IMPACTS OF MAXIMIZING PLUG-IN ELECTRIC VEHICLE PENETRATION ON URBAN POWER DISTRIBUTION NETWORK

R.M. Wanigasuriya

(128787A)

Degree of Master of Science in Electrical Installations

Department of Electrical Engineering

University of Moratuwa
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Rohini Manike Wanigasuriya

(128787A)

Thesis/Dissertation submitted in partial fulfillment of the requirements for the degree of Master of Science in Electrical Installations

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DECLARATION

I declare that this is my own work and this dissertation does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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The above candidate has carried out research for the Masters Dissertation under my supervision.

Signature of the supervisor: Date

Dr. Upuli Jayatunga,
Senior Lecturer, Department of Electrical Engineering
University of Moratuwa

Signature of the co-supervisor: Date

Dr. Lidula Widanagama Achchige,
Senior Lecturer, Department of Electrical Engineering
University of Moratuwa

DEDICATION

To my loving mother

Deelin Wanigasuriya,

who made all of this possible,

for her endless

encouragement and patience.

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ABSTRACT

Electrified vehicles are a recent developing trend in transportation. It is a good solution for the reduction of fossil fuel usage on the transportation and hence the reduced CO_2 emission. Plug-in Electric Vehicles (PEVs) are driven by the electricity stored in its battery and therefore zero tailpipe emission. Thus, PEVs attract much interests of public due to its environmental friendliness and they will possibly emerge widely in city areas in the short-term future mainly for short distance travels. Most of the countries provide incentives (tax credits, grants) to purchase plug-in electric vehicles as promotion of green vehicle. During last two years usage of PEVs was increased in Sri Lanka. PEVs are becoming more popular due to the reduction of importing tax and the developing infrastructure in Sri Lanka. However, in worldwide, increasing number of PEVs will become a substantial load to the existing power grid which can be characterized as an unusual type of load. Therefore, it is essential to pre-investigate the inevitable impacts on the power system. Lot of studies has been carried out worldwide to investigate the both positive and negative impacts on power grid. But in Sri Lankan context, a proper study had not been carried out to examine the challenges we have to face due to the increasing penetration of PEVs. Thus this research study is aimed to evaluate the level of impact due to the residential and fast charging of increasing number of PEVs. Anticipated impacts on power system such as voltage drop, voltage unbalance, transformer overloading, line losses and current harmonic effect are addressed in this study. Charging behavior of PEVs is unpredictable due to the variation of travel needs and the driving patterns. This study basically evaluates the impacts on distribution network due to this uncoordinated charging of increasing number of PEVs. It also addresses the mitigation methods and the maximum number of PEVs can be charged during off-peak hours from the distribution feeder modeled.

Key words: Plug-in Electric Vehicles, Voltage drop, Voltage unbalance, Transformer overloading, current harmonics

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

Abbreviation	Description
AC	Alternative Current
BEV	Battery Electric Vehicle
CEB	Ceylon Electricity Board
CEM	Clean Energy Ministerial
CO_2	Carbon Dioxide
DC	Direct Current
EV	Electric Vehicle
EVI	Electric Vehicles Initiative
EVSE	Electric Vehicle Supply Equipment
FFT	Fast Fourier Transform
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
LECO	Lanka Electricity Company
LV	Low Voltage
MV	Medium Voltage
NEMA	National Electrical Manufacturers' Association
PCC	Point of Common Coupling
PEV	Plug-in Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
PV	Photovoltaic
SCR	Silicon-Controlled Rectifier
TDD	Total Demand Distortion
THD	Total Harmonic Distortion
UK	United Kingdom
USA	United States of America
USD	United States Dollar
V2G	Vehicle to Grid

LIST OF APPENDICES

1. INTRODUCTION

1.1 Background

As technology develops, environmental pollution also increases due to undesirable exploitation of resources and exhausts. Therefore, as a solution, world is moving towards green energy technologies. While transportation in many countries is based on oil, few countries have been attempting to conserve energy and the environment through the use of green vehicles. Among green vehicles, vehicle which utilizes electricity as the fuel is known as Electric Vehicle (EV). There are three types of EVs namely Hybrid Electric Vehicle (HEV), Plug-in Hybrid Vehicle (PHEV), Battery Electric Vehicle (BEV). Among those EVs, which can be charged by plugging into an electric source are called Plug-in Electric Vehicles (PEVs). It has both advantages and disadvantages compared to conventional internal combustion engine vehicles. It is environmental friendly because it has zero tail pipe emission. Penetration of electric vehicles also reduces the dependency on oil. Electric vehicles also have few drawbacks compared to conventional internal combustion engine vehicles due to unavailability of sufficient infrastructure. However, the increasing popularity of electric vehicles introduces greater impact on the power system in a country.

Most of the countries provide incentives (tax credits, grants) to purchase plug-in electric vehicles as promotion of green vehicle (Eg: Japan, China, Europe, USA, Canada etc.). China has the largest market for PEVs with 351,000 units sold during year 2016. Tesla is considered to be the best highway capable all-electric car with a total global sales nearly 13,000 units in September 2016 [1]. Figure 1.1 shows the global sales of PEVs. Global sales of plug-in passenger cars stand at 773,600 units for year 2016, which is 42% higher than last year. It points out how electric vehicles are becoming popular among world community gradually.

During last few years, electric vehicle is promoted as the newest eco-friendly trend in Sri Lankan transportation system. The Ministry of power and energy has planned to make 10% of road transportation to be powered by electricity by 2020 [2].

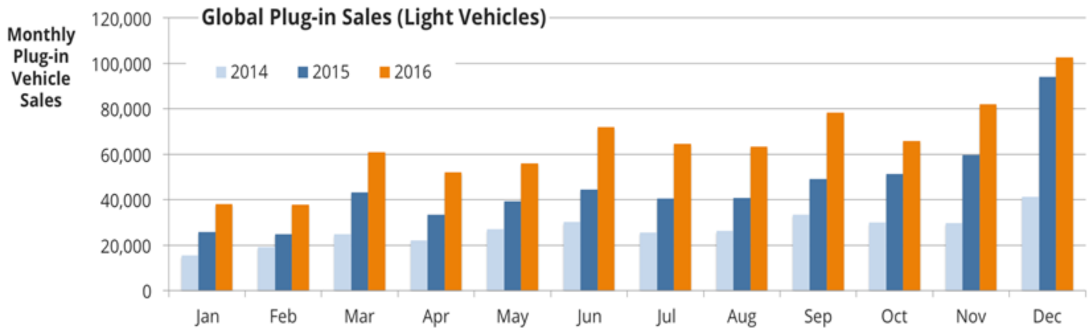


Figure 1:1: Global PEV sales

During the last two years, electric vehicles have induced interest among Sri Lankans as well and the Sri Lankan government has reduced electric vehicle importing tax to 5% by the interim budget in 2015, as an inducement to increase the market of electric vehicles. However, there was only a marginal increase of registration of electric vehicles. Demand for electric cars was not growing rapidly due to several limitations. Non-availability of sufficient recharging infrastructure, cost of ownership, range anxiety, un-awareness of the benefits are the main reasons for the deliberate growth of the demand. However, the situation has been changing. Sri Lankan government has proposed to reduce tax on PEVs having lower power rating of 100 kW. Ceylon Electricity Board (CEB), Lanka Electricity Company (LECO) and several private companies are currently engaged in establishing charging points in places like restaurants, supermarkets (where people spend more time). Further changes like, providing charging facilities at concessionary rates during off peak hours are also underway. Hence, today we can see many PEVs on the roads due to tax reduction and developing charging infrastructure facilities.

1.2 Problem statement

As PEVs are driven by electricity, penetration of PEVs will have a greater impact on Sri Lankan power system. Nevertheless, it is an environmentally sound transportation method with a zero tailpipe emission. PEVs have both positive and negative impact on the power system. Integrating of PEVs will be a better solution for Supply/Demand matching, thus improving the system load factor. As PEVs are driven by the energy stored in the battery, it requires to be recharged by plugging into an electric source. This is an unusual type of load to the distribution networks as it draws about 15 A continuously for 6 to 8 hours. In accordance with the Sri Lankan Government's plan to have 10% electric road transportation by 2020, if the 10% of passenger cars are replaced with PEVs, it would need about 75 MW power requirement during the night peak (see Appendix I). PEV interfacing consists of power electronics, which may induce harmonic currents. Consequently 10% penetration level may introduce many problems to power system network such as stability issues, capacity issues, power quality issues etc. Many studies have been carried out to find the impact on distribution networks in several cities in the world such as New South Wales [3], Gothenburg [4] etc. Those studies show that extended penetration will increase load demand thus, causing line capacity usage stress by overflow, potential congestions, voltage drops at distant nodes, transformer overloading and increased network losses [5]. Thus, uncontrolled charging of PEVs may introduce stress on power system especially, during the night peak, if the problem is not addressed properly. Hence, it is essential to identify the potential issues and remedial actions prior to reaching the higher level of PEV penetration over the next few years.

1.3 Objectives and Methodology

The main objective of this research project is to identify and analyze the level of impacts due to the uncoordinated charging of Plug-in Electric Vehicles (PEVs). Considering different test networks, voltage profile of the feeder, distribution transformer loading, power loss, unbalance due to residential PEV charging and harmonic propagation due to commercial charging have been studied. The results are compared with the regulation limits where applicable. Based on the results of analysis, mitigation actions are proposed to minimize the negative impacts.

With the goal of investigating the negative impacts of increasing PEV penetration on Sri Lankan power distribution network, background information on PEV penetration was studied in the Sri Lankan context as a market survey as presented in Chapter 3. The IEEE 33 test bus network is used to investigate the basic power quality impacts on the network due to PEVs considering the location of PEV connected, varying levels of PEV penetrations and the type of charging topology. Accordingly, the IEEE

33 test bus network was modeled using PSCAD power system simulation software and analyzed to obtain the level of anticipated impacts on power distribution network due to both single phase and three phase PEV charging as discussed in Chapter 4. Further, several LECO distribution feeders were modeled with the collected data and were analyzed under various scenarios to identify the level of anticipated impacts in reality as given in Chapter 5. The results are compared with the regulation limits practiced in Sri Lanka. DC fast charger was modeled in PSCAD to analyze the voltage and current harmonic distortion due to fast charging. In the case of violation of regulation limits, mitigation actions are proposed and shown how the impacts are minimized.

2. LITERATURE REVIEW

2.1 Introduction

As the technology develops, environmental pollution is also increasing at a higher rate. While world is moving towards the green concept, electrified transportation plays a dominant role in reducing greenhouse gas emission and fuel oil dependency. One of the best solutions is Plug-in Electric Vehicle (PEV), which utilizes stored electricity in its battery. PEV technology is also growing with time while increasing the popularity. Although PEVs bring an attractive prospect in the fields of environmental, energy and transportation, it also causes a lot of problems in power grid's security and stability. As higher penetration of PEVs have greater impact on electric grid and PEV has increasingly become a hot spot in worldwide research field. Governments of many countries such as China, USA, Japan, and Norway are also promoting the green vehicles such as PEVs. While the demand of PEVs is growing, the impacts on electric gird will also be significant. Therefore, many researches have been carried out to investigate the impacts on electric grid prior to the higher penetration of PEVs.

Uncertainties on data availability concerning PEV penetration, battery charging typologies, geographical PEV concentration and drivers' habits make it difficult to foresee and to estimate PEV impact on electric distribution networks. However, many researches have been carried out based on several cities which have high PEV penetration [3], [4]. Most of the work is concentrated on discussing the effects of higher levels of PEV penetration on power networks with the concern on enhanced power flows in distribution lines and cables, transformer overloads, voltage drops at distant nodes, phase unbalances and harmonic distortions. On the other hand, possible consequences are increment of losses, reduction of equipment life, need for capacity increments, adequate monitoring and preventive maintenance. To study the effects on electric grid, several distribution network models such as Cigré LV network [5], typical distribution feeder of each country [3], [4] are considered. Few common hypotheses can be identified. Most of the researches concerns about the uncoordinated charging during night peak time. Several PEV penetration levels

(5%, 10%, 20%, and 30%) are considered based on the number of users and the total load, and PEV charging is modeled as constant power load [5].

2.2 General Overview of Plug-in Electric Vehicles

An Electric Vehicle is an automobile that is propelled by one or more electric motors, using electrical energy stored in rechargeable batteries or another energy storage device. Electric motors give electric cars instant torque, creating strong and smooth acceleration [6]. There are three types of Electric vehicles:

- Hybrid Electric Vehicle (HEV) – A vehicle which is powered by conventional or alternative fuels as well as electrical energy stored in a battery is called Hybrid Electric Vehicle. The battery is charged through regenerative braking and the internal combustion engine or other propulsion source and is not plugged in to charge.
- Plug-in Hybrid Vehicle (PHEV) – A vehicle which is powered by conventional or alternative fuel and electrical energy stored in a battery is called Plug-in Hybrid Vehicle. PHEV can be plugged into an electrical power source to charge the battery in addition to charge through regenerative braking and internal combustion engine or other propulsion source. PHEVs primarily rely on the battery, and the Internal Combustion Engine (ICE) is used only when battery is mostly depleted, during rapid acceleration or high speeds, or for climate control. Typically, the battery of a PHEV has a driving range of 10 to 40 miles in addition to the ICE. When relying solely on the battery, the PHEV produces no tailpipe emissions. The ICE of a PHEV also produces less emission than conventional vehicles, and is more efficient in its fuel usage.
- Battery Electric Vehicle (BEV) – A vehicle which is powered solely by electrical energy sored in a rechargeable battery is called a Battery Electric Vehicle. Battery is charged by plugging into an electrical power source or through regenerative braking. It does not produce any tailpipe emission but lower full charge range compared to a full tank range of a conventional ICE

vehicle. Typically, a fully charged EV of 25kWh battery capacity has a range of 70 to 90 miles, depending on driving habits and conditions.

Both Plug-in Hybrid Vehicle (PHEV) and Battery Electric Vehicle (BEV) are commonly known as Plug-in Electric Vehicles (PEVs) due to the common characteristics of them. But conventional Hybrid vehicle is not considered as a PEV as it cannot be charged by plugging into an electric power source. In this research study, PEV term is intentionally used to talk about the all-electric car that is BEV. With a non-polluting method of electricity generation, the entire electrification process can be considered as no emission. Most popular PEVs in worldwide is listed in Table 2.1 [7].

Table 2.1: Popular PEV models in the world

Type	**Motor Capacity**	**Battery**	**Charging**	**Range**	**Max. speed**
Nissan Leaf	80kW AC Synchronous Motor	24kWh Li-ion Battery	3.3kW(6.6kW) Charger 230V,15A for 6 hours	150km	144km/h
BMW i3	125kW AC Synchronous Motor	18.8kWh Li-ion Battery		200km	150km/h
Mitsubishi MIEV	49kW AC Synchronous Motor	16kWh Li-ion Battery	240V,15A for 6 hours	160km	130km/h
Tesla S Model	423.6kW AC Induction Motor	70/85kWh Li-ion Battery	10kW on board charger 85-265 V,1-40 A	390km/ 426km	155km/h
Volkswagen e-Golf	85kW AC Synchronous Motor	24.2kWh Li-ion Battery		150km	140km/h
Mitsubishi Outlander	120kW AC Synchronous Motor	12kWh Li-ion Battery	230V,15A for 5 hours	60km	170km/h

2.3 Plug-in Electric Vehicle Technology

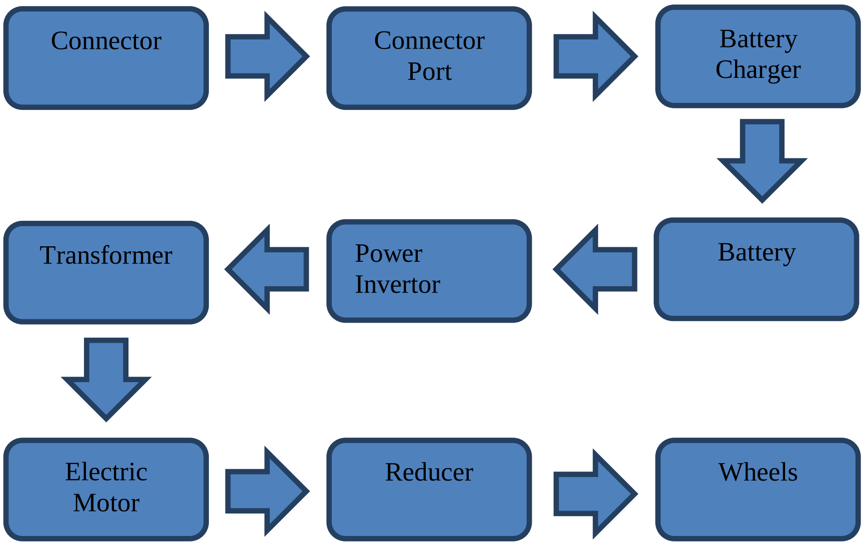


Figure 2:1: Components of a PEV

Operational aspect of electric cars is very stimulating. Almost all the components are same as those in other type of cars other than the engine. One of the major true differences between the ICEV and the PEV is the electric motor. Most of the PEV are employed with AC synchronous motors. Several types of rechargeable batteries like, Lithium ion, Lead acid and Nickel metal hydride batteries are employed in PEVs. Among them Lithium ion batteries give the best performances, higher range, light weight but higher in cost.

The three key components of an electric car are Electric motor, Controller and Battery [8]. PEV is powered by plugging it into an electric source via the connector. The onboard charger in the vehicle convert single phase 230 V AC into 400 V DC and feed the rechargeable battery. When the user switches on the car, the current is passed from the battery. The controller takes power from the battery and passes it on to the electric motor. Before passing the current to motor, the inverter converts the 400V DC into a maximum of 400 V AC, which is suitable for powering the motor. The electric motor then converts electrical energy to mechanical energy [9]. The mechanical energy moves the vehicle forward. Energy flow of the PEV is shown in Figure 2.1.

As the electric car moves, the forward momentum generated by electric motor can be used to charge the batteries when you apply the brakes. This is a phenomenon commonly referred to as regenerative braking and can recover up to about 15% of used energy for acceleration [8]. This is done by applying generated momentum in braking process to the car batteries. Even though this is effective, it does not sufficient to recharge the car fully. However regenerative braking contributes to the high efficiency of the electric vehicles in particular in city traffic. In addition, the wear of the vehicle brakes is reduced by the regenerative braking system.

2.3.1 PEV charging

PEV is charged by connecting PEV to an external electric source via Electric Vehicle Supply Equipment (EVSE). EVSE ensures that electric vehicles are safely charged to the appropriate battery capacity.

There are three charging topologies. Comparison of three charging topologies is summarized in the Table 2.2 [10] and Level 1, 2 and 3 EVSEs are shown in Table 2.3 [11] [12] [13]. Several domestic socket outlets which used for Level 1 charging are shown in Figure 2.2 [14]. PEVs are consisted of various types of connectors. Some connectors are specific to each country. Thus, it is a dilemma to interface PEVs with the electricity network because some models of PEV are consisted with special connectors such as Tesla.

Figure 2:2: Domestic socket outlets used for level 1 charging [14]

Table 2.2: Charging Topologies

Level	Voltage source	Amperage	Voltage	Power	Connector	Time	Range per hour of charging
Level 1	Single phase AC	12-16A	120V	1.3-1.9kW	J1772 standard connector	8-10 hours	3- 8 km
Level 2	Single phase AC	Up to 80A	208-240V	Up to 19.2kW	J1772 standard connector	6-8 hours	16-32 km
Level 3	DC	Up to 200A	208-600V	50-150 kW	Most of the fast chargers CHAdeMO standard connector	30 mins	96-128 km

Table 2.3: EVSE for various charging topologies

Level 1charging [11]	
Level 2 charging [12]	
DC fast charging [13]	

2.3.2 Charging characteristics

- Constant voltage charging

Power is supplied from an AC source via a combination of a rectifier and a step down transformer to provide the DC constant voltage for charging the battery [14]. When the constant voltage is applied current flows into the battery and very high current will flow at the beginning in case of fully discharged battery. The Lead acid cells employed in car batteries and backup power systems are generally used constant voltage chargers. Moreover, Lithium-ion cells often use constant voltage systems, but with higher complex circuitry in order to protect both the batteries and the user [14]. The variation of voltage and current during constant voltage charging process is shown in Figure 2.3.

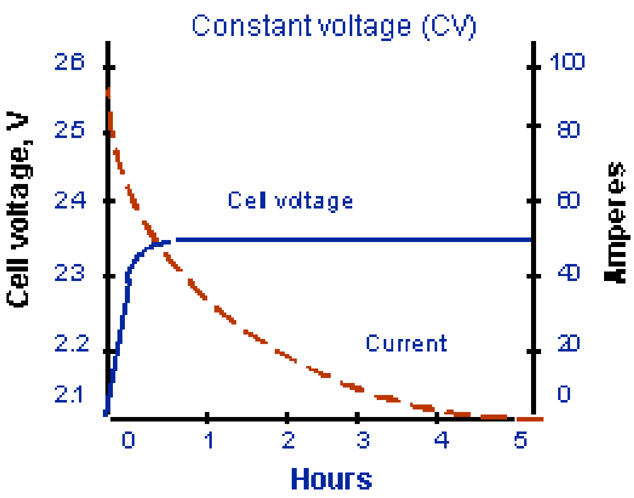


Figure 2:3: Constant voltage charging characteristic [15]

- Constant current charging

In this type of charging voltage applied to the battery is varied to maintain the constant current flow. Charging is terminated when the voltage reaches the level of a full charge. This method is usually applied for Nickel-cadmium and Nickel-metal hydride batteries [15].

- Stage charging

This is a combination of constant current and constant voltage charging. Charging cycle starts with a constant high current until the voltage reach its set value and then changes to constant voltage mode. This design avoids the high current at the beginning of constant voltage charging, and overcharging at the later stage of the constant current charging. Variation of voltage and current during stage charging process is shown in Figure 2.4. This is the most sophisticated charging method used in most common fast chargers which increases life of the battery by reducing the heat during charging cycle. Moreover stage charging leans towards to increase the battery performance [15].

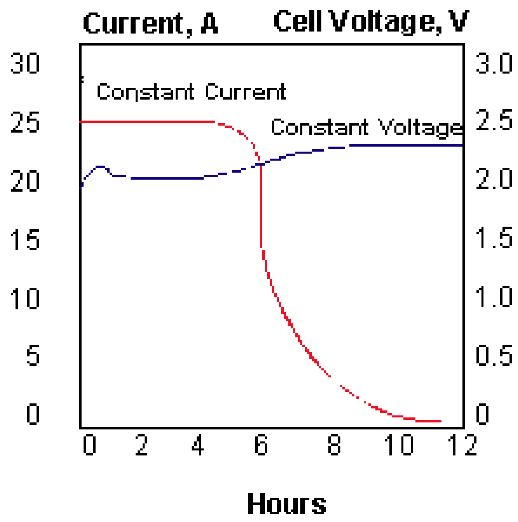


Figure 2:4: Stage charging characteristics [15]

- Pulse charging

Being one of the advanced charging methods, very high current pulses are applied until the voltage reaches to its set value. The charging rate can be varied by controlling the width of the pulses. During the charging process, there are short rest periods of 20 ms to 30 ms to allow the chemical actions in the battery to stabilize by equalizing the reaction throughout the bulk of the electrode before resuming the charge [6]. Furthermore, this method can reduce unwanted chemical reactions at the electrode surfaces such as gas formation. The major advantage of pulse charging is the significant heat reduction which allows the charger to operate at high voltage rate even when the battery is almost full. In addition, reduction of heat results in higher energy efficiency. Hence, pulse charging can reduce charging time considerably [15]. Pulse variation during pulse charging process is shown in Figure 2.5.

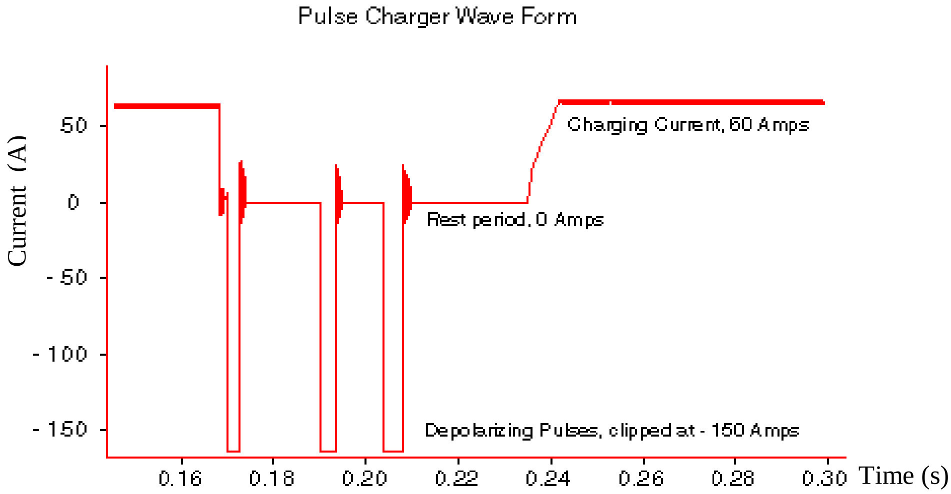
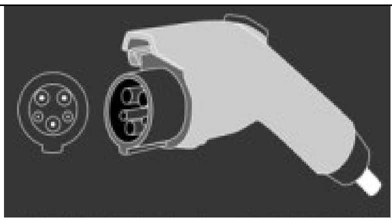


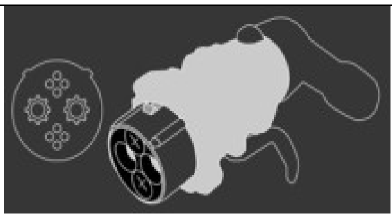
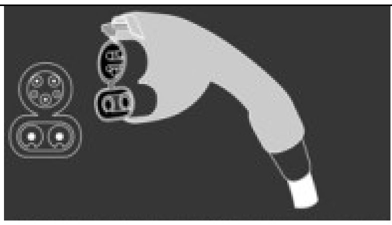
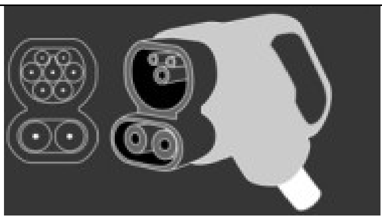
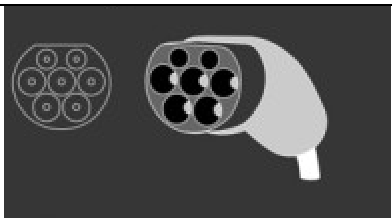
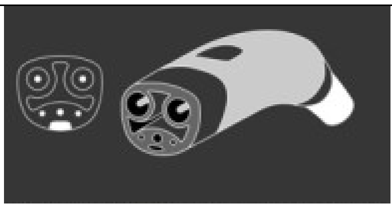
Figure 2:5: Pulse charging characteristics [15]

2.3.3 Connector types

There are various types of charging connectors employed in different models of PEVs. Common connector types and their usage are summarized in Table 2.4 [16] [17]. Other than the standards listed in Table 2.4, China proposes a specific standard GB/T 20234 and Italy uses IEC 62196 Type 3. Tesla models are charged from a specific supercharger unless otherwise they require expensive adapters to charge. This is an obstacle for implementing charging points because different PEV models use different charging standards and connectors.

Table 2.4: Commonly used connector types and standards

Standard	PEV Port & Connector	Countries	PEVs
SAE J1772	 Single Phase • 120V / 230V • 19 kW Maximum	Japan, USA, Australia, Korea [14]	Nissan Leaf Mitsubishi i-MiEV KIA Soul EV

Standard	PEV Port & Connector	Countries	PEVs
CHAdeMO Communication CAN	 DC 500V • 60 kW maximum	Japan	Nissan Leaf, Mitsubishi i-MiEV, Kia Soul EV
SAE J1772 Combo 1 Communication PLC	 DC 200V – 600V • 125 kW maximum	USA, Germany	GM Chevrolet Spark EV
CCS Combo 2 Communication PLC IEEE P1901	 DC 200V to 850V • 170kW Max	USA, Germany	BMW i3 BMW i8
IEC 62196 Type 2 Mennekes	 3 phase / Single phase • 250V to 400V • 22kW Maximum	European union, Australia	BMW i3 BMW i8
Tesla	 Single/Three Phase • 110V / 250V / 450V • 48 kW Maximum		Tesla Model S Tesla Model X

2.4 Pros and Cons of Plug-in Electric Vehicles

PEV has several advantages and disadvantages when comparing with ICE vehicle when considering environmental, operational, economical aspects.

2.4.1 Benefits

- Zero tailpipe emission

As PEV is powered by the electric energy stored in its battery, it does not emit any greenhouse gas. With a strong grid mix of renewables such as hydro, wind and solar or for electric car drivers with home solar, the emissions benefits are dramatic. Average weight of CO_2 emitted per kWh of electricity generated is 0.6993 kg [18] while average weight of CO_2 emitted per liter of gasoline burnt is 2.3 kg [19]. According to the above data, percentage reduction of CO_2 emission from ICEV to PEV is 34.5% [20]. Thus replacing ICEVs with PEVs will cause to 34.5% annual reduction of CO_2 emission [20]. Even though the electricity is generated from burnt fossil fuels, PEV is environmental friendlier than a conventional ICEV. It has been predicted that higher PEV penetration will reduce carbon dioxide emissions by 30% in U.S.A, 40% in UK, 19% in China [21] with the current energy mix.

- Smooth riding

An electric car is very quiet and very smooth. A gearless or single gear design in some PEVs eliminates the need for gear shifting, giving such vehicles both smoother acceleration and smoother braking. Because the torque of an electric motor is a function of current, not rotational speed, electric vehicles have a high torque over a larger range of speeds during acceleration, as compared to an internal combustion engine. As there is no delay in developing torque in PEVs, drivers report generally high satisfaction with acceleration. For example, the Tesla Roadster prototype can reach 100 km/h (62 mph) in 4 seconds with a motor rated at 185 kW (248 hp) [21].

