School of Electrical Engineering, Computing and Mathematical Sciences

Optimal Online Charging Coordination of Plug in Electric Vehicles in Unbalanced Grids for Ancillary Voltage Support

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This thesis is presented for the Degree of
Doctor of Philosophy
of
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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made. This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Signature:

Date: 24/07/2019

I wish to dedicate this thesis to my beloved family

Ali,

Avina & Davin,

My parents

Abstract

It is anticipated that the future innovative smart grids (SGs) will host high penetrations of renewable distributed generation (DG) systems predominantly photovoltaic and wind power as well as appliances and loads such as plug-in electric vehicles (PEVs). The expected large growth in the PEV market will challenge safe, efficient, and optimal operations of SGs, particularly at distribution levels with unbalanced configurations and load distributions. PEVs can operate in grid to vehicle (G2V) or vehicle to grid (V2G) modes to charge and discharge their batteries. The main issues associated with PEVs are their time-variant and portable (if not always charged/discharge at homes) nature and random plug-in times. The main motivations for PEV adoption are environmental issues, dilapidation of conventional fossil fuels, as well as voltage ancillary services when operated in V2G mode.

This PhD thesis will first highlight the detrimental impacts of non-uniformly distributed and randomly plugged-in single-phase and three-phase PEVs on unbalanced four-wire distribution networks. Then, it will propose and develop an optimal online charge control through genetic algorithm for G2V coordination of PEVs (OL-C-TP) in unbalanced systems by considering two different scenarios based on optimal/variable price and fixed price for importing active power.

Moreover, the algorithm will be extended also to include V2G coordination and offer ancillary voltage support (OL-CD-TPQ) by considering two different methods based on the utility time-of-day prices for exporting reactive power and droop controller for decentralized exporting of reactive power. Then the performance of OL-CD-TPQ by switching PEVs in three phase unbalanced networks is improved. The unbalanced load flow and optimal online charge/discharge control genetic algorithm will be coded in MATLAB and detailed simulations will be carried out for the unbalanced distribution network studied under the Perth Solar City Project in Western Australia to investigate and validate the performance of the proposed approaches.

Attribution

STATEMENT OF ATTRIBUTION BY OTHERS

The purpose of this statement is to summarise and clearly identify the nature and extent of the intellectual input by the candidate and any co-authors.

Article 1 title: Optimal online charging of electric vehicles considering voltage unbalance factor
Article 2 title: An Online Coordinated Charging/Discharging Strategy of Plug-in Electric Vehicles in Unbalanced Active Distribution Networks with Ancillary Reactive Service in the Energy Market
Article 3 title: Online Centralized Charging Coordination of PEVs with Decentralized Var Discharging for Mitigation of Voltage Unbalance
Article 4 title: Stochastic Assessment of Plug-in Electric Vehicles Charging in LV Distribution Network on Voltage Unbalance

Attribution of Prof. Arindam Ghosh

Article	Literature review	Concept design	Software modelling	Experimental results	Data analysis	Discussion	Paper writing	Thesis Chapter
3		✓				✓		2,4,5
4		✓				✓		2,3

Attribution of Dr Xiangjing Su

Article	Literature review	Concept design	Software modelling	Experimental results	Data analysis	Discussion	Paper writing	Thesis Chapter
2						✓		2,4,6
3						✓		2,4,5
4						✓		2,3

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Article	Literature review	Concept design	Software modelling	Experimental results	Data analysis	Discussion	Paper writing	Thesis Chapter
1						✓		2,4
2						✓		2,4, 6

Attribution of Prof. M. A. S. Masoum

Article	Literature review	Concept design	Software modelling	Experimental results	Data analysis	Discussion	Paper writing	Thesis Chapter
1		✓				✓		2,4

[Student] [Supervisor]

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Finally and most importantly, in loving memory of my father; Professor Parviz Jabalameli, who has been my father, guide and philosopher. He was an inspiring figure for me and many of his students over the years. Although he is not here to give me strength and support, I always feel his presence that used to urge me to strive to achieve my goals in life.

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Abbreviations

AI	Artificial Intelligence
BWS	Backward Sweep
BFS	Backward/Forward Sweep
DG	Distributed Generation
DoD	Depth of Discharge
ESS	Energy Storage Systems
FWS	Forward Sweep
GA	Genetic Algorithm
G2V	Grid-to-vehicle Charging
ICE	Internal Combustion Engine
kW	Kilo Watt
kWh	Kilo Watt-hour
Li-ion	Lithium-ion
LV	Low Voltage
MCS	Monte Carlo Simulation
OLTC	Online Tap Changer
OL-C-TP	Optimal Online Charge Control
OL-CD-TPQ	Optimal Online Charge/Discharge Control
PV	Photovoltaic
PEV	Plug-in Electric Vehicle
PCC	Point of Common Coupling

PF	Power Factor
R/X	Ratio of real (R) and reactive (X) component of Transmission/Distribution Line
SG	Smart Grid
SM	Smart Meter
SoC	State of Charge
VAR	Volt Ampere Reactive
V2G	Vehicle-to-grid Charging
V2H	Vehicle to Home
VR	Voltage Regulator
VU	Voltage Unbalance
WA	Western Australian

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Chapter 1

Introduction

1.1 Research Motivation

Many countries, including Australia, are facing rapid growth in demand, coupled with the rise in the price of electricity. In addition, there are increasing concerns about clean air, climate change, and rapid depletion of conventional fossil fuel sources. The Department of the Environment and Energy of Australia [1] states that the transport sector is one of the highest significant Australian energy consumers, as shown in Figure 1.1. Furthermore, according to Figure 1.2, less than 2% of the energy produced comes from renewable resources. It means most of the energy production comes from non-renewable sources, which leads to increased greenhouse gas emission. Moreover, the transport sector always had steady growth and a significant share of greenhouse gas pollutions due to population growth. Australian Government in [2] presented the transport as the second largest greenhouse producing sector in the country (18%). This amount was 100 MtCO2e in 2017, which is an increase of 3.4% from 2016. Therefore, it is essential to consider sustainable and commercial methods to diminish energy consumptions and environmental issues in this sector. In this regard, many researchers are investigating to find the solutions for the problems of growing consumption on transportation and electricity usage as well as carbon emission.

