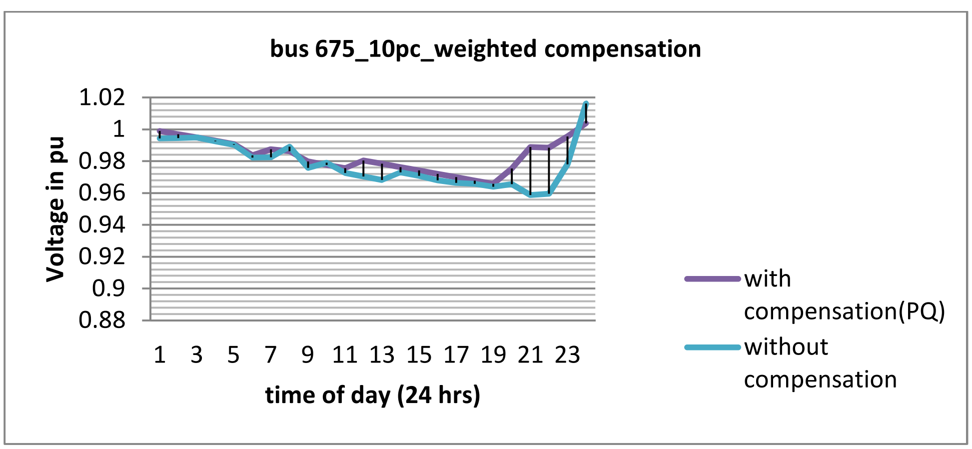


Figure 5-5. Bus675 10% PHEV penetration uncompensated voltage profile v/s weighted compensated voltage profile

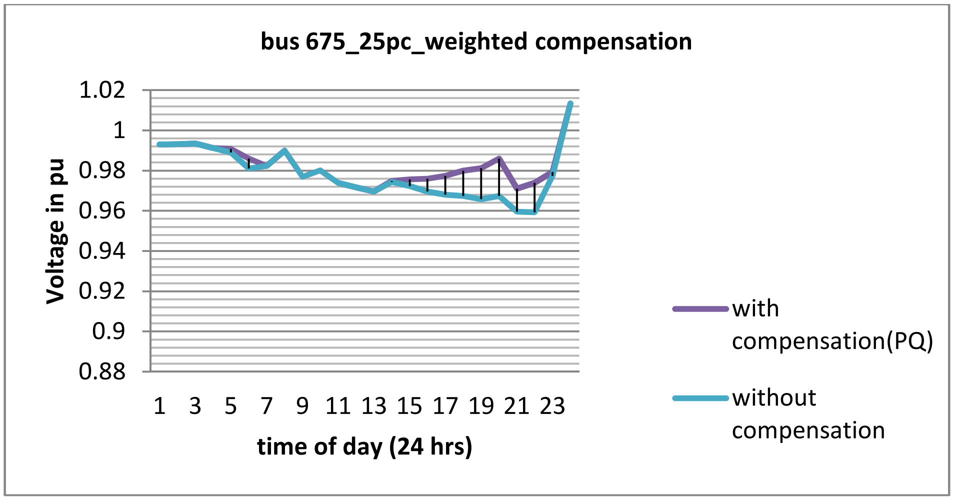


Figure 5-6. Bus675 25% PHEV penetration- uncompensated voltage profile v/s weighted compensated voltage profile

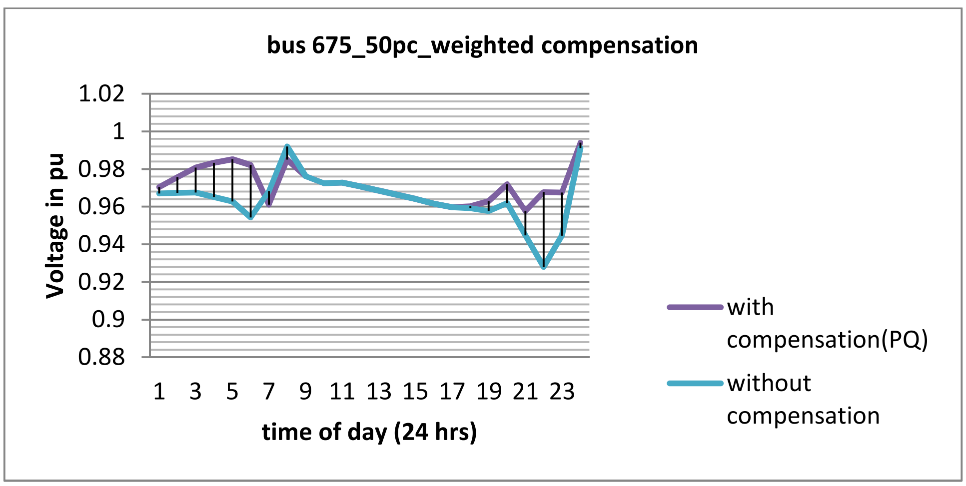


Figure 5-7. Bus675 50% PHEV penetration- uncompensated voltage profile v/s weighted compensated voltage profile

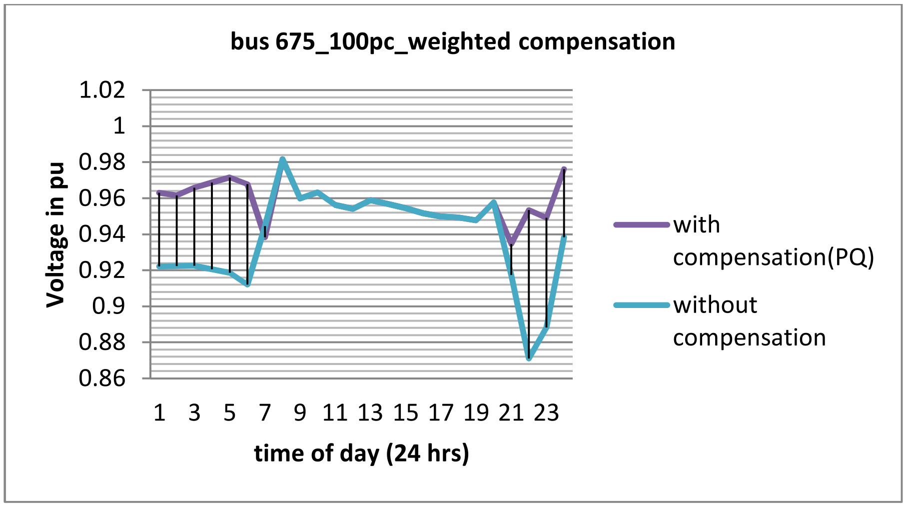


Figure 5-8. Bus675 100% PHEV penetration- uncompensated voltage profile v/s weighted compensated voltage profile

5.3.3. Maximum Improvement

The table shows the maximum improvement recorded after the compensation is applied on the bus for a particular PHEV penetration case. The maximum compensation for each PHEV penetration level is calculated by calculating the difference of compensated voltage and uncompensated voltage at every instance of the hour for each PHEV penetration level.

Table 5.2. Maximum improvement

bus675	**Maximum improvement**
10% PHEV	3.02%
25% PHEV	1.91%
50% PHEV	4.24%
100% PHEV	9.47%

5.3.4. Results (Reactive power injection)

This section shows a comparison of graphs between the voltage output profiles at bus 675 without compensation versus the improved voltage profile after only the reactive compensation is applied. These results are recorded and compared for each PHEV penetration level, the compensation injected is reactive power only.

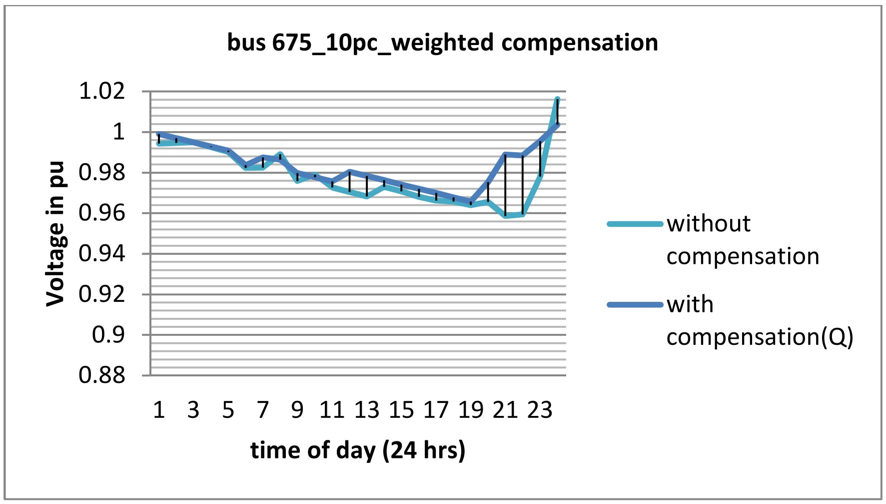


Figure 5-9. Bus675 10% PHEV penetration-uncompensated voltage profile v/s weighted compensated voltage profile