- Less maintenance

PEVs are consist of fewer moving parts, fewer fluids to change, regenerative braking which reduces brake wear and generally electrical system (battery, motor and associated electronics). Hence, PEVs require less maintenance than a conventional ICEV. The batteries in PEVs are generally designed to last for the expected lifetime of the vehicle. Nissan Leaf offers 8-year/100,000 mile warranty for their batteries [22].

- Home recharging

PEVs can be recharged at home without reaching a filling station. Owner need to park it in the garage and plug it into a wall socket. It is very convenient to daily travelers because when they wake up the next morning, and they have a car ready to go another 80 to 100 miles depending on the model. That is plenty for everybody except long travelers.

- Low operational cost

The cost to recharging an electric car can also be a fraction of the cost of refueling a conventional ICEV with gasoline. PEV has a considerable efficiency compared to internal combustion models. Depending on how they're driven, today's light-duty PEVs can exceed 100 mpge and can drive 100 miles consuming only 25-40 kWh [23]. Average mileage of a Nissan Leaf per full charge is 84 miles [22]. Fuel economy of a similar size ICEV is 12km per liter of gasoline [20]. Cost saving per km is Rs.5.26 according to Sri Lankan context (See Appendix I). Fuel cost will be zero when PEV is used along with Solar PV generation.

- Energy efficiency

Increased energy efficiency is a primary advantage of a PEV as compared to one powered by an internal combustion engine. Vehicles powered by internal combustion engines operate by converting energy stored in fossil fuels to mechanical energy through the use of a heat engine. Heat engines operate with very low efficiencies because heat cannot be converted directly into mechanical energy. Electric vehicles convert stored electric potential into mechanical energy. Electricity can be converted into mechanical energy at very high efficiencies. The greater efficiency of electric vehicles is primarily because most energy in a gasoline-powered vehicle is released as waste heat.

- Safety

PEV battery packs are encased in sealed shells and meet testing standards that subject batteries to conditions such as overcharge, vibration, extreme temperatures, short circuit, humidity, fire, collision, and water immersion. Manufacturers design these vehicles with insulated high-voltage lines and safety features that deactivate the electrical system when they detect a collision or short circuit. PEVs tend to have a lower center of gravity than conventional vehicles, making them more stable and less likely to roll over. Emergency response for electric drive vehicles is not significantly different from conventional vehicles. Electric drive vehicles are designed with cutoff switches to isolate the battery and disable the electric system, and all high-voltage power lines are colored orange [9].

2.4.2 Considerations

- Range anxiety

Fear of battery running out of energy before reaching the destination called the "Range Anxiety". This term is always associated with PEVs due to most affordable electric cars only have about 80 to 100 miles of range, and take hours to fully refuel. But 100 miles range is plenty for most day-to-day driving.

- Longer recharging time

Generally a PEV takes about 6-8 hours to charge the battery fully [24]. Thus PEV must be charged over the night. Fully charged PEV can run about 125 km. PEVs commonly can add about 32 km of range in an hour of charging from a 240-volt source of electricity [10]. Since PEV cannot be refueled in 5 to 10 minutes as refueling an ICEV, longer road trips are not advisable.

- Less availability of charging infrastructure

Charging facility is very rare compared to conventional filling station. Conventional filling stations are available in 5 km range but charging facilities are not so common at the moment. There are about 100 charging points are located in island wide in Sri

Lanka. On the other hand charging points are concentrated to mostly to Western and Southern provinces [25].

- Higher cost of ownership

Although fuel costs for PEVs are generally lower cost of ownership can be significantly higher. However, prices are likely to decrease as production volumes increase and initial costs can be offset by fuel cost savings, tax credits, and state incentives. Cost of ownership of a moderate capacity PEV is around 3 to 4 million rupees in Sri Lanka. Sri Lankan government gives tax credits for PEVs less than 100 kW motor to promote environmental friendly vehicle among Sri Lankans [27].

- Hazard to pedestrians

PEVs produced much less roadway noise as compared to vehicles propelled by an ICE. However, the reduced noise level from electric engines may not be beneficial for all road users, as blind people or the visually-impaired consider the noise of combustion engines a helpful aid while crossing streets, hence PEVs could pose an unexpected hazard. Some models of PEVs are consist with an electric warning sound, so that blind people, other pedestrians and cyclists can hear them coming and detect from which direction they are approaching [21].

- Cost of recharging infrastructure facilities

Level 2 chargers can be mounted on wall for home charging or commercial charging. Its cost is not very much higher but the cost of establishing DC fast charger is higher as well as the cost of ownership. A dedicated transformer must be allocated for a DC fast charger. Total expense for establishing a DC fast charger would be about 4.5 million rupees. There must be good revenue to cover the higher capital cost. If there is low level of concentration of PEVs in the particular area, establishing a DC fast charger would be a loss.

2.5 Anticipated Effects on Distribution Network

Larger penetration of PEVs may leads to several issues on existing power grid. Those anticipated effects on distribution network are discussed under this section.

- Increasing night peak demand

Most of the studies have been carried out for PEV charging during the peak hour condition. Without extra information and benefits from the utilities, PEV users tend to charge their vehicle as soon as they reach home, and hence it coincides with the daily night peak. This is known as uncoordinated charging. It has revealed that increasing penetration of PEVs will cause a steeper rise in the night peak demand [5], [28].

- Violation of voltage regulation limits

Significant amount of power losses and voltage deviations can be induced by wide adoption of PEVs. Voltage profiles of distribution feeders were analyzed to identify the effects of various percentages of PEV penetration levels [28] and connecting arrangements. Those studies reveal that voltage of each node is decreased with the increasing PEV penetration level [28], [29], [30]. One of the severe issues is voltage drops below the regulation limits at distant nodes of distribution feeder with the higher penetration levels such as 20%, 30% [5], [28], [29]. Different nodes of distribution feeder models have different PEV accommodation capabilities. Generally a node closer to the distribution transformer is able to support larger number of PEVs while the remote nodes can accommodate less since the higher voltage drop and the power losses during the long distance power delivery [29].

- Transformer overloading and degradation

PEV utilizes electricity which is approximately three times a typical house uses once plugged. When the number of PEVs per customer increases, transformer loading is proportionally increases. But, the percentage of overloading is lesser when the PEVs are charged during off-peak hours [28].

Due to the transformer overloading, aging of transformer increases and it varies with the charging topologies. For example percentage of transformer aging is 1.05% at 120 V peak-charging while it is 1.72% at 240 V peak-charging of one PEV for a 25 kVA transformer. Transformer aging depends on the peak/ off-peak charging as overloading of the transformer is most probable if peak-charging of PEVs is adopted [28].

- Voltage unbalance

Single phase on-board chargers are more common in the market for PEVs with battery capacity less than 100 kWh. Thus most of the PEV users charge their vehicle at the home via a normal socket outlet. It draws about 16 A current at 240 V AC. PEV is a larger single phase domestic load. Hence, uncoordinated single phase PEV charging causes unequal load distribution among three phases making phase unbalances. The voltage unbalance in distribution feeders, created by the higher penetration of PEVs is expected to be a significant power quality problem. Higher number of PEVs led to higher phase diversity. Hence, higher the number of PEVs switched at the same moment lesser the current unbalance. But, in [28] it has shown that both high and low diversity of PEV charging can maintain the voltage unbalance within the regulation limits. When the natural unbalance is considered as 1%, percent voltage unbalance may exceed the regulation limit of 2% for both only one phase charging and random phase charging as shown in [30]. It has also revealed that the voltage unbalance is prone to occur at the beginning and end of single phase charging process of higher number of PEVs as they are plugging in and out at different times [30].

- Increased losses

PEV injection causes additional losses in the distribution network. PEV charging draws higher current with respect to conventional household load. High current flow along power lines leads to increased line losses. Simulation results have shown that losses tend to increase proportionally with rising PEV penetration and are significantly affected by charging time and the charging level [28]. Peak charging causes more losses than off-peak charging as shown in [28].

- Harmonic distortion

With the increasing popularity on using PEVs, the development of charging infrastructure is accelerated. Battery chargers are not like ordinary inductive or capacitive load, they are non-liner loads due to the presence of power semiconductors such as diodes or SCRs. As sinusoidal voltage waveform apply pressure on non-linear loads, hence fundamental current waveform distorted and harmonic will be generated. Total current harmonic distortion is dependent on the charging algorithm, which may range from 5% to 100% [31]. Without appropriate compensation, such harmonic current distortion causes serious problems on the system stability. When a large population of PEVs is adopted, consequent harmonics impact to the power system expected to be serious. Due to the high current, DC fast charging has a considerable impact on the power quality especially at the connection of point [32]. Thus, prior to construction of charging stations harmonic problems need to be properly addressed in order to minimize harmonic propagation along the distribution feeders. It has revealed that odd harmonics such as 5th, 7th, 11th, 13th, 17th, 19th harmonic content is higher and for higher levels of harmonics, the higher the number, the smaller the harmonic amplitude [33]. Fast Fourier Transform (FFT) analysis of current waveform of a 9 kW three phase charger shows that the amplitude of the current total harmonic distortion is 6.7% [33]. In [31] it has shown that the THD is a monotonic increasing function of the battery voltage. The maximum and minimum values of THD are found to be 30.6% to 25.8% respectively [31]. In [31], it has shown that how THD decreases as the number of PEVs being charged per station increases and it converges to 25.1%. Furthermore the simulation results also imply that several nearby chargers, which are originally design for one or two PEVs, should be grouped together and connected to the same bus, so that the harmonic distortion can minimized. Integrating PV solar system can be applied to compensate the harmonic generated due to the DC fast charging of PEVs as proposed in [32]. Solar PV system acts as an active filter and minimizes the THD from 12.2% to 4.1% in a harmless manner [32].

2.6 Vehicles-to-Grid Technology

PEV not only draw power from the grid, it also delivers the stored energy in the batteries back to the electric grid during idle times. It is referred as Vehicle to Grid (V2G) concept [34]. To enable V2G technology there should be a connection to the grid for power flow, control or logical connection necessary for communication with the operator, and controls and metering on-board vehicle. V2G technology can be beneficial to the grid in three aspects.

- Demand management

V2G technology can be used to peak power generation. Typically peak power is very expensive and generated by power plants which can be switched on for short periods. Higher PEV penetration could reduce the peak power generated at higher cost by delivering the power of the V2G batteries available on the system. The amount of peak power shaving is depended on the penetration level and the availability of the capacity. Besides that, PEVs can consume power in off-peak period to reduce daily peak and valley load. Simulation results in [34] have shown that how PEVs can contribute for peak load shaving and valley filling of the daily load profile of central China. The maximum power load of peak day has decreased to 169,000 MW from 180,000 MW, and the minimum load has increased to 130,000 MW from 115,000 MW [34].

- Spinning reserve

Spinning reserves refer to additional generating capacity that can provide power generally within 10 minutes, to make up generation failure cases. Generators providing spinning reserves run at low or partial speed and thus are already synchronized to the grid. Although the spinning reserves are the highest value component of the power generation chain, they are only used about ten times a year with an average duration of ten minutes. These properties are favorable for PEVs, since they are “spinning” for many hours as long as being plugged in to grid, and they can generate power with their batteries’ electricity storage, or so called smart storage. Amount of smart storage also depend on the penetration level and the availability of PEVs which are connected to grid. It has shown in [28] that a

PEV penetration of 0.4% in Nova Scotia, provides a battery capacity of 54 MWh and that could maintain the entire provincial spinning reserve capacity of approximate 36 MW [28].

- Regulation service

Regulation is used to regulate the grid frequency by matching generation to load demand. Regulation must be under direct real-time control of the grid operator, with the generating unit capable to receive operation signals and respond within a minute or less by increasing or decreasing its output power. With the function of smart storage, PEV can discharge power to grid when the frequency of the grid is low and charge power when the frequency is high. With control upon battery charging current, aggregated vehicles can follow regulation signals [35].

- Integration of renewable energy

The most important role of V2G may ultimately be in emerging power markets to support renewable energy. The two main largest renewable sources available, photovoltaic (PV) and wind turbines are both intermittent. At low levels of penetration, the intermittency of renewable energy can be handled by existing mechanisms for managing load and supply fluctuations. However, as renewable energy exceeds 10% of the power supply, additional resources are needed to match the fluctuating supply to the already fluctuating load. Intermittency can be managed either by backup or storage. “Backup” refers to generators that can be turned on to provide power when the renewable source is insufficient. “Storage” has the advantage of additionally being able to absorb excess power, but adds the constraint that giving back power is duration-limited. PEV has the favorable characteristic. PEV can be used either as “backup” or “storage”. Thus higher penetration of PEVs may leads to higher integration of renewable energy sources. It has shown that frequency deviation is lesser in case of renewable energy source output decreases when it is integrated with smart storage of PEV [28]. Thus PEV smart storage can play a vital role in maximizing the integration of renewable energy sources to the electric grid.

3. GLOBAL AND LOCAL OVERVIEW OF PEV PENETRATION

3.1 PEV Penetration in the world

Global threshold of 2 million PEVs on the road is exceeded by the end of 2016. This is result of great efforts deployed jointly by governments and industry over the past ten years. Figure 3.1 shows evolution of the global PEV sales from 2010 to 2015 [36]. United States was the largest market for PEVs until 2015. But, USA was overtaken by China in 2016 with a plug-in passenger car sale of 351,000 during year 2016 [1]. China has also become home to the strongest global deployment of e-scooters and electric buses.

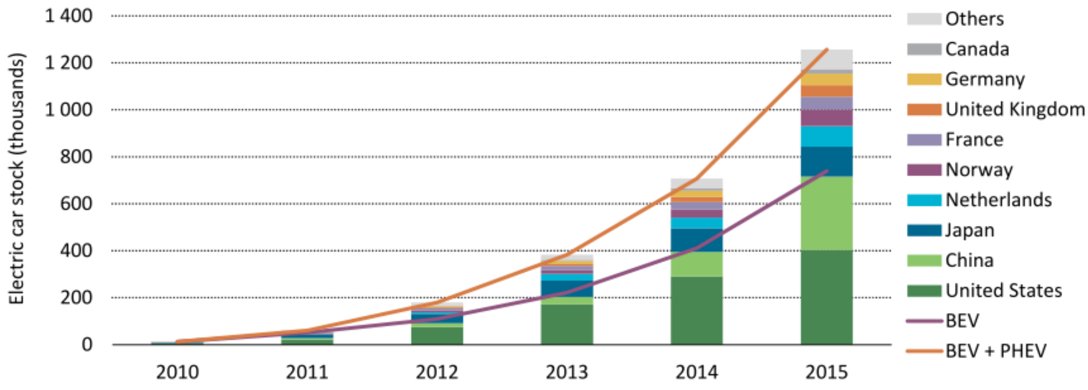


Figure 3:1: Global PEV volume [36]

Growing global PEV sales have been supported by motivated targets and government and industry combined effort. Governments have extended their support by lowering taxes on importing electric vehicle, industries have been developing their technologies to extend the vehicle range thus reducing the consumer barriers for purchasing PEVs in a number of countries. Countries such as USA, United Kingdom, China, Japan, India, Italy, Portugal, South Korea, Spain, Sweden provides rebates on registrations, tax exemptions and waivers on fees (e.g. tolls, parking) to promote PEVs in their countries. Figure 3.2 shows the market share of PHEVs and BEVs along with the amount of purchase incentives provided by several countries in 2015.

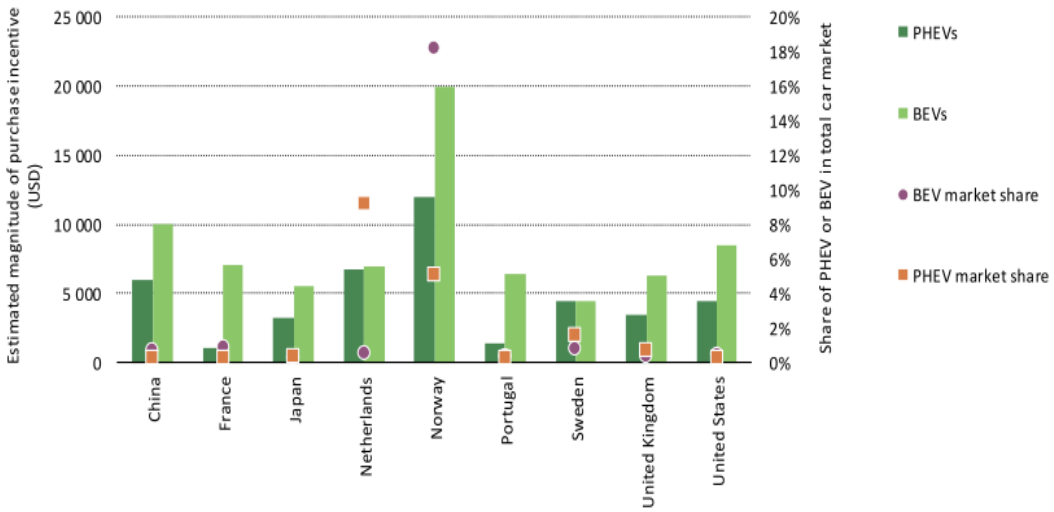


Figure 3:2: PEV purchase incentives in USD in several countries [36]

Substantial new implementation of electric vehicle supply equipment (EVSE) can be observed in 2015, on par with the growth of the global PEV volume. Government policies encourage the implementation of publicly accessible charging infrastructure by direct investing and public-private partnerships. Figure 3.3 shows the total available global EVSE outlets in 2015, reached 1.45 million. The growth of the publicly accessible charging infrastructure was comparable in 2015 (71%) to the growth of the global EV stock (78%). Publicly available fast chargers encountered for 28000, 44% out of that located in China.

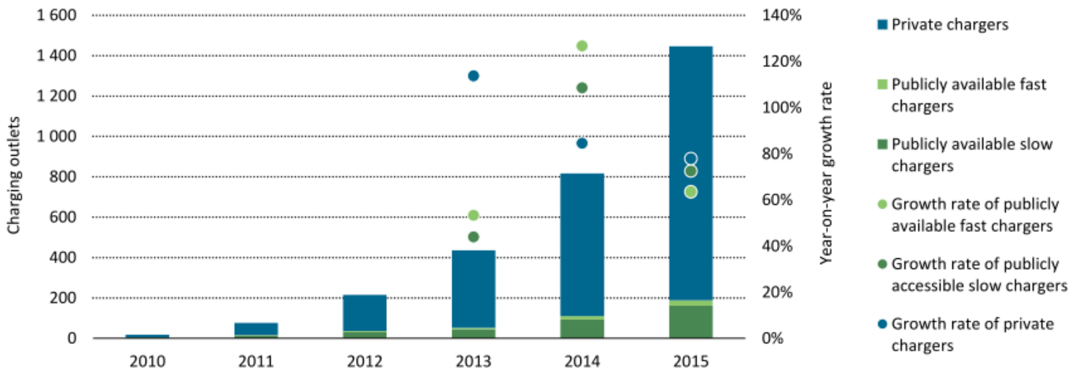


Figure 3:3: Worldwide charging stations [36]

Portland International Airport which has installed 42 Level 1 Power Post PEV charging stations is shown in Figure 3.4 [37]. Therefore people can charge their PEVs during parking time.

Figure 3:4: Portland Airport Level 1 charging station [37]

Further the battery energy density needs to be improved to enable longer range for lower cost. Technological progress and economies of scale are critical to move towards cost parity with ICEVs. PEV manufactures are predicting that range will be exceeding 300 km in near future. Nissan Leaf 2016 model has already reached the range of 270 km [24]. Sekisui Chemical has developed a material that can triple the capacity of lithium ion batteries, allowing electric vehicles to travel about 600 km on a single charge, roughly as far as gasoline-powered cars can go without refilling [26].

Governments support, developing infrastructure and technology lead to growing PEV demand all over the world. This growth can be clearly identified by the global PEV stock growing from 2005 to 2015 as included in Appendix II. The global PEV volume surpassed 2 million in 2016 [1]. It is greater than the estimated value in 2010. The market shares of electric cars rose above 1% in seven countries: Norway, the Netherlands, Sweden, Denmark, France, China and the United Kingdom. Market shares reached 23% in Norway and nearly 10% in the Netherlands as shown in Figure 3.5 [36].

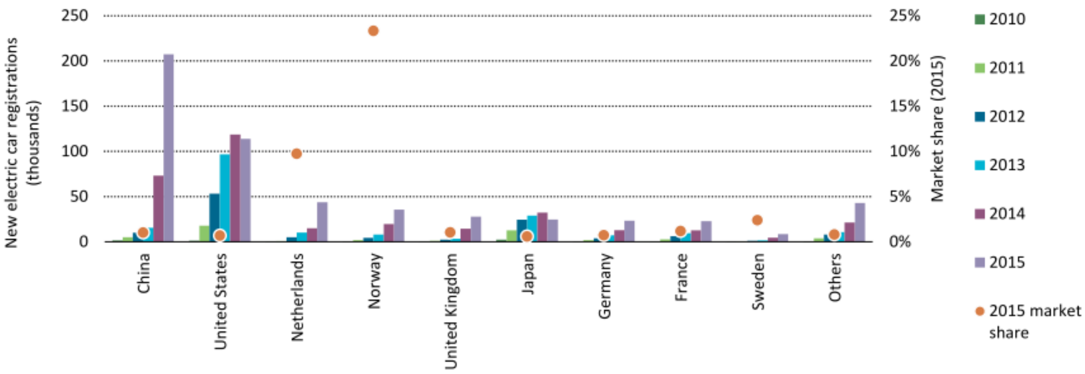


Figure 3:5: Worldwide new PEV registration and Market share [36]

PEVs of all types lie at the heart of future sustainable transport systems. "EVI 20 by 20" target calls for an electric car fleet of 20 million by 2020 globally. The EVI is a multi-government policy forum established in 2009 under the Clean Energy Ministerial (CEM), and they have dedicated to accelerate the deployment of EVs worldwide. The EVI counts 16 member governments as of today (Canada, China, France, Germany, India, Italy, Japan, Korea, the Netherlands, Norway, Portugal, South Africa, Spain, Sweden, the United Kingdom and the United States), representing most of the global PEV stock and including the largest and most rapidly growing PEV markets worldwide. China and the United States are co-chairs of the initiative, and the EVI secretariat is hosted by the IEA. The Paris Declaration on Electro-Mobility and Climate Change and Call to Action sets a global deployment target of 100 million electric cars and 400 million electric 2 and 3 wheelers in 2030 [36].

The climate change related benefits of PEVs can be fully harvested under the condition that their use is coupled with a decarbonized grid, an additional challenge for countries that are largely dependent on fossil fuels for power generation. The efficiency of PEVs is also well suited to deliver climate change-related benefits, but GHG emission savings can be maximized only once PEVs are coupled with a low-carbon power generation mix. Investment in PEV roll-out can support this transition, e.g. increasing the opportunities available to integrate variable renewable energy. Early PEV adoption also brings other immediate benefits such as air quality improvements and reduced noise.

3.2 PEV Penetration in Sri Lanka

PEVs are becoming popular among Sri Lankans since 2014. Most of the countries have their own targets to increase the electric mobility. Ministry of power and energy has planned to make 10% of road transportation to be powered by electricity by 2020 [2].

Initially, 90 of PEVs were registered in the Department of Motor Traffic during year 2014 [38]. Although very deliberate growth was shown at the beginning, with the importing tax reduction to 5% by the interim budget in 2015, registrations of PEVs were increased gradually as shown in Figure 3.6 and Table 3.1. While the Nissan Leaf is the most popular model of electric cars registered so far, few Tesla cars being registered in Sri Lanka as well. In overall, 3.1% of total vehicles registered in 2015 are BEVs [38]. All PEVs (combination of all electric vehicles and plug-in hybrid vehicles) registered in 2015 are 42% of total vehicle registration. Total vehicle registration categorized into fuel types can be shown in Figure 3.7. Total vehicle registration in 2014 & 2015 are included in Appendix III [38].

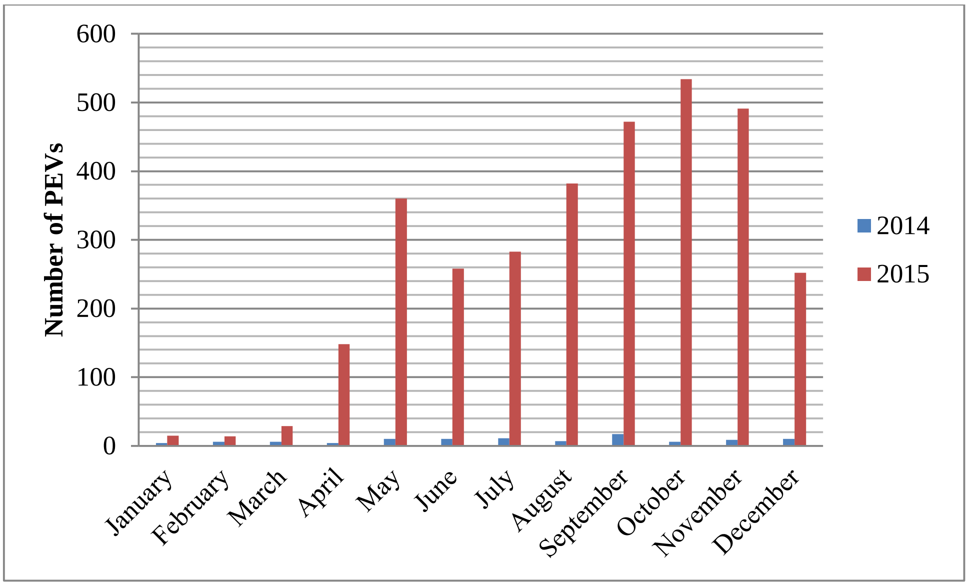


Figure 3:6: New PEV registrations in Sri Lanka in 2014 and 2015

Table 3.1: New PEV registrations in Sri Lanka in 2014 and 2015

Month	2014	2015
January	4	15
February	6	14
March	6	29
April	4	148
May	10	360
June	10	258
July	11	283
August	7	382
September	17	472
October	6	**534**
November	9	491
December	10	252
Total	**100**	**3238**

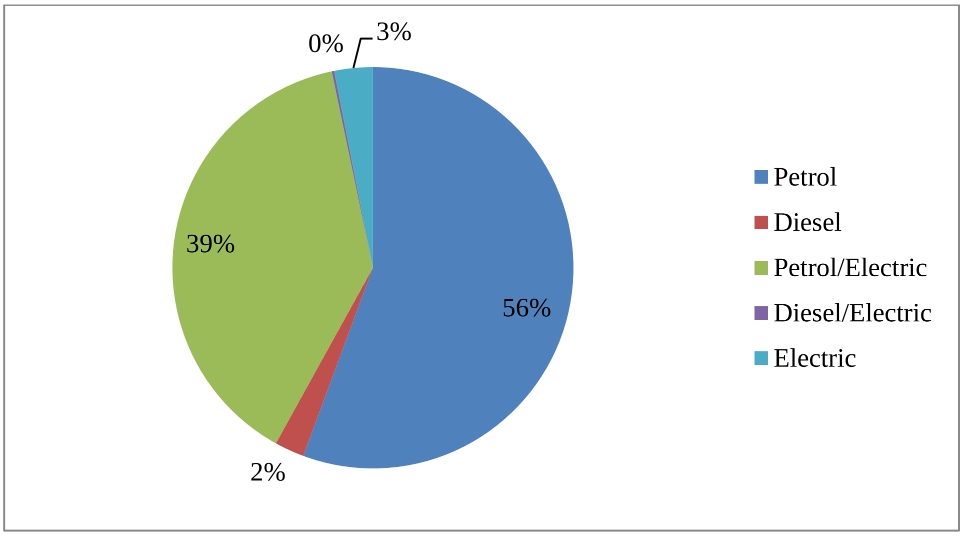


Figure 3:7: New vehicle registrations in Sri Lanka 2015 - Fuel type categorization

3.3 Initiatives for PEV integration in Sri Lanka

Customs duty on electric vehicles with motor capacity less than 100 kW has been reduced. Therefore, the customs duty of Rs.2.9 million on a Nissan Leaf electric vehicle would be reduced to Rs.1.7 million [27]. People are showing a keen interest in electric motor cars, which are environmental friendly and economically viable.

Power and Energy Ministry, Ceylon Electricity Board, Wasana Trading Lanka (Pvt) Limited are get together and have taken several steps to establish about 100 charging stations island wide [25]. However, most of them are concentrated on Western and Sothern provinces as shown in Appendix IV.

CEB has promoted a new time of use tariff system for three phase domestic consumers having 30A or above supply connections [39]. PEV users who are supplied with three phase 30A electricity connection, can be switched to the new time of use tariff system and experience low rate of Rs.13.00 for off peak (22:30 – 05:30hrs) PEV charging. Level 2 commercial charging is charged under the industrial tariff category [40].

Figure 3:8: Vega super electric car

Most of the PEV users are professionals because of its environmental friendliness. Greater attraction to PEV can be perceived by entering to the field of manufacturing PEVs. Sri Lankan company called CodeGen, has already manufactured a super electric car known as Vega. Vega has designed, developed and test for the drive. But it has not started commercial manufacturing yet. It is a high performance super car which costs about 20 million [41]. Their intention is to manufacture 20-30 cars per year for the niche market that wants a unique super car that no one else has. Vega shown in Figure 3.8 competes with PEV model like Rimac, Tesla. They have manufactured this super electric car as an indication of their capability of manufacturing. They can easily manufacture low capacity PEVs such as bikes, three-wheelers motor cars. Their primary goal was to inspire to nation on innovations.