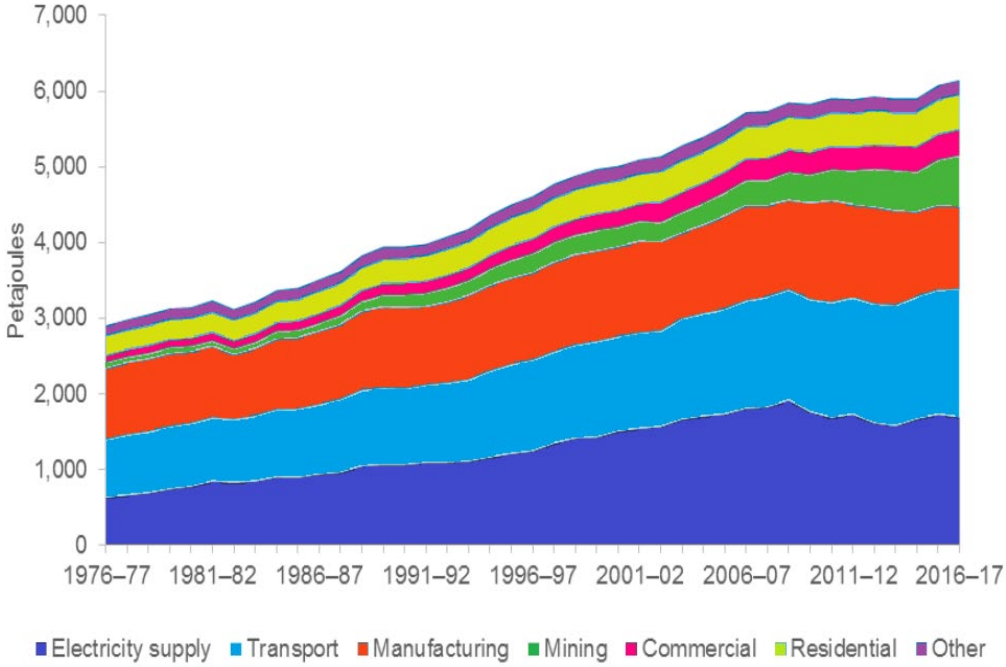


Figure 1.1. Australian energy consumption by sector [1]

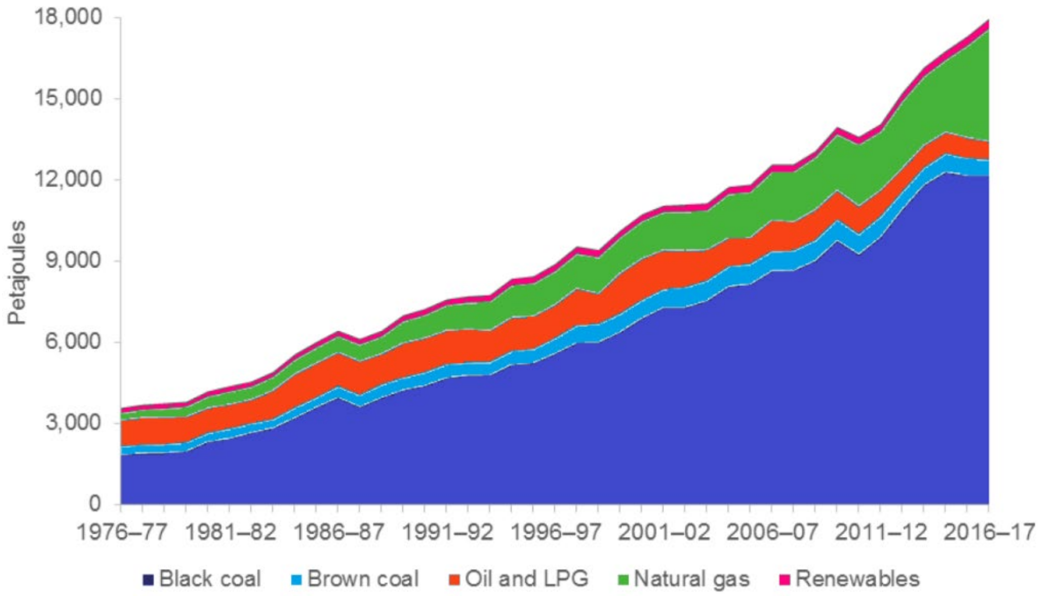


Figure 1.2. Australian energy production by fuel type [1]

There are also some legal requirements for less polluting and more environmentally friendly procedures for automobile manufacturers and utility companies. One of these solutions is using alternative vehicle technologies such as Plug-in Electrical Vehicle (PEV). During the last decades, there has been a significant increase in usage of PEVs. Electric vehicles are more efficient for converting energy per miles travelled. The Parliament of Australia in [3] reported that the ratio of the cost per kilometre for a PEV to an Internal Combustion Engine (ICE) based car is 3:10 cents. Although presently the majority of vehicle owners concern about the high initial investment in PEV, the incentives from governments along with reducing manufacturing costs will encourage people to buy PEVs instead of ICE vehicles in the coming years. According to Bloomberg [4], the market of PEVs can reach to 60M per year by 2040 from around 1M in 2017, as shown in Figure 1.3.