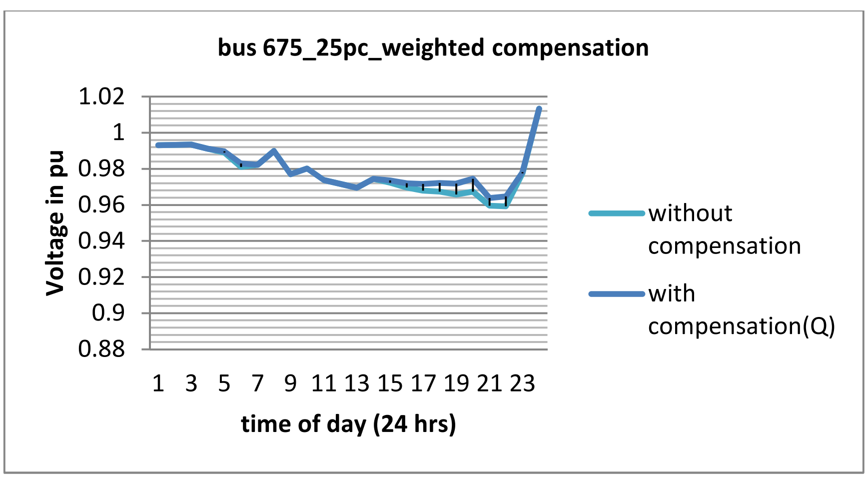


Figure 5-10. Bus675 25% PHEV penetration-uncompensated voltage profile v/s weighted compensated voltage profile

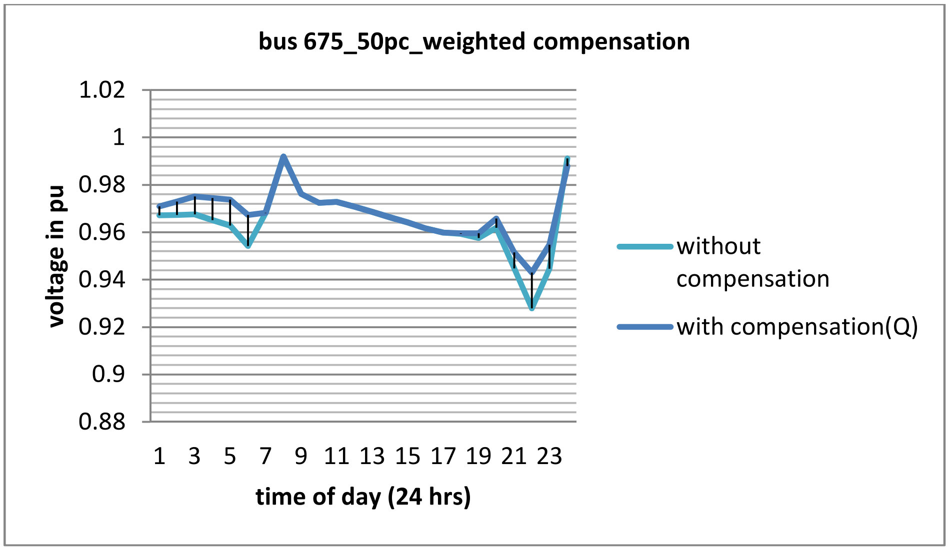


Figure 5-11. Bus675 50% PHEV penetration-uncompensated voltage profile v/s weighted compensated voltage profile

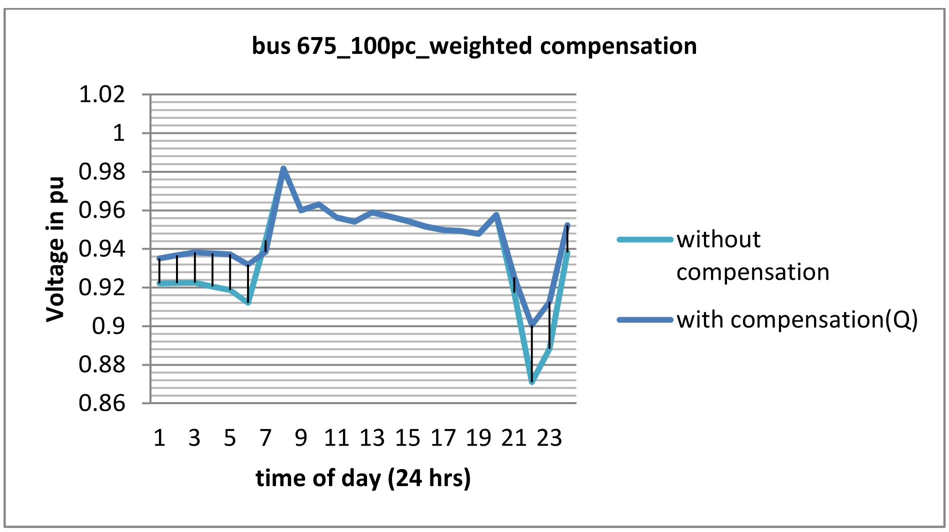


Figure 5-12. Bus675 100% PHEV penetration-uncompensated voltage profile v/s weighted compensated voltage profile

5.3.5. Maximum Improvement

The table shows the maximum improvement recorded after the compensation is applied on the bus for a particular PHEV penetration case. The maximum compensation for each PHEV penetration level is calculated by calculating the difference of compensated voltage and uncompensated voltage at every instance of the hour for each PHEV penetration level.

Table 5.3. Maximum improvement

bus675	**Maximum improvement**
10% PHEV	3.16%
25% PHEV	0.74%
50% PHEV	1.63%
100% PHEV	3.38%

5.4. Remote Compensation

As discussed in section 5.2 and 5.3 for local individual and local weighted compensation methods, the compensation is made on the same bus as the reference bus. For the remote compensation method, it is assumed that the target bus "w" is looking at load flow changes on reference bus "v". To simulate the best results the target bus is chosen to be bus 675 i.e. "w" and the reference bus is chosen to be bus 671, "v". By looking at the sensitivity matrix bus 671 has the high voltage sensitivity for active and reactive power changes, Svp_{vw} and Svq_{vw} , and also considering the fact that bus 671 is far away from the source of the system hence the sensitivity to change in load is high. For these reasons bus 671 is considered appropriate to be the reference bus.

As discussed in section 4.8.1 with the PHEV loads increasing on the bus, the voltage deviations occurred are captured in 4.8.1. This section describes how these deviations are quantified to obtain the necessary active/reactive power injections on the bus.

5.4.1. Description and Calculations

The remote compensation evaluates the correction for the target bus looking at the bus voltage sensitivities due to the load flows on reference bus. The target bus is “w” and the reference bus is “v” hence adopting the equation 5.5 is now

$$\Delta Vv = Svp_{vw}.\Delta Pw + Svq_{vw}.\Delta Qw \tag{5.13}$$

The values of voltage sensitivities are obtained from [1] Appendix A.2. To simplify equation 5.6 further, in an ideal voltage regulation case on the reference bus “v”, the voltage deviation is equated to zero. Thus for ideal case equation 5.13 is equated to zero.

$$\frac{\Delta Qw}{\Delta Pw} = \frac{Q-Qo}{P-Po} = -\frac{Svp_{vw}}{Svq_{vw}} \tag{5.14}$$

Equation 5.14 simplified to be

$$Qw = -\frac{Svp_{vw}}{Svq_{vw}}(Pw - Po) + Qo \tag{5.15}$$

In equation 5.8 the voltage sensitivities, Svp_{vw} and Svq_{vw} are obtained from Appendix A.2. The sensitivity matrix is used from [1] is an 11X11 matrix. The Sij is the sensitivity picked from the matrix, where i and j are row and column of the sensitivity matrix. For the individual correction the target bus is the also the reference bus. The operating set points for the equation 5.15, Qo=0 and Po is the average active power at the bus. The average power at the bus is calculated as the average power over a period of 24 hours.

The active/reactive power injections for “w” bus675, residential bus are calculated based on equation 5.15 for each penetration level of PHEV. For each bus the sensitivities, Svp_{vw} and Svq_{vw} are picked. And the average power Po is calculated from the 24 hour load value. And the P and Q injections are calculated for each instance of the 24 hour load.

Once the active/reactive power injections are calculated, they are injected into the bus and the power flow is run in OpenDSS to generate the voltage profiles at the bus for each penetration level. The next section shows the results of injecting these into the system.

5.4.2. Results (Active and reactive power injections) – Voltage Profiles

The results show a comparison of graphs between the regular voltage output profiles at bus 675 versus the improved voltage profile after the corrective active/reactive compensation is applied. The results are recorded and compared for each PHEV penetration level to show a comparison of graphs for with compensation and without compensation.