CodeGen also developed a web based clouded network called chargeNET, to interconnect the charging points located in island wide. PEV users can obtain the membership of chargeNET. Membership card is shown in Figure 3.9. They can use their membership card to charge their PEVs at a lower rate (Rs.125/= per hour charging) than non-members (Rs.200/- per hour of charging) [42] [43]. Remote monitoring of chargers, authentication of members can be performed through the chargeNET. ChargeNET mobile app is very useful for PEV users to find a charging station, their availability, turn on/off charging remotely and balance home electricity usage with the use of inbuilt energy usage and reports [41]. ChargeNET mobile app interface is shown in Figure 3.10. Sri Lankan charging network's geographical distribution is shown in Figure 3.11 [43].

Figure 3:9: chargeNET membership card [43]

Figure 3:10: chargeNET mobile application [43]

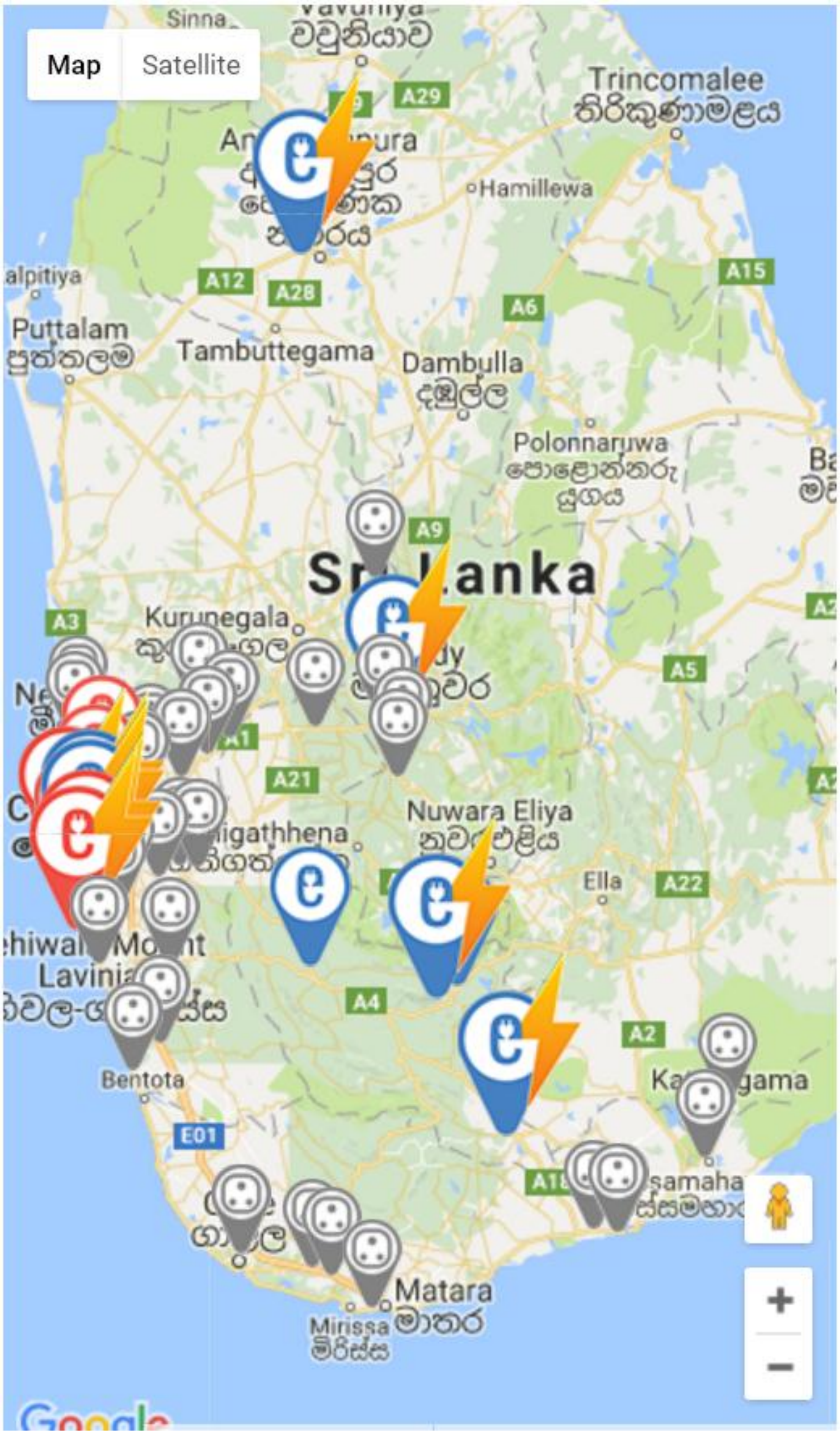


Figure 3:11: chargeNET map [43]

In chargeNET map, charging stations indicated in red colour are in use. Blue colour charging stations are available for charging. Charging stations illustrated with grey colour must be contacted to check the availability.

4. IMPACTS OF INCREASING PEVS ON MV DISTRIBUTION NETWORK

4.1 Introduction

Increasing demand for PEVs will lead to create considerable impact on power distribution network. A reliable data requirement is essential in comprehensive system studies to investigate the level of those impacts. IEEE 33 node test feeder is modeled using PSCAD power system simulation software to analyze the effects of PEV integration on voltage profile and harmonics of MV distribution network. Impacts due to residential PEV charging are summarized in Section 4.2. In Section 4.3, DC fast charger is modeled using PSCAD and adopted it to IEEE 33 test network in order to analyze the impacts due to DC fast charging of PEVs.

4.2 Analysis of IEEE 33 network with Residential PEV charging

With the aim of achieving generalized results, IEEE 33 node test feeder is modeled and analyzed under several scenarios, instead of modeling a specific feeder of the Sri Lankan power system. The data used for the modeling IEEE 33 node test feeder is tabulated in Appendix V [29]. Graphical representation of IEEE 33 node test feeder is shown in Figure 4.1. The analysis is done under the following assumptions:

- Loads are balanced three phase, constant power loads during the night peak of the day.
- The base voltage of IEEE 33 node test feeder is 12.66 kV. Therefore, infinite source of 12.66 kV is used and the voltage of the source end is kept at 1.04 pu in order to maintain the voltage of the farthest node within the regulation limit.
- Resistor and inductor are used to represent the line resistance and reactance respectively.
- Nissan Leaf is one of the most popular PEVs. Its charging power is 3.3 kW [22]. Therefore, PEV load is assumed as 3.3 kW constant power load [44].

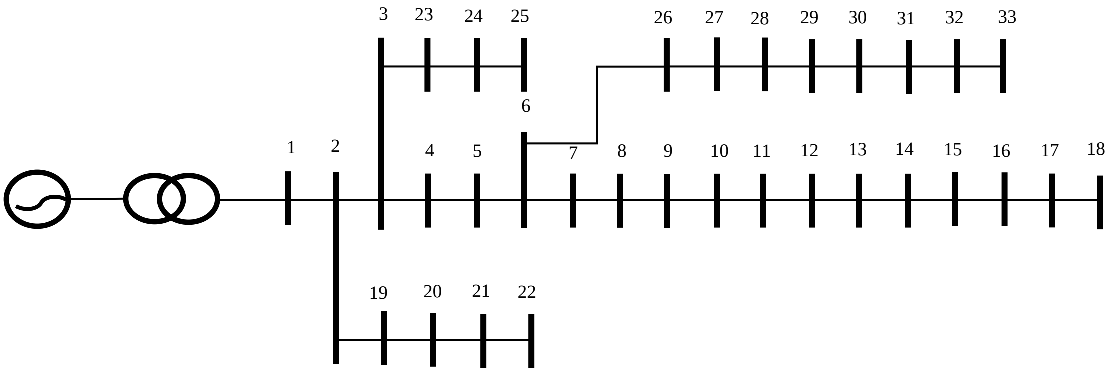


Figure 4:1: IEEE 33 node test feeder

4.2.1 Impact on voltage profile due to residential PEV charging

Each node of IEEE 33 node test feeder represents 12.66/ 0.4kV distribution transformer. PEV load is a large load compared to household load which lasts for 6 to 8 hours. Each PEV connected to the network is assumed as single phase 3.3 kW constant power load [44] of unity power factor. It is assumed that PEVs are charged during night peak (as soon as the users return their homes). PEV load of each node is connected through a distribution transformer. Modeled IEEE 33 node test feeder is simulated in PSCAD under below listed scenarios to obtain the results for voltage profile. PEV load is not equally distributed among each node. It is assumed that the number of PEVs connected to each node is corresponds to their base loads.

- Case 1- Residential PEV load connected to each node is 10% of its total load
- Case 2- Residential PEV load connected to each node is 15% of its total load
- Case 3- Residential PEV load connected to each node is 20% of its total load

The number of PEVs connected to each node for each case is shown in Table 4.1.

Table 4.1: Number of PEVs connected at each node

Receiving Node	10% EVs	15% EVs	20% EVs
2	4	5	7
3	3	4	6
4	4	7	9
5	2	3	4
6	2	3	4
7	7	10	14
8	7	10	14
9	2	3	4
10	2	3	4
11	2	2	3
12	2	3	4
13	2	3	4
14	4	7	9
15	2	3	4
16	2	3	4
17	2	3	4
18	3	4	6
19	3	4	6
20	3	4	6
21	3	4	6
22	3	4	6
23	3	5	6
24	14	21	28
25	14	21	28
26	2	3	4
27	2	3	4
28	2	3	4
29	4	6	8
30	19	29	38
31	5	8	10
32	7	11	14
33	2	3	4
Total Nos. of PEVs	**138**	**205**	**276**

To obtain results for each case, modeled IEEE 33 node test feeder is simulated with additional PEV loads. The results obtained through the simulations is summarized by plotting voltage (in per unit) against each node and shown in Figure 4.2.

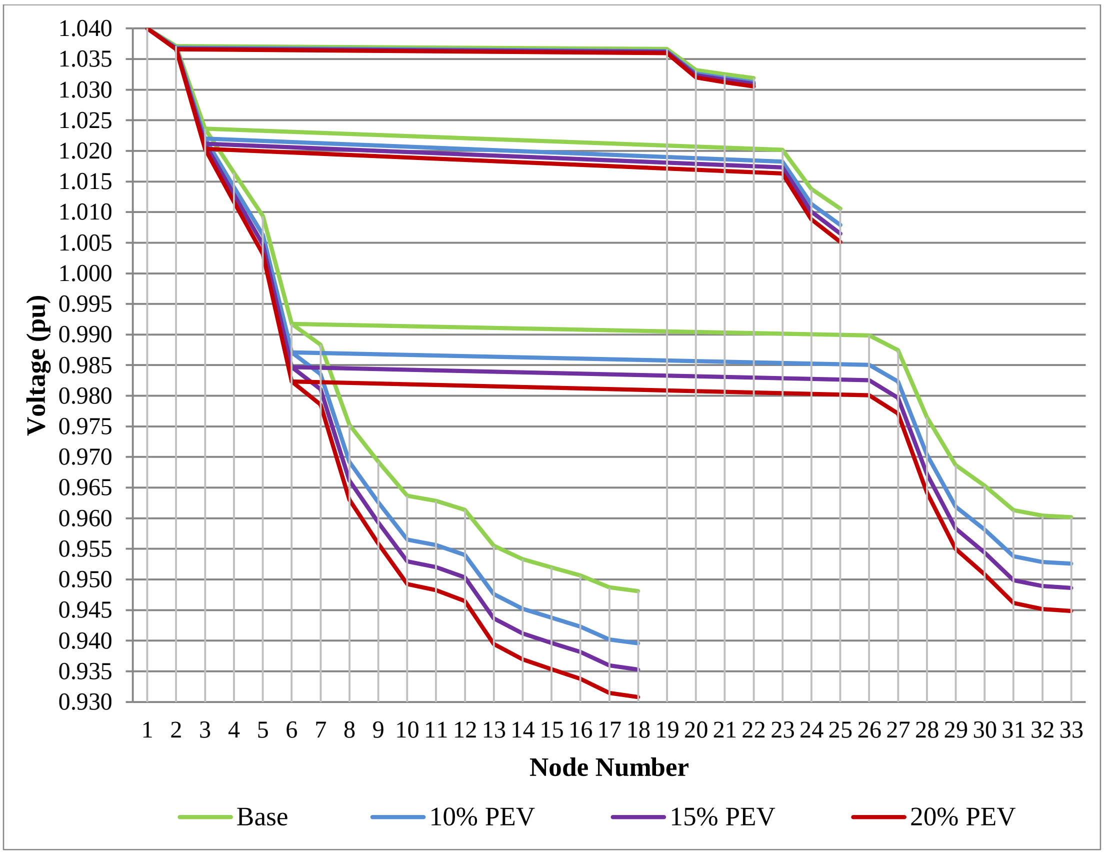


Figure 4:2: Voltage profile along IEEE 33 node test feeder for various PEV loading cases

As sub feeders start from node 2, 3 and 6, their voltages are connected to other nodes of the particular sub feeder in order to indicate the physical distribution of nodes. The lowest voltage results in the farthest end. Voltage of 18th node is 0.948 pu which corresponds to the lowest voltage along the test feeder for the base case. With the increasing PEV load, voltage decreases in each node as illustrated in Figure 4.2. When 10% PEV load is connected to each node, the voltage of the farthest end becomes 0.939 pu. It violates the voltage regulation limit of 0.94 pu. Even with 10% of PEV load is integrated to each node, voltage regulation limits are violated. The number of nodes which violates the regulation limit, increases with the increasing PEV penetration level as shown in the Figure 4.2. For 10%, 15% and 20% additional PEV load injection results in voltage violations in 1, 4 and 6 number of nodes respectively for each case. Consequently, it results in power quality issues at the consumer ends as distribution transformer tap setting cannot be adjusted online. The minimum voltage variations for different cases are shown in Figure 4.3. It illustrates how farthest end voltage drops with the increasing PEV load.

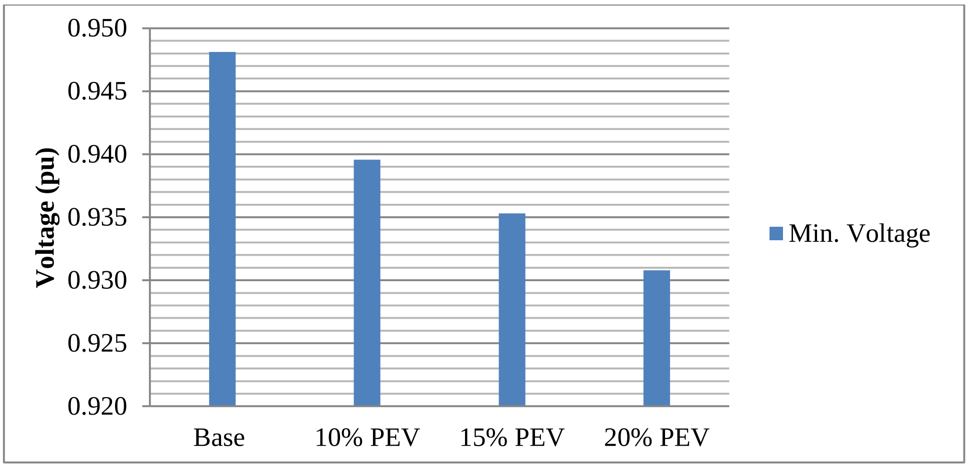


Figure 4:3: Minimum voltage variation for various PEV loading case

4.2.2 Power Loss due to Residential PEV charging

Power loss is calculated from the simulation results for the aforementioned cases. Graphical representation is shown in Figure 4.4, and it indicates how power loss is increased with increasing PEV load. When 10% PEV load is connected to the feeder power losses are more than 5% of total load of the MV feeder.

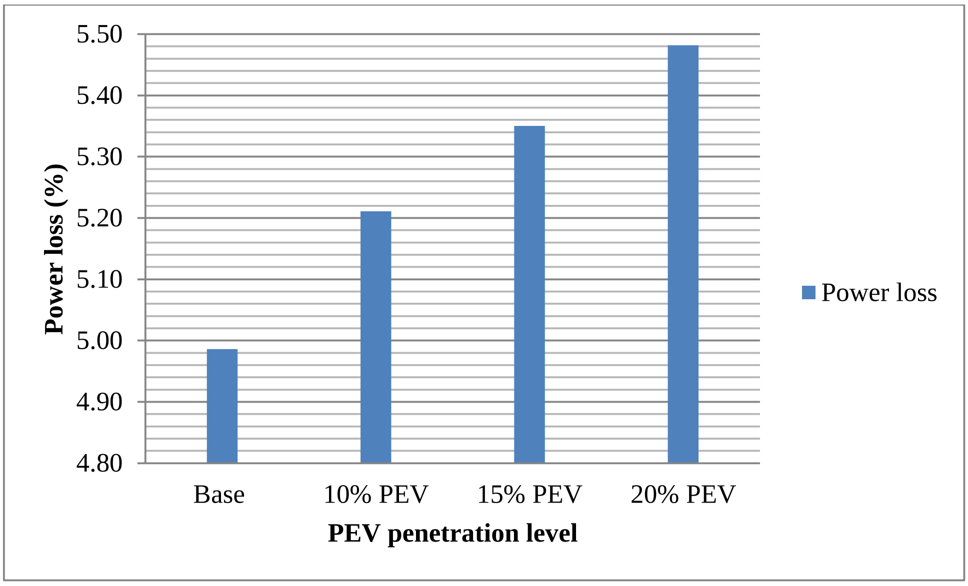


Figure 4:4: Power loss due to Residential PEV charging

4.3 Analysis of IEEE 33 network with DC fast charging

DC fast chargers are installed with dedicated transformers, which are connected to MV distribution network. In Sri Lanka 25 kW semi fast chargers and 50 kW fast chargers are installed in 100 charging stations. Charging infrastructure facilities are grown along with the PEV demand. Therefore, the effects due to DC fast charging to be considered. IEEE 33 node test feeder is used to study the impact on voltage profile and harmonics of MV distribution network due to the DC fast charging.

4.3.1 DC fast charger modeling

DC fast charger is an off-board PEV charger which can charge a PEV within 20 to 40 minutes. It obtains three phase supply from the utility and converts to higher DC voltage through three phase rectifier bridge and capacitor filter. Then it is turned into high frequency pulse voltage after the high frequency power change unit, which is required for charging the battery [33]. Figure 4.5 shows the block diagram of a DC fast charger design.

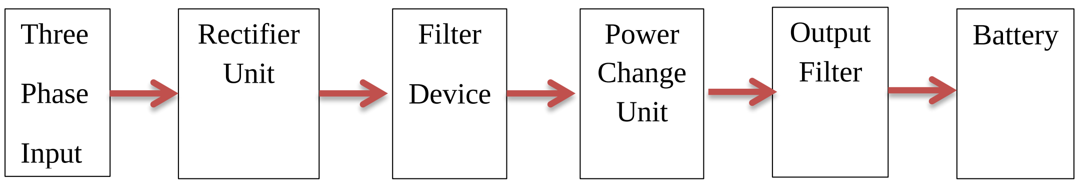


Figure 4:5: Block diagram of DC fast charger [33]

There are few charging methods as mentioned in Chapter 2. To avoid drawbacks of constant current and constant voltage charging, stage charging method is used for DC fast charger modeling. First stage is constant current with a limited voltage and the latter stage is constant voltage with a limited current. Non-linear resistor is used instead of power change unit, to obtain approximately equivalent fast charger model. Data obtain from the ABB Tera 53 data sheet, is used to model 50kW DC fast charger [45].

4.3.1.1 Modeling of non-linear resistor

Figure 4.6 presents the power output corresponds to charging of a 2015 Nissan Leaf model by ABB Tera 53 charger [45]. Non-liner resistor to be modeled in order to obtain the power output of the ABB Tera 53 charger. With the aim of modeling non-linear resistor, following steps are followed.

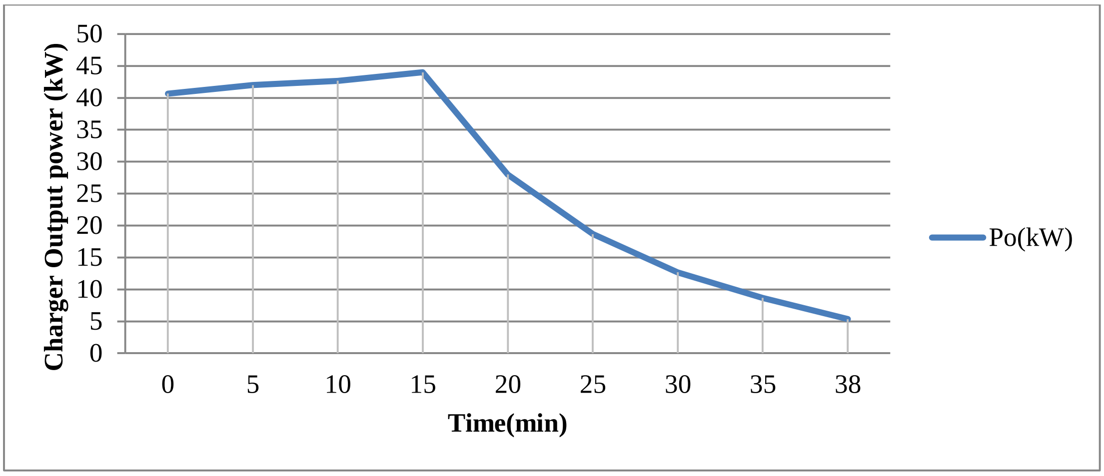


Figure 4:6: ABB Tera 53 charger output when charging a 2015 Nissan Leaf model

Three phase rectifier bridge output voltage is given by Equation 4.1.

$$V_I = \frac{3\sqrt{3}V_{peak,ph}}{\pi} \dots\dots\dots\dots\dots\dots 4.1$$

$$V_I = \frac{3\sqrt{3} \times \sqrt{2} \times (400/\sqrt{3})}{\pi} = 540.19V$$

Rectifier output voltage will be the input voltage to the power conversion unit. Non-linear resistor which is equivalent to the power conversion unit is modeled as Equation 4.2 [33].

$$R = \frac{V_I}{I_I} = \frac{V_I^2}{P_I} = \frac{\eta V_I^2}{P_O} \dots\dots\dots\dots\dots\dots 4.2$$

$V_{peak,ph}$	- Supply input to the rectifier bridge	= 230√2 V
V_I	- Input DC voltage to the power conversion unit	= 540.19 V
I_I	- Input DC current to the power conversion unit	
P_I	- Input power to the power conversion unit	
P_O	- Output power of the power conversion unit	
η	- Efficiency power conversion unit	= 92.8% [45]
R	- Non-linear resistor	
$P_O(t)$	- Time varying power output of the conversion unit	

$$R = \frac{0.928 \times 540.19^2}{P(t)_o} \ldots\ldots\ldots\ldots\ldots\ldots 4.3$$

The variation of non-linear resister is obtained from the Equation 4.3 and plotted against the time as shown in Figure 4.7.

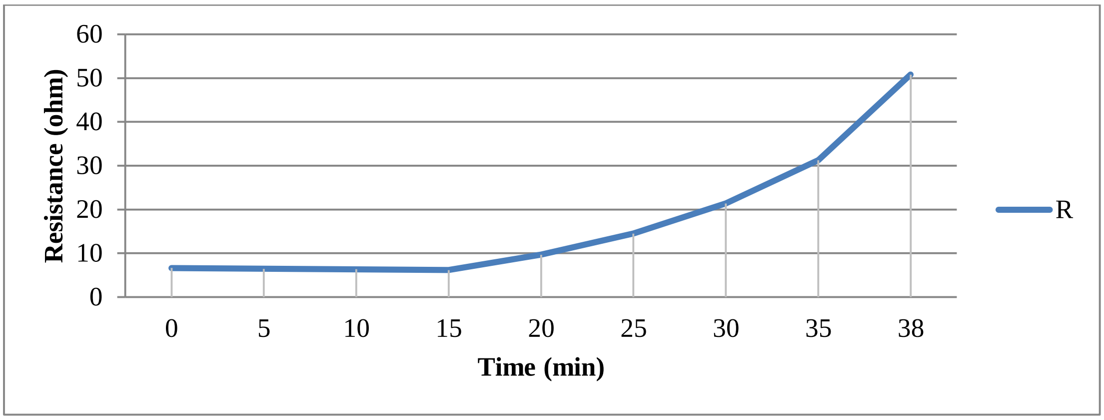


Figure 4:7: Non-linear resistor variation with time

To model this variation with time, simple exponential equation is derived from the curve fitting method of MS Excel and it is shown as Equation 4.4. Modeled and actual non-linear resistances are plotted against time shown in Figure 4.8. It indicates that both actual and derived values are very much similar to each other. It is modeled in PSCAD as indicated in Figure 4.9. Simulation result of non-linear is shown in Figure 4.10

$$R = \begin{cases} 1.6501e^{1.305}, \; 0 < t < 15 \\ 1.6501e^{0.087t}, 15 \leq t \leq 38 \end{cases} \ldots\ldots\ldots\ldots\ldots\ldots 4.4$$

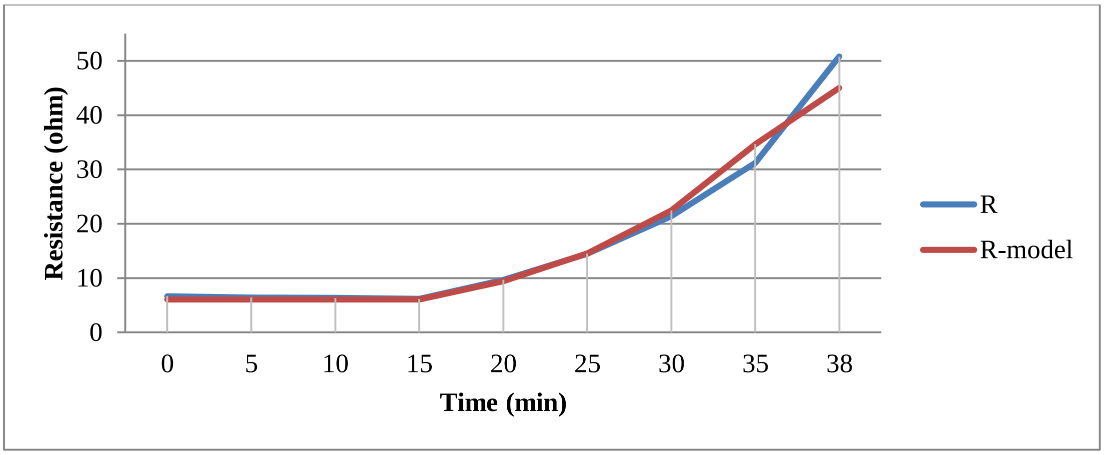


Figure 4:8: Comparison of actual and modeled non-linear resistance

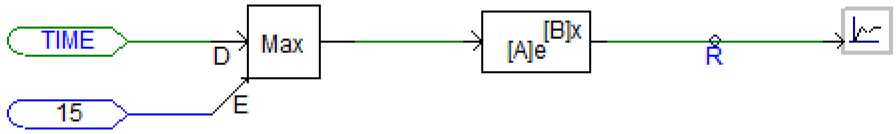


Figure 4:9: Non-linear resistor model

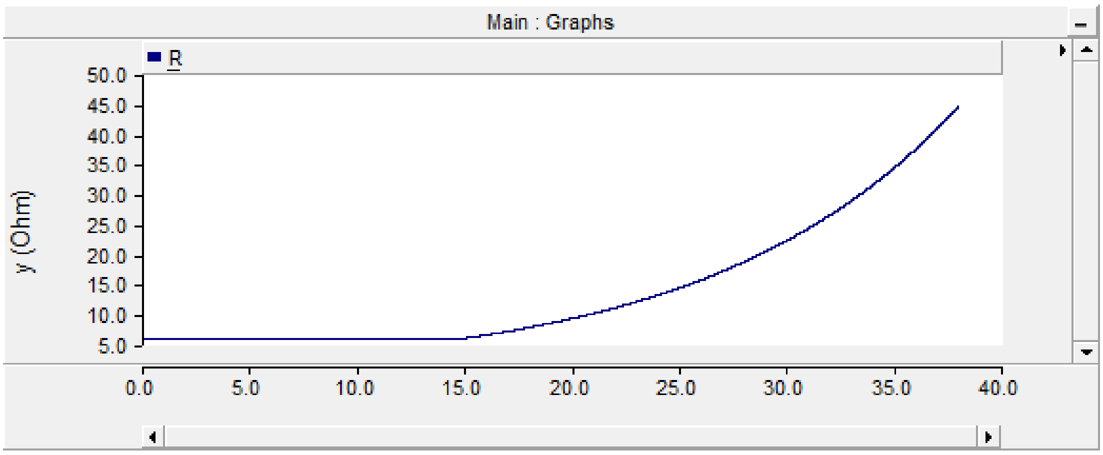


Figure 4:10: Non-linear resistor simulation in PSCAD

4.3.1.2 DC fast charger model

In order to simulate DC fast charger as real as possible, charger is supplied by 11/0.4kV, 100kVA transformer. Three phase 400V AC voltage becomes 540V DC when going through the three phase rectifier bridge and capacitor filter. The modeled non-linear resistor is used instead of power conversion unit which has an efficiency of 92.8% [45]. The modeled DC fast charger is shown in Figure 4.11.