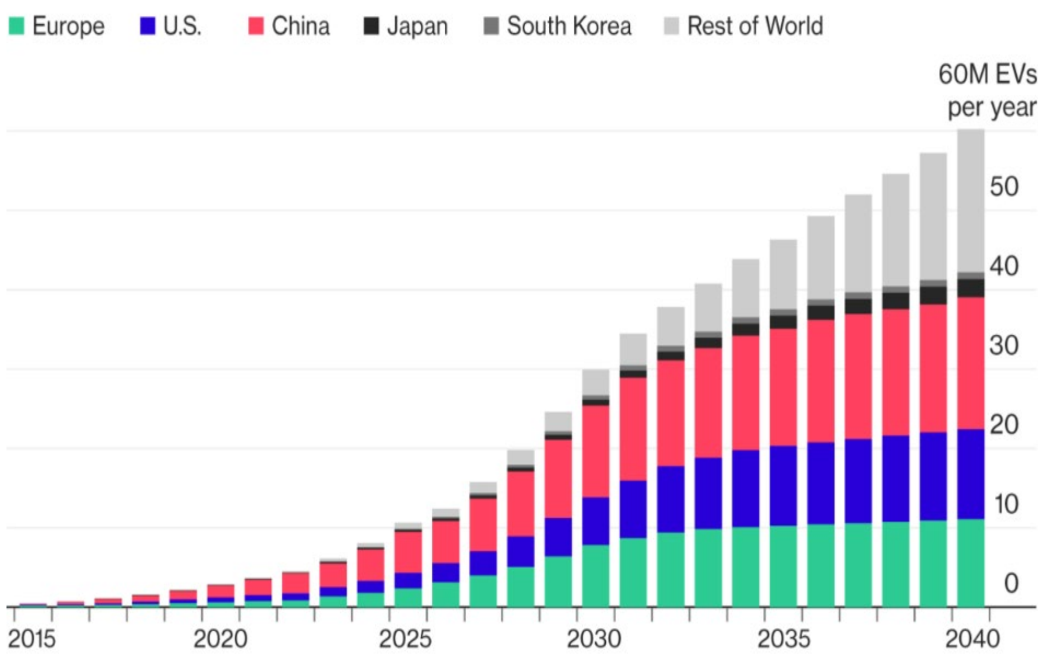


Figure 1.3. Global EV revolution [4]

It is envisaged that random (uncoordinated) PEV charging levels can have an adverse effect on the grid performance as the PEV penetration level increases. The utilities, therefore, should make sure that the grid is equipped to manage these extra loads for the reliability, and security of the network. One of the major challenges of the growth of PEV as loads is the excessive pressure on the existing grid assets resulting in power quality issues. In this regard, voltage and voltage unbalance (VU) are critical in low voltage (LV) distributed systems.

The loads are distributed equally in three phases by utilities more often. Despite the balanced network voltage at the supply side, when transferred to customer it might become unbalanced for several reasons like unequal system impedance and uneven small or large single-phase loads such as Grid to Vehicle (G2V) charging [5, 6]. The utility tries to keep the voltage within standard ranges. However, as a result of an increasing number of PEVs and their residential charging, it can be expected that the voltage unbalance will rise as PEVs are expected to be randomly placed along with distribution feeders [7]. This means that all the consumers may not buy PEVs, and the battery sizes of PEVs will differ. Therefore, this is imperative to lay a groundwork now such that, as the PEV penetration increases, the VU and voltage constraint violations are kept in check [8].

Comprehensive investigations are needed to study the effects of PEV charging loads on the transmission and distribution of electricity; generation source and energy market and also detect limitations on the grid. It is clear that the limitations of the existing power grid cannot resolve these types of critical issues. Correspondingly, the existing system needs to be improved by intelligent coordinated control and smart distribution technologies. Smart charge/discharge of PEV batteries can assist on better employment of current facilities, especially by PEV coordinated charging [9]. Consequently, this can help voltage regulation and minimize voltage unbalance factor.

In addition, PEVs can also bring extensive profits to the electricity network. According to [10], the average daily distance for Australia (considering all cities) travelled by drivers is between 12 km-20 km, and the average travelling time during a day (travelling to and from work) is almost 53 minutes. So, nearly 90% of a day (almost 22 hours) vehicles are parked and are idle. Therefore, due to the PEVs availabilities in parking, the energy storage of electric vehicles can be considered as an opportunity for the integration of "intermittent" energy sources into the grid [11]. Therefore, PEVs can act as transport devices, as well as controllable loads and distributed energy resources. Using PEVs discharging and coordinate charging during peak demand ours a power grid can be supported. This will reduce the upgrade investment even if the electricity demand grows. This strategy is also more effective as the power supply source placed closer to the end users, which result in less loss. Considering these features, PEVs can be considered as suitable sources for short-term ancillary services in the network [12].

This concept, which is referred to as the vehicle-to-grid or V2G mode is interesting for utility companies, power system operators, and energy users. From the utilities' point of view, distributed generation (DG) sources are better to be located nearby the loads in distribution networks due to the economical, technical, and environmental advantages. However, the high penetration of such sources leading to several challenges to distribution grid like power variation, voltage rise, VUF issue, and low voltage stability [13].

On the other hand, the industry has devoted extensive efforts to explore alternative energy resources for transportation as a solution to reduce air pollution, noise and transport dependency on fossil fuels. Application of large scale PEVs also has the ability to support efficient utilisation of renewable resources if the PEV charging loads are coordinated with peak output periods of renewable sources. Coordination of PEV charging with renewable DGs can also reduce the ratings of expensive energy storage systems (ESSs) required for optimal operation. This can be done by directly transferring most of the DG output energy to the vehicle batteries.