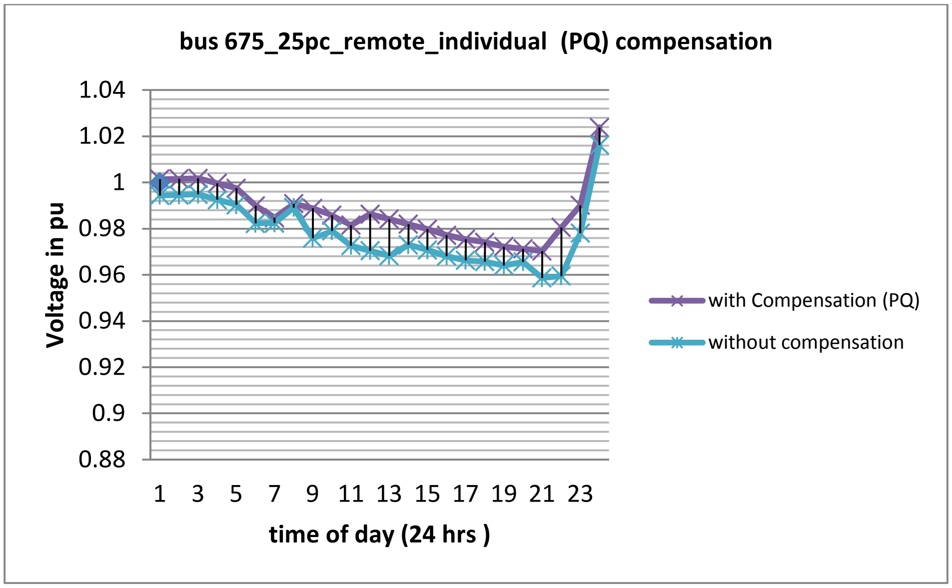


Figure 5-13. Bus675 10% PHEV penetration- uncompensated voltage profile v/s compensated voltage profile

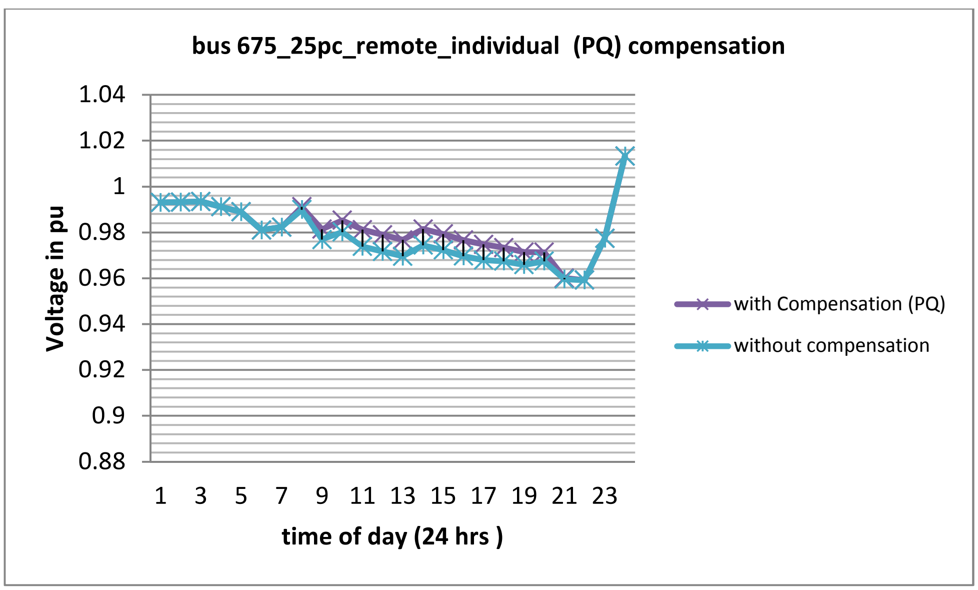


Figure 5-14. Bus675 25% PHEV penetration- uncompensated voltage profile v/s compensated voltage profile

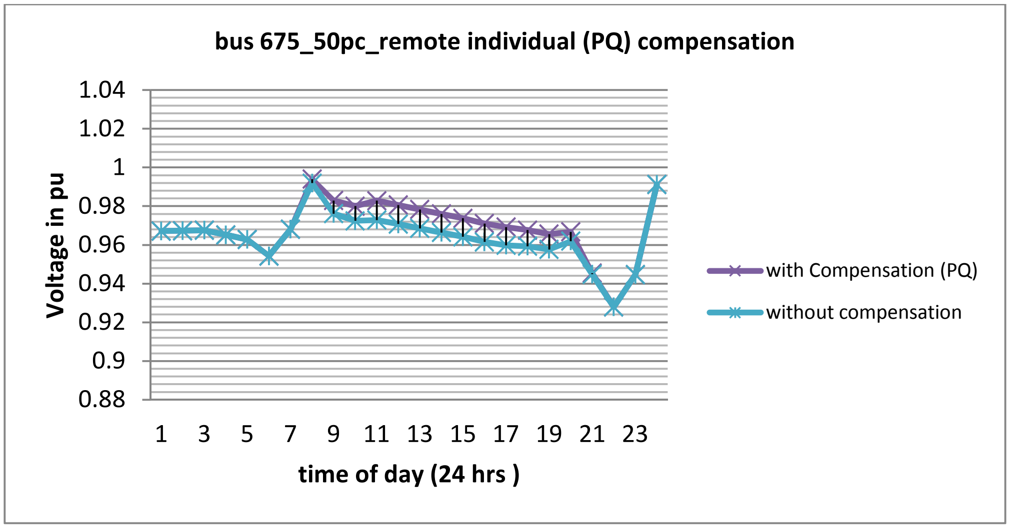


Figure 5-15. Bus675 50% PHEV penetration- uncompensated voltage profile v/s compensated voltage profile

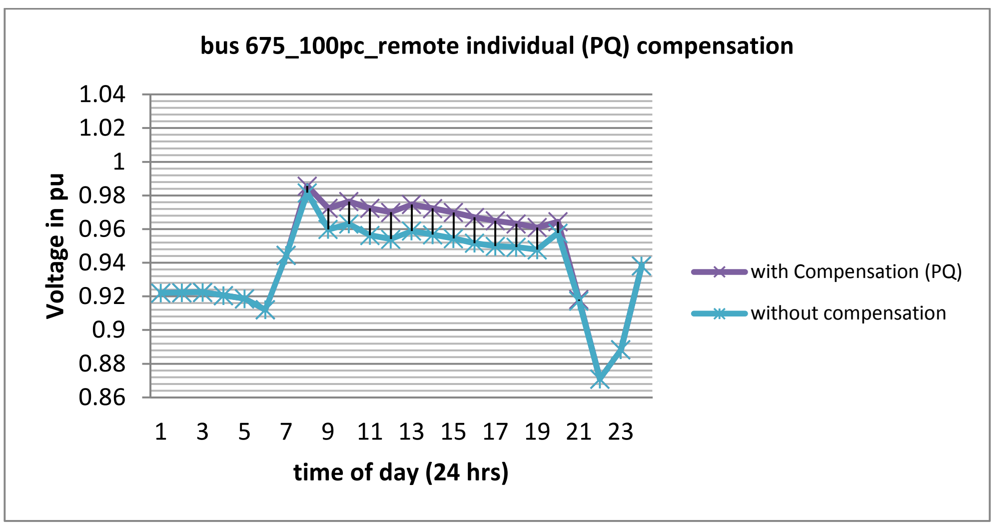


Figure 5-16. Bus675 100% PHEV penetration- uncompensated voltage profile v/s compensated voltage profile

5.4.3. Maximum Improvement

The following table 5.4 shows the maximum improvement recorded after the compensation is applied on the bus for a particular PHEV penetration case. The maximum compensation for each PHEV penetration level is calculated by taking the difference of compensated voltage and uncompensated voltage at every instance of the hour for each PHEV penetration level

Table 5.4. Maximum improvement

bus675	**Maximum improvement**
10% PHEV	2.19%
25% PHEV	0.74%
50% PHEV	1.01%
100% PHEV	1.68%

5.4.4. Results (Reactive Power Injections) – Voltage Profiles

The results show a comparison of graphs between the regular voltage output profiles at bus 675 versus the improved voltage profile after the corrective reactive compensation is applied. The results are recorded and compared for each PHEV penetration level to show a comparison of graphs for with compensation and without compensation.

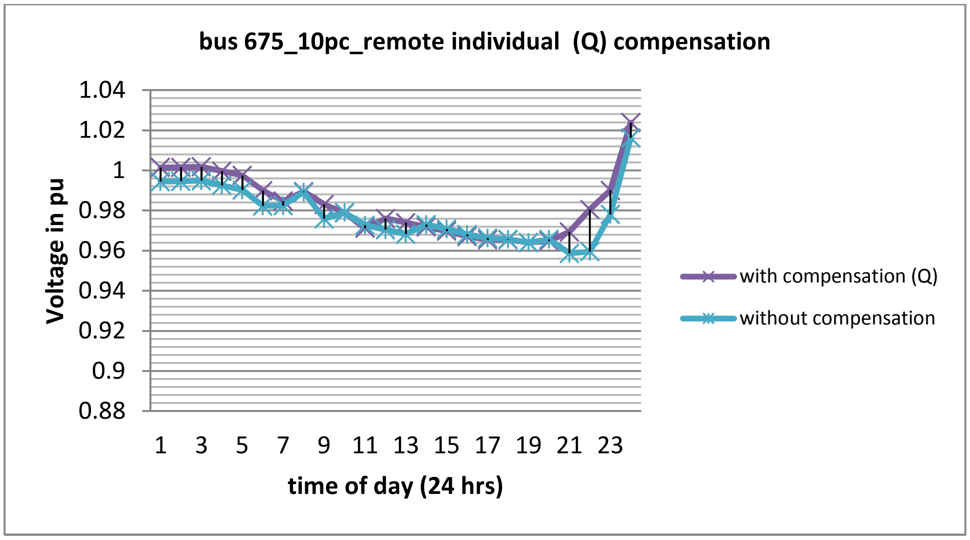


Figure 5-17. Bus675 100% PHEV penetration- uncompensated voltage profile v/s compensated voltage profile