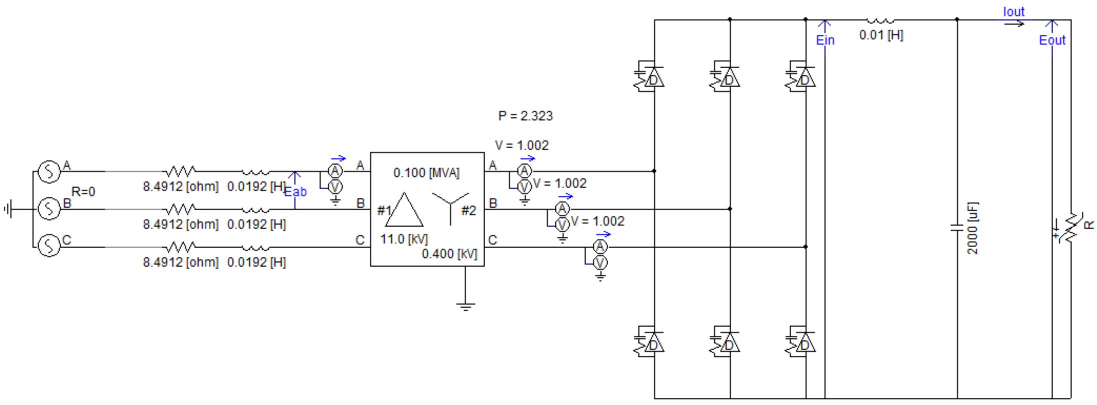


Figure 4:11: PSCAD model of DC fast charger

4.3.2 Impact on voltage profile due to DC fast charging

A 10% of full load of the feeder corresponds to use of 9 fast chargers of 50 kW capacity. Five DC fast charging stations are modeled, four of them consist of two DC fast chargers and the other one consists of one DC fast charger. To analyze the voltage profile of the IEEE 33 node test feeder due to DC fast charging, PSCAD model is simulated under few scenarios mentioned below,

- Case 1: Charging Centers are located at Front nodes
- Case 2: Charging Centers are located at Random nodes
- Case 3: Charging Centers are located at Far end nodes

Table 4.2: PEV charging center locations

Charging Center	**PEV CC1**	**PEV CC2**	**PEV CC3**	**PEV CC4**	**PEV CC5**
Nos. of DC Fast Chargers	2	2	2	2	1
Case 1	2	19	3	4	23
Case 2	14	20	25	9	29
Case 3	18	22	25	33	17

Charging center locations summarized in Table 4.2 and case 3 is illustrated in Figure 4.12. Feeder configuration in Figure 4.12 can be observed in voltage profile of IEEE 33 test feeder in Figure 4.13.

When PEV charging centers are connected at front end nodes, it does not make any considerable effect to voltage profile of the MV network as indicated in Figure 4.13. But when fast charging centers are located randomly and at far end nodes, voltage of far end nodes are dropped below the regulation limit. In the worst case scenario, voltages of 15^{th} to 18^{th} node violate the regulation limit. The locations of the PEV charging centers directly affect the voltage profile of the MV distribution network according to the simulation results.

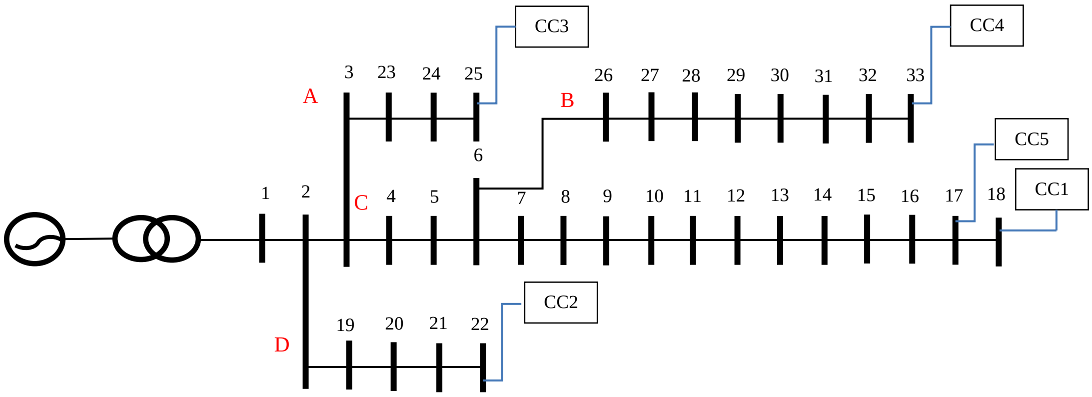


Figure 4:12: Five Charging Centers are connected at the end nodes of IEEE 33 node feeder

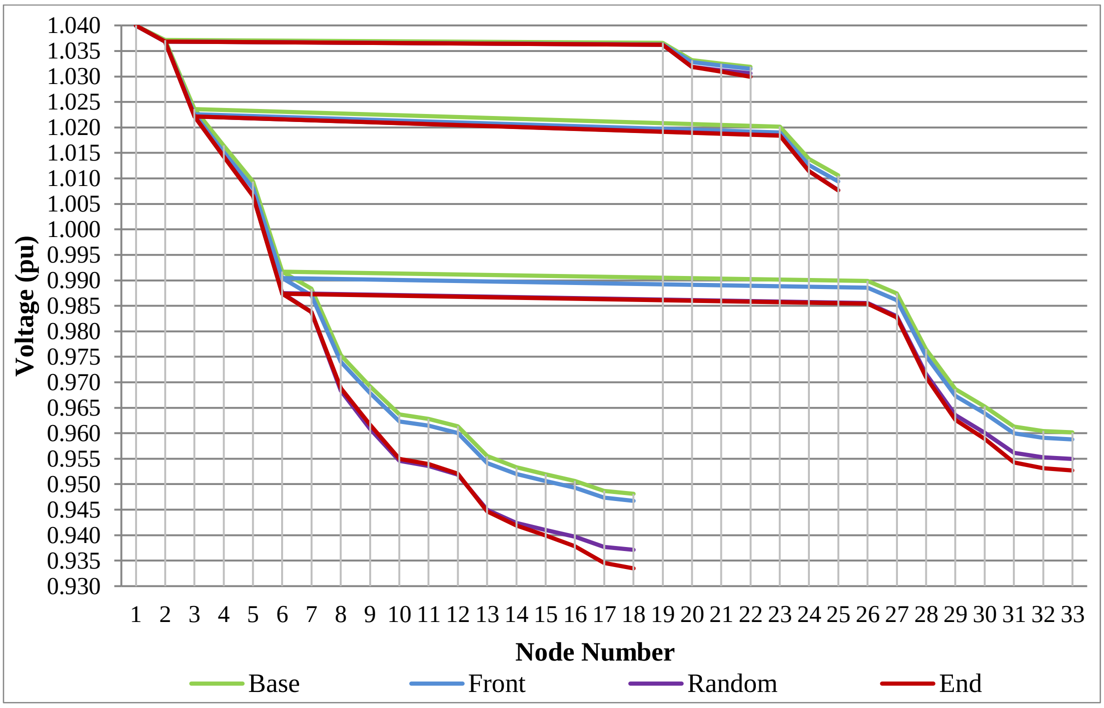


Figure 4:13: Voltage profile of the IEEE 33 node test feeder for various charging centers locations

In order to study the capability of managing DC fast chargers in each sub feeder, Case 3 is divided into 4 sub categories. The numbers of DC fast chargers connected to each sub feeder is varied in each case as illustrated in Table 4.3.

Table 4.3: Number of charging centers at each sub feeder end

Nos. of DC Fast Chargers	Sub feeder A	Sub feeder B	Sub feeder C	Sub feeder D
Case 3.1	2	2	3	2
Case 3.2	3	2	2	2
Case 3.3	2	2	2	3
Case 3.4	2	2	1	4

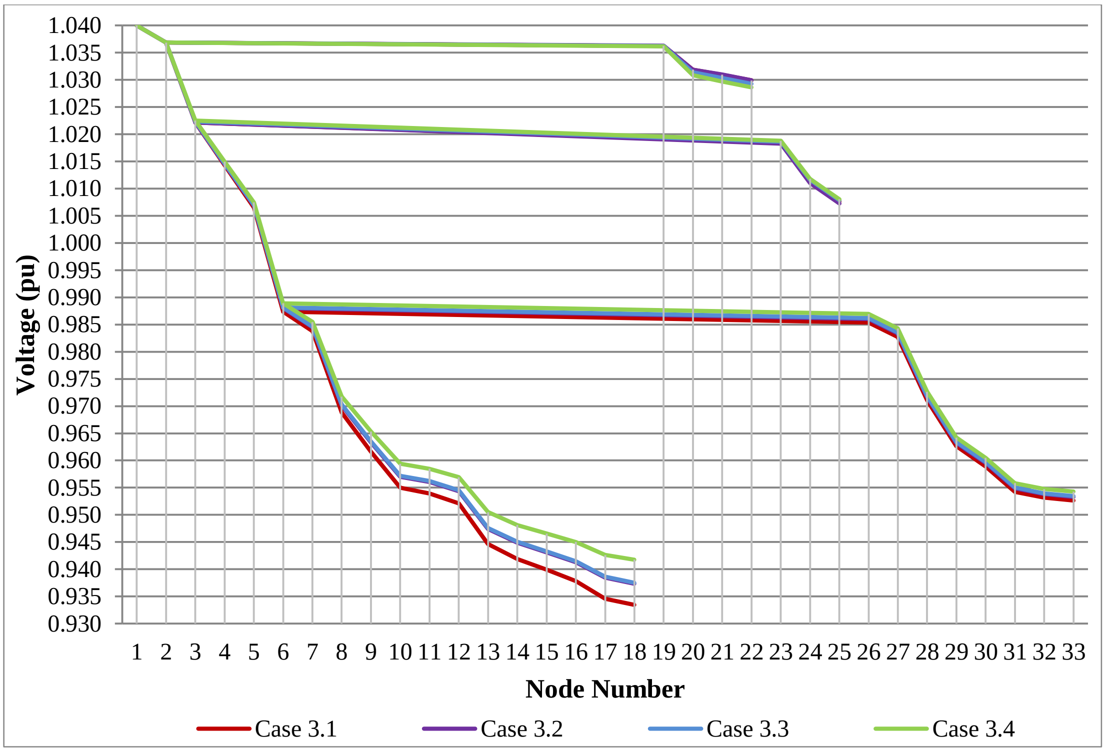


Figure 4:14: Voltage profile of IEEE 33 node test feeder with varying number of DC fast chargers each sub feeder end

Voltage profile of IEEE 33 node test feeder with different number of DC fast chargers connected to each sub feeder is illustrated in Figure 4.14. In case 3.1 more DC fast chargers are connected at the longest sub feeder, *feeder-C* ends. Hence, it violates the regulation limits. In case 3.4, longest sub feeder is loaded with one DC fast charger while the shortest sub feeder is loaded with four DC fast chargers. Then it does not violate the voltage regulation limits. Hence, shorter sub feeder can tolerate more DC fast chargers than longer sub feeders without causing any violation.

4.3.3 Power Loss due to DC fast charging stations

Power loss is obtained through the simulation for aforementioned cases. Power loss results are illustrated in Figure 4.15. When PEV charging stations connected at front nodes of sub feeders, power loss is very low compared to the cases where PEV charging centers are connected randomly and far ends of each sub feeder. If the PEV charging stations are concentrated to nodes which are closer to the source end, the effects on MV feeder can be accommodated without any capacity improvements.

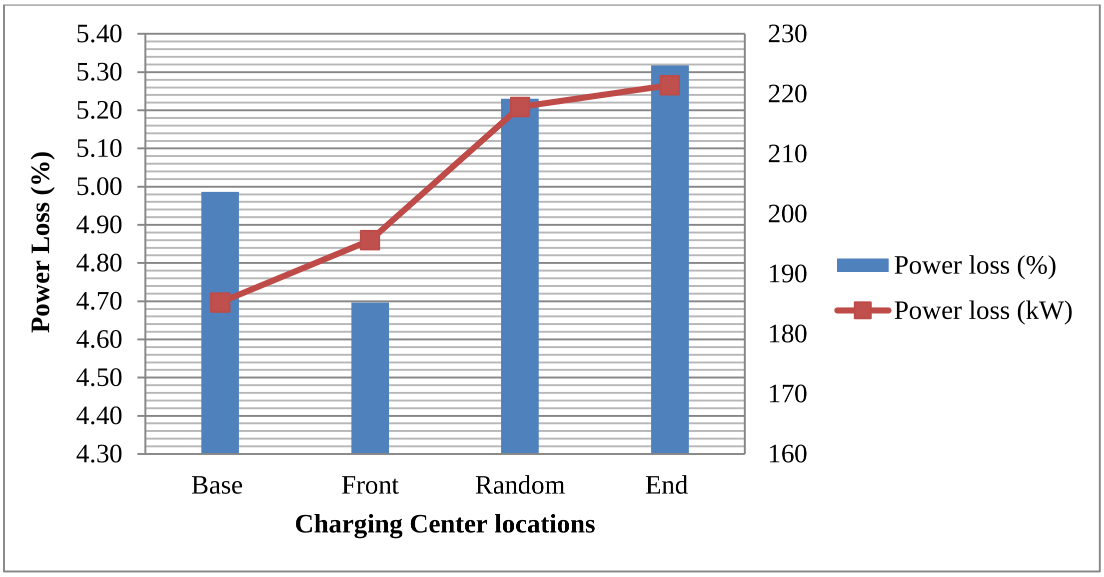


Figure 4:15: Power loss due to DC fast charging stations

4.3.4 Effect of voltage and current harmonics due to DC fast charging

4.3.4.1 Voltage and current harmonic distortion of a single DC fast charging station

Once the DC fast charger model is simulated in PSCAD following results are obtained. Since fast charger is non-linear, input current and voltage waveforms are distorted and illustrated in Figure 4.16 and 4.17. Even current waveform is highly distorted, voltage waveform distortion is negligible.

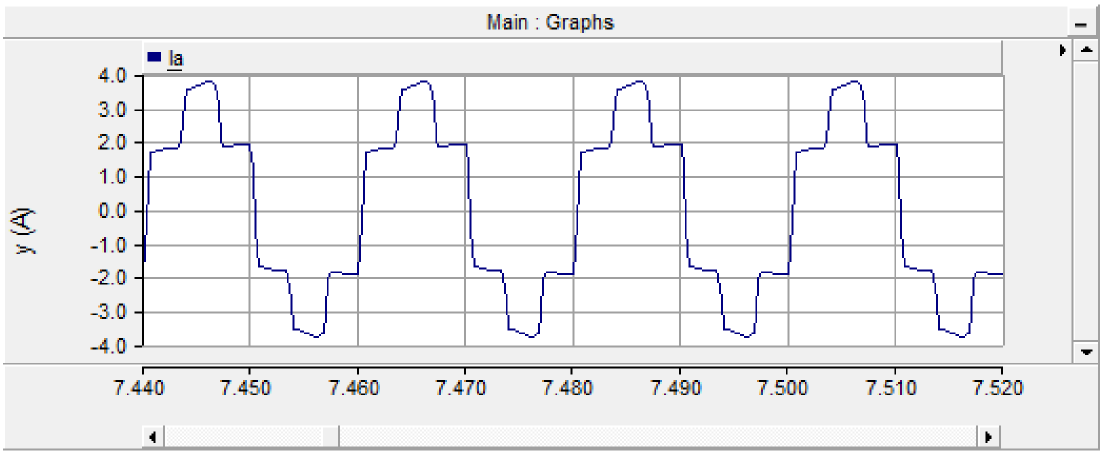


Figure 4:16: Distorted Input Current waveform of DC fast charger

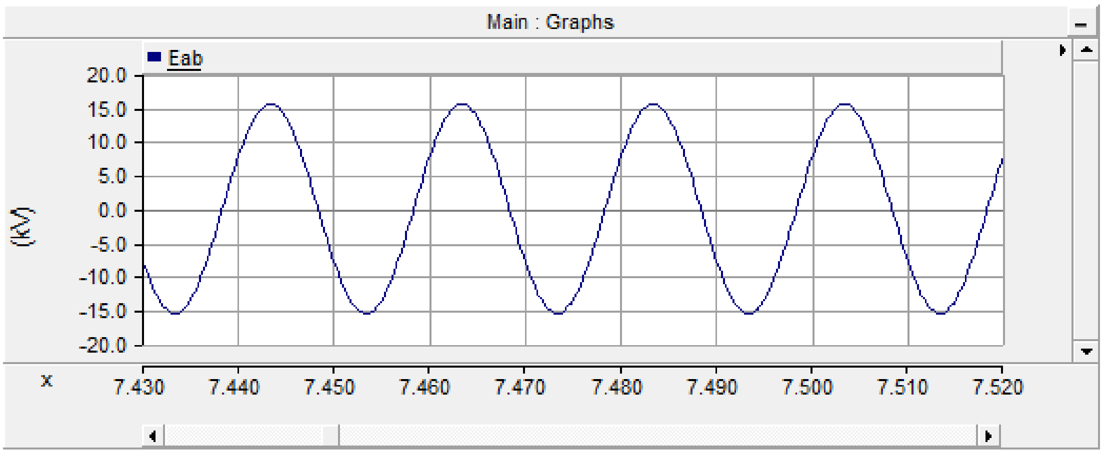


Figure 4:17: Input Voltage waveform of DC fast charger

DC output voltage, current and power variation during the charging process is shown in Figure 4.18, 4.19 and 4.20 respectively.

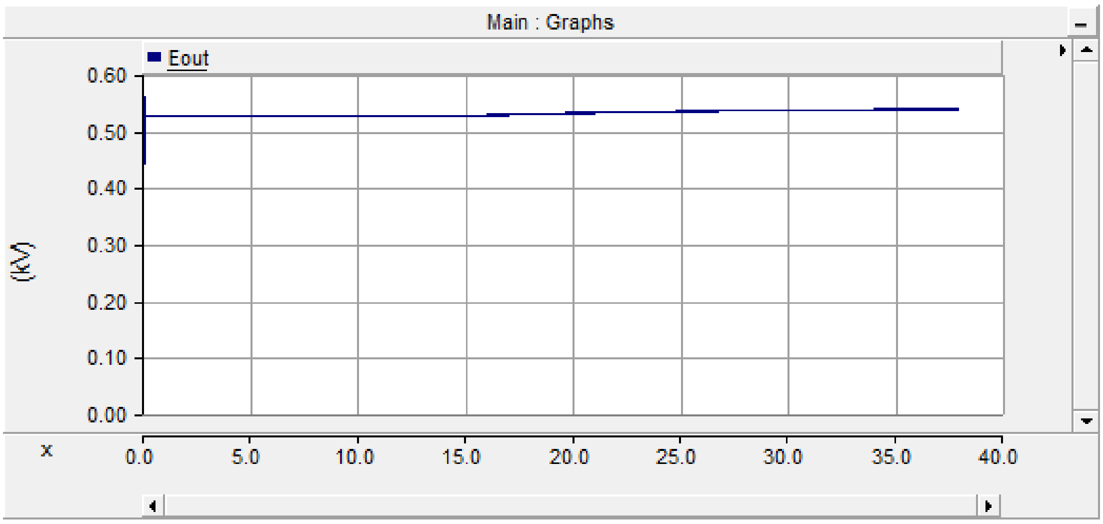


Figure 4:18: Output Voltage of DC fast charger

DC output voltage is approximately constant during the charging process. DC output current is constant during constant current mode and decreasing during constant voltage mode. DC fast charger power output is same as the ABB Tera 53 charger power output and varied with time as per the non-linear resistor variation.

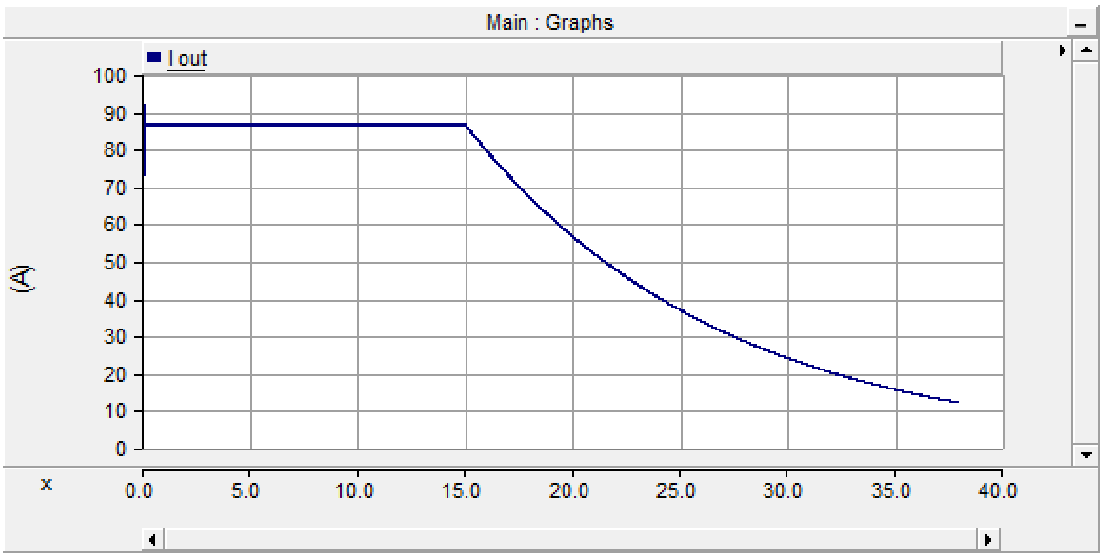


Figure 4:19: Output current of DC fast charger

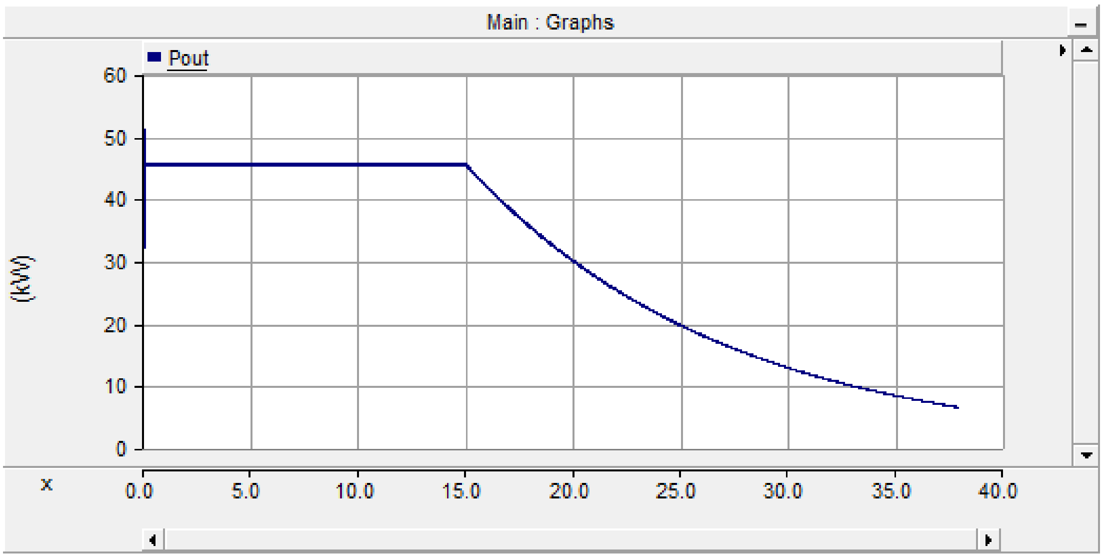


Figure 4:20: Output power of DC fast charger

Input voltage and current waveforms are fed to an on-line frequency scanner which can perform Fast Fourier Transform analysis on phase quantities and output up to 255 harmonics. The output of on-line frequency scanner is gone through the harmonic distortion calculator which measures both the total and individual harmonic distortion of an input signal. Then the calculated total and individual harmonic distortion are given to output channels. The process of obtaining Total Harmonic Distortion (THD) is shown in Figure 4.21. Total Demand Distortion (TDD) of input current is 28.45% and voltage THD is 0.088%. Even current harmonic distortion is considerable, voltage harmonic distortion is negligible. Individual current harmonic components' magnitude and phase are shown in Figure 4.22 and 4.23 respectively.

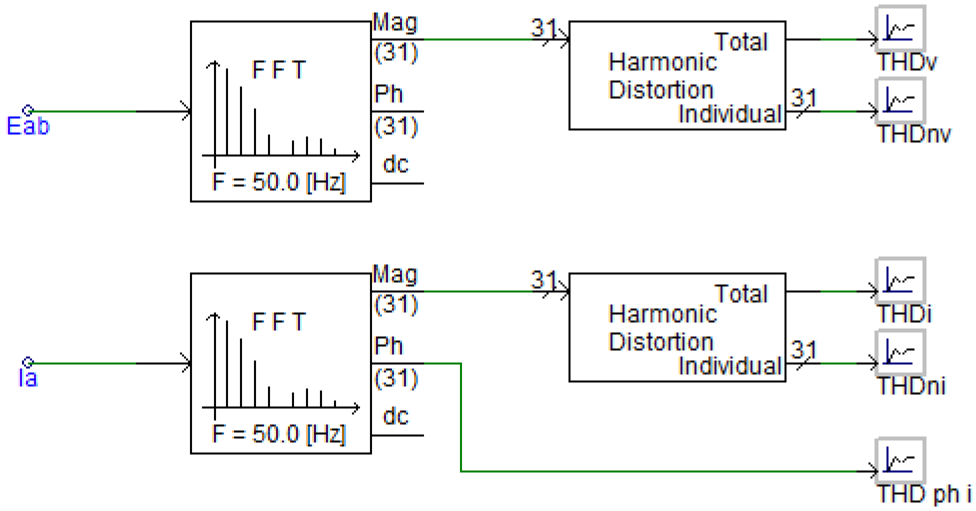


Figure 4:21: Harmonic distortion calculation in PSCAD

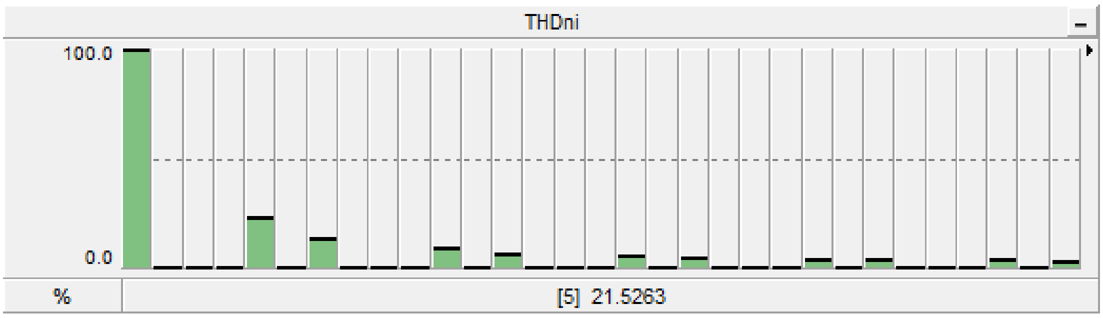


Figure 4:22: Individual harmonic component magnitude of input current waveform

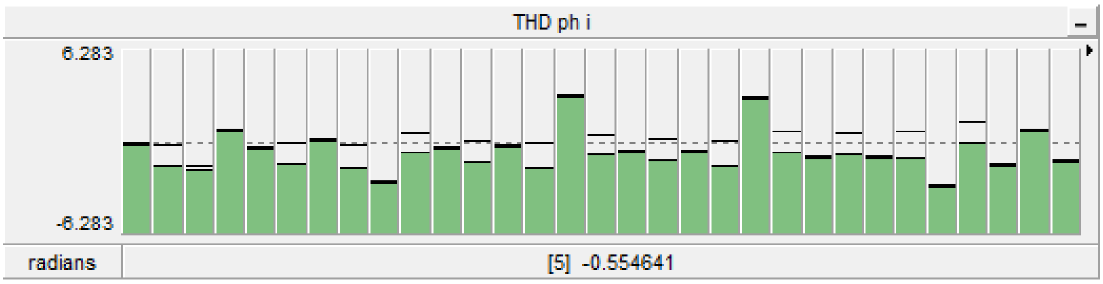


Figure 4:23: Individual harmonic component phase of input current waveform

5th and 7th harmonic components are considerable in the distorted current waveform as illustrated in Figure 4.22. Magnitudes of individual harmonic components generated from a DC fast charger are summarized as in Table 4.4. The regulation limits are referred to IEEE 519 standard [46].

Table 4.4: Individual harmonic magnitude generated by the DC fast charger

Individual Harmonic component	Individual Harmonic component magnitude	IEEE 519 Standard limits
3	0.036	12.0
5	21.526	12.0
7	12.637	12.0
9	0.032	12.0
11	8.288	5.5
13	6.387	5.5
17	5.063	5.0
19	4.263	5.0
21	0.101	5.0
23	3.480	2.0
25	3.061	2.0
27	0.366	2.0
29	2.678	2.0
31	2.186	2.0
TDD	**28.45**	**15.0**

5^{th} harmonic is dominated as shown in the simulation results. According to the IEEE 519 standard current harmonic distortion limits, current harmonics generated by the DC fast charger are exceeding the harmonic limits at the point of common coupling. The simulation result is verified by the fact of TDD range of 9.3% to 30.7% given in the data sheet of ABB Tera 53 DC fast charger [45].

4.3.4.2 Voltage and current harmonic effect on MV network

In order to analyze the harmonic propagation along the MV network due to DC fast charging, 9 DC fast chargers are connected to the IEEE 33 node test feeder. Then analyze the harmonic distortion of the voltage and current signals at the source end. DC fast chargers are modeled inside a module in order keep legibility. IEEE 33 node test feeder is simulated with connected DC fast charger modules under three different scenarios to study the harmonic propagation along the feeder. PEV charging center locations in each scenario are indicated in Table 4.5.

- Case 1 – PEV charging stations are connected at front nodes
- Case 2 – PEV charging stations are connected random nodes
- Case 3 – PEV charging stations are connected at end nodes

Table 4.5: Charging Center locations for each case

Charging Center	**PEV CC1**	**PEV CC2**	**PEV CC3**	**PEV CC4**	**PEV CC5**
Nos. of DC Fast Chargers	2	2	2	2	1
Case 1	2	19	3	4	23
Case 2	14	20	25	9	29
Case 3	18	22	25	33	17

In case 1, two off DC fast chargers are connected to 19th node of the IEEE 33 node test feeder as a module which is indicated in the Figure 4.24.