Among the existing DG technologies, wind power and photovoltaic (PV) systems have been applied more than others, particularly in residential distribution networks [14]. Furthermore, due to the recent governmental feed-in tariffs for grid-connected PV systems, their environmental friendly usage and rising electricity prices, these small-scale systems are becoming increasingly popular within the residential and commercial networks [14]. For instance, the Department of the Environment and Energy reports that renewable energy sources were 16% in 2016-17 with a 100% increase during the past decade. A survey, published by Roy Morgan shows that almost one out four Australian residential have "Solar Electric Panel" by March 2017. South Australia is the leader by 32.8%, followed by Queensland 30.2 %, and Western Australia 26.6% [15].

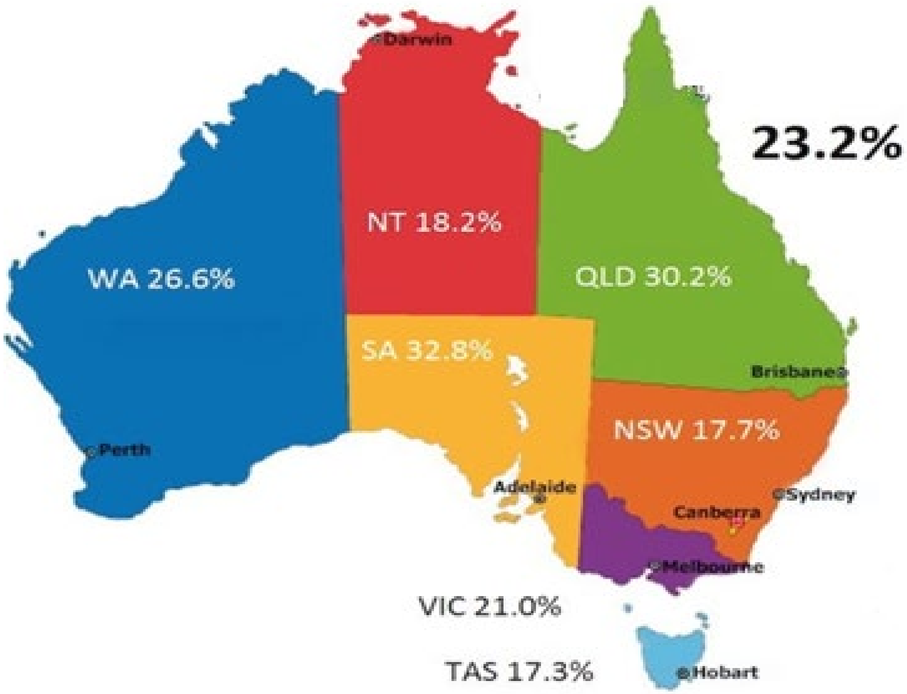


Figure 1.4. Australian home solar electric panel [15]

Currently, with a small number of PEVs in the market, the network issues are negligible. However, with high PEV penetration levels in the near future, it is essential to make sure about efficient and reliable operations of the networks. There will be various challenges associated with V2G and G2V activities. To overcome these challenges, long term planning and feasibility studies need to be done in which several variations such as load growth, PEV models, schedule programming, effects on network and advanced technologies should be considered.

In this regard, this dissertation tries to resolve some issues of incorporating large numbers of PEVs on the electric grid through control and optimization techniques. This also considers the charging PEVs from available rooftop PVs that can provide low carbon electricity to PEVs. The solutions to power quality problems should include charging control, grid voltage regulation, and VUF minimization.

1.2 Research Objectives

The main objective of this thesis is to investigate the optimal online charge/discharge control for both real and reactive power for G2V/V2G coordination. The specific tool used is genetic algorithm (GA), and through this tool, both PEVs and PVs are used to improve voltage profile and to reduce VUF in LV distribution networks. The specific research objectives are as follows:

- Analysing the detrimental impacts of non-uniformly distributed and randomly plugged-in single-phase and three-phase PEVs on voltage profile and VUF through unbalanced four-wire distribution networks.
- Formulation of optimal online charge control through GA (called OL-C-TP) for G2V coordination of PEVs in unbalanced girds that will minimize the costs associated with energy generation, voltage deviations and VUF by considering two different scenarios based on optimal/variable price and fixed price.
- Inclusion of distributed PV and daytime PEV charging option (at offices, parking lots, commercial and industrial feeders).
- Proposing and developing an optimal online centralized charge and decentralized var discharge control algorithm (called OL-CD-TPQ) for G2V and V2G coordination in unbalanced grids based on droop controller for decentralized exporting of reactive power to analyse the impact of PEV reactive capability on voltage profile and VUF improvement.
- Development of the optimal online centralized charge/discharge control algorithm (called OL-CD-TPQ) for G2V and V2G coordination in unbalanced grids based on utility market pricing signals for active and reactive power to maximize the profit while exporting reactive power for ancillary voltage control.
- Proposing an improvement in the performance of OL-CD-TPQ by considering switching PEVs between phases of an unbalanced network while complying with network operation criteria such as voltage profile, generation, VUF and

distribution transformer loading limits. The flowchart of the research objectives is shown in Figure 1.5.