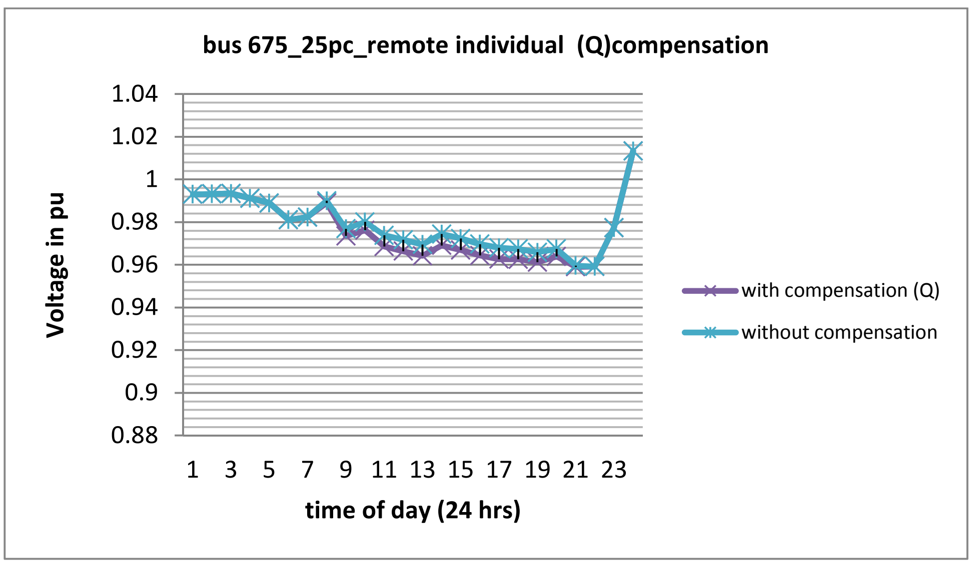


Figure 5-18. Bus675 100% PHEV penetration- uncompensated voltage profile v/s compensated voltage profile

5.5. Conclusion

This chapter provides a strategy to balance out the impact of PHEV on the residential network. The corrective action provides local and remote methods of power injections on the bus. The process to calculate the local active/reactive power injections for each case – local and remote are explained. The resultant voltage profiles on the residential bus 675 are shown. The comparison of voltage profiles has been produced. From the graphs it is evident that the scheme has provided a significant improvement in the voltages for the cases where the voltage deviation was observed to be highest in each of the PHEV loading scenarios. The results show the residential bus voltage profile improvement in each of the PHEV penetration case.

The maximum improvement obtained in the local individual compensation case is 2.19% and in the local weighted compensation (for active/ reactive power injections) shows significant improvement of 9.4%. And local weighted compensation (for reactive power injections) shows improvement of 3.38%. The third type of compensation, remote compensation where the injections were made based on the power flows seen on a reference bus gives an improvement of 1.68%. It is evident that the individual weighted compensation results show an even better improvement percentage on the bus voltage profile since the active/reactive power injections made on the bus take into account the sensitivity of all the load buses in the network, and all the injections made are local.

The results show that the corrective strategy suggested in the study provides the desired improvements in the voltage profiles which had deviated from the normal voltage, profile after adding the PHEV load. The injections which are local in nature can be made through battery packs or in the PHEV's case the PHEV battery backup or even small diesel generator sets. The case where the injections are computed and are provided by the PHEV is not a part of this study.

6. CONCLUSION

6.1. Summary of the Work

The research study presents a descriptive overview of PHEVs and the various concepts that govern the operation and impacts of PHEV. The impact of PHEVs is quantified by running simulations for various scenarios. The first part of results includes the simulation of PHEV load on the distribution IEEE-13 bus network. The various kinds of load profiles for regular loads are demonstrated and the PHEV charging profiles are listed for different cases. Solutions are run for the various charging profiles. For uncoordinated charging the voltage deviates 12.5% below the normal case, at the residential bus 675 for the highest (100%) PHEV penetration. For coordinated charging the voltage deviation is 11.4% below the normal case for the same residential bus 675 for highest PHEV penetration. The resultant voltage deviation observed in the case of coordinated charging is lower as compared to the uncoordinated charging however it still lies in unacceptable range according to the standards.

The next part of the study explains a corrective strategy for local and remote power injections on the residential bus. These active/reactive power injections are based on the voltage sensitivity analysis due to the PHEV loads. The active and reactive power injections are calculated for the individual and weighted sensitivity of the bus. Running the simulation yields results which can be conditioned to establish a comparison of voltage profiles for residential bus 675 for various PHEV penetrations. Significant improvements are observed for individual and weighted compensation methods. Following is the highlights of maximum improvements obtained for each of the cases.

Table 6.1 Maximum improvement in compensation cases

	Case description (compensation)	**Maximum improvement(as compared to base case instance for 100% PHEV load)**
1	Local - individual compensation (Reactive only)	2.19%
2	Local - weighted compensation (Active and Reactive)	9.4%
3	Local - weighted compensation (Reactive only)	3.38%
4	Remote - individual compensation (Active and Reactive)	1.68%

6.2. Significance of the Results

The scheme provides improvement in the voltage regulation with schemes for various cases as shown in the table above. As compared to the solution proposed by earlier studies in this field i.e. coordinated charging, shows an improvement of 1.13% as compared to uncoordinated charging. However the scheme from this study provides compensation and shows improvement in the voltage regulation from 2% to 9.4%. Also the scheme is not dependent on the user preferences or behavior.

6.3. Limitations of the Scheme Proposed

- The assumptions made for the study can be improved for better results.
- Also real time data for PHEVs can provide realistic simulations and results.
- The scheme does not show any significant improvement in the voltage regulation for higher PHEV penetration for remote reactive only compensation, due to the vastness of system

6.4. Future Work

The results of this study can be taken further to a next level of analysis and findings. This study focuses on the impact of PHEVs on the IEEE 13 bus network based on the different charging profiles on the bus. The future study can introduce V2G concept to the bus. Along with the charging profiles, the V2G power to grid profiles can be monitored and comparison can be studied. Also the local active and reactive power injection strategy based here suggests a diesel generator or other kind of local dispatch-able power source. This power source can be considered to be a fleet of PHEVs. The coordination between charging and the injection can be established and a two way energy flow model can be achieved with the PHEVs in the distribution network.

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APPENDIX A. OPENDSS CODE FUNCTION

Code function for OpenDSS – for a 100% PHEV penetration – coordinated charging

Clear

!PHEV 100 percent penetration case - IEEE-13Nodeckt_100pcPHEV.dss

!

! This script is based on a script developed by Tennessee Tech Univ students

! Tyler Patton, Jon Wood, and David Woods, April 2009

!

! Script has been adapted from the Sourceforge.net for IEEE13 bus project by Anushree Sharma may2012

new circuit.IEEE13Nodeckt

set Editor=D:\Notepad++\notepad++.exe

~ basekv=115 pu=1.0001 phases=3 bus1=SourceBus

~ Angle=30 ! advance angle 30 deg so result agree with published angle

~ MVASC3=500 MVASC1=500 ! Rated MVA ~ ANS

!SUB TRANSFORMER DEFINITION

! Although this data was given, it does not appear to be used in the test case results

! The published test case starts at 1.0 per unit at Bus 650. To make this happen, we will change the impedance

! on the transformer to something tiny by dividing by 1000 using the DSS in-line RPN math

New Transformer.Sub Phases=3 Windings=2 XHL=(8 1000 /)

~ wdg=1 bus=SourceBus conn=delta kv=115 kva=5000 %r=(.5 1000 /) XHT=4

~ wdg=2 bus=650 conn=wye kv=4.16 kva=5000 %r=(.5 1000 /) XLT=4

! FEEDER 1-PHASE VOLTAGE REGULATORS

! Define low-impedance 2-wdg transformer

New Transformer.Reg1 phases=1 XHL=0.01 kVAs=[1666 1666]

~ Buses=[650.1 RG60.1] kVs=[2.4 2.4] %LoadLoss=0.01

new regcontrol.Reg1 transformer=Reg1 winding=2 vreg=122 band=2 ptratio=20 ctprim=700 R=3   X=9

New Transformer.Reg2 phases=1 XHL=0.01 kVAs=[1666 1666]

~ Buses=[650.2 RG60.2] kVs=[2.4 2.4] %LoadLoss=0.01

new regcontrol.Reg2 transformer=Reg2 winding=2 vreg=122 band=2 ptratio=20 ctprim=700 R=3   X=9

New Transformer.Reg3 phases=1 XHL=0.01 kVAs=[1666 1666]

~ Buses=[650.3 RG60.3] kVs=[2.4 2.4] %LoadLoss=0.01

new regcontrol.Reg3 transformer=Reg3 winding=2 vreg=122 band=2 ptratio=20 ctprim=700 R=3   X=9

!TRANSFORMER DEFINITION

New Transformer.XFM1 Phases=3   Windings=2 XHL=2

~ wdg=1 bus=633   conn=Wye kv=4.16   kva=500   %r=.55   XHT=1_

~ wdg=2 bus=634   conn=Wye kv=0.480   kva=500   %r=.55   XLT=1

!LINE CODES

redirect IEEELineCodes.dss

// these are local matrix line codes

// corrected 9-14-2011

New linecode.mtx601 nphases=3 BaseFreq=60

~ rmatrix = (0.3465 | 0.1560 0.3375 | 0.1580 0.1535 0.3414)