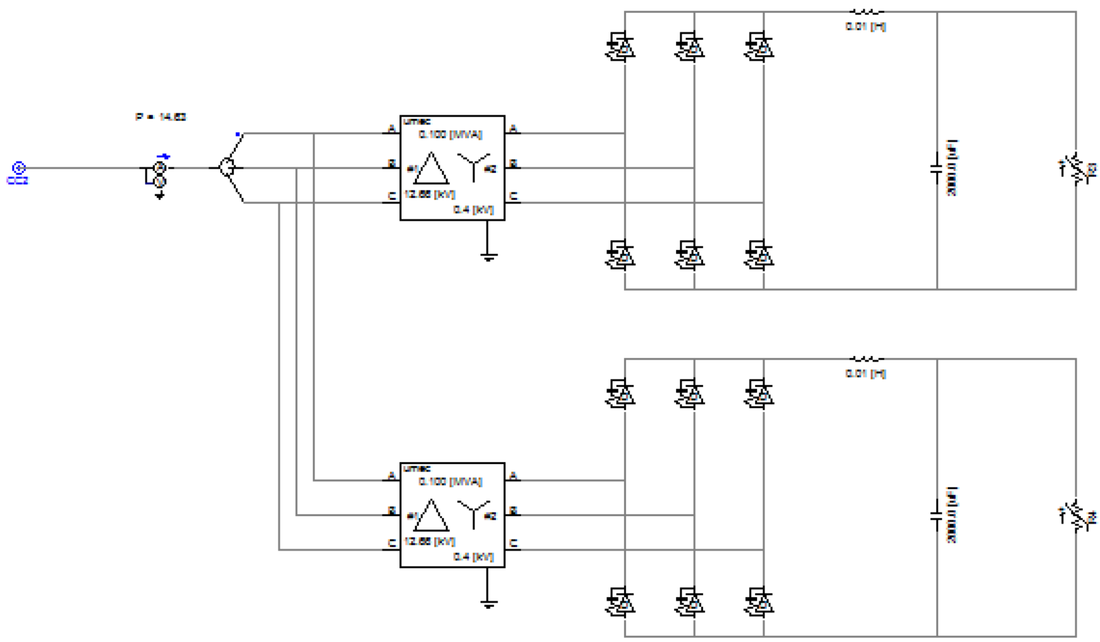


Figure 4:24: PSCAD PEV CC2 module

Table 4.6: Simulation THD results for each case

Case	Voltage THD	Current THD	IEEE 519 Standard Limits	
			Voltage THD	Current THD
Case 1	0.002	2.351	5%	5%
Case 2	0.002	2.078		
Case 3	0.002	2.026		

Total harmonic distortion (THD) of voltage and current signals are tabulated for three scenarios in Table 4.6. Only current harmonic individual components' magnitudes are summarized in Table 4.7 because individual voltage harmonic components are negligible.

Table 4.7: Individual current harmonic magnitudes for each case

Individual Harmonic component	Individual Harmonic component magnitude			IEEE 519 Standard limits
	Case 1	Case 2	Case 3	
3	0.000	0.001	0.002	4.0
5	1.774	1.606	1.577	4.0
7	1.141	1.016	0.992	4.0
9	0.010	0.001	0.001	4.0
11	0.695	0.589	0.566	2.0
13	0.540	0.446	0.426	2.0
15	0.001	0.001	0.007	2.0
17	0.363	0.278	0.258	1.5
19	0.295	0.218	0.201	1.5
21	0.003	0.001	0.001	1.5
23	0.196	0.134	0.119	0.6
25	0.160	0.104	0.092	0.6
27	0.006	0.006	0.005	0.6
29	0.102	0.070	0.059	0.6
31	0.083	0.047	0.040	0.6
TDD	**2.351**	**2.078**	**2.026**	**5.0**

Voltage and current THD seems to be increased when DC fast charging stations are located closer to the source. Highest THD of voltage and current are reported in the case 1, i.e. when DC fast chargers are connected to front nodes of the IEEE 33 test feeder. Current harmonic individual component magnitudes and phases of case 1 are indicated in Figure 4.25 and 4.26 respectively.

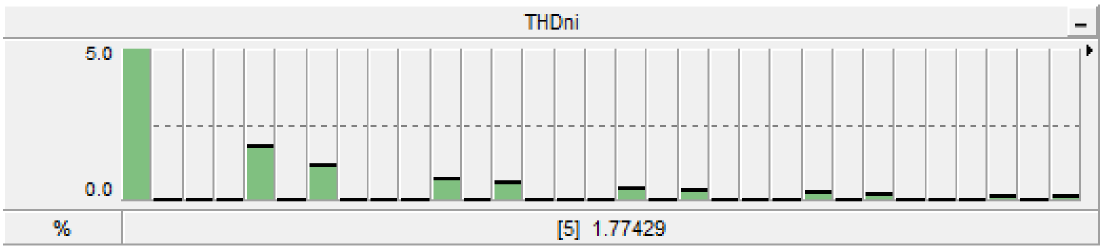


Figure 4:25: Individual current harmonic component magnitudes of Case 1

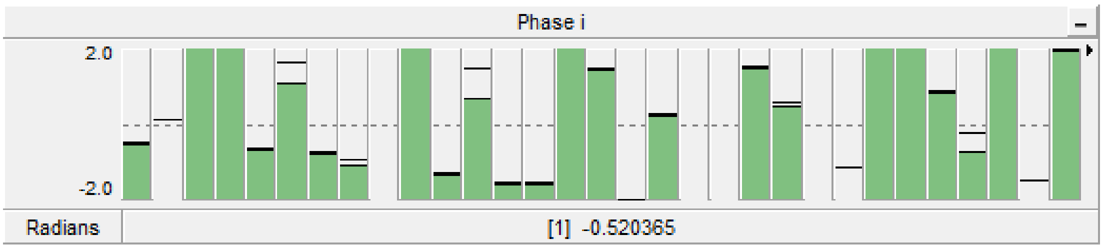


Figure 4:26: Individual current harmonic component phases of Case 1

When simulation results are compared with the IEEE 519 standard values, they are within the specified limits. Hence, the harmonic distortion at the source end due to the PEV charging with fast chargers, can be neglected.

5. IMPACTS OF INCREASING PEVS ON LV DISTRIBUTION NETWORK

5.1 LECO LV Feeder modeling

In order to study the effect of PEV charging on LV distribution network, three different LECO (Lanka Electricity Company) distribution feeders were modeled in PSCAD simulation platform. Urban residential feeders are selected as the PEV concentration is high in urban areas compared to rural areas. Detailed feeder information which is used for modeling is given in Appendix VI [47], [48].

Three feeders are selected in a way that they have different loading levels of 93%, 72.5% and 60% for *feeder* 1, 2 and 3 respectively. The intension of analyzing differently loaded feeders is to find out the severity of PEV charging effects varying with the feeder loading. This chapter includes the analysis of residential PEV charging effects on distribution feeders such as voltage limit violations, transformer loading, power losses and voltage unbalance. General overview of three feeders is included in Table 5.1. Graphical representations of three feeders are illustrated in Figures 5.1, 5.2 and 5.3 and more details are included in Appendix VI.

Table 5.1: General overview of three LECO distribution feeders

	Feeder 1	**Feeder 2**	**Feeder 3**
Transformer ID	AZ0202	AZ0203	AZ0221
Transformer Capacity (kVA)	160	160	250
Location	Kotte	Kotte	Pitakotte
No. of Poles	62	57	51
No. of consumers	387	278	328
ADMD (kVA)	0.38	0.41	0.45
Power Factor	0.9	0.9	0.9

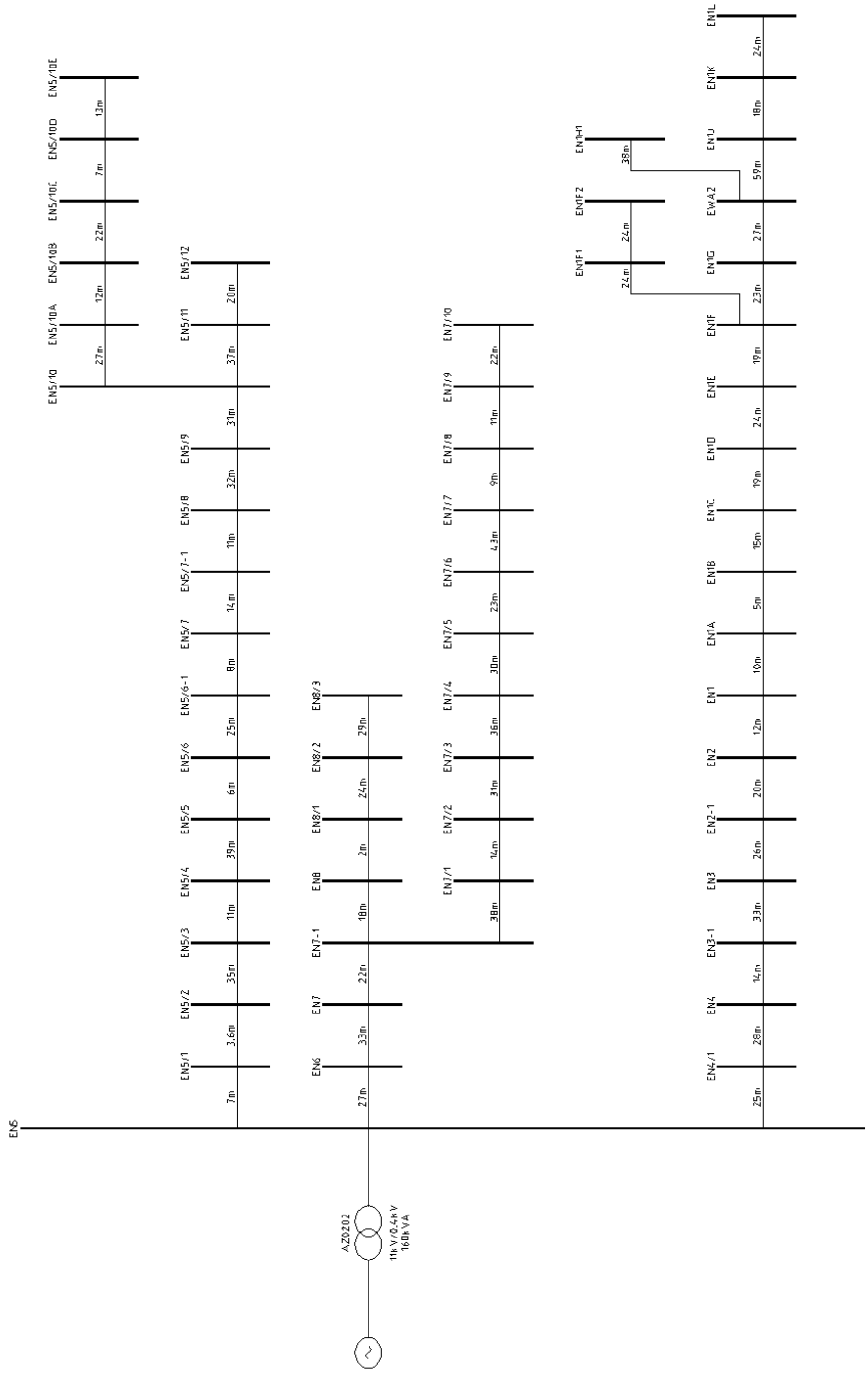


Figure 5:1: Graphical representation of Feeder 1

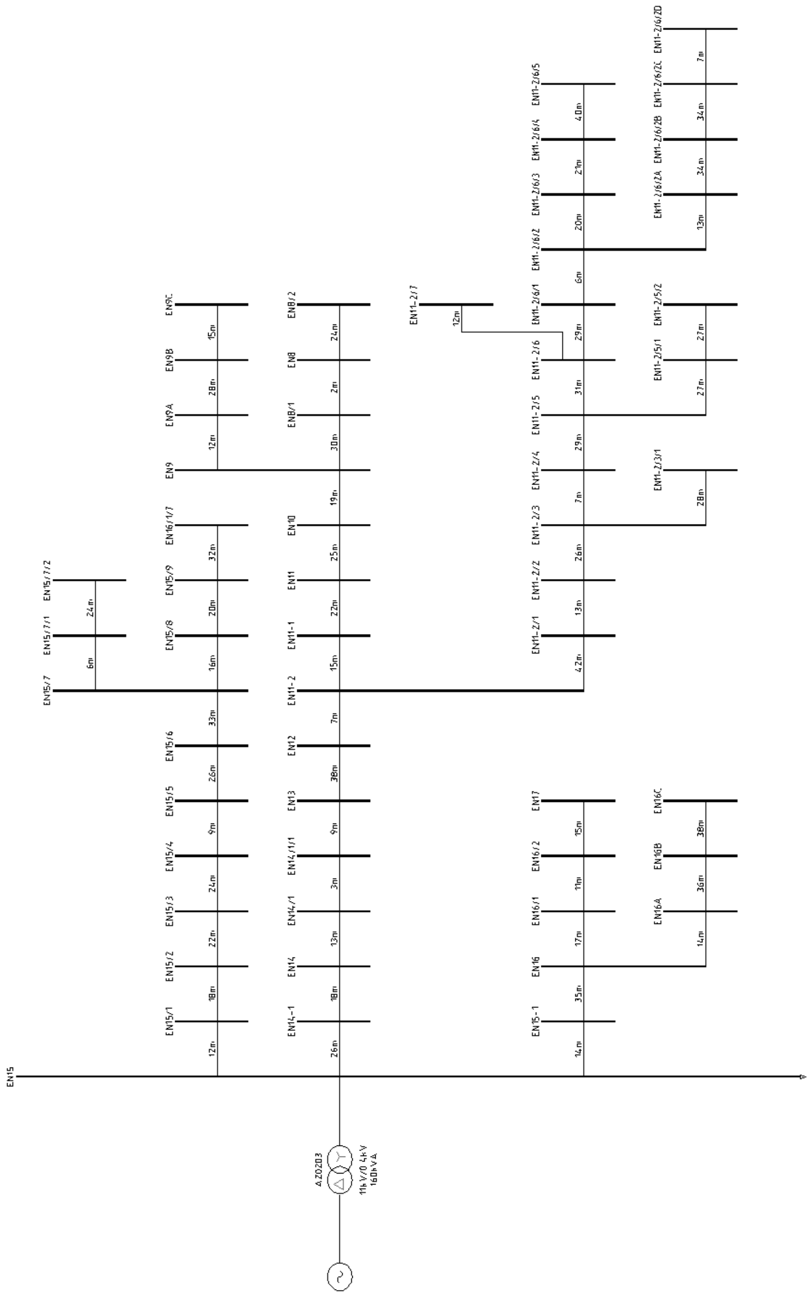


Figure 5:2: Graphical representation of Feeder 2

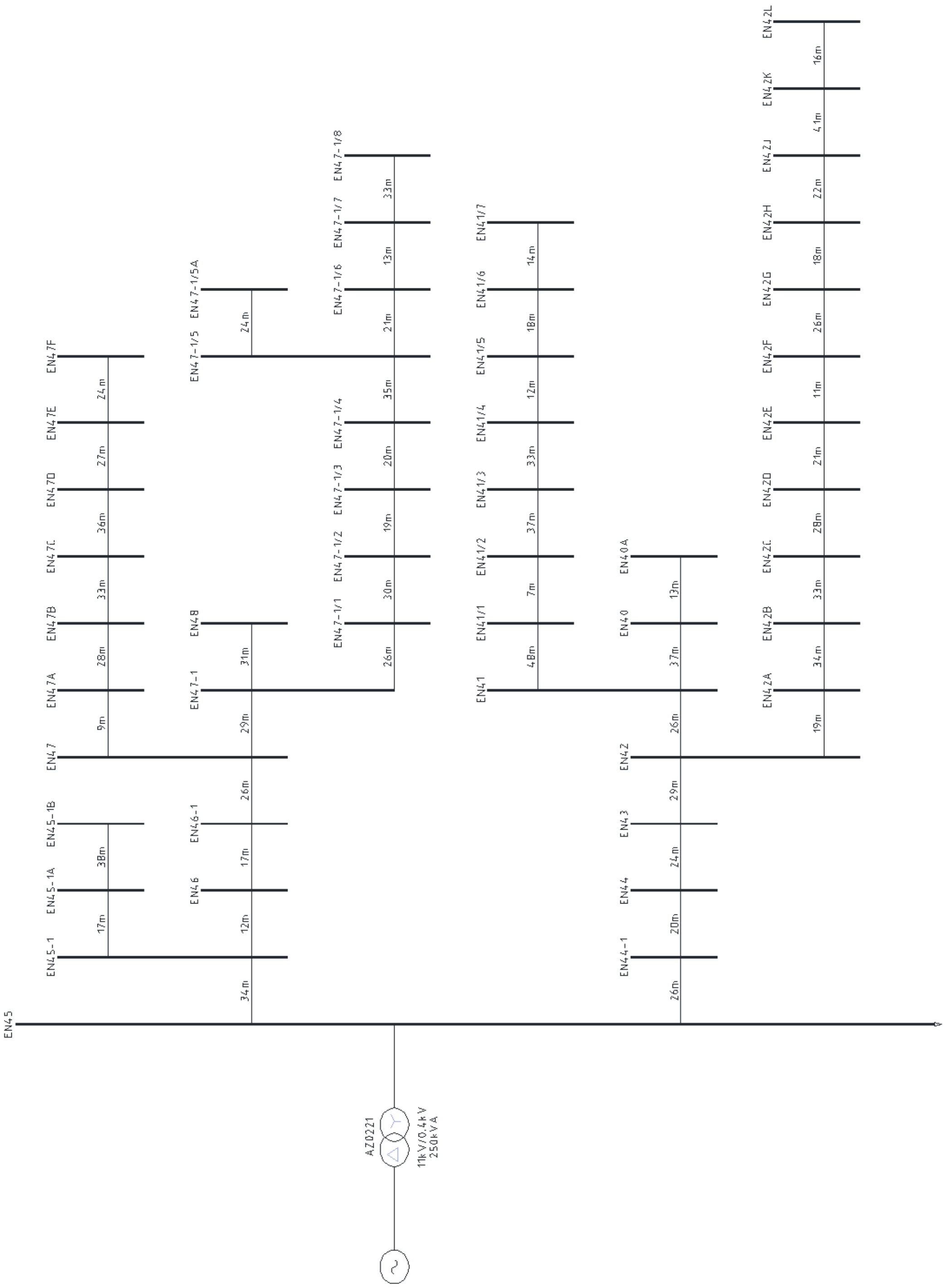


Figure 5:3: Graphical representation of Feeder 3

Few assumptions have been made in order to create LV feeder models as applicable for the analysis of effect on voltage profile, transformer loading, power loss and voltage unbalance.

- As source impedance details are not available, source which supplies the distribution transformer, is considered as an infinite source.
- Base voltage is assumed as 0.4kV.
- Transformer is modeled using the data received from LECO. Transformer tap setting is adjusted in order to maintain the voltage within the regulation limit during both peak and off-peak hours.
- Each pole is considered as a Bus during modeling in PSCAD.
- Aggregated load connected to each pole is calculated using ADMD (After Diversity Maximum Demand) approach, and assumed as constant power loads during night peak time.
- Single phase residential loads connected to each pole distributed among all three phases in the sequence of Phase A, B and C in order to simulate the natural unbalance.
- Majority of PEVs in Sri Lanka is Nissan Leaf. Its charging power is 3.3kW. Therefore single phase PEV charging load is assumed as 3.3kW constant power load [44].

5.2 Impact on Voltage profile of LV Network

Selected three LV distribution feeders of different loading were modeled and analyzed under few scenarios as shown in Figure 5.4. Voltage profile along the feeder due to single phase residential PEV charging is analyzed under different scenarios as listed below separately. Three different PEV penetration levels are analyzed by adding 10%, 20% and 30% PEV loads out of total base load.

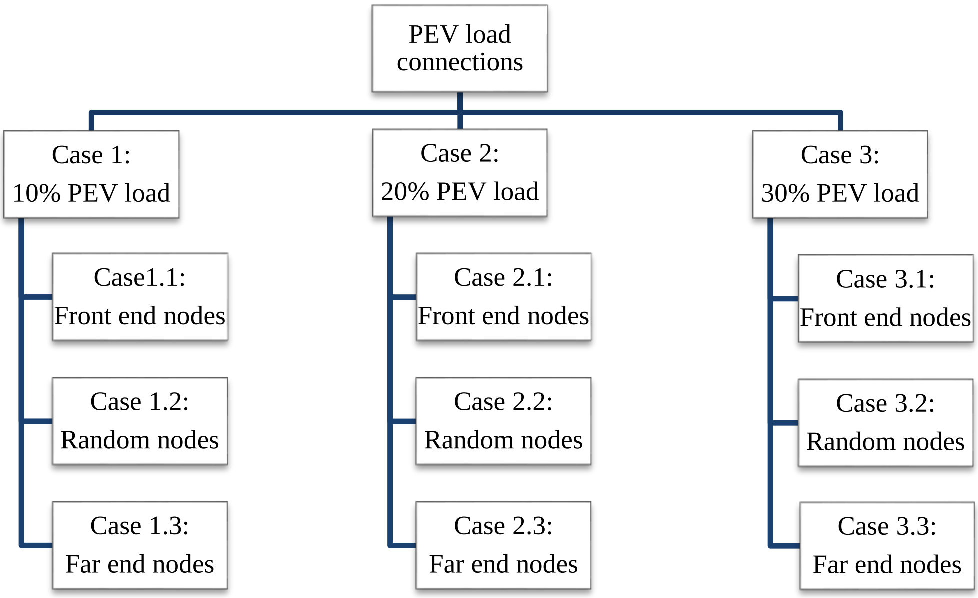


Figure 5:4: Different cases for analyzing impacts on distribution feeders

Number of PEVs corresponds to each PEV load level is determined based on the total load during night peak. Table 5.2, 5.3 and 5.4 show the pole numbers where PEVs were connected under each scenario.

Table 5.2: PEV location configuration matrix of Feeder 1

PEV No.	**Feeder 1**								
	10% PEV			**20% PEV**			**30% PEV**		
	1.1	**1.2**	**1.3**	**2.1**	**2.2**	**2.3**	**3.1**	**3.2**	**3.3**
1	EN6	EN6	EN710	EN51	EN7	EN512	EN6	EN1B	EN83
2	EN51	EN512	EN510E	EN55	EN510C	EN510E	EN54	EN571	EN510E
3	EN41	EN1	EN1L	EN6	EN512	EN83	EN54	EN571	EN510E
4	EN7	EN78	EN1H1	EN71	EN710	EN710	EN53	EN2	EN1F2
5				EN31	EN1F	EN1L	EN72	EN78	EN710
6				EN31	EN1F	EN1L	EN71	EN74	EN512
7				EN41	EN1A	EN79	EN21	EN83	EN1L
8				EN8	EN83	EN511	EN21	EN83	EN1L
9				EN53	EN57	EN1H1	EN4	EN4	EN1G
10							EN51	EN51	EN510
11							EN7	EN1H1	EN78
12							EN31	EN510B	EN1H1
13							EN31	EN510B	EN1H1
PEV load	**13.2**			**29.7**			**42.9**		

Table 5.3: PEV location configuration matrix Feeder 2

PEV No.	Feeder 2								
	10% PEV			20% PEV			30% PEV		
	1.1	1.2	1.3	2.1	2.2	2.3	3.1	3.2	3.3
1	EN15/1	EN15/6	EN11-2/7	EN15/1	EN15/1	EN16/1/7	EN15/1	EN15/4	EN15/7/2
2	EN14-1	EN11	EN11-2/6/5	EN15/2	EN15/8	EN9C	EN15/2	EN15/9	EN16/1/7
3	EN15-1	EN11-3/2/1	EN11-2/6/2D	EN14-1	EN8/1	EN11-2/7	EN15/2	EN14-1	EN9C
4				EN14	EN11-2/7	EN11-2/6/5	EN14-1	EN12	EN8/2
5				EN14	EN11-2/2	EN11-2/6/2D	EN14/1	EN9A	EN11-2/7
6				EN16	EN11-2/6/5	EN11-2/5/2	EN14/1	EN11-2/2	EN11-2/6/5
7				EN16A	EN16/2	EN16C	EN13	EN11-2/5/2	EN11-2/5/2
8							EN15-1	EN11-2/6/2B	EN11-2/6/2D
9							EN16A	EN17	EN17
10							EN16A	EN16B	EN16C
PEV Load (kW)	**9.9**			**23.1**			**33**		

Table 5.4: PEV location configuration matrix Feeder 3

PEV No.	Feeder 3								
	10% PEV			20% PEV			30% PEV		
	1.1	1.2	1.3	2.1	2.2	2.3	3.1	3.2	3.3
1	EN45-1	EN45-1A	EN47-1/5A	EN45-1	EN47A	EN45-1B	EN45-1	EN45-1A	EN45-1B
2	EN46	EN47-1/6	EN47-1/8	EN45-1A	EN47D	EN47F	EN45-1A	EN47B	EN47F
3	EN44-1	EN41/5	EN41/7	EN46	EN46-1	EN48	EN46	EN48	EN47F
4	EN41	4N42F	EN42L	EN47	EN47-1/3	EN47-1/5A	EN46	EN47-1/2	EN48
5				EN44-1	EN47-1/5A	EN47-1/8	EN46-1	EN47-1/4	EN47-1/5A
6				EN44	EN41/4	EN41/7	EN47	EN47-1/8	EN47-1/8
7				EN41	EN43	EN40A	EN44-1	EN44-1	EN47-1/8
8				EN41/1	EN40A	EN42L	EN44	EN40A	EN41/7
9				EN42A	EN42F	EN42L	EN44	EN41/1	EN41/7
10							EN41	EN41/7	EN40A
11							EN41/1	EN42A	EN40A
12							EN42A	EN42D	EN42L
13							EN42B	EN42J	EN42L
PEV Load (kW)	**13.2**			**29.7**			**42.9**		

Per unit voltage at each pole of three feeders are plotted separately in Figure 5.5, 5.6 and 5.7. For easy comparison, the worst voltages values revealed through the simulations are plotted together. Effect on voltage profile is measured mainly based on the violation of voltage regulation lower limit of 0.94 pu. Voltage profile gives a clear representation of the physical connections of poles by connecting voltages of poles.

- Highlights on *Feeder 1* analysis

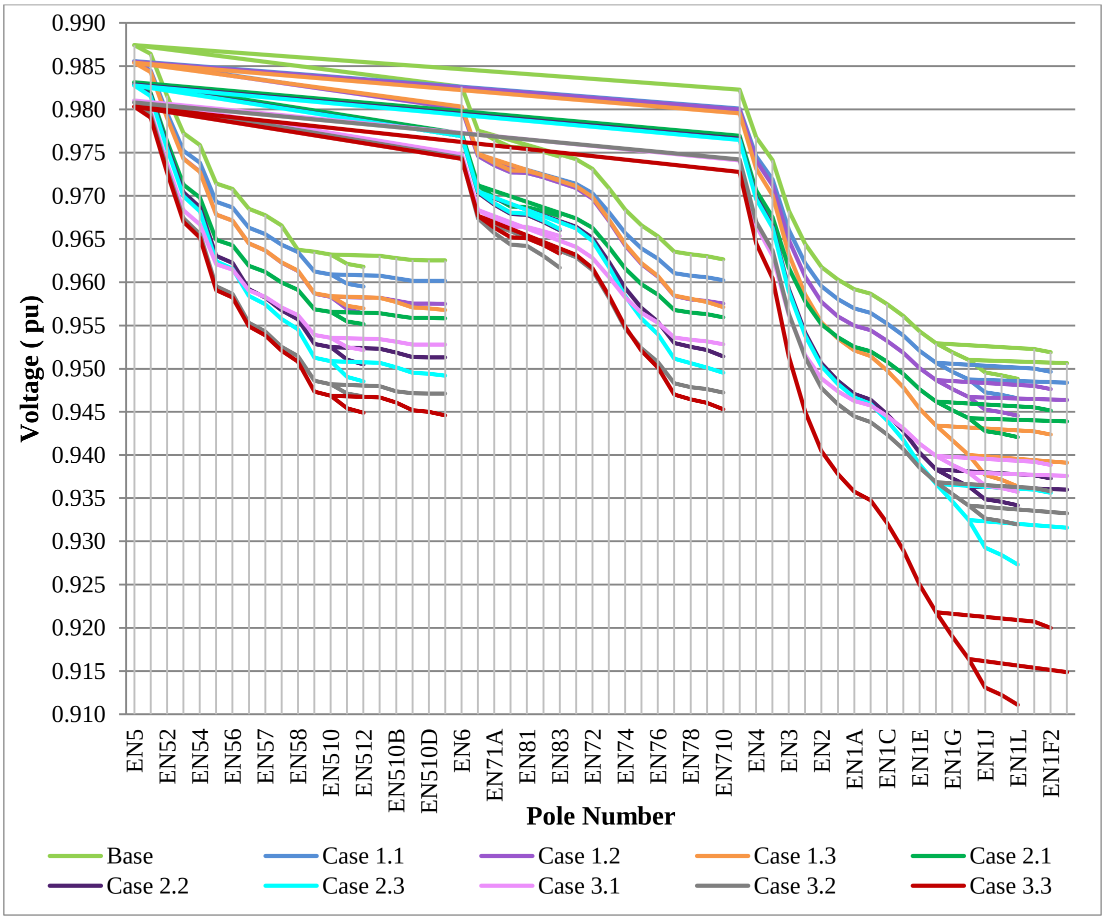


Figure 5:5: Voltage profile of Feeder 1 under nine cases

Distribution transformer of *Feeder 1* is loaded up to 93% of its full load. When 10% PEV load out of total consumer load are connected to *Feeder 1*, definitely the distribution transformer capacity will be exceeded during the night peak time. Thus 10% PEV load connected at the far ends will cause voltage regulation limit violation as shown in Figure 5.5. But *Feeder 1* can tolerate 20% PEV load whilst it is concentrated to front end poles. 30% PEV load always causes the voltage violations at far end nodes.

- Highlights on *Feeder 2* analysis

Distribution transformer of *Feeder 2* is loaded up to 72.5% of its full load. 10% PEV load connected at the far ends will cause voltage regulation limit violation in *Feeder 2* as well. But *Feeder 2* can tolerate 30% PEV load whilst it is concentrated to front end poles as illustrated in Figure 5.6. Voltage drops at far end poles beyond the regulation limit as a result of connecting 20% and 30% PEV loads randomly and at far end poles.