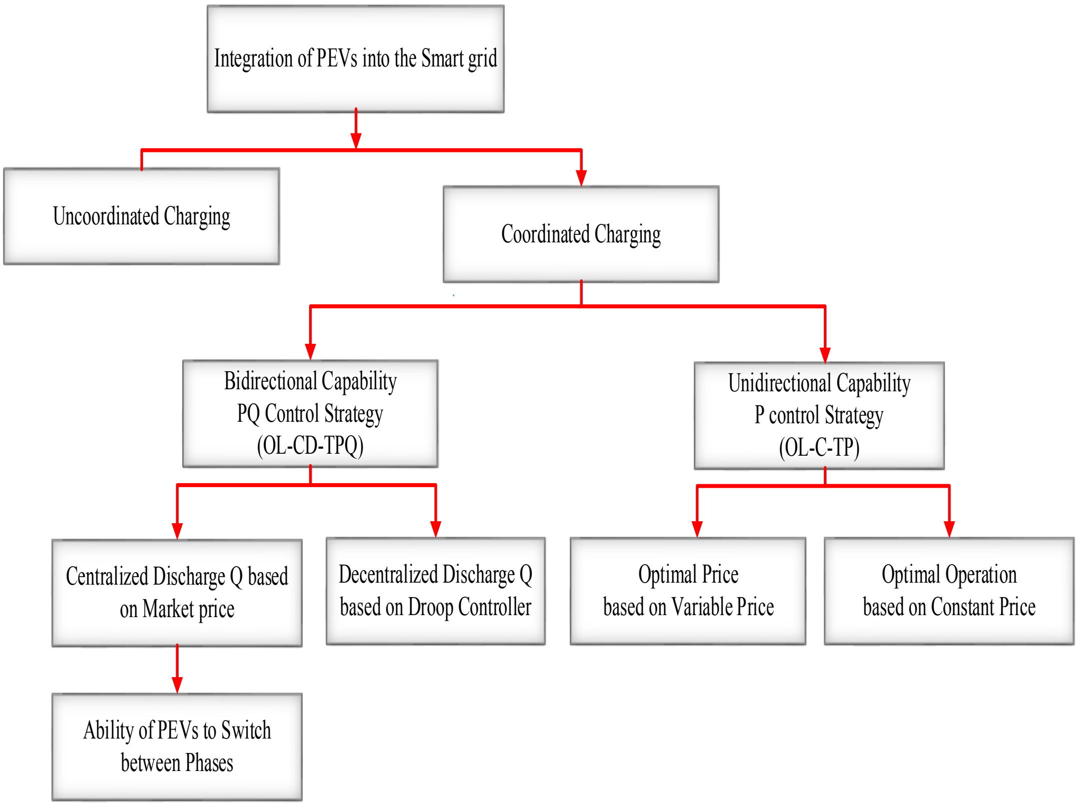


Figure 1.5. Research objectives

1.3 Research Significance

This research develops a GA based online charging (OL-C) of PEVs for both G2V and V2G modes of PEVs when they are connected in unbalanced networks with the aim of improving voltage profile and reducing VUF. The main contributions of the thesis are:

- Proposing an online GA optimization based coordination charging algorithm (OL-C-TP) for G2V, aiming to improve smart grid performance by considering the network constraints in unbalanced LV distribution network.
- Including distributed PVs and daytime PEV charging.

- Proposing a coordinated charging/var discharging (OL-CD-TPQ) algorithm for G2V/V2G coordination of PEVs in unbalanced grids to further improve the voltage profile and reduce the overall network VUF.

- Coordinating PEVs through active and reactive power control based on variable pricing/contract scenarios for selling reactive power to improve node voltage profiles, reduce the overall network VUF and the total system cost.

- Improving performance of OL-CD-TPQ by switching PEVs in three-phase unbalanced networks.

To accomplish these tasks, the unbalanced load flow and optimal online charge/discharge control genetic algorithm are coded in MATLAB, and detailed simulations are carried out. A practical network is chosen validate the performance of the proposed approaches, which is the Perth Solar City Project in Western Australia.

1.4 Thesis Structure

The thesis is organised in 8 chapters. The outlines of the Chapters are as follows:

- **Chapter 1** (**Introduction**) is the preliminary chapter outlining the motivation, objectives, and contributions of the thesis.

- **Chapter 2 (Background and Literature Review)** provides a brief review of the relevant background and the literature related to this study regarding SG, PEV battery charging schemes and review their impacts and applications in smart grids.

- **Chapter 3 (Impact of Plug-in Electric Vehicles Charging in Low Voltage Distribution Network on Voltage and Voltage Unbalance)** highlights the detrimental impacts of non-uniformly distributed and randomly plugged-in single-phase and three-phase PEVs on voltage profile and voltage unbalance.

- **Chapter 4 (Online Coordinated Charging PEVs in Unbalanced Smart Grid)** proposes and develops an optimal online charge control based on genetic algorithm (OL-C-TP) for G2V coordination of PEVs in unbalanced grids, called

P-Control Strategy, which will improve the network performance by controlling the time of charging while maintaining the voltage constraints.

- **Chapter 5 (Coordinate Charging through both Real and Reactive Power Control)** presents a hybrid strategy of centralized GA-based centralized PEV charging and decentralized PEV var discharging for unbalanced distribution networks. It aims to minimize VUF by making smart PEV charging/discharging decisions simultaneously. In addition to the online centralized PEV charging coordination (OL-C-TP) of Chapter 4, the proposed strategy also relies on decentralized discharging to provide PEV inverter reactive support at selected nodes based on droop control to further locally improve the voltage profile and reduce the overall network VUF.

- **Chapter 6 (Coordinated Charging/Discharging Strategy of PEVs with Ancillary Reactive Service in Energy Market)** presents a centralized PEV coordination method that relies on the P/Q consumption/injection control. This approach also performs a central voltage quality improvement algorithm by discharging PEV batteries at selected single-phase residential houses based on day-ahead reactive power price signal for offering voltage regulation.

- It is important to note that the reactive power capability of PEV inverter is investigated in both Chapters 5 and 6. However, in Chapter 5, the droop controller is applied for injecting Q, but in Chapter 6 day, ahead reactive power price is considered for selling Q for voltage improvement.

- **Chapter 7 (Online Centralized Coordination through Feeder Switching)** investigates the capability of dynamic PEV load transfer within the three phases of a distribution network to propose a new hybrid PEV coordination approach. In addition to the online centralized battery charging and var discharging, this approach performs local voltage profiles improvement by switching PEV at selected single-phase residential houses such that a PEV can be switched from a heavily loaded phase to a (relatively) lightly loaded phase.

- **Chapter 8 (Conclusions and Recommendations)** summarizes the thesis outcomes and suggests the potential future works that can be carried out.