~ xmatrix = (1.0179 | 0.5017 1.0478 | 0.4236 0.3849 1.0348)

~ units=mi

New linecode.mtx602 nphases=3 BaseFreq=60

~ rmatrix = (0.7526 | 0.1580 0.7475 | 0.1560 0.1535 0.7436)

~ xmatrix = (1.1814 | 0.4236 1.1983 | 0.5017 0.3849 1.2112)

~ units=mi

New linecode.mtx603 nphases=2 BaseFreq=60

~ rmatrix = (1.3238 | 0.2066 1.3294)

~ xmatrix = (1.3569 | 0.4591 1.3471)

~ units=mi

New linecode.mtx604 nphases=2 BaseFreq=60

~ rmatrix = (1.3238 | 0.2066 1.3294)

~ xmatrix = (1.3569 | 0.4591 1.3471)

~ units=mi

New linecode.mtx605 nphases=1 BaseFreq=60

~ rmatrix = (1.3292)

~ xmatrix = (1.3475)

~ units=mi

New linecode.mtx606 nphases=3 BaseFreq=60

~ rmatrix = (0.7982 | 0.3192 0.7891 | 0.2849 0.3192 0.7982)

~ xmatrix = (0.4463 | 0.0328 0.4041 | -0.0143 0.0328 0.4463)

~ Cmatrix = [257 | 0 257 | 0 0 257]

~ units=mi

New linecode.mtx607 nphases=1 BaseFreq=60

~ rmatrix = (1.3425)

~ xmatrix = (0.5124)

~ cmatrix = [236]

~ units=mi

!LOADSHAPE DEFINITIONS ~~ANS

new loadshape.resi 24 1.0 mult=[0.5 0.48 0.465 0.48 0.5 0.55 0.6 0.63 0.7 0.725 0.75 0.775 0.8 0.825 0.85 0.88 0.9 0.925 0.95 0.975 0.965 0.88 0.75]

new loadshape.comm 24 1.0 mult=[0.45 0.48 0.5 0.52 0.53 0.6 0.7 0.8 0.89 0.92 1 1 1 1 1 1 1 0.97 0.96 0.94 0.8 0.6 0.5 0.5]

new loadshape.phevresi 24 1.0 mult=[1 1 1 1 1 1 0.5 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.5 1 1 1]

new loadshape.phevcomm 24 1.0 mult=[0.05 0.05 0.05 0.05 0.05 0.05 0.7 0.8 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 0.8 0.7 0.6 0.5 0.5]

!LOAD DEFINITIONS !

New Load.671 Bus1=671 Phases=3 Conn=Delta Model=1 kV=4.16 kW=1155 kvar=358 daily=comm ! changed all load to be single phase ~ANS

New Load.671phev Bus1=671 Phases=3 Conn=Delta Model=1 kV=4.16 kW=1155 kvar=358.05 daily=phevcomm

New Load.634a Bus1=634.1 Phases=1 Conn=Wye Model=1 kV=0.277 kW=160 kvar=110 daily=resi

New Load.634b Bus1=634.2 Phases=1 Conn=Wye Model=1 kV=0.277 kW=120 kvar=90 daily=resi

New Load.634c Bus1=634.3 Phases=1 Conn=Wye Model=1 kV=0.277 kW=120 kvar=90 daily=resi

New Load.634phev Bus1=634.3 Phases=1 Conn=Wye Model=1 kV=0.277 kW=400 kvar=124 daily=phevresi

New Load.645 Bus1=645.2 Phases=1 Conn=Wye Model=1 kV=2.4 kW=170 kvar=125 daily=resi

New Load.645phev Bus1=645.2 Phases=1 Conn=Wye Model=1 kV=2.4 kW=170 kvar=52.7 daily=phevresi

New Load.646 Bus1=646.2.3 Phases=1 Conn=Delta Model=2 kV=4.16 kW=230 kvar=132 daily=comm

New Load.646phev Bus1=646.2.3 Phases=1 Conn=Delta Model=2 kV=4.16 kW=230 kvar=71.3 daily=phevcomm

New Load.692 Bus1=692.3.1 Phases=1 Conn=Delta Model=5 kV=4.16 kW=170 kvar=151 daily=comm

New Load.692phev Bus1=692.3.1 Phases=1 Conn=Delta Model=5 kV=4.16 kW=170 kvar=52.7 daily=phevcomm

New Load.675a Bus1=675.1 Phases=1 Conn=Wye Model=1 kV=2.4 kW=485 kvar=190 daily=resi

New Load.675b Bus1=675.2 Phases=1 Conn=Wye Model=1 kV=2.4 kW=68 kvar=60 daily=resi

New Load.675c Bus1=675.3 Phases=1 Conn=Wye Model=1 kV=2.4 kW=290 kvar=212 daily=resi

New Load.675phev Bus1=675.3 Phases=1 Conn=Wye Model=1 kV=2.4 kW=835 kvar=258.85 daily=phevresi

New Load.611 Bus1=611.3 Phases=1 Conn=Wye Model=5 kV=2.4 kW=170 kvar=80 daily=resi

New Load.611phev Bus1=611.3 Phases=1 Conn=Wye Model=5 kV=2.4 kW=170 kvar=52.7 daily=phevresi

New Load.652 Bus1=652.1 Phases=1 Conn=Wye Model=2 kV=2.4 kW=128 kvar=86 daily=resi

New Load.652phev Bus1=652.1 Phases=1 Conn=Wye Model=2 kV=2.4 kW=128 kvar=39.6 daily=phevresi

New Load.670a Bus1=670.1 Phases=1 Conn=Wye Model=1 kV=2.4 kW=17 kvar=10 daily=comm

New Load.670b Bus1=670.2 Phases=1 Conn=Wye Model=1 kV=2.4 kW=66 kvar=38 daily=comm

New Load.670c Bus1=670.3 Phases=1 Conn=Wye Model=1 kV=2.4 kW=117 kvar=68 daily=comm

New Load.670phev Bus1=670.3 Phases=1 Conn=Wye Model=1 kV=2.4 kW=200 kvar=62 daily=phevcomm

!CAPACITOR DEFINITIONS

New Capacitor.Cap1 Bus1=675 phases=3 kVAR=600 kV=4.16

New Capacitor.Cap2 Bus1=611.3 phases=1 kVAR=100 kV=2.4

!Bus 670 is the concentrated point load of the distributed load on line 632 to 671 located at 1/3 the distance from node 632

!LINE DEFINITIONS

New Line.650632 Phases=3 Bus1=RG60.1.2.3 Bus2=632.1.2.3 LineCode=mtx601 Length=2000 units=ft

New Line.632670 Phases=3 Bus1=632.1.2.3 Bus2=670.1.2.3 LineCode=mtx601 Length=667 units=ft

New Line.670671 Phases=3 Bus1=670.1.2.3 Bus2=671.1.2.3 LineCode=mtx601 Length=1333 units=ft

New Line.671680 Phases=3 Bus1=671.1.2.3 Bus2=680.1.2.3 LineCode=mtx601 Length=1000 units=ft

New Line.632633 Phases=3 Bus1=632.1.2.3 Bus2=633.1.2.3 LineCode=mtx602 Length=500 units=ft

New Line.632645 Phases=2 Bus1=632.3.2 Bus2=645.3.2 LineCode=mtx603 Length=500 units=ft

New Line.645646 Phases=2 Bus1=645.3.2 Bus2=646.3.2 LineCode=mtx603 Length=300 units=ft

New Line.692675 Phases=3 Bus1=692.1.2.3 Bus2=675.1.2.3 LineCode=mtx606 Length=500 units=ft

New Line.671684 Phases=2 Bus1=671.1.3 Bus2=684.1.3 LineCode=mtx604 Length=300 units=ft

New Line.684611 Phases=1 Bus1=684.3 Bus2=611.3 LineCode=mtx605 Length=300 units=ft

New Line.684652 Phases=1 Bus1=684.1 Bus2=652.1 LineCode=mtx607 Length=800 units=ft

New Monitor.M675 Element=Load.675c terminal=1 mode=0 ! voltages and currents!comm

New Monitor.M634 Element=Load.634b terminal=1 mode=0 ! voltages and currents!resi

New Monitor.M611 Element=Load.611 terminal=1 mode=0 ! voltages and currents!resi

New Monitor.M671 Element=Load.670b terminal=1 mode=0 ! voltages and !comm

!SWITCH DEFINITIONS

New Line.671692   Phases=3 Bus1=671   Bus2=692 Switch=y r1=1e-4 r0=1e-4 x1=0.000 x0=0.000 c1=0.000 c0=0.000

//Set Voltagebases=[115, 4.16, .48]

calcv

Solve

BusCoords IEEE13Node_BusXY.csv

!---

!----------------Show some Results ---

!---

Show Voltages LN Nodes

// Show Currents Elem

//Show Powers kVA Elem

// Show Losses

// Show Taps

!---

!---

! Alternate Solution Script

! To force the taps to be same as published results, set the transformer taps manually and disable the controls

!---

```
!Commenting transformer regulations for now ~ANS
//Transformer.Reg1.Taps=[1.0 1.0625]
//Transformer.Reg2.Taps=[1.0 1.0500]
//Transformer.Reg3.Taps=[1.0 1.06875]
Set mode=daily number=24
Solve
Show monitor M675
Show monitor M634
Show monitor M611
Show monitor M671
//Set Voltagebases=[115, 4.16, .48]
calcv
Solve
BusCoords IEEE13Node_BusXY.csv
!plot circuit Power max=2000 n n C1=$00FF0000
!Export VOltages voltages.csv
```