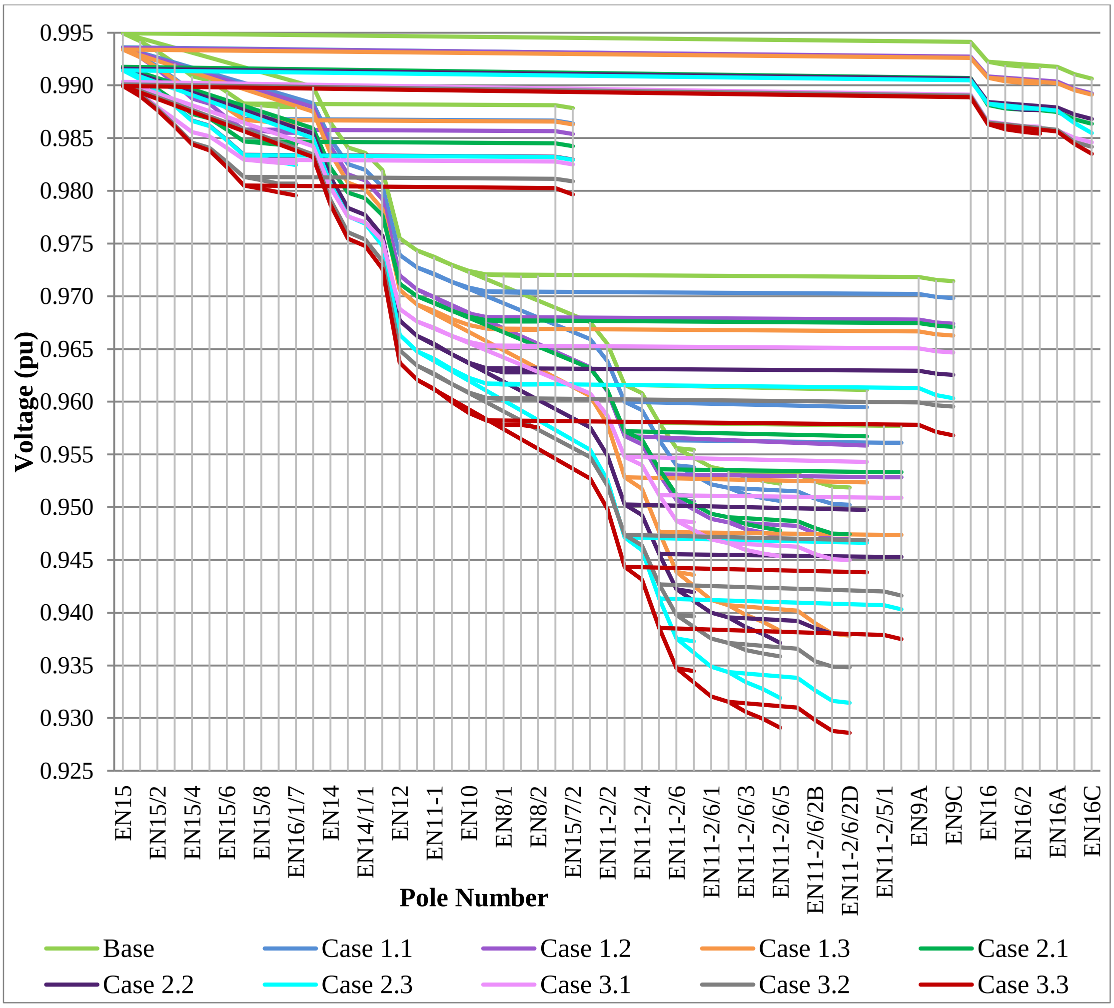


Figure 5:6: Voltage profile of Feeder 2 under nine cases

- Highlights on *Feeder 3* analysis

Its distribution transformer is loaded up to 60% of its full load. *Feeder 3* can tolerate 10% PEV load disregarding its locations. As illustrated in Figure 5.7, 20% and 30% PEV load are acceptable whilst they are concentrated to front end poles only.

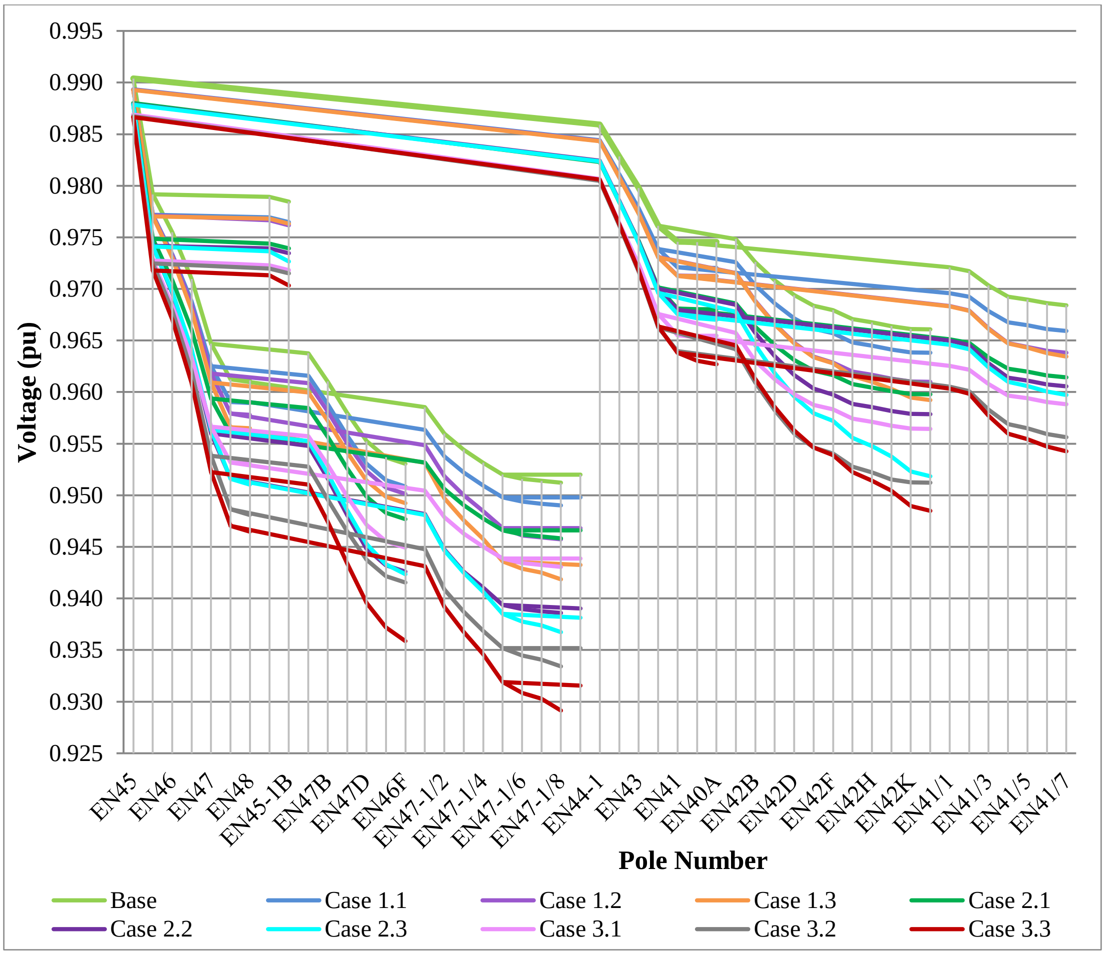


Figure 5:7: Voltage profile of Feeder 3 under nine cases

Sub feeders are illustrated as branches in the voltage profiles. All three feeders can tolerate 10% PEV load while they are connected randomly and front end poles. But when 10% PEV load is concentrated to far end nodes violation is begun in *Feeder 1* and *2*. The simulations results regarding 10% of PEV load, reveal that 10% PEV load penetration level can be accepted by the lightly loaded distribution feeder but highly loaded feeders cannot. Analysis on voltage profile reveals two points. One is differently loaded distribution feeder can accept different number of PEV connections. Lower the transformer loading, higher the allowable PEV load penetration. The second point is the voltage profile of the distribution feeder is directly affected by the location of PEV load connection.

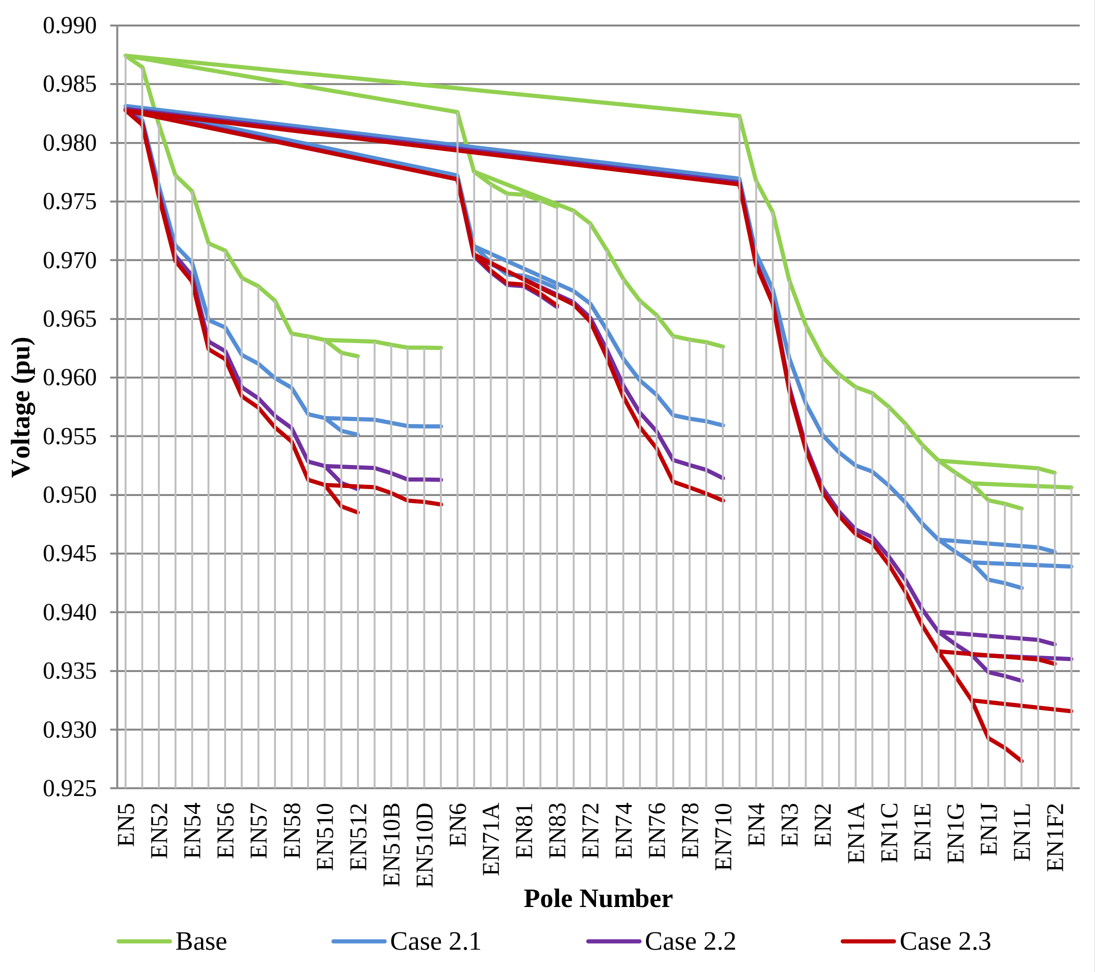


Figure 5:8: Voltage profile of Feeder 1 under 20% PEV load at different locations

The influence of the location of PEV connection for the same PEV load is demonstrated in Figure 5.8. Higher the distance to the transformer from the point of PEV load connection, greater the impact on the voltage profile. It can also be verified by the recorded minimum voltage variation of each feeder shown in Figure 5.9. Minimum voltage always reported from the farthest end of the mostly loaded sub feeder.

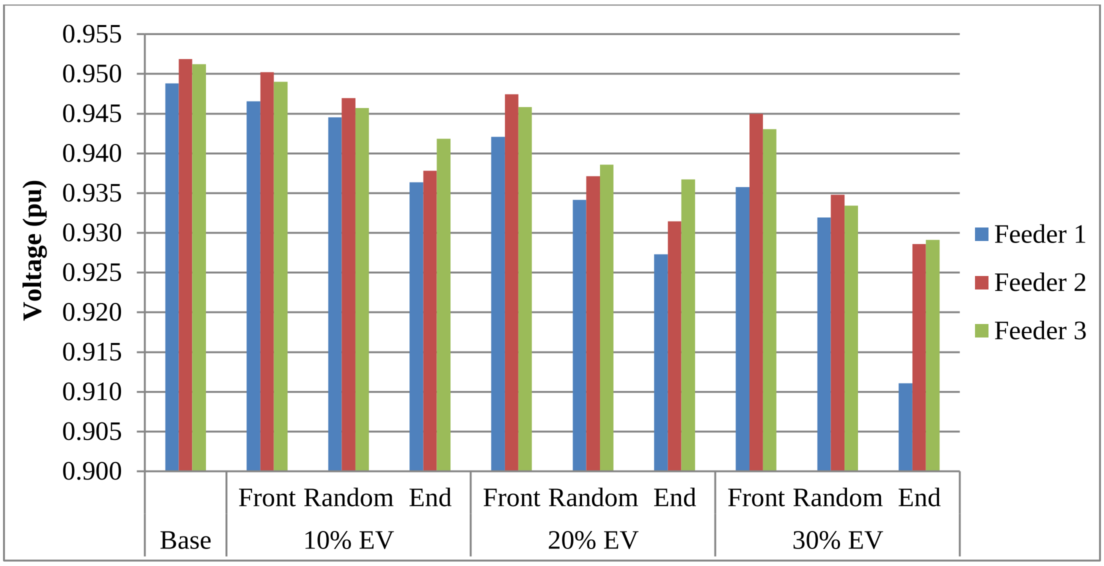


Figure 5:9: Minimum voltage variation of distribution feeders for different cases

Minimum voltage variation gives the clear picture of voltage regulation limit violations in all three feeders under nine different cases. Voltage violations are always found when PEVs are connected at far end poles and becoming worse with the increasing PEV load. The extent of voltage drop is lesser when PEV load concentrated to front end poles.

Voltage regulation limit violation not happens until PEV load connected to front end nodes of *Feeder 2* as shown in Figure 5.9. But the extent of voltage drop of *Feeder 3* is lesser compared to highly loaded *Feeder 1*.

5.3 Impact on Transformer loading

An optimum loading level for a typical distribution transformer can be considered to be 80% of its full load in order to retain the maximum efficiency [49]. Impact on transformer loading also studied under the nine cases mentioned in Section 5.2. Summary of simulation results are plotted for each feeder in Figure 5.10.

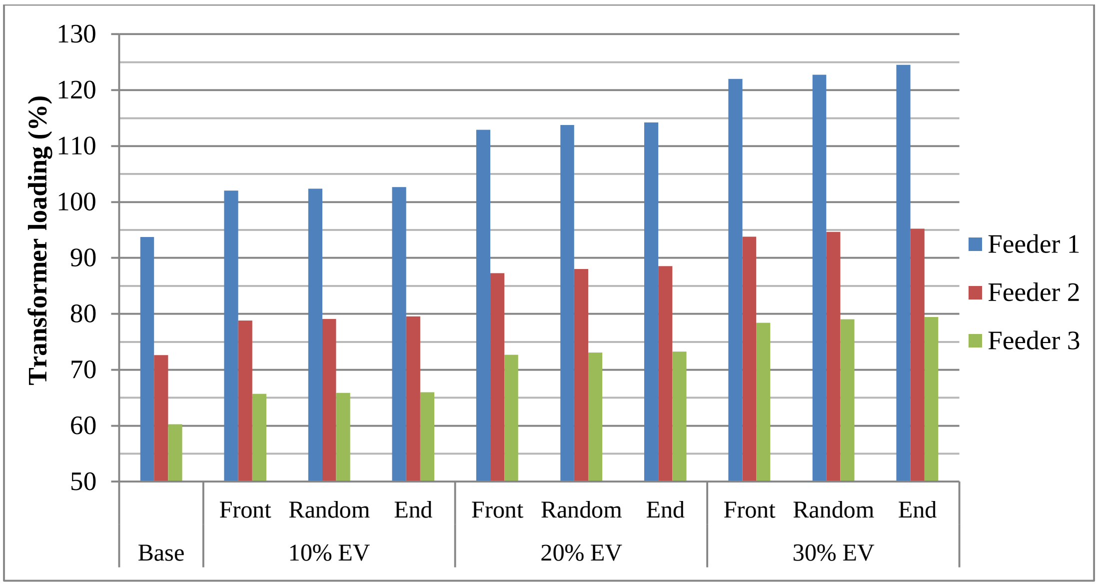


Figure 5:10: Transformer loading of distribution feeders for different cases

Addition of 10% PEV load causes overloading of *Feeder 1* transformer as it is already loaded up to 93%. Connection of 30% PEV load at far end poles, results in nearly 25% of overloading of the transformer as illustrated in Figure 5.10. But 80% normally loaded distribution transformer can tolerate 125% loading for 2 hours [50]. Therefore PEV load can be withstood by *Feeder 1* transformer during peak hour. But when increasing PEV load coincides with the electricity demand growth, this situation would be worse. Consequently capacity improvement would be necessary for already loaded distribution feeders to cater both increasing PEV load and the demand growth.

A small increase in transformer loading can be noticed with varying locations of the PEV load. It implies that PEV load locational effect is lower on transformer loading. Lightly loaded *Feeder 2* and *3* distribution transformers are not exceeded their capacity at any case disregarding the location of PEV load connection as shown in Figure 5.10.

5.4 Power Losses due to PEV charging

Generally losses are increasing with the increasing demand. Transformer losses are not included as the power is measured at the secondary terminal of the transformer.

Calculated power losses are plotted against each case described in Section 5.2 and shown in Figure 5.11.

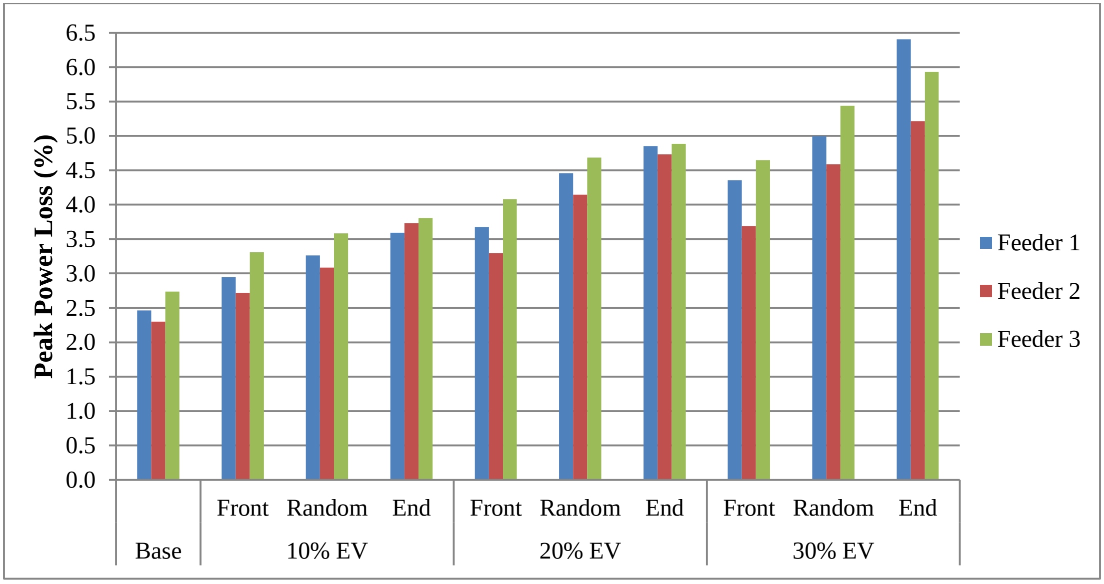


Figure 5:11: Power losses of distribution feeders for different cases

Power losses increase with the increasing PEV load as well as the distance to the PEV load as illustrated in Figure 5.11. 30% PEV load connected at far end cause more than 6% power loss as most of the distant nodes are highly loaded.

Power losses of *Feeder 2* are lesser compared to *Feeder 1* and *3* as the numbers of PEVs are lesser corresponding to PEV load levels. As illustrated in Figure 5.11 power loss of *Feeder 3* are nearly similar to the *Feeder 1* power loss as the numbers of PEVs are same for corresponding PEV load levels.

Peak power losses are compared with the base load power losses. Losses are increased with the increasing PEV penetration level. Increase of power losses can be noticed in same PEV penetration level due to the variation of PEV load connection location. Power losses are greater when PEVs connected in the far end points of the distribution feeder. When PEVs are connected to far end points of the feeder, they draw high current continuously for 6 to 8 hours along a longer distance. That causes the increase of power losses compared to the connection to front end points and randomly selected points.

5.5 Impact on voltage unbalance of LV distribution feeder

Voltage unbalance occurs due to asymmetrical load distribution among three phases. Distribution networks are considered have some level of natural unbalance as single phase connections are more dominant in residential feeders and the load balancing is not practical. If unusual voltage unbalance reported, utility takes measurements of distribution transformers, and then it will be rectified by adjusting the connections among three phases. But it is done at regular time periods. Thus natural voltage unbalance is always retaining.

5.5.1 Quantification of voltage unbalance

Voltage unbalance can be derived according to two international definitions. NEMA (National Electrical Manufactures' Association) defines voltage unbalance as the percentage ratio between the maximum voltage deviation from the average line voltage and the average line voltage [51] which is shown in the Equation 5.1. IEC standard defines degree of voltage unbalance as the ratio of the negative sequence voltage component to the positive sequence voltage component [52] as shown in the Equation 5.2. In Sri Lankan distribution code voltage unbalance is defined according to the NEMA definition [53]. Hence NEMA definition is used for calculation of the voltage unbalance factor (VUF).

$$VUF = \frac{Maximum\ deviation\ from\ the\ average\ three\ line\ voltage}{Average\ three\ line\ voltages} \times 100\% \ldots\ldots\ldots\ldots 5.1$$

$$VUF = \frac{V_2}{V_1} \times 100\% \ldots\ldots\ldots\ldots 5.2$$

According to the distribution code of Sri Lanka, unbalance caused by individual loads should be kept within 1.3%, although short term deviations (less that 1 minute) may be allowed up to 2% [53].

5.5.2 Voltage Unbalance due to Residential PEV charging

Most of the PEV users have single phase electricity supply. While they plug their PEV to the wall socket, it draws a larger current from the particular phase causing unbalance among three phases. Considering this fact, impact of single phase PEV charging on voltage unbalance of LV distribution feeders is studied. In order to represent the natural voltage unbalance, number of connections of each feeder is divided among three phases on the basis of phase sequence A, B and C as shown in Figure 5.12.

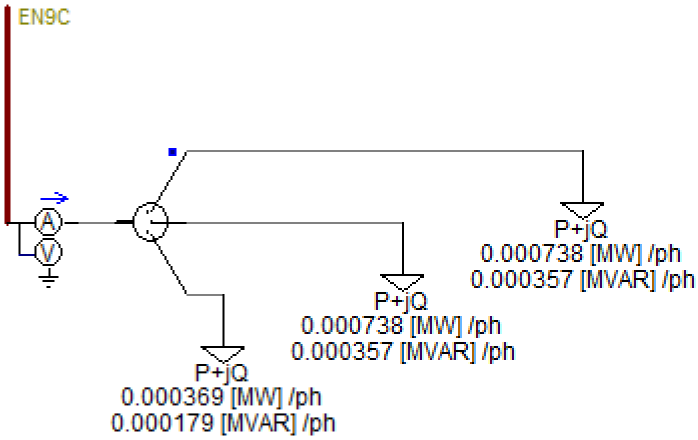


Figure 5:12: Unbalance base load model of Feeder 2

Natural voltage unbalance due to the base load of each feeder is shown in Figure 5.13.

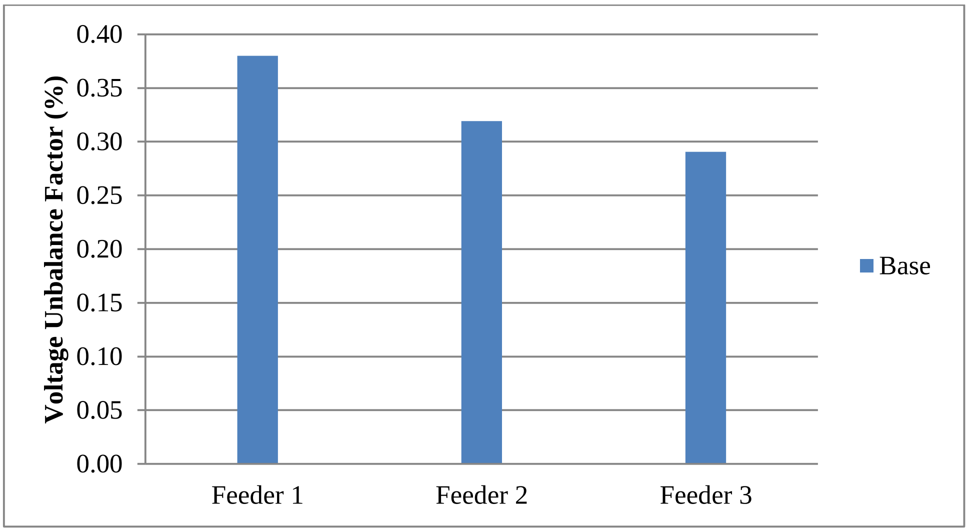


Figure 5:13: Voltage unbalance under base load of each feeder

PEV users already have their electricity connection prior to purchasing of PEV. Thus utility had considered only their household electricity consumption and given the connection considering the phase balance. Earlier power consumption will be changed once purchasing of PEV. Utility will have to rearrange the phase connection of PEV user in order to retain phase balance. There may be few PEV users connected to the same feeder. For the purpose of analyzing the worst case, all PEV users are connected to the Phase A. The probability of connecting all PEV users to same phase is very low, but it is not impossible. For example, if there are four PEVs are available, their existing connection may be connected to the same phase as the electricity connection established prior to the purchasing of PEVs. Each feeder is modeled and simulated under three PEV penetration levels and shown in Figure 5.14.

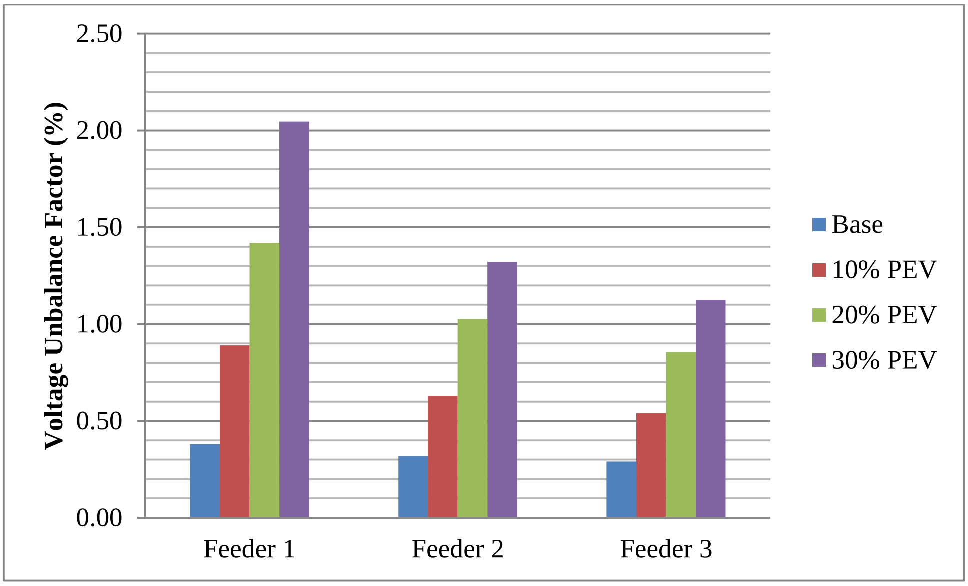


Figure 5:14: Voltage unbalance caused by the single phase PEV charging

Voltage unbalance is measured at the secondary terminals of the distribution transformer. According to the simulation results, 30% PEV load connection to the *Feeder 1* will cause for exceeding the regulation limit of 2%. Hence unbalance caused by the residential PEV charging can be tolerated up to 20% PEV load increase in case of highly loaded feeder. As mentioned before, the probability of 30% PEV loads connecting to the same feeder is very low. Hence, unbalance caused by the single phase PEV charging can be catered by the feeders which have very low natural unbalances.

6. MITIGATION ACTIONS ON DISTRIBUTION FEEDERS

Chapter 4 and 5 contain the impacts on MV and LV distribution systems due to increasing demand of single phase and three phase charging of PEVs. Some mitigation actions to be taken to cater the increasing PEV load with the minimized effects on MV and LV distribution networks. Shifting of PEV loads to the off-peak hours may have considerable benefits in reducing negative impacts on the power network under a high penetration level of PEVs. Therefore off peak PEV charging is analyzed using the LECO *Feeder 1* model as it recorded the worst results. Under off-peak PEV charging voltage profile, transformer loading and losses are analyzed.

6.1 Minimizing the impact on voltage profile of the MV and LV network

10% residential PEV charging load can be marginally tolerated by the MV network. But DC fast charging stations which are connected to far end nodes of MV network can make a greater impact on voltage profile during night peak hours.