Chapter 2

Background and Literature Review

2.1 Introduction

The existing grid needs to be improved as the result of a fast-growing economy, which requires high-quality power supplies. This concern is more noticeable in low voltage (LV) distribution feeders in consequence of the connection of residential and smaller commercial consumers into the grid. On the other hand, due to the depletion of fossil fuel reserves and also for environmental concerns, automobile industry is slowly shifting towards electric or hybrid cars. The existing utility grid owing to increasing demand faced serious grid issues such as low voltage, voltage drops and unbalanced that can affect the limit capacity of the networks. Moreover, the inclusion of rooftop PVs complicates the problem further. Therefore, for the integration of plug-in electric vehicles (PEVs) in networks that are stressed, optimisation methods need to be developed considering feeder capacity and voltage boundaries violations. The inclusion of PEVs in the electrical grid is one of the interesting topics for many researchers where two different aspects have been considered:

- The effect of the PEVs on the network
- The PEVs potential to support the grid

In this regard, this Chapter presents a background review surrounding the main concepts relevant to the research work carried out in this thesis. This Chapter first explains background information about intelligent grid in Section 2.2. Then shows the PEV modelling and addresses the challenges associated with high PEV impact on the distribution grid in Sections 2.3 and 2.4. Following this, the challenges regarding smart charging coordination and EV energy scheduling strategies are discussed in Section 2.5. Then in Section 2.6 the application of PEV as an intelligent load that can be controlled in the smart grid will be reviewed. The chapter ends with the summary in Section 2.8.

2.2 Smart Grid Vision

The smart grid (SG) is considered as a modern electric power grid in which cyber secure digital communications technology is applied to respond to the local changes in the power usages. The overview of a smart grid is shown in Figure 2.1. It can be observed from this figure that a power grid contains fossil fuel based generation, renewable energy based generation, large industrial and domestic loads. Under the umbrella of a smart grid, these must work cohesively, for which measuring devices like smart meters and PMUs, smart appliances and PEVs, smart grid coordination through grid management system are employed though a two-way digital data communication network. By using computer processing, a smart grid is capable of collecting information, monitor, and control through this two-way communication system. Self-healing technology is also utilised to reach a secure, efficient, and sustainable system [1]. According to [16] the essential factors, which need to be considered for future SG, are as follow:

- **Reliability and Power Quality:** The quality of power supply and continuous operation without interruptions like voltage drop, spikes or frequency distortions are vital characteristics for a reliable smart grid system. So, the system needs to be protected against issues such as voltage fluctuations, harmonics and interruptions. [17].

- **Economy:** Like most other technical innovations, the economy or cost management has an important role in wide applications. Considering the renewable energy supports and optimization systems, it is expected the smart grid help the economy by reducing total production and distribution costs and a lower price for the consumers in the future.

- **Environment:** Negative environmental impacts associated with generation, distribution and usage of electricity can be reduced by the smart grid through smart usage of renewable energy sources and storage systems [18, 19]. The PEVs has a positive impact on the environment since they do not generate greenhouse gases. However, their integration to the grid needs to be carefully controlled.
- **Efficiency:** The efficiency in production and transfer of electricity can be improved by control methodology in smart grids.
- **Security:** Security is one of the main components of a smart grid. A secure system will protect the grid and its consumers from cyber-attacks. Moreover, a secure grid will be able to recover itself quickly following any natural disaster [20, 21].
- **Motivating:** Smart grid communication between customer and utility should be persuasive for the end users. The right opportunity should be given to the customers to manage their energy consumption in terms of price, habit or any other preferences.

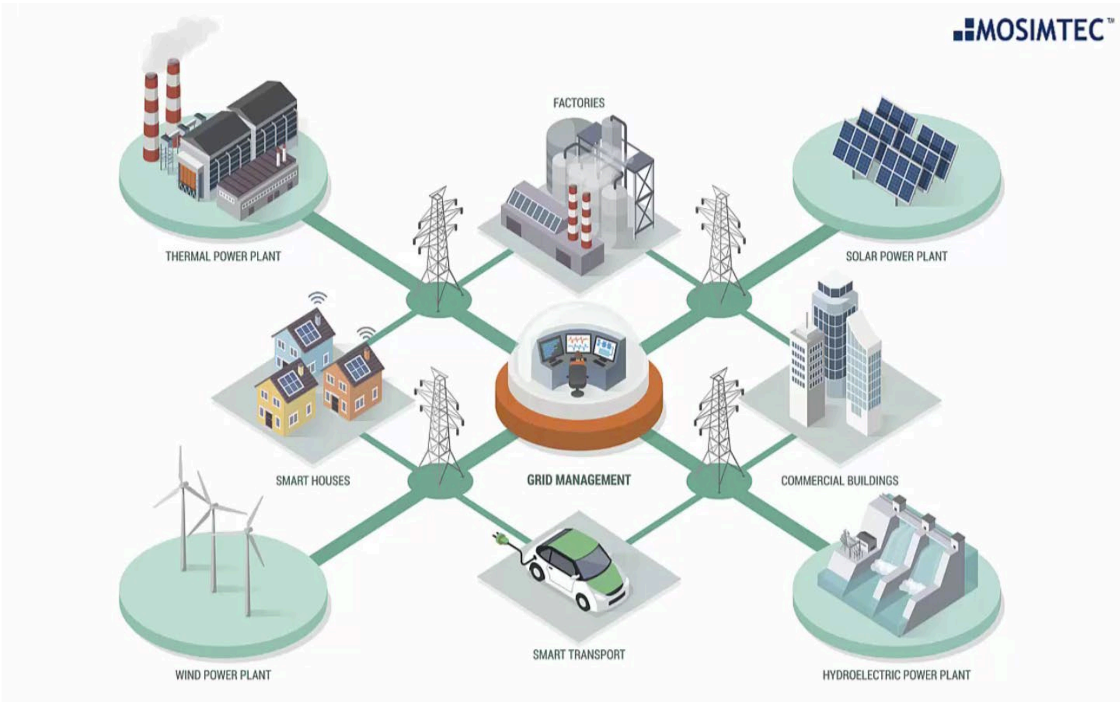


Figure 2.1. Smart grid vision [22]

Several articles have appeared in the literature examining the reliable communication among smart grid components. Several algorithms and protocols to manage these power sources have been developed. To achieve their essential obligations, these power and communication connections need to be reliable, scalable and secure [23] [24]. However, reliability cannot be easily achieved without a comprehensive effort which includes managing peoples' demand, their habits, and preferences as well as considering a group of algorithm and intelligent design for the smart grid.