APPENDIX B. VOLTAGE SENSITIVITIES MATRICES

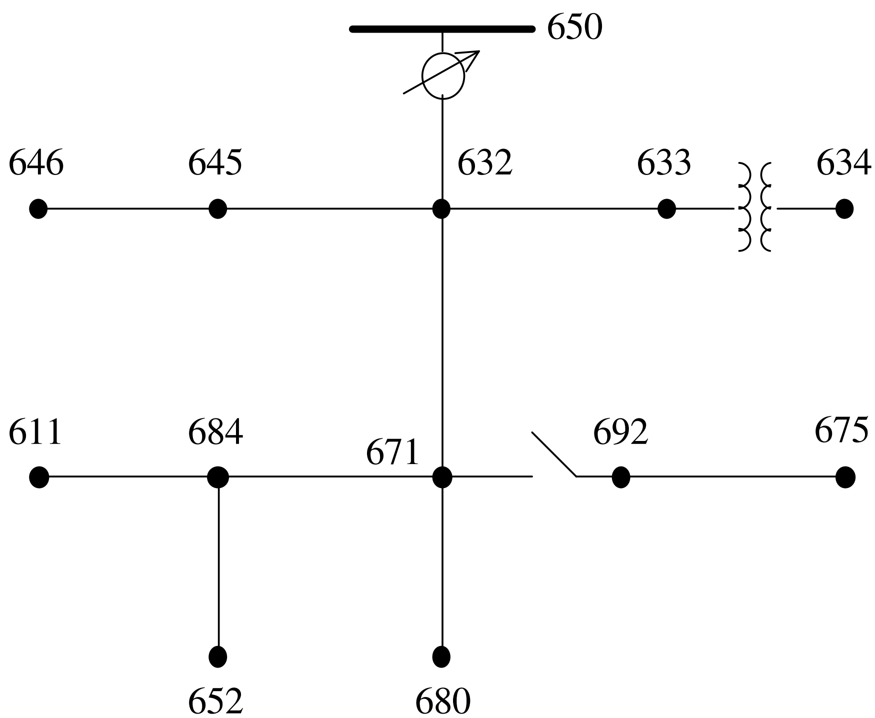
Bus voltage Sensitivities from [1]

$$
Svp = \begin{vmatrix}
0.0288 & 0.0290 & 0.0333 & 0.0291 & 0.0292 & 0.0316 & 0.0316 & 0.0318 & 0.0312 & 0.0313 & 0.0309 \\
0.0288 & 0.0359 & 0.0407 & 0.0291 & 0.0292 & 0.0316 & 0.0316 & 0.0319 & 0.0313 & 0.0313 & 0.0309 \\
0.0294 & 0.0367 & 0.1454 & 0.0297 & 0.0298 & 0.0322 & 0.0322 & 0.0325 & 0.0319 & 0.0320 & 0.0316 \\
0.0288 & 0.0291 & 0.0334 & 0.0409 & 0.0410 & 0.0316 & 0.0316 & 0.0319 & 0.0313 & 0.0314 & 0.0309 \\
0.0288 & 0.0291 & 0.0334 & 0.0409 & 0.0479 & 0.0316 & 0.0316 & 0.0319 & 0.0313 & 0.0314 & 0.0310 \\
0.0289 & 0.0292 & 0.0335 & 0.0292 & 0.0293 & 0.0449 & 0.0449 & 0.0453 & 0.0445 & 0.0446 & 0.0441 \\
0.0289 & 0.0292 & 0.0335 & 0.0292 & 0.0293 & 0.0449 & 0.0508 & 0.0453 & 0.0445 & 0.0446 & 0.0441 \\
0.0290 & 0.0292 & 0.0335 & 0.0292 & 0.0293 & 0.0450 & 0.0450 & 0.0523 & 0.0446 & 0.0447 & 0.0441 \\
0.0289 & 0.0291 & 0.0334 & 0.0292 & 0.0292 & 0.0449 & 0.0449 & 0.0452 & 0.0513 & 0.0514 & 0.0508 \\
0.0289 & 0.0291 & 0.0334 & 0.0292 & 0.0293 & 0.0449 & 0.0449 & 0.0452 & 0.0513 & 0.0701 & \mathbf{0.0508} \\
0.0288 & 0.0291 & 0.0334 & 0.0291 & 0.0292 & 0.0448 & 0.0448 & 0.0451 & 0.0512 & 0.0513 & 0.0576
\end{vmatrix}
$$

$$
Svq = \begin{vmatrix}
0.1179 & 0.1181 & 0.1213 & 0.1181 & 0.1181 & 0.1182 & 0.1182 & 0.1182 & 0.1180 & 0.1180 & 0.1177 \\
0.1180 & 0.1290 & 0.1325 & 0.1182 & 0.1183 & 0.1183 & 0.1183 & 0.1183 & 0.1181 & 0.1182 & 0.1179 \\
0.1204 & 0.1316 & 0.3379 & 0.1206 & 0.1206 & 0.1207 & 0.1207 & 0.1207 & 0.1205 & 0.1205 & 0.1202 \\
0.1181 & 0.1183 & 0.1214 & 0.1300 & 0.1301 & 0.1184 & 0.1184 & 0.1184 & 0.1181 & 0.1182 & 0.1179 \\
0.1181 & 0.1183 & 0.1215 & 0.1301 & 0.1370 & 0.1184 & 0.1184 & 0.1184 & 0.1182 & 0.1182 & 0.1179 \\
0.1185 & 0.1187 & 0.1219 & 0.1187 & 0.1187 & 0.1562 & 0.1562 & 0.1562 & 0.1559 & 0.1559 & 0.1555 \\
0.1185 & 0.1187 & 0.1219 & 0.1187 & 0.1187 & 0.1562 & 0.1749 & 0.1562 & 0.1559 & 0.1559 & 0.1555 \\
0.1186 & 0.1188 & 0.1220 & 0.1188 & 0.1189 & 0.1564 & 0.1564 & 0.1603 & 0.1561 & 0.1561 & 0.1557 \\
0.1183 & 0.1185 & 0.1216 & 0.1185 & 0.1185 & 0.1559 & 0.1559 & 0.1559 & 0.1634 & 0.1635 & 0.1631 \\
0.1183 & 0.1185 & 0.1217 & 0.1185 & 0.1186 & 0.1560 & 0.1560 & 0.1560 & 0.1635 & 0.1705 & \mathbf{0.1632} \\
0.1180 & 0.1182 & 0.1214 & 0.1182 & 0.1183 & 0.1556 & 0.1556 & 0.1556 & 0.1631 & 0.1632 & 0.1696
\end{vmatrix}
$$

Bus matrix is in the order – [632, 633, 634,645, 646, 671, 680, 675, 684, 652, 611]

APPENDIX C. IEEE 13 NODE TEST FEEDER DATA



Overhead Line Configuration Data:

Config.	Phasing	Phase	Neutral	Spacing
		ACSR	ACSR	ID
601	B A C N	556,500 26/7	4/0 6/1	500
602	C A B N	4/0 6/1	4/0 6/1	500
603	C B N	1/0	1/0	505
604	A C N	1/0	1/0	505
605	C N	1/0	1/0	510

Underground Line Configuration Data:

Config.	Phasing	Cable	Neutral	Space ID
606	A B C N	250,000 AA, CN	None	515
607	A N	1/0 AA, TS	1/0 Cu	520

Line Segment Data:

Node A	Node B	Length(ft.)	Config.
632	645	500	603
632	633	500	602
633	634	0	XFM-1
645	646	300	603
650	632	2000	601
684	652	800	607
632	671	2000	601
671	684	300	604
671	680	1000	601
671	692	0	Switch
684	611	300	605
692	675	500	606

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

Capacitor Data:

Node	Ph-A	Ph-B	Ph-C
	kVAr	kVAr	kVAr
675	200	200	200
611			100
Total	200	200	300

Regulator Data:

Regulator ID:	1		
Line Segment:	650 - 632		
Location:	50		
Phases:	A - B -C		
Connection:	3-Ph,LG		
Monitoring Phase:	A-B-C		
Bandwidth:	2.0 volts		
PT Ratio:	20		
Primary CT Rating:	700		
Compensator Settings:	Ph-A	Ph-B	Ph-C
R - Setting:	3	3	3
X - Setting:	9	9	9
Volltage Level:	122	122	122

Spot Load Data:

Node	Load	Ph-1	Ph-1	Ph-2	Ph-2	Ph-3	Ph-3
	Model	kW	kVAr	kW	kVAr	kW	kVAr
634	Y-PQ	160	110	120	90	120	90
645	Y-PQ	0	0	170	125	0	0
646	D-Z	0	0	230	132	0	0
652	Y-Z	128	86	0	0	0	0
671	D-PQ	385	220	385	220	385	220
675	Y-PQ	485	190	68	60	290	212
692	D-I	0	0	0	0	170	151
611	Y-I	0	0	0	0	170	80
	TOTAL	1158	606	973	627	1135	753

Distributed Load Data:

Node A	Node B	Load	Ph-1	Ph-1	Ph-2	Ph-2	Ph-3	Ph-3
		Model	kW	kVAr	kW	kVAr	kW	kVAr
632	671	Y-PQ	17	10	66	38	117	68

Impedances

Configuration 601:

```
          Z (R +jX) in ohms per mile
 0.3465  1.0179   0.1560  0.5017   0.1580  0.4236
                  0.3375  1.0478   0.1535  0.3849
                                   0.3414  1.0348
         B in micro Siemens per mile
           6.2998   -1.9958   -1.2595
                     5.9597   -0.7417
                               5.6386
```

Configuration 602:

```
          Z (R +jX) in ohms per mile
0.7526  1.1814   0.1580  0.4236   0.1560  0.5017
                 0.7475  1.1983   0.1535  0.3849
                                  0.7436  1.2112
         B in micro Siemens per mile
           5.6990   -1.0817   -1.6905
                     5.1795   -0.6588
                               5.4246
```

Configuration 603:

```
          Z (R +jX) in ohms per mile
 0.0000  0.0000   0.0000  0.0000   0.0000  0.0000
                  1.3294  1.3471   0.2066  0.4591
                                   1.3238  1.3569
         B in micro Siemens per mile
           0.0000    0.0000    0.0000
                     4.7097   -0.8999
                               4.6658
```

Configuration 604:

```
          Z (R +jX) in ohms per mile
 1.3238  1.3569   0.0000  0.0000   0.2066  0.4591
                  0.0000  0.0000   0.0000  0.0000
                                   1.3294  1.3471
         B in micro Siemens per mile
           4.6658    0.0000   -0.8999
                     0.0000    0.0000
                               4.7097
```

Configuration 605:

```
          Z (R +jX) in ohms per mile
 0.0000  0.0000   0.0000  0.0000   0.0000  0.0000
                  0.0000  0.0000   0.0000  0.0000
                                   1.3292  1.3475
         B in micro Siemens per mile
           0.0000    0.0000    0.0000
                     0.0000    0.0000
                               4.5193
```

Configuration 606:

```
          Z (R +jX) in ohms per mile
0.7982  0.4463   0.3192  0.0328   0.2849 -0.0143
                 0.7891  0.4041   0.3192  0.0328
                                  0.7982  0.4463
         B in micro Siemens per mile
          96.8897    0.0000    0.0000
                    96.8897    0.0000
                              96.8897
```

Configuration 607:

```
          Z (R +jX) in ohms per mile
 1.3425  0.5124   0.0000  0.0000   0.0000  0.0000
                  0.0000  0.0000   0.0000  0.0000
                                   0.0000  0.0000
         B in micro Siemens per mile
          88.9912    0.0000    0.0000
                     0.0000    0.0000
                               0.0000
```

Power-Flow Results

```
-  R A D I A L   F L O W   S U M M A R Y - DATE:  6-24-2004 AT 15:33: 2 HOURS ---
SUBSTATION:  IEEE 13;   FEEDER:  IEEE 13
--------------------------------------------------------------------------------
SYSTEM        PHASE             PHASE             PHASE              TOTAL
INPUT -------(A)-------|-------(B)-------|-------(C)-------|-------------------
kW   :      1251.398   |       977.332   |      1348.461   |       3577.191
kVAr :       681.570   |       373.418   |       669.784   |       1724.772
kVA  :      1424.968   |      1046.241   |      1505.642   |       3971.289
PF   :         .8782   |         .9341   |         .8956   |          .9008

LOAD  --(A-N)----(A-B)-|--(B-N)----(B-C)-|--(C-N)----(C-A)-|---WYE-----DELTA--
kW   :   785.6    385.0|  424.0    625.7|  692.5    553.4|  1902.1   1564.0
 TOT :      1170.563   |      1049.658   |      1245.907   |       3466.128
                       |                 |                 |
kVAr :   393.0    220.0|  313.0    358.1|  447.9    369.5|  1153.9    947.7
 TOT :       613.019   |       671.117   |       817.450   |       2101.586
                       |                 |                 |
kVA  :   878.4    443.4|  527.0    720.9|  824.8    665.4|  2224.8   1828.7
 TOT :      1321.367   |      1245.865   |      1490.137   |       4053.481
                       |                 |                 |
PF   :   .8943    .8682|  .8045    .8679|  .8397    .8316|   .8550    .8553
 TOT :         .8859   |         .8425   |         .8361   |          .8551

LOSSES ------(A)-------|-------(B)-------|-------(C)-------|-------------------
kW   :        39.107   |        -4.697   |        76.653   |        111.063
kVAr :       152.585   |        42.217   |       129.850   |        324.653
kVA  :       157.517   |        42.478   |       150.787   |        343.124

CAPAC --(A-N)----(A-B)-|--(B-N)----(B-C)-|--(C-N)----(C-A)-|---WYE-----DELTA--
R-kVA:   200.0       .0|  200.0       .0|  300.0       .0|   700.0       .0
 TOT :       200.000   |       200.000   |       300.000   |        700.000
                       |                 |                 |
A-kVA:   193.4       .0|  222.7       .0|  285.3       .0|   701.5       .0
 TOT :       193.443   |       222.747   |       285.276   |        701.466
```

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--- **V O L T A G E   P R O F I L E** ---- DATE: 6-24-2004 AT 15:33:12 HOURS ----

SUBSTATION: IEEE 13; FEEDER: IEEE 13

NODE	MAG (A-N)	ANGLE (A-N)	MAG (B-N)	ANGLE (B-N)	MAG (C-N)	ANGLE (C-N)	mi.to SR
650	1.0000 at	.00	1.0000 at	-120.00	1.0000 at	120.00	.000
RG60	1.0625 at	.00	1.0500 at	-120.00	1.0687 at	120.00	.000
632	1.0210 at	-2.49	1.0420 at	-121.72	1.0174 at	117.83	.379
633	1.0180 at	-2.56	1.0401 at	-121.77	1.0148 at	117.82	.474
XFXFM1	.9941 at	-3.23	1.0218 at	-122.22	.9960 at	117.35	.474
634	.9940 at	-3.23	1.0218 at	-122.22	.9960 at	117.34	.474
645			1.0329 at	-121.90	1.0155 at	117.86	.474
646			1.0311 at	-121.98	1.0134 at	117.90	.530
671	.9900 at	-5.30	1.0529 at	-122.34	.9778 at	116.02	.758
680	.9900 at	-5.30	1.0529 at	-122.34	.9778 at	116.02	.947
684	.9881 at	-5.32			.9758 at	115.92	.815
611					.9738 at	115.78	.871
652	.9825 at	-5.25					.966
692	.9900 at	-5.31	1.0529 at	-122.34	.9777 at	116.02	.852
675	.9835 at	-5.56	1.0553 at	-122.52	.9758 at	116.03	.947