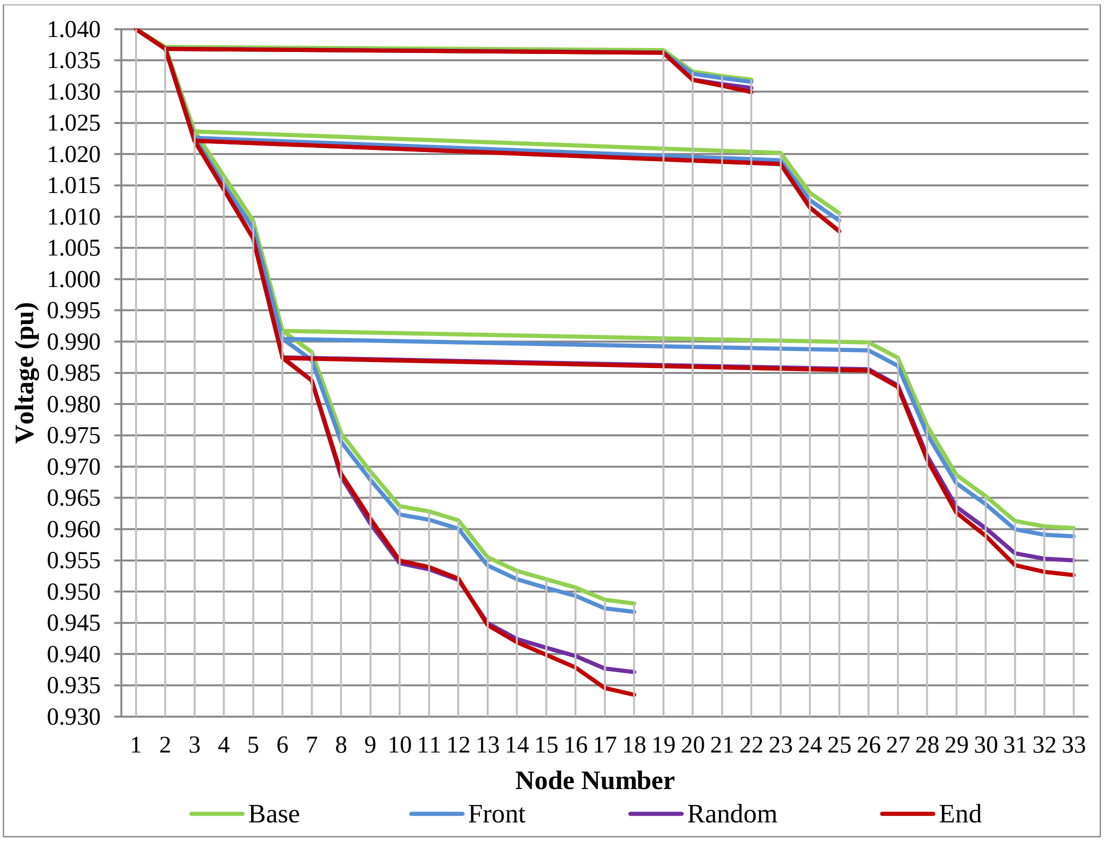


Figure 6:1: Voltage profile of MV network - DC fast chargers connected at different locations

DC fast charging stations do not have specific charging time. Hence the location where the charging station is connected to be considered in order to minimize the impact on the voltage profile of the MV network as shown in Figure 6.1. If charging stations are established closer to the primary substation, it will have negligible impact on voltage profile of the MV network.

Residential PEV charging during night peak time has a greater impact on voltage profile of the LV distribution feeders. Hence, in order to minimize the impact on voltage profile residential PEV charging can be shifted to off-peak time during the day. According to the derived off-peak loading pattern, LECO *Feeder 1* is re-modeled and simulated under aforementioned scenarios given in Section 5.2. In order to make a clear impression of lesser impacts of off-peak PEV charging both peak and off-peak voltage profiles are plotted together in Figure 6.2.

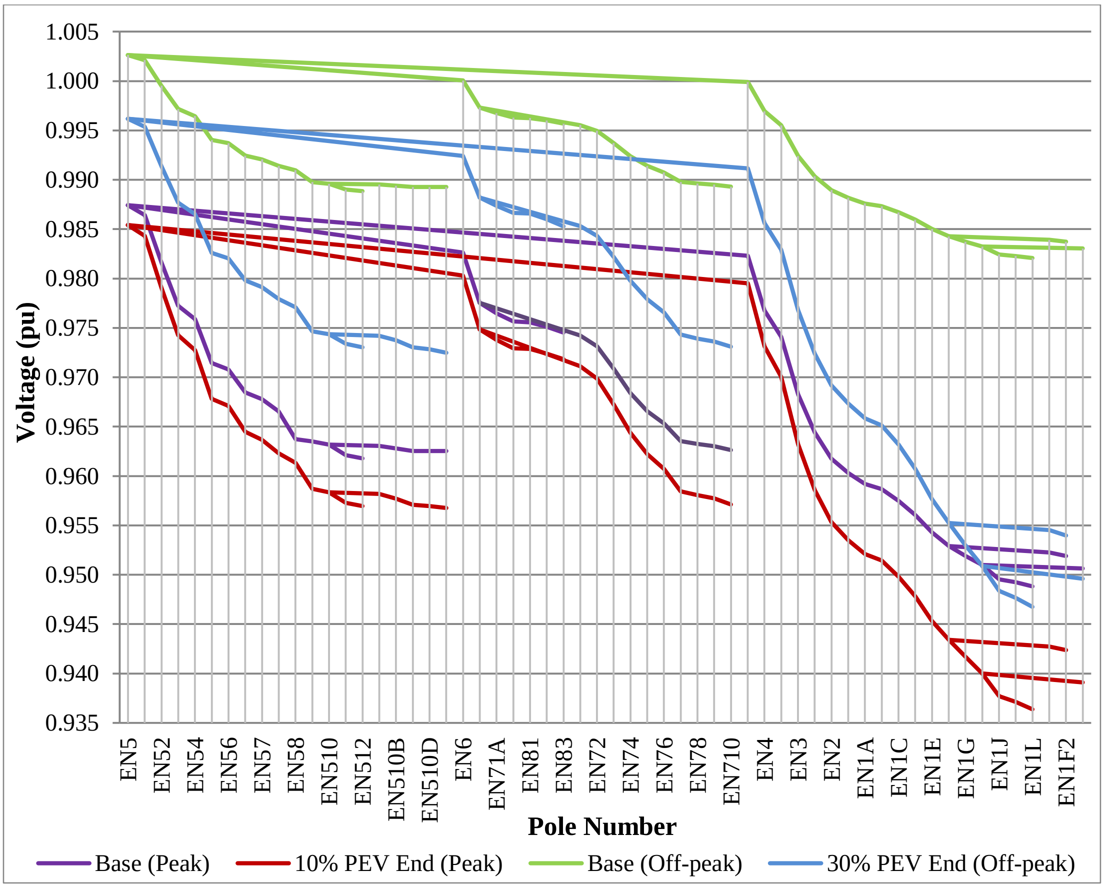


Figure 6:2: Voltage profile of Feeder 1 - Peak Vs. Off-peak PEV charging

Figure 6.2 shows that the connection of 30% PEV at the far end points during off-peak does not violate the regulation limit while connection of 10% PEV load at the far end points during peak does. Hence the impacts on voltage profile of LV distribution feeder can be rectified by shifting the residential single phase PEV charging to off-peak hours.

6.2 Minimizing the impacts on transformer loading

LECO *Feeder 1* is exceeded its capacity even under the 10% PEV load connection during the peak time. Thus, capacity exceeding of already loaded distribution transformer can be stopped during peak time by shifting residential PEV load to off-peak hours.

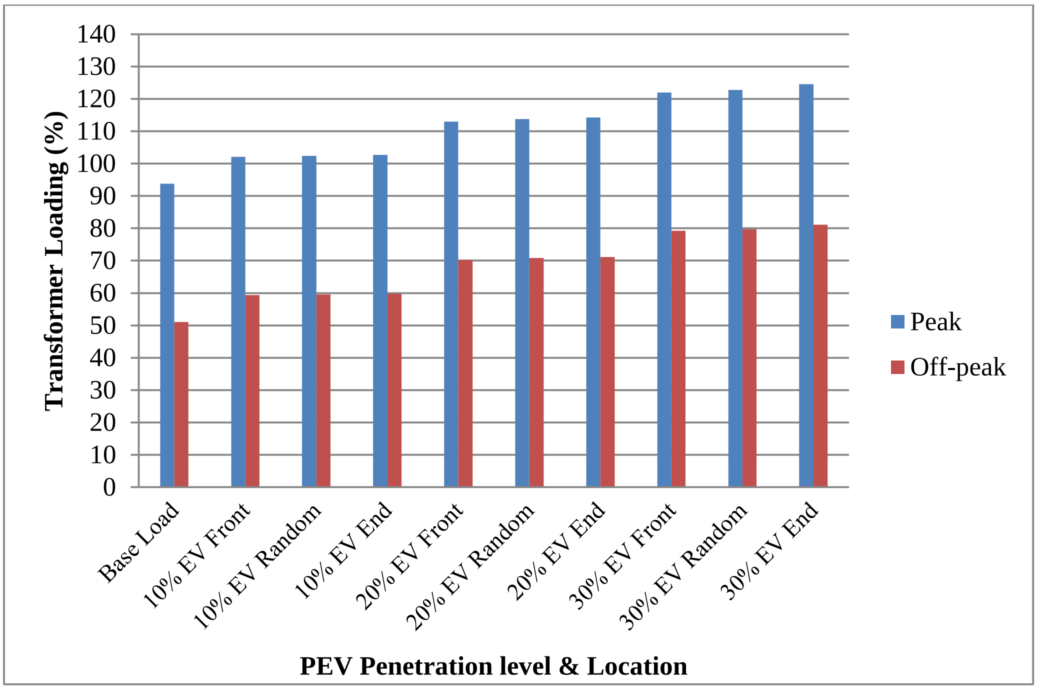


Figure 6:3: Transformer loading of Feeder 1 - Peak Vs. Off-peak PEV charging

As shown in Figure 6.3, transformer capacity is not exceeded at any of the above PEV penetration level. Hence shifting residential PEV load to off-peak hours will be a greater solution instead of capacity improvements.

6.3 Minimizing the power loss due to PEV charging

As shown in previous sub sections, off-peak PEV charging has negligible impacts on LV distribution feeder. Similarly power loss of *Feeder 1* has been reduced. Power losses are very low compared to the losses caused by peak PEV charging as shown in Figure 6.4. But off-peak PEV charging will cause considerable increase in power losses compared to off-peak base load.

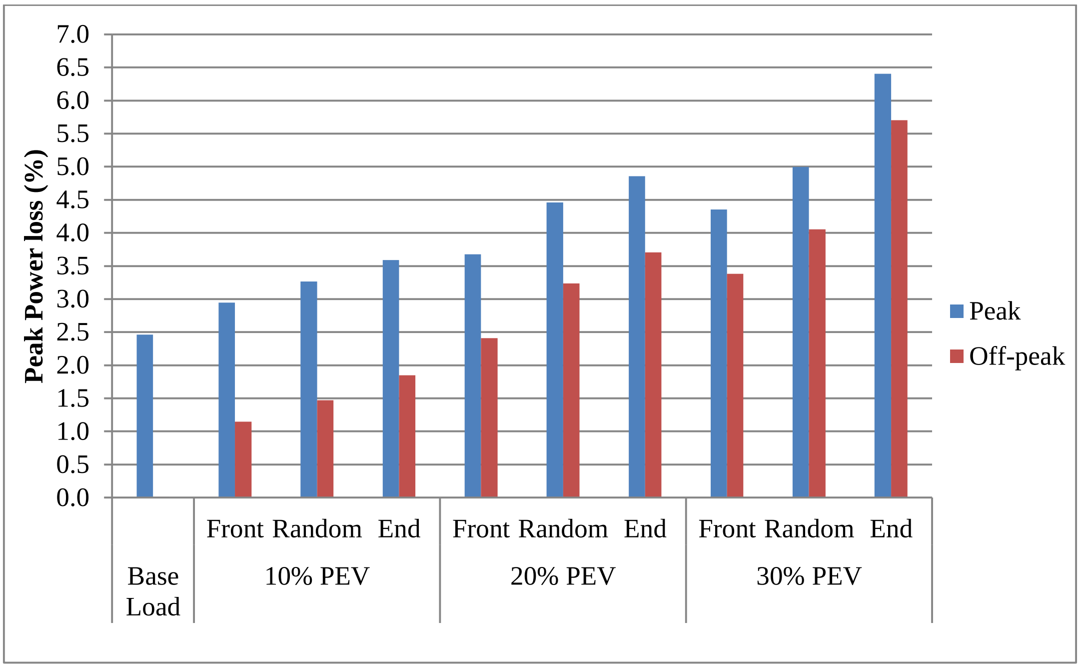


Figure 6:4: Power Losses in Feeder 1 - Peak Vs. Off-peak PEV charging

6.4 Minimizing the unbalance due to PEV charging

Voltage unbalance caused by the single phase PEV charging does not violate regulation limit of 2% until 20% of PEV load connected to *Feeder 1*. But when 30% of PEV load is connected to the *Feeder 1*, voltage unbalance exceeds the regulation limit.

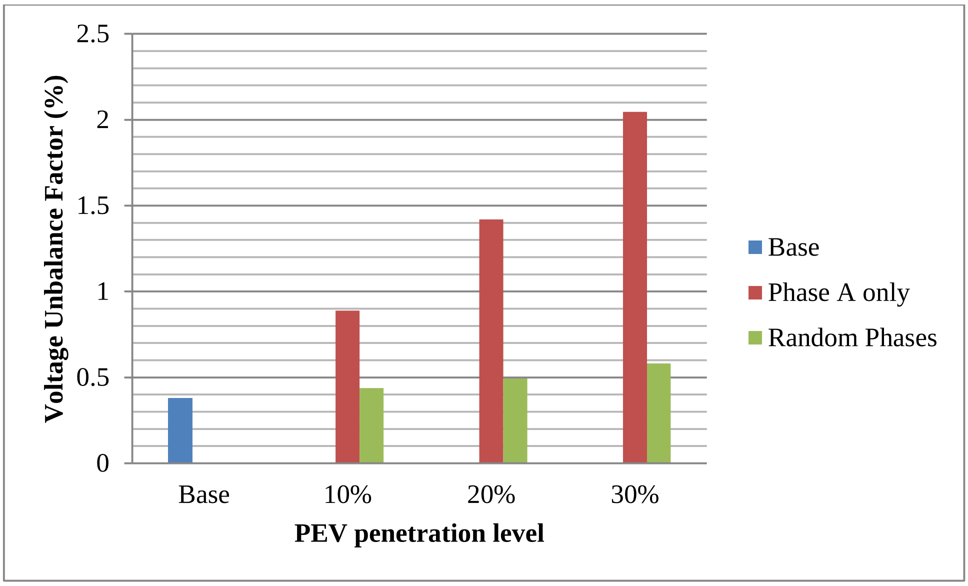


Figure 6:5: Voltage unbalance of Feeder 1 – Phase "A" only Vs. Random Phase PEV charging

Hence electricity connections of PEV users must be re-adjusted among three phases. Voltage unbalance can be rectified by increasing the phase diversity of PEV users. It can be shown in Figure 6.5. When PEV user connections are diversified among three phases, voltage unbalance can be retain below 1% even under the 30% of PEV load.

6.5 Maximum PEV Penetration for selected LECO feeders

Charging infrastructure is developing day by day and importing tax has been reduced. In order to cater the increasing PEV load in the near future, impacts on power distribution network due to uncoordinated PEV charging to be minimized. Thus residential PEV charging load can be shifted to off-peak hours by introducing time of day tariff system to single phase customers as well as three phase customers. If PEVs are charged during off-peak (22.30 to 05.30 hours) most of the effects on LV distribution feeder can be minimized as discussed in above Section 6.1, 6.2, and 6.3.

Identifying the maximum allowable PEV load is essential for the adoption of increasing PEV load, without further influence on power distribution network. Impact on LV distribution feeder due to residential PEV charging is greater than the MV distribution feeder. Hence LV distribution feeders are analyzed in order to find the maximum allowable PEV load. Maximum number of PEVs is determined based upon the voltage regulation criteria and the transformer capacity. Maximum numbers of PEVs allowable for three distribution feeders are summarized in Table 6.1. Percentage PEV load is defined based on the night peak load of each feeder.

Table 6.1: Maximum number of PEVs allowable for each feeder

	Peak				Off-peak			
	Front End		Far End		Front End		Far End	
	Nos	% of max. load	Nos	% of max. load	Nos	% of max. load	Nos	% of max. load
Feeder 1	3	6.73	2	4.49	22	49.37	17	38.15
Feeder 2	13	37.64	3	8.69	29	83.96	18	52.11
Feeder 3	17	38.01	5	11.18	49	109.43	22	49.19

Off-peak PEV charging can be allowed more number of PEVs than peak time PEV charging without violating any limit. PEV handling capacity also depends on the loading level and geographical configuration of the feeder.

7. CONCLUSIONS

7.1 Conclusions

Increasing PEV demand will create some issues on power distribution network as identified by this research study. But PEV charging has not become a critical problem to the existing power distribution network under the present PEV penetration level. The approached conclusions according to the simulation results are summarized.

- A greater influence has been created by PEV charging on voltage profile of MV and LV network. As the PEV penetration level increases, voltage of each node decreases. Voltage violations occur at distant nodes with the increasing PEV load. Voltage of the farthest node of IEEE 33 network reported as 0.939 pu, 0.935 pu and 0.930 pu respectively for 10%, 15% and 20% residential PEV charging load.
- Not only the increasing PEV load but the locations of PEV connection also influence the voltage profile of the particular feeder. IEEE 33 network can tolerate nine DC fast chargers while they are connected to closer nodes or random nodes. But when they are connected to far end nodes of each sub feeder, it causes voltage violations. Same observation can be seen in the LECO distribution feeders. LECO *Feeder 1* can accommodate 10% residential PEV charging load if it is concentrated to front end poles or randomly distributed poles. But the same 10% PEV load connected at far end poles causes voltage violations in the LECO *Feeder 1*.
- The short feeders have higher charging load handling capability than the long feeders. In case of IEEE 33 network analysis, four DC fast chargers are connected at the shortest sub feeder and one is connected at the longest sub feeder end without causing violations at any node. Thus, 10% PEV DC fast charging load can be accepted if short feeders are thoroughly loaded.
- Even heavily loaded distribution transformer feeder could accommodate increasing PEV load during peak time at the moment. As transformer can withstand 25% overloading due to 30% PEV charging for two hours during

night peak. But increasing PEV penetration will make stress on already loaded distribution transformers when it coincides with electricity demand growth.

- Irrespective of the peak or off-peak charging, increasing PEV load causes higher power losses of the distribution feeder. But the loss during off-peak PEV charging is lesser than peak PEV charging. 30% PEV load causes 6.4% and 5.7% of power loss in the LECO *Feeder 1* respectively during peak and off-peak hours.
- Voltage unbalance in distribution feeders due to the increasing single phase PEV load is expected to be higher. But analysis shows that the voltage unbalance caused by the increasing single phase PEV load in LECO distribution feeders are within the acceptable limits. Simulated voltage unbalance results may be different from the real situation. Since the load is modeled based on the ADMD approach, it may deviate from actual load distribution among three phases. Hence the accuracy of voltage unbalance studies may not be acceptable.
- Current total harmonic distortion at the PCC of single DC fast charging stations is not acceptable. The modeled ABB Tera 53 DC fast charger causes 28.45% of total harmonic distortion of current waveform violating the limit of 15% at PCC. 5^{th} harmonic component is dominant among the individual harmonic resulting 21% of fundamental magnitude. However the harmonic analysis of IEEE 33 network shows the current and voltage total harmonic distortion is tolerable at the source end. In this analysis only fast charging stations are considered as non-linear loads. But in reality MV network may be consists of many other neighborhood harmonic generating loads. Hence the effect on harmonic propagation in MV network due to increasing DC fast charging cannot be predicted accurately. However this analysis can be extended to obtain accurate results with more practical data.
- Off-peak PEV charging will reduce the burden on voltage profile of the distribution network, transformer loading and power losses. Even though the heavily loaded LECO *Feeder 1* cannot tolerate 10% PEV load during night

peak, it can accommodate 38% PEV load during off-peak hours without causing any violations in the voltage or the transformer capacity as illustrated in Table 6.1. Power loss also reduced by 0.7% when 30% PEV load is shifted from peak to off-peak. Hence, off-peak PEV charging can be recommended to mitigate most of the effects due to PEV charging.

- Peak and off-peak PEV accommodation capacity of 400m long, 160kVA distribution transformer feeder is given in the Table 7.1.

Table 7.1: PEV accommodation capacity of an urban distribution feeder

% of Transformer loading	Front End		Far End	
	Max. No. of PEVs	% of PEV load	Max. No. of PEVs	% of PEV load
90%	3	6.19	2	4.13
80%	10	20.63	6	12.38
70%	15	30.94	12	24.75
60%	20	41.25	17	35.06
50%	25	51.56	21	43.31
40%	29	59.81	26	53.63

7.2 Limitations

Major limitation of this study is finding real data regarding PEV diffusion over the geographical area and measured values of distribution feeder consumer loads. Assumption on the load modeling based on ADMD approach may deviate from actual load distribution over the three phases and hence the accuracy of voltage unbalance studies may not be acceptable. Further, actual PEV penetrations of the selected feeders are not known and the selection is based on the fact that more PEVs can be widely dispersed in urban areas. If number of PEVs could be obtained based on the vehicle density in the particular area, analysis would be more practical.

Only peak PEV charging was considered for analyzing the impacts on the distribution feeder. If the load profiles of each pole can be modeled and simulated, impact on load profile would be analyzed due to PEV charging throughout the day. But the worst possibility is analyzed through the simulations. Even the actual data is not available, simulations and analysis had been carried out based on the assumptions, in order to represent the worst possible real situation as much as possible. Hence this analysis can be extended to identify the impacts on power distribution feeders in Sri Lanka along with realistic data.

7.3 Suggestions for further study

PEV demand is growing day by day due to environmental friendliness, low operational and maintenance cost, tax reductions and developing charging infrastructure. A local company has already started manufacturing a super electric car. Thus, PEVs have attracted the interest of Sri Lankan community. Hence, further research studies are required in order to meet the challenges arisen from the growing PEV penetration in Sri Lanka.

This research mainly discussed the impacts on the power distribution network due to the DC fast charging and single phase residential PEV charging only during the peak hours. Charging facilities are being developing and may be available in parking lots, office premises in near future. Hence there is a possibility of increasing PEV charging load at any time of the day. Charging of PEVs throughout the day must be analyzed in order to study the impact on load profile of the distribution feeders.

In order to minimize the effect due to uncoordinated PEV charging, off-peak PEV charging can be promoted by developing TOU tariff scheme for single phase customer. Study the viability of integrating such tariff scheme would be beneficial to the power system as well as the PEV owners.

There are more key research areas related to PEVs. Adoption of Vehicle to Grid (V2G) concept to Sri Lankan power system is one of the vast research areas. Under V2G concept, how to integrate PEVs in demand management, frequency regulation and as a spinning reserve to be further studied. PEV integration along with renewable energy sources is another research area. Some PEV owners already use domestic solar panel with net-metering. Smart charging of PEVs is another key research field.

Current harmonics produced by the DC fast chargers are not in acceptable range. Hence further studies are essential, along with real data in order to compensate generated current harmonics by DC fast chargers.

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APPENDIX I

Total PEV Load calculation:

Data :- 3.3kW charger (Nissan Leaf)

Total number of passenger cars - 672502 by 2015 [38].

Assumptions :- 10% of Passenger cars are replaced with PEVs [2]

Each EV charge once in three days

Each car will charge at night peak time on a day (at 7.00 pm)

$$Total\ PEV\ load = 672502 \times 10\% \times \frac{1}{3} \times 3.3\ kW = 73975.22kW \approx 74MW$$

** If total number of passenger cars in 2015 are replaced with PEVs night time peak demand of Sri Lankan load curve will rise by 74 MW.

Fuel cost calculation

Data : Fuel Economy of a Nissan Leaf = 24kWh/135.18km = 0.178kWh/km [22]

Average cost of a kWh = Rs.25 [39]

Fuel Economy of a ICEV = 1/12 l/km = 0.083 l/km [20]

Cost of a petrol liter = Rs.117 [54]

Assumption: PEV is charged within day hours and consumer has three phase electricity connection.

$$Fuel\ cost\ per\ km\ of\ a\ PEV = \frac{0.178kWh}{km} \times Rs.\frac{25}{kWh} = Rs.\frac{4.45}{km}$$

$$Fuel\ cost\ per\ km\ of\ an\ ICEV = 0.083\frac{l}{km} \times Rs.\frac{117}{l} = Rs.\frac{9.71}{km}$$

$$Fuel\ cost\ saving\ from\ ICEV\ to\ PEV = Rs.9.71 - Rs.4.45 = Rs.5.26$$

APPENDIX II

Global PEV stock from 2005 to 2015 (in thousands)

Country	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Canada							0.52	2.60	5.71	10.78	18.45
China						1.43	6.50	16.40	31.74	104.91	312.29
France	0.01	0.01	0.01	0.01	0.11	0.30	2.93	9.25	18.88	31.50	54.29
Germany	0.02	0.02	0.02	0.09	0.10	0.25	2.34	6.13	13.25	26.03	49.22
India				0.37	0.53	0.88	1.33	2.76	3.13	4.02	6.02
Italy	0.53	0.53	0.53	0.60	0.60	0.64	0.76	1.42	2.47	3.99	6.13
Japan					1.08	3.52	16.14	40.58	69.46	101.74	126.40
Korea						0.06	0.34	0.85	1.45	1.52	4.33
Netherlands				0.01	0.15	0.27	1.14	6.26	28.67	43.76	87.53
Norway				0.25	0.39	0.79	2.80	7.21	15.42	35.21	70.82
Portugal						0.02	0.22	0.32	0.53	0.82	2.00
South Africa									0.03	0.05	0.29
Spain						0.07	0.65	1.20	2.21	3.66	5.95
Sweden		0.12	0.13	0.13	0.16	0.19	0.37	1.25	2.65	7.09	14.53
United Kingdom					0.19	0.29	1.37	3.78	7.28	21.86	49.67
United States	1.12	1.12	1.12	2.58	2.58	3.77	21.50	74.74	171.44	290.22	404.09
Others*							1.73	4.48	8.76	19.59	44.89
Total	**1.67**	**1.78**	**1.79**	**4.04**	**5.89**	**12.48**	**60.65**	**179.23**	**383.09**	**706.77**	**1256.90**

* Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, Greece, Hungary, Iceland, Ireland, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Poland, Romania, Slovak Republic, Slovenia, Switzerland, Turkey.