The aggregators can play an important role in the above goals. They can communicate between electricity companies and customers by supplying demanded power to consumers. Also, they can negotiate on behalf of the customers with power generation companies regarding prices and demands [25]. Furthermore, they can transmit and install control devices such as smart meters which can read the consumed power per time unit at the customer side [26]. Also, the customers, with information received from aggregators, can manage appliance operation during peak times.

2.3 Integration of PEVs in Smart Grid

These days, an increasing number of PEVs is playing an important role on worldwide automobile market. Many governments are encouraging using PEVs or PHEVs to take the benefits of green energy operation [9]. The advantages of PEVs in comparison to fossil fuels based vehicles are highlighted in [7]. Some of the benefits are:

- **Energy Security:** Australia has a diverse energy source such as coal, solar and wind. A PEV will use the energy produced through these sources, the need of importing petroleum products from abroad. Lower petroleum usages can result in a better portfolio of local electrical energy generated.

- **More Environmental Friendly:** PEVs do not produce fossil emissions and greenhouse gases by themselves. However, if PEVs are charged through fossil fuel based generators, the net balance of greenhouse gas emission may be zero. If the PEVs are charged during the times when renewable generation is high, the impact on environment is reduced. The other important issue that needs to be considered in the pollution in large cities all around the world, predominantly due to vehicular emissions. This is a a cause of various diseases amongst the populace. Large uptake of PEVs will go a long way to clean up these cities, thereby improving the health of their inhabitants.

- **Creating a Stronger Economy:** PEVs and its related infrastructure will generate a boost to the economy for good reasons. Especially for those countries that import fossil fuels, using PEVs will be a cheaper solution for the consumers. This can also justify the costs and investments for infrastructure like building stations and network improvements on shifting to PEVs.

- **Reducing Total CO_2:** The carbon and greenhouse gases emissions are much less if we use more renewable resources for generating electricity and then use PEVs for transportation. So, global warming and climate issues as results of increasing carbon emissions will slow down. We can also save the depleting fossil-fuel energy sources for the future generations, who might have much more efficient use of them, given the rate at which technology is progressing.

- **Lower Cost per Mile:** A significant attraction and moving acceleration to PEVs market is the energy cost per kilometre commute. Using actual pricing for electricity and fossil fuel and technology that enable to commute each kilometre by any PEVs or conventional gasoline/petrol cars, show about 75% saving on transportation costs. The challenge is a more initial budget to own PEVs in comparison with internal combustion (IC) engine based vehicle. However, it will be sorted out quickly by improving technology and brand varieties in the PEV market. In some countries, government subsidies also help to overcome the initial barrier.

Noting all the above benefits for the PEVs, it is predicted that fossil fuels vehicles will gradually be replaced by PEVs. Integration of PEVs to power system needs to be managed and controlled by smart grid algorithms. To make it happen, the PEV modelling and charging methods need much attention.

2.3.1 PEV: Modelling and Charging

One of the main components of PEVs is the battery capacity, which enables pure electric driving. The size of the battery considerably effects on vehicle cost [27]. Table 2.1 shows a list of some recent PEVs and EVs model in Australia. Regarding battery technology, the lithium-ion (Li-ion) battery is the most preferable kind of rechargeable battery in the EV sector owing to higher energy density, lightweight, less memory effect and ability to be recharged several times [28]. Reference [29] gives some data and comparison between Li-ion and lead-acid batteries. It reports that not only lead-acid batteries are three times larger than Li-ion batteries, but they can also supply less than one-third energy in compared to Li-ion batteries. Besides, Li-ion batteries life cycle is almost three times of that of lead-acid ones. According to the latest research such as [30], the present primary battery energy storage technology available for EVs is the Li-ion battery. Therefore, the growth of the PEV market can be directly related to developments of Li-ion battery technology. Generally, a Li-ion battery can be specified by nominal voltage, capacity (Ah), charging speed, and discharge current. Other parameters are gravimetric energy density (Wh/kg), minimum and maximum cell voltage, internal resistance, State-of-health (SoH), State of Charge (SoC), operating temperature range, power and energy density and weight [28].

Li-ion batteries are charged using a mixed voltage and current constant ratio CI/CV. At the start of charging, the current should remain constant till the voltage reaches to its nominal value. After that, the voltage should remain fixed not to damage the battery during charging. However, the current gradually decreases while it reaches a full SoC [31].