p 1

----------- **VOLTAGE REGULATOR DATA** ---- DATE: 6-24-2004 AT 15:33:16 HOURS --

SUBSTATION: IEEE 13; FEEDER: IEEE 13

[NODE]	[VREG]	[SEG]	[NODE]	MODEL	OPT	BNDW
650	RG60	632	632	Phase A & B & C, Wye	RX	2.00

PHASE	LDCTR	VOLT HOLD	R-VOLT	X-VOLT	PT RATIO	CT RATE	TAP
1		122.000	3.000	9.000	20.00	700.00	10
2		122.000	3.000	9.000	20.00	700.00	8
3		122.000	3.000	9.000	20.00	700.00	11

```
                                                                            p  1
-  R A D I A L  P O W E R  F L O W  ---  DATE:  6-24-2004 AT 15:33:27 HOURS ---
SUBSTATION:  IEEE 13;   FEEDER:  IEEE 13
-------------------------------------------------------------------------------
   NODE      VALUE          PHASE A          PHASE B          PHASE C     UNT O/L<
                            (LINE A)         (LINE B)         (LINE C)        60.%
----------------------*--------A-------*-------B-------*-------C-------*--------
NODE: 650       VOLTS:   1.000      .00   1.000 -120.00   1.000  120.00 MAG/ANG
kVll   4.160           NO LOAD OR CAPACITOR REPRESENTED AT SOURCE NODE

TO NODE RG60  <VRG>..:  593.30  -28.58  435.61 -140.91  626.92   93.59 AMP/DG <
<RG60  > LOSS=   .000:    (   .000)        (   .000)        (   .000)    kW
----------------------*--------A-------*-------B-------*-------C-------*--------
NODE: RG60      VOLTS:   1.062      .00   1.050 -120.00   1.069  120.00 MAG/ANG
                  -LD:     .00      .00     .00     .00     .00     .00 kW/kVR
kVll   4.160      CAP:              .00             .00             .00 kVR

FROM NODE 650   <VRG>:  558.40  -28.58  414.87 -140.91  586.60   93.59 AMP/DG <
<RG60  > LOSS=   .000:    (   .000)        (   .000)        (   .000)    kW
TO NODE 632   .......:  558.40  -28.58  414.87 -140.91  586.60   93.59 AMP/DG <
<632   > LOSS= 59.716:    ( 21.517)        ( -3.252)        ( 41.451)    kW
----------------------*--------A-------*-------B-------*-------C-------*--------
NODE: 632       VOLTS:   1.021    -2.49   1.042 -121.72   1.017  117.83 MAG/ANG
                  -LD:     .00      .00     .00     .00     .00     .00 kW/kVR
kVll   4.160      CAP:              .00             .00             .00 kVR

FROM NODE RG60  .....:  558.41  -28.58  414.87 -140.91  586.60   93.59 AMP/DG <
<632   > LOSS= 59.716:    ( 21.517)        ( -3.252)        ( 41.451)    kW
TO NODE 633   .......:   81.33  -37.74   61.12 -159.09   62.70   80.48 AMP/DG
<633   > LOSS=   .808:    (   .354)        (   .148)        (   .306)    kW
TO NODE 645   .......:                  143.02 -142.66   65.21   57.83 AMP/DG <
<645   > LOSS=  2.760:                     (  2.540)        (   .220)    kW
TO NODE 671   .......:  478.29  -27.03  215.12 -134.66  475.50   99.90 AMP/DG <
<671   > LOSS= 35.897:    ( 10.484)        ( -6.169)        ( 31.582)    kW
----------------------*--------A-------*-------B-------*-------C-------*--------
NODE: 633       VOLTS:   1.018    -2.56   1.040 -121.77   1.015  117.82 MAG/ANG
                  -LD:     .00      .00     .00     .00     .00     .00 kW/kVR
kVll   4.160      CAP:              .00             .00             .00 kVR

FROM NODE 632   .....:   81.33  -37.74   61.12 -159.09   62.71   80.47 AMP/DG
<633   > LOSS=   .808:    (   .354)        (   .148)        (   .306)    kW
TO NODE XFXFM1.......:   81.33  -37.74   61.12 -159.09   62.71   80.47 AMP/DG <
<XFXFM1> LOSS=  5.427:    (  2.513)        (  1.420)        (  1.494)    kW
----------------------*--------A-------*-------B-------*-------C-------*--------
NODE: XFXFM1    VOLTS:    .994    -3.23   1.022 -122.22    .996  117.35 MAG/ANG
                  -LD:     .00      .00     .00     .00     .00     .00 kW/kVR
kVll    .480      CAP:              .00             .00             .00 kVR

FROM NODE 633   .....:  704.83  -37.74  529.73 -159.09  543.45   80.47 AMP/DG <
<XFXFM1> LOSS=  5.427:    (  2.513)        (  1.420)        (  1.494)    kW
TO NODE 634   .......:  704.83  -37.74  529.73 -159.09  543.45   80.47 AMP/DG <
<634   > LOSS=   .000:    (   .000)        (   .000)        (   .000)    kW
```

```
- R A D I A L  P O W E R  F L O W --- DATE:  6-24-2004 AT 15:33:27 HOURS ---
SUBSTATION:  IEEE 13;   FEEDER:  IEEE 13
-------------------------------------------------------------------------------
   NODE      VALUE         PHASE A         PHASE B         PHASE C     UNT O/L<
                           (LINE A)        (LINE B)        (LINE C)        60.%
---------------------*--------A-------*-------B-------*-------C-------*--------
NODE: 634       VOLTS:    .994   -3.23   1.022 -122.22    .996  117.34 MAG/ANG
                 Y-LD:  160.00  110.00  120.00   90.00  120.00   90.00 kW/kVR
kVll    .480    Y CAP:             .00             .00             .00 kVR

FROM NODE XFXFM1.....:  704.83  -37.74  529.73 -159.09  543.45   80.47 AMP/DG <
<634    > LOSS=   .000:    (   .000)       (   .000)       (   .000)    kW
---------------------*--------A-------*-------B-------*-------C-------*--------
NODE: 645       VOLTS:                   1.033 -121.90   1.015  117.86 MAG/ANG
                 Y-LD:                  170.00  125.00     .00     .00 kW/kVR
kVll   4.160    Y CAP:                             .00             .00 kVR

FROM NODE 632   .....:                  143.02 -142.66   65.21   57.83 AMP/DG <
<645    > LOSS=  2.760:                    (  2.540)       (   .220)    kW
TO NODE 646   .......:                   65.21 -122.17   65.21   57.83 AMP/DG
<646    > LOSS=   .541:                    (   .271)       (   .270)    kW
---------------------*--------A-------*-------B-------*-------C-------*--------
NODE: 646       VOLTS:                   1.031 -121.98   1.013  117.90 MAG/ANG
                 D-LD:                  240.66  138.12     .00     .00 kW/kVR
kVll   4.160    Y CAP:                             .00             .00 kVR

FROM NODE 645   .....:                   65.21 -122.18   65.21   57.82 AMP/DG
<646    > LOSS=   .541:                    (   .271)       (   .270)    kW
---------------------*--------A-------*-------B-------*-------C-------*--------
NODE: 671       VOLTS:    .990   -5.30   1.053 -122.34    .978  116.02 MAG/ANG
                 D-LD:  385.00  220.00  385.00  220.00  385.00  220.00 kW/kVR
kVll   4.160    Y CAP:             .00             .00             .00 kVR

FROM NODE 632   .....:  470.20  -26.90  186.41 -131.89  420.64  101.66 AMP/DG <
<671    > LOSS= 35.897:    ( 10.484)       ( -6.169)       ( 31.582)    kW
TO NODE 680   .......:     .00     .00     .00     .00     .00     .00 AMP/DG
<680    > LOSS=   .000:    (  -.001)       (   .001)       (   .000)    kW
TO NODE 684   .......:   63.07  -39.12                   71.15  121.62 AMP/DG
<684    > LOSS=   .580:    (   .210)                       (   .370)    kW
TO NODE 692   .......:  229.11  -18.18   69.61  -55.19  178.38  109.39 AMP/DG
<692    > LOSS=   .008:    (   .003)       (  -.001)       (   .006)    kW
---------------------*--------A-------*-------B-------*-------C-------*--------
NODE: 680       VOLTS:    .990   -5.30   1.053 -122.34    .978  116.02 MAG/ANG
                  -LD:     .00     .00     .00     .00     .00     .00 kW/kVR
kVll   4.160      CAP:             .00             .00             .00 kVR

FROM NODE 671   .....:     .00     .00     .00     .00     .00     .00 AMP/DG
<680    > LOSS=   .000:    (  -.001)       (   .001)       (   .000)    kW
```



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- R A D I A L  P O W E R  F L O W --- DATE:  6-24-2004 AT 15:33:27 HOURS ---
SUBSTATION:  IEEE 13;   FEEDER:  IEEE 13
-------------------------------------------------------------------------------
   NODE      VALUE         PHASE A         PHASE B         PHASE C     UNT O/L<
                           (LINE A)        (LINE B)        (LINE C)        60.%
---------------------*--------A-------*-------B-------*-------C-------*--------
NODE: 684       VOLTS:    .988   -5.32                    .976  115.92 MAG/ANG
                  -LD:     .00     .00                     .00     .00 kW/kVR
kVll   4.160      CAP:             .00                             .00 kVR

FROM NODE 671   .....:   63.07  -39.12                   71.15  121.61 AMP/DG
<684    > LOSS=   .580:    (   .210)                       (   .370)    kW
TO NODE 611   .......:                                   71.15  121.61 AMP/DG
<611    > LOSS=   .382:                                    (   .382)    kW
TO NODE 652   .......:   63.07  -39.12                                 AMP/DG
<652    > LOSS=   .808:    (   .808)                                    kW
---------------------*--------A-------*-------B-------*-------C-------*--------
NODE: 611       VOLTS:                                    .974  115.78 MAG/ANG
                 Y-LD:                                  165.54   77.90 kW/kVR
kVLL   4.160    Y CAP:                                           94.82 kVR

FROM NODE 684   .....:                                   71.15  121.61 AMP/DG
<611    > LOSS=   .382:                                    (   .382)    kW
---------------------*--------A-------*-------B-------*-------C-------*--------
NODE: 652       VOLTS:    .983   -5.25                                 MAG/ANG
                 Y-LD:  123.56   83.02                                 kW/kVR
```

```
kVll   4.160    Y CAP:             .00                                kVR

FROM NODE 684   .....:   63.08  -39.15                                AMP/DG
<652   > LOSS=   .808:    (   .808)                                   kW
---------------------*--------A-------*-------B-------*-------C-------*--------
NODE: 692       VOLTS:    .990   -5.31   1.053 -122.34    .978  116.02 MAG/ANG
                 D-LD:     .00     .00     .00     .00  168.37  149.55 kW/kVR
kVll   4.160    Y CAP:             .00             .00             .00 kVR

FROM NODE 671   .....:  229.11  -18.18   69.61  -55.19  178.38  109.39 AMP/DG
<692   > LOSS=   .008:    (   .003)       (  -.001)       (   .006)    kW
TO NODE 675   .......:  205.33   -5.15   69.61  -55.19  124.07  111.79 AMP/DG <
<675   > LOSS=  4.136:    (  3.218)       (   .345)       (   .573)    kW
---------------------*--------A-------*-------B-------*-------C-------*--------
NODE: 675       VOLTS:    .983   -5.56   1.055 -122.52    .976  116.03 MAG/ANG
                 Y-LD:  485.00  190.00   68.00   60.00  290.00  212.00 kW/kVR
kVll   4.160    Y CAP:          193.44          222.75          190.45 kVR

FROM NODE 692   .....:  205.33   -5.15   69.59  -55.20  124.07  111.78 AMP/DG <
<675   > LOSS=  4.136:    (  3.218)       (   .345)       (   .573)    kW
```