Source: Global EV Outlook 2016, International Energy Agency (IEA) - Table 6

APPENDIX III

New vehicle registrations of Sri Lanka in 2014 [38]

Class of Vehicle	Motor cars					3 Wheelers							Buses		Motor Cycles			Dual Purpose Vehicles				Single Cab			Special Purpose Vehicle			Motor Lorry									L.V.Tractors			Total
						Motor Tricycle Car	Motor Tricycle				Motor Tricycle Van																	Lorry			Prime Mover	Ambu-lanses		Herses		Lorry Trailer	Hand Tractor	Tractor	Tractor Trailer	
Month	Die.	Petrol	Petrol/ Electric	Die/ Elec	Elec-tric	Petrol	Diesel	Petrol	Elec-tric	Pet/ Elec	Die.	Pet.	Diesel	Pet.	Pet/ Ele	Ele	Petrol	Diesel	Ele	Pet/ Ele	Pet.	Diesel	Pet.	Ele	Die.	Ele	Pet.	Die.	Die/ Ele	Pet.	Die.	Die.	Pet.	Die.	Pet.	Non Fuel	Diesel	Diesel	Non Fuel	
January	401	1,095	902		4		440	5,476			25	3	170		2	8	16,559	207			45	1,472	27		53		1	312			31			1	2	7	602	187	149	28,181
February	362	753	772		6		402	4,714			30	2	122			8	13,982	204			32	873	29		59		1	270			1	88			1	7	419	99	145	23,381
March	291	843	897		6		455	5,802			31	4	240		1	4	16,190	195			41	1,337	31		60			292			8	2			3	15	407	125	182	27,462
April	370	957	1,074		4		465	6,321			19	4	174		2	19	17,432	144			29	1,191	28		43			226		1	1	1	2			2	248	76	89	28,922
May	287	909	1,180		10		388	5,341			18	3	167			24	15,965	237			56	1,321	37		41		1	249			8	1				6	404	101	158	26,912
June	259	908	1,471		10		479	5,619			26	2	169			27	16,758	152			54	1,419	25		64		4	342			12	1			4	7	335	101	149	28,397
July	254	1,018	1,953		11		555	6,560			27	3	190	1	1	20	20,026	216			44	1,609	45		80			366			10	2				12	355	125	159	33,642
August	186	891	1,998		7		482	5,939			27	2	279			21	19,404	191			54	1,494	34		79		5	310			26					19	258	153	221	32,080
September	237	1,230	3,409		17		494	7,012			31	1	519		1	24	24,412	206			58	1,648	34		106			355			20	3	1		3	21	324	218	189	40,573
October	199	832	3,002		6		485	6,740			24	1	589			22	35,592	162			52	1,535	38		71			371			6	3			1	26	503	303	163	50,726
November	134	795	2,899		9		485	6,389			19	2	532			11	37,272	182			47	1,294	31		57			336			22	1	2			12	587	313	199	51,630
December																																								0
Total	2,980	10,231	19,557	0	90		5,130	65,913	0	0	277	27	3,151	1	7	188	233,592	2,096	0	0	512	15,193	359	0	713	0	12	3,429	0	1	145	102	5	1	14	134	4,442	1,801	1,803	371,906

New vehicle registrations of Sri Lanka in 2015 [38]

Class of Vehicle	Motor cars					3 Wheelers: Motor Tricycle Car	3 Wheelers: Motor Tricycle				3 Wheelers: Motor Tricycle Van		Buses		Motor Cycles			Dual Purpose Vehicles			
Month	Die.	Petrol	Petrol/ Electric	Die/ Elec	Elec- tric	Petrol	Diesel	Petrol	Elec- tric	Pet/ Elec	Die.	Pet.	Diesel	Pet.	Pet/ Ele	Ele	Petrol	Diesel	Ele	Pet/ Ele	Pet.
January	178	2,099	4,371		15		512	7,810			28		744	1		7	30,004	578		2	313
February	165	2,043	2,819	29	14		491	7,184	1		31	2	291			10	25,568	550	1	2	313
March	200	3,581	2,978	19	29		762	11,716			47	5	496		1	7	42,171	561	1	2	502
April	246	3,177	2,362	15	148		749	10,063			23	1	180			4	26,886	484			498
May	156	3,475	2,731	16	360		649	10,261	1		34	2	288			3	27,574	488			517
June	178	4,646	3,366	21	258		769	10,700			40		256		1	10	30,987	590	4	1	567
July	219	5,889	4,042	19	283		825	11,464		2	44	3	326			21	33,351	631	4	1	590
August	168	5,425	3,806	21	382		620	9,709	1		36	6	345		2	28	26,529	555	6	1	687
September	315	9,182	5,016	32	472		785	11,575	1		30	5	337		1	13	30,513	669	7	3	737
October	248	6,922	3,960	15	534		476	7,786			33	4	271		1	17	32,176	562	6	2	603
November	232	6,948	3,213	10	491		604	12,571			31	2	316		4	16	32,380	484	5		420
December	183	5,415	2,220	19	252		751	10,260			39	3	289		2	31	32,571	363	2		245
Total	2,488	58,802	40,884	216	3,238		7,993	121,099	4	2	416	33	4,139	1	12	167	370,710	6,515	36	14	5,992

Class of Vehicle	Single Cab			Special Purpose Vehicle			Motor Lorry: Lorry			Motor Lorry: Prime Mover	Motor Lorry: Ambu- lanses		Motor Lorry: Herses		Motor Lorry: Lorry Trailer	L.V.Tractors: Hand Tractor	L.V.Tractors: Tractor	L.V.Tractors: Tractor Trailer	Total
Month	Diesel	Pet.	Ele	Die.	Ele	Pet.	Die.	Die/ Ele	Pet.	Die.	Die.	Pet.	Die.	Pet.	Non Fuel	Diesel	Diesel	Non Fuel	
January	1,626	37		58		1	373			18	5	1	1	2	8	478	111	164	49,545
February	1,668	46		55			376			26	6			1	25	323	150	157	42,347
March	2,379	85		76			404		1	34	1		1		23	387	223	197	66,889
April	1,995	69		52		1	302		1	22	1				11	267	313	124	47,994
May	1,959	90		96			905			20	3				9	494	470	159	50,760
June	2,334	81		284		1	380		1	19	3	1		1	28	606	294	193	56,620
July	2,393	78		168		2	443			22	5			1	10	567	226	210	61,839
August	2,048	92		81			401			30		1		3	18	346	282	185	51,814
September	2,477	120		88			488			31	1			2	27	284	424	189	63,824
October	1,860	94		65			436	1	1	18		2			14	574	654	161	57,496
November	2,586	102	2	81		1	405			29				2	17	736	588	147	62,423
December	2,592	86		100		4	437		1	47		2			20	764	416	242	57,356
Total	25,917	980	2	1,204	0	10	5,350	1	5	316	25	7	2	12	210	5,826	4,151	2,128	668,907

Source: Department Of Motor Traffic

Note: 21 diesel/electric motor cars are included in the category of petrol/electric motor cars in the month of January 2015

APPENDIX IV

Charging stations' location details in Sri Lanka [25]

Western Province				
Gampaha District				
	Name of the Location	Address	Contact Person	Contact Numbers
1	Wasana Trading Lanka	No. 310, Negombo Road, Welisara, Ragama	Mr. Viraj	077-2239900, 011-2241333
2	Wasana Speed Service Station	No.291, Negombo Road, Welisara, Ragama	Mr. Denesh	077-3833834, 011-2239900
3	S R B Traders	No. 305, Negombo Road, Welisara, Ragama	Mr. M S G B Fernando	077-7626217
4	W M M Fernando & Sons	No. 275, Negombo Road, Tudella, Jaela	Mr. K A K N Jude Perera	071-6822709, 011-2231075
5	Chathura Enterprises	No. 3/B/3R, National Housing Scheme, Raddolugama	Mr. S A Nimal	072-2774482, 011-2291666
6	Rising Motors	No. 53/2/A, Colombo Road, Kattuwa, Negombo	Mr. Rasika Fernandopulle	077-7580380, 031-2277950
7	View Bright Service Center	No. 07, Negombo Road, Kochchikade	Mr. R A Jude Silva	077-2392522
8	Lora Lanka Filling Station	No. 08, Gampaha Road, Ekala, Jaela	Mrs. K D M B Lora	077-2975238, 011-2236928
9	Lora Lanka Filling Station	No. 156, Kotugoda, Jaela	Mr. K S Kumara Perera	077-2975238, 011-2236928
10	Ranathunga Motor Traders	No. 285 C, Bulathkade Junction, Asgiriya, Gampaha	Mr. J K Mahesh Ranathunga	077-0772888
11	Karunarathna Motors Auto Zoon (Pvt) Ltd	No. 188/1/A, Wilibula, Henegama	Mr. Anura Puspakumara	077-8710500, 033-2247771
12	Lanka Filling Station	No. 65/2, Ovitigama, Pugoda	Mr. D H A Gunawardana	077-6384343, 011-2404418, 011-2405250
13	Dissanayake Transport & Filling Station	No. 207/4/16, Wilibula, Henegama	Mr. D A S S Dissanayake	072-2212240, 033-2268935
14	Thilaka Traders	No. 571/2, Colombo Road, Nittambuwa	Mr. K Thilakasiri	071-6215655, 033-2287051
15	Kubeeda Wheel Alignment Center	No. 403 B, Negombo Road, Nittambuwa	Mr. P K Chandana Wijithasiri	071-2252563, 033-3555077
16	Jayasingha Auto Engineers	Marapola, Veyangoda	Mr. S A K Jayasingha	077-3664246, 033-2289888
17	Lanka Filling Station	No. 61/A/8, Kandy Road, Weweldeniya	Mr. S N Kandanarachchi	077-2097533, 033-2284482
18	Lanka Filling Station	No. 02, Pohonnaruwa, Mirigama	Mr. H A L K Perera	077-3479124, 033-2276408
19	K O G Enterprises	No. 23, Mary Bisho Mawatha, Gampaha	Mr. L H Karunanayake	077-7266167, 033-2231810
20	Senevirathna & Sons	No. 09, Yakkala Road, Gampaha	Mr. R V Sarath Henri	077-1925694, 033-2222443
21	Jayakody Auto Sale	No. 251/A, Colombo Road, Gampaha	Mr. Chamath Jayakody	077-7755750, 072-2755750
22	Mahara M P C S	Mahara Jun ction, Kandy Road, Mahara, Kadawatha	General Manager	077-2663917, 011-2925213
23	Mahara M P C S	Malwathuhiripitiya, Buthpitiya, Gampaha	General Manager	077-7592562, 011-2925213
24	Stephans Filling Station	No. 534, New Hunupitiya Road, Dalugama, Kelaniya	Mr. Raja Samarathunga	071-4203577, 011-2913803

Colombo District				
	Name of the Location	Address	Contact Person	Contact Numbers
25	Miyurasa Hotel & Rest	No. 1613, Avissawella Road, Ranala, Kaduwela	Mr. G P Gunawardana	077-5357057, 011-2415485
26	Mahagedara Hotel	No. 121/1, High Level Road, Pahala Kosgama, Kosgama	Mr. Upul Weligamage	071-5965765, 036-2254120
27	Red Chilee Restaurant	Opposite Linea Aqua, Kapugoda, Hanwella	Mrs. I M C Kumari	071-4892198, 011-2406907
28	Cool Zoon Auto Mart	No. 287/E/7, Hokandara Road, Thalawatugoda	Mrs. Chandrani Wijesiriwardana	077-7356630, 011-2774147
29	Right Automobiles	No. 549/B, Kotte Road, Petakotte	Mr. Ranjan Pathirage	077-4308863, 076-7455144
30	S P Filling Station	No. 456, Athurugiriya Road, Hokandara Road, Arangala	Mr. A H Samsan Diyas	077-7780527, 011-2185585
31	Machan - Pannipitiya	No. 179/5, Highlevel Road, Pannipitiya	Mr. N D N Coory	072-7746025, 011-2746749
32	Mrs. R K C Gunasekara	No. 159/1, Pitipana Junction, Homagama	Mrs. R K C Gunasekara	071-6734608, 011-2892581
33	B K S Filling Station	No. 133, New Galle Road, Moratuwa	Mr. B Ajith Sanjeewa	072-7850850, 011-2649038
34	Kool Land	No. 2809, New Galle Road, Egoda Uyana, Moratuwa	Mr. Keerthi Kumara	077-3014620, 011-4213337
35	Panadura EV Center	No. 101, Main Street, Panadura	Mr. Rangana Sampath	071-9199696, 038-2246333
36	Auto Care Center	No. 210, Galle Road, Walana, Panadura	Mr. Amila Abeyrathna	077-4797155, 038-2238393
37	Ranaweera Trade Center	No. 19 B, Near the Southern Highway, Siripura, Dodangoda	Mr. K K D G Ranaweera	071-8209055, 034-2280292
38	Horana EV Center	No. 479, Panadura Road, Horana	Mr. R S Kahaduwa	071-9199696
39	K P K Motors	No. 310 C, Rathnapura Road, Horana	Mr. K P Kumarasingha	077-7259793, 072-2873893
40	B N C Gest House	No. 13, Galle Road, Polkatuwa, Beruwala	Mr. K N R de Silva	077-3580113, 034-2276185

Southern Province				
Galle District				
	Name of the Location	Address	Contact Person	Contact Numbers
41	Apex Health Care	No. 500/C, Kahaduwa Watta Junction, Hiribura Road, Galle	Mr. K D Mahinda	077-4275776
42	Athula Auto Traders	No. 34, Godakanda Road, Karapitiya, Galle	Mr. A B K Weeraman	077-7612609, 091-2226047
43	Namal Filling Station	Labuduwa Road, Karapitiya, Galle	Mr. G K J Wimaladasa	071-4922382, 091-2244819
44	Ranjika Stores	Akuressa Road, Paragoda, Imaduwa, Galle	Mr. Priyantha Rathnayake	077-7184663
45	Dilmini Stores	Kadaduwage Watta, kokmaduwa, Weligama	Mr. Priyantha Rathnayake	077-7184663

Matara District				
	Name of the Location	Address	Contact Person	Contact Numbers
46	Sujith Auto Electricals	No. 445, Galle Road, Pamburana, Matara	Mr. Sujith Senaweera	077-7328336, 041-2229016
47	Sujith Auto Electricals	No. 446, Galle Road, Pamburana, Matara	Mr. Sujith Senaweera	077-7328336, 041-4935668

Hambantota District				
	Name of the Location	Address	Contact Person	Contact Numbers
48	Hotel Chamila	Kataragama	Mr. H R K Chandrasena	076-7253395, 047-2235217
49	Amaraweera Industries	Molakepupathana, Tissamaharama	Mr. D A Chularathna	071-8440962, 047-2239599
50	W K Transport (Pvt) Ltd	Ratalawewa, 2nd Road, Miriggawila, Hambantota	Mr. D Viswa Kularathna	071-3364677
51	W K Transport (Pvt) Ltds	Miriggawila, Hambantota	Mr. D Viswa Kularathna	071-3364677
52	Mr. Dilan Gunawardana	No. 22, Miriggawila, Hambantota	Mr. Dilan Gunawardana	077-4610000, 047-2222323
53	Chamila Motors	Port Access, Hambantota	Mr. Chamila Prashad	077-6404088
54	Ruhunu Lanka IOC	Tangalle Road, Ambalantota	Mr. A A M Nanayakkara	077-7909778, 047-2223401
55	Senumi Automobiles	Tissa Road, Walava, Ambalnatota	Mrs. Malsha Ravihari	077-4610000

North Western Province				
Puttalam District				
	Name of the Location	Address	Contact Person	Contact Numbers
56	Binasha Trading (Pvt) Ltd	Nainamadama East, Nainamadama	Mr. Franklin Fernando	077-7554732, 031-2250344
57	Lanka Filling Station	Chilaw Road, Katuneriya	Mr. W W A K J Fernando	077-3406810, 031-2245343
58	Premith Service Station	No. 24/1, New Road, Wennappuwa	Mr. J Punsiri Jayaweera	077-6038080
59	Mr. Susil Antony Thisera	No. 20, Thalawila Church, Thalawila	Mr. Susil Antony	071-1932910
60	Mr. Susil Antony Thisera	Near the St. Anna's School, Thalawila	Mr. Susil Antony	071-1515459

Puttalam District				
	Name of the Location	Address	Contact Person	Contact Numbers
61	Lanka Filling Station – Giriulla	Nalla, Mathikade Junction, Giriulla	Mr. P M S Pathirage	071-6892645, 071-6892651, 037-2288777
62	Mr. P V C A Vithanage	No. 4/18,' Uthsahaya', Sri Sumangala Mawatha, Polgahawela	Mr. P V C A Vithanage	077-3414173, 037-2241546
63	New Jayasekara Auto Motors	No. 209, Wilgoda Circular Road, Kurunegala	Mr. Sunil Devasurendra	071-2769308, 037-2231366
64	S S Bakers	"Ambasevana", Puttalam Road, Kelimunai, Mahakeliya, Maspotha	Mr. N K Arunashantha	077-8504273, 037-2239594
65	Darshana Lanka Battery Center	Colombo Road, Waduragala, Kurunegala	Mr. A D S Puspakumara	077-7515990
66	Duminda AC & Electrical Service	Katugampala Road, Labuyaya, Kuliyapitiya	Mr. Duminda Nawarathna	077-2778956, 037-2281764
67	Wenuja Tyre Mart	No. 999, Kurunegala Road, Alawwa	Mr. J A A P Jayasuriya	077-5000633

Sabaragamuwa Province				
Kegall District				
	Name of the Location	Address	Contact Person	Contact Numbers
68	Warakapola Tyre Service	No. 246, Kandy Road, Warakapola	Mr. R M P Rajapaksha	077-6747084, 035-2267383
69	Tilanis Family Restaruant	Kandy Road, Mangalagama, Molagoda, Kegalle	Mr. E H T A Pathirana	077-2351223, 035-2228961
70	Prasanna Motor Engineers	No. 204, Kandy Road, Meepitiya, Kegalle	Mr. A P S Aluthgama	077-6588561, 035-2221567

Rathnapura District				
	Name of the Location	Address	Contact Person	Contact Numbers
71	New Lakmini Tyre Mart	No. 207, Haputale Road, Batugedara, Rathnapura	Mr. K P C Lalindra Karthiarachchi	071-6270642, 045-2232980
72	D W Filling Station	Ganegama, Pelmadulla	Mrs. P D Wanniarchchi/Mr. D Charith	071-1494311, 071-1494249, 045-2274471
73	Sisira Food Cabin	No. 183/1, Haputale Road, Kiridigala, Balangoda	Mr. N D Sisil	077-7411133, 045-2286660

Central Province				
Kandy District				
	Name of the Location	Address	Contact Person	Contact Numbers
74	Unic Service Station	Colombo Road, Pilimathalawa	Mr. L B K Puspadeniya	071-8286234, 071-3692008
75	Sunimali Brassware	Gadaladeniya Road, Pilimathalawa	Mr. J M G Ekanayaka	077-6567884, 081-2577378
76	Lanka Filling Station	No. 08, B, Kandy Rod, Weligalla, Gelioya	Mr. Harsha Gardihewa	077-8332613, 081-2312394
77	Sun Auto Electricals	No. 138, Kandy Road, Weligalla, Gelioya	Mr. S M Sooriyadasa	077-7276797, 081-5624114
78	The Kichan Café	Nuwaraeliya Road, Store Field, Gampola	Mr. S G Jayasingha	077-6800783, 081-2350078
79	Meepitiya Motors	No. 34, Ginigathhena Road, Meepitiya, Nawalapitiya	Mr. A C A Goffor	077-6624615, 054-2222098
80	Single Tree Hotel	No. 8/1, Opposite Gregory Lake, Haddan Hill Road, Nuwaraeliya	Mr. Krishantha Aruna	077-3560116, 072-5166487, 052-2223009
81	Single Tree Restaruant	No. 8, Opposite Gregory Lake, Haddan Hill Road, Nuwaraeliya	Mr. Krishantha Aruna	077-3560116, 072-5166487, 052-2223009

Matale District				
	Name of the Location	Address	Contact Person	Contact Numbers
82	Marutheluwa Medical Stores	No. 860, Aluviharaya, Matale	Dr. A M L B Abeysingha	071-3347105, 066-2223776

North Central Province				
Anuradhapura District				
	Name of the Location	Address	Contact Person	Contact Numbers
83	Deepthi Motors	No. 334/108, Main Street, Anurdhapura	Mr. Deepthi Uyanwatta	077-5123950, 025-2222770
84	Deepthi Filling Station and Service (Pvt) Ltd	Puttalam Road, Anuradhapura	Miss. Ramesha Uyanwatta	078-9392821, 025-2222516, 025-2223934
85	Kold Group (Pvt) Ltd	No. 715, 2nd Stage, Anuradhapura	Mr. L A L H J Abeysingha	077-7304428, 025-2235595

Polonnaruwa District				
	Name of the Location	Address	Contact Person	Contact Numbers
86	Pulathishe Farm	No. 07, Batticaloa Road, Kaduruwela, Polonnaruwa	Mr. W Shantha	077-2225815, 077-8971343, 027-2052257
87	Pulathishe Farm	No. 163/1, Monarathenna, Palugasdamana, Polonnaruwa	Mr. W Shantha	077-2225815, 077-8971343, 027-2052257
88	Suja Holiday	24 Mile Post, Badiwewa, Jayanthipura, Polonnaruwa	Mr. A H T Jayatissa	071-4490245

Northern Province				
Vanni District				
	Name of the Location	Address	Contact Person	Contact Numbers
89	A M T Service Station	Munrumurippu, Kandy Road, (A 09), Vavuniya	Mr. Chaminda Senanayake	024-4925902, 077-2019833
90	A M T Filling Station	Munrumurippu, Kandy Road, (A 09), Vavuniya	Mr. Chaminda Senanayake	024-5679570, 077-7666620

Uva Province				
Badulla District				
	Name of the Location	Address	Contact Person	Contact Numbers
91	Victory Motor Service	Padiyathalawa Road, Mahiyangana	Mr. T A Nawarathna	077-1705980, 077-7731115, 055-2257315
92	N S Motors	No. 01/B, Badulla Road, Mahiyangana	Mr. H S R Ranjith	077-6916887, 055-5612686
93	T R Engineering	No. 05, Badulupitiya Road, Badulla	Mrs. M D C K Wijesingha	071-8244918, 071-4467728, 055-2222571
94	W N P Builders	No. 4/A, Badulla Road, Thanthiriya, Bandarawela	Mr. P S Rajapaksa	077-6991378, 057-2225058

APPENDIX V

IEEE 33 node test feeder data:

Line Number	Sending Bus	Receiving Bus	Real Power (kW)	Reactive Power (kVar)	Resistance (ohm)	Reactance (ohm)
1	1	2	100	60	0.0922	0.0477
2	2	3	90	40	0.4930	0.2511
3	3	4	120	80	0.3660	0.1864
4	4	5	60	30	0.3811	0.1941
5	5	6	60	20	0.8190	0.7070
6	6	7	200	100	0.1872	0.6188
7	7	8	200	100	1.7114	1.2531
8	8	9	60	20	1.0300	0.7400
9	9	10	60	20	1.0400	0.7400
10	10	11	45	30	0.1966	0.0650
11	11	12	60	35	0.3744	0.1238
12	12	13	60	35	1.4680	1.1550
13	13	14	120	80	0.5416	0.7129
14	14	15	60	10	0.5910	0.5260
15	15	16	60	20	0.7463	0.5450
16	16	17	60	20	1.2890	1.7210
17	17	18	90	40	0.7320	0.5740
18	2	19	90	40	0.1640	0.1565
19	19	20	90	40	1.5042	1.3554
20	20	21	90	40	0.4095	0.4787
21	21	22	90	40	0.7089	0.9373
22	3	23	90	50	0.4512	0.3083
23	23	24	420	200	0.8980	0.7091
24	24	25	420	200	0.8960	0.7011
25	6	26	60	25	0.2030	0.1034
26	26	27	60	25	0.2842	0.1447
27	27	28	60	20	1.0590	0.9337
28	28	29	120	70	0.8042	0.7006
29	29	30	200	600	0.5075	0.2585
30	30	31	150	70	0.9744	0.9630
31	31	32	210	100	0.3105	0.3619
32	32	33	60	40	0.3410	0.5302

APPENDIX VI

<u>LECO Distribution Feeder Data:</u>

- *Feeder 1* Transformer Details:

Transformer ID	:	AZ0202
Capacity (kVA)	:	160
Base Year	:	2015
Location	:	Kotte
Branch	:	Kotte
CSC	:	Kotte
ADMD (KVA)	:	0.38
Power Factor	:	0.90
Growth (%)	:	3

Feeder	Pole ID	Conductor	Pole Span (m)	Nos. of connections	Power (kVA)
F1		***ABC 70***			
	EN5		0	0	0.000
	EN5/1		7	8	3.040
	EN5/2		36	9	3.420
	EN5/3		35	1	0.380
	EN5/4		11	9	3.420
	EN5/5		39	11	4.180
	EN5/6		6	9	3.420
	EN5/6-1		25	3	1.140
	EN5/7		8	3	1.140
	EN5/7-1		14	11	4.180
	EN5/8		11	5	1.900
	EN5/9		32	11	4.180
	EN5/10		31	7	2.660
	EN5/11		37	12	4.560
	EN5/12		20	15	5.700
F1-1		***ABC 50***			
	EN5/8A		17	0	0.000
	EN5/8B		11	0	0.000
F1-2		***ABC 50***			
	EN5/10A		27	5	1.900
	EN5/10B		12	7	2.660
	EN5/10C		22	10	3.800
	EN5/10D		7	0	0.000
	EN5/10E		13	1	0.380
F2		***ABC 50***			
	EN6		27	16	6.080
	EN7		33	13	4.940
	EN7-1		22	1	0.380
	EN8		18	4	1.520

Feeder	Pole ID	Conductor	Pole Span (m)	Nos. of connections	Power (kVA)
F2-1		***ABC 50***			
	EN7/1		38	6	2.280
	EN7/2		14	3	1.140
	EN7/3		31	3	1.140
	EN7/4		36	5	1.900
	EN7/5		30	5	1.900
	EN7/6		23	8	3.040
	EN7/7		43	6	2.280
	EN7/8		9	8	3.040
	EN7/9		11	2	0.760
	EN7/10		22	8	3.040
F2-2		***ABC 50***			
	EN8/1		2	14	5.320
	EN8/2		24	0	0.000
	EN8/3		29	13	4.940
F3		***ABC 50***			
	EN4/1		25	5	1.900
	EN4		28	6	2.280
	EN3-1		14	8	3.040
	EN3		33	19	7.220
	EN2-1		26	10	3.800
	EN2		20	7	2.660
	EN1		12	8	3.040
	EN1A		10	5	1.900
	EN1B		5	15	5.700
	EN1C		15	3	1.140
	EN1D		19	1	0.380
	EN1E		24	1	0.380
	EN1F		19	0	0.000
	EN1G		23	7	2.660
	EWA*2		27	0	0.000
	EWA*1		15	0	0.000
	EWA		7	0	0.000
	EN1J		37	5	1.900
	EN1K		18	0	0.000
	EN1L		24	11	4.180
F3-1		***ABC 50***			
	EN1F1		24	8	3.040
	EN1F2		24	10	3.800
F3-2		***ABC 50***			
	EN1H1		38	6	2.280
Total	**62**			**387**	**147.060**

- *Feeder 2* Transformer Details:

Transformer ID	:	AZ0203
Capacity (kVA)	:	160
Base Year	:	2015
Location	:	Kotte
Branch	:	Kotte
CSC	:	Nawala
ADMD (kVA)	:	0.41
Power Factor	:	0.9
Growth (%)	:	3

Feeder	**Pole ID**	**Conductor**	**Pole Span (m)**	**Nos. of connections**	**Power (kVA)**
F1		***ABC 70***			
	EN15		0	2	0.820
	EN15/1		12	8	3.280
	EN15/2		18	2	0.820
	EN15/3		22	1	0.410
	EN15/4		24	5	2.050
	EN15/5		9	3	1.230
	EN15/6		26	7	2.870
	EN15/7		33	4	1.640
	EN15/8		16	1	0.410
	EN15/9		20	7	2.870
	EN16/1/7		32	0	0.000
F1-1		***ABC 50***			
	EN15/7/1		6	11	4.510
	EN15/7/2		24	7	2.870
F2		***ABC 70***			
	EN14-1		26	6	2.460
	EN14		18	8	3.280
	EN14/1		13	0	0.000
	EN14/1/1		3	0	0.000
	EN13		9	8	3.280
	EN12		38	2	0.820
	EN11-2		7	12	4.920
	EN11-1		15	5	2.050
	EN11		22	10	4.100
	EN10		25	4	1.640
	EN9		19	0	0.000
	EN8/1		30	0	0.000
	EN8		2	3	1.230
	EN8/2		24	0	0.000
F2-2		***ABC 50***			
	EN11-2/1		42	0	0.000
	EN11-2/2		13	8	3.280
	EN11-2/3		26	11	4.510
	EN11-2/4		7	9	3.690

Feeder	Pole ID	Conductor	Pole Span (m)	Nos. of connections	Power (kVA)
	EN11-2/5		29	6	2.460
	EN11-2/6		31	2	0.820
	EN11-2/6/1		29	2	0.820
	EN11-2/6/2		6	0	0.000
	EN11-2/6/3		20	9	3.690
	EN11-2/6/4		21	6	2.460
	EN11-2/6/5		40	4	1.640
F2-2-1		***ABC 50***			
	EN11-2/3/1		28	11	4.510
F2-2-2		***ABC 50***			
	EN11-2/5/1		27	6	2.460
	EN11-2/5/2		27	0	0.000
F2-2-3		***ABC 50***			
	EN11-2/7		10	8	3.280
F2-2-4		***ABC 50***			
	EN11-2/6/2A		13	4	1.640
	EN11-2/6/2B		34	3	1.230
	EN11-2/6/2C		34	3	1.230
	EN11-2/6/2D		7	6	2.460
F2-3		***ABC 50***			
	EN9A		12	7	2.870
	EN9B		28	1	0.410
	EN9C		15	5	2.050
F3		***ABC 70***			
	EN15-1		14	3	1.230
	EN16		35	9	3.690
	EN16/1		17	6	2.460
	EN16/2		11	9	3.690
	EN17		15	2	0.820
F3-1		***ABC 50***			
	EN16A		14	10	4.100
	EN16B		36	5	2.050
	EN16C		38	7	2.870
Total	**57**			**278**	**113.98**

- *Feeder 3* Transformer Details:

Transformer ID	:	AZ0221
Capacity (kVA)	:	250
Base Year	:	2015
Location	:	Pitakotte
Branch	:	Kotte
CSC	:	Kotte
ADMD (KVA)	:	0.45
Power Factor	:	0.90
Growth (%)	:	3

Feeder	Pole ID	Conductor	Pole Span (m)	Nos. of connections	Power (kVA)
F1		***ABC 50***			
	EN45		0	8	3.600
	EN45-1		34	5	2.250
	EN46		12	23	10.350
	EN46-1		17	14	6.300
	EN47		26	10	4.500
	EN47-1		29	7	3.150
	EN48		31	2	0.900
F1-1		***ABC 50***			
	EN45-1A		17	1	0.450
	EN45-1B		38	7	3.150
F1-2		***ABC 50***			
	EN47A		9	3	1.350
	EN47B		28	3	1.350
	EN47C		33	9	4.050
	EN47D		36	10	4.500
	EN47E		27	18	8.100
	EN46F		24	14	6.300
F1-3		***ABC 50***			
	EN47-1/1		26	10	4.500
	EN47-1/2		30	2	0.900
	EN47-1/3		19	10	4.500
	EN47-1/4		20	17	7.650
	EN47-1/5		35	7	3.150
	EN47-1/6		21	3	1.350
	EN47-1/7		13	5	2.250
	EN47-1/8		33	3	1.350
F1-4		***ABC 50***			
	EN47-1/5A		24	0	0.000
F2		***ABC 70***			
	EN44-1		26	14	6.300
	EN44		20	21	9.450
	EN43		24	1	0.450
	EN42		29	16	7.200
	EN41		26	5	2.250
	EN40		37	1	0.450
F2-1		***ABC 50***			
	EN44-1/1		5	0	0.000
	BUILD2		5	0	0.000
F2-2		***ABC 50***			
	EN42A		19	1	0.450
	EN42B		34	7	3.150
	EN42C		33	1	0.450
	EN42D		28	2	0.900
	EN42E		21	5	2.250
	EN42F		11	3	1.350
	EN42G		26	9	4.050
	EN42H		18	1	0.450
	EN42J		22	5	2.250
	EN42K		41	3	1.350

Feeder	Pole ID	Conductor	Pole Span (m)	Nos. of connections	Power (kVA)
	EN42L		16	1	0.450
F2-3		***ABC 70***			
	EN41/1		48	0	0.000
	EN41/2		7	11	4.950
	EN41/3		37	4	1.800
	EN41/4		33	8	3.600
	EN41/5		12	2	0.900
	EN41/6		18	5	2.250
	EN41/7		14	11	4.950
F2-4		***ABC 50***			
	EN40A		13	0	0.000
Total	**51**			**328**	**147.600**