Table 2.1 PEVs and EVs in Australia [32]

PEV Models	Operating Mode	Battery Capacity [kW]
Audi A3 E-Tron	Plug-in Hybrid	8.8 kWh Lithium-ion
BMW 330e	Plug-in Hybrid	7.6 kWh Lithium-ion
BMW X5	Plug-in Hybrid	9 kWh Lithium-ion
Chevrolet Volt	Plug-in Hybrid	16 kWh Lithium-ion
Mercedes S 550e	Plug-in Hybrid	8.7 kWh Lithium-ion
Mitsubishi Outlander	Plug-in Hybrid	12 kWh Lithium-ion
Nissan Leaf	EV	24 kWh Lithium-ion
Renault ZE	EV	40 kWh Lithium-ion
Tesla Model 3	EV	60 kWh Lithium-ion
Mitsubishi i-MiEV	EV	16 kWh Lithium-ion
Volvo XC90 T8	EV	9.6 kWh Lithium-ion
Hyundai Ionic EV	EV	28 kWh Lithium-ion

2.3.2 Charger Characteristic

The bidirectional charger has the ability to charge and discharge PEV’s battery while producing minimal harmonic currents. So, it supports absorbing power from the grid (G2V) and can provide power to a network (V2G) or a building or other PEVs [33].To avoid harmonic currents and poor power factor, the charger is needed functions efficiently (smoothly) in both charging and discharging mode. The standard bidirectional chargers for three-phase and single-phase are shown in Figure 2.2. Both chargers have the same topology. However, the AC-DC converter types naturally differ [33].

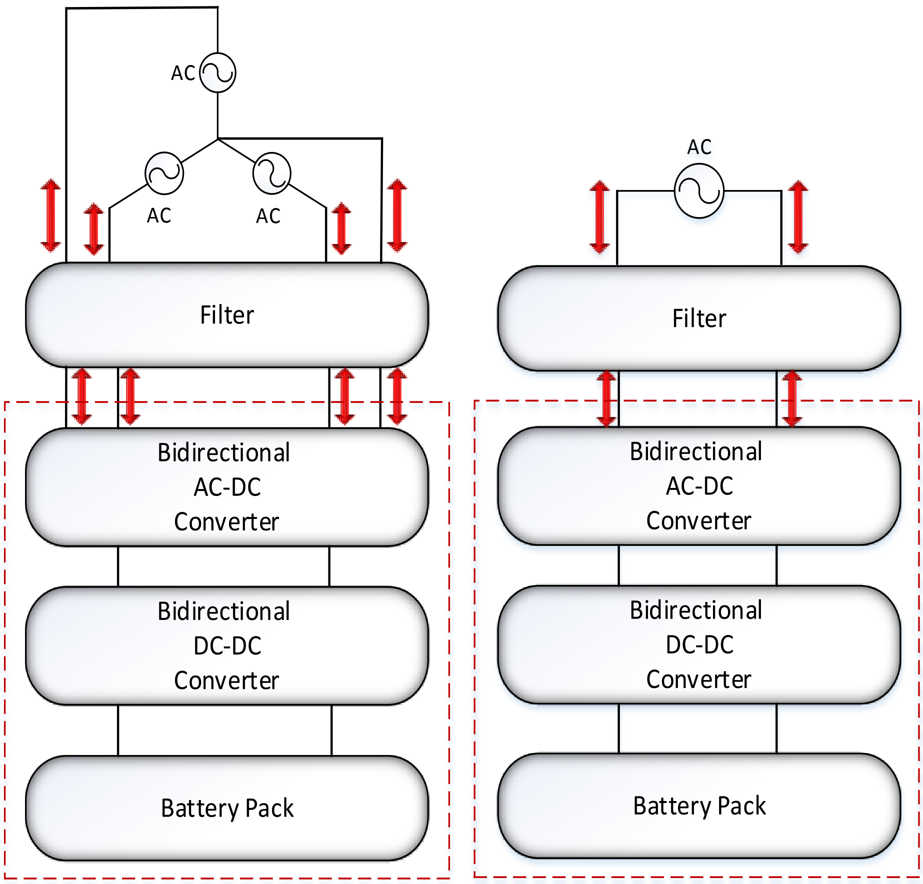


Figure 2.2. General bi-directional charger topology single/three phase [33].

There are several standards for EV charging. In Australia, a maximum of 2.4 kW can be supplied by standard 240V single phase outlet. A PEV owner, who needs to charge his vehicle quicker, may consider a higher charging level. 15A and 20A outlets for single-phase and three-phase (which are quicker) have power rating approximately between 4 kW and 14.4 kW respectively. PEVs can be charged in various places like a private garage and charging stations and can have a direct connection with the level of charging PEVs [34].

2.3.3 Communications

As mentioned before the main aim of introducing smart grid is efficient data communication. One of the advantages of this that the energy transfers to or from the

PEVs can be optimised. It means that the PEV charging will require smart charging to intergrade in smart grid infrastructures with two-way communication capability. According to [35], generally two connection methods are available for communication between PEVs and aggregator.

The first connection is over line signalling method, and the second one is controlled or wireless communication approach which mainly links the wires access, locating on-board metering. PEV verification and privacy protection for PEV and owners are necessary to have secure wireless communication between the aggregator and owners. In addition, as suggested by [35] it is required the on-board charger equipped with "Telematics" communication unit which is necessary for the real-time communications. This capability is used for the information transmission, GPS geographic location data, and getting data from aggregator and control centre [35]. In addition, it can be managed by the charging during the lowest electricity rates to support demand control on the network.

The SAE standards (e.g. SAE J1850, SAE J2293, and SAE J2836, etc.) recommend several protocols for vehicle-utility communication. There are different types of potential candidates for communicating between switches and controllers, like a wireless sensor, Wi-Fi, WiMAX, and satellite communications. References [36, 37] mentioned various technologies could be applied to PEV charging stations which are included power line communications (PLC), IEEE 802.15.4 (Zigbee), Zwave, LORA technology, and cellular networks. Among all these technologies, a Zigbee based platform is the most popular one to test the PEVs charging. In this research work, it is assumed that data from the central controller to the owner controller are transferred through ZigBee based communication.

Figure 2.3 presents an example of the concept of a control panel with communication for a residential/charging station that has been suggested by Pacific Northwest National Laboratory (PNNL) in [38]. In this model, the owner needs an initial set up of the controller and plug in the vehicle. The wireless signals transfer data among the consumers and PEVs based on the amount of electricity required, cost of power and decision to charge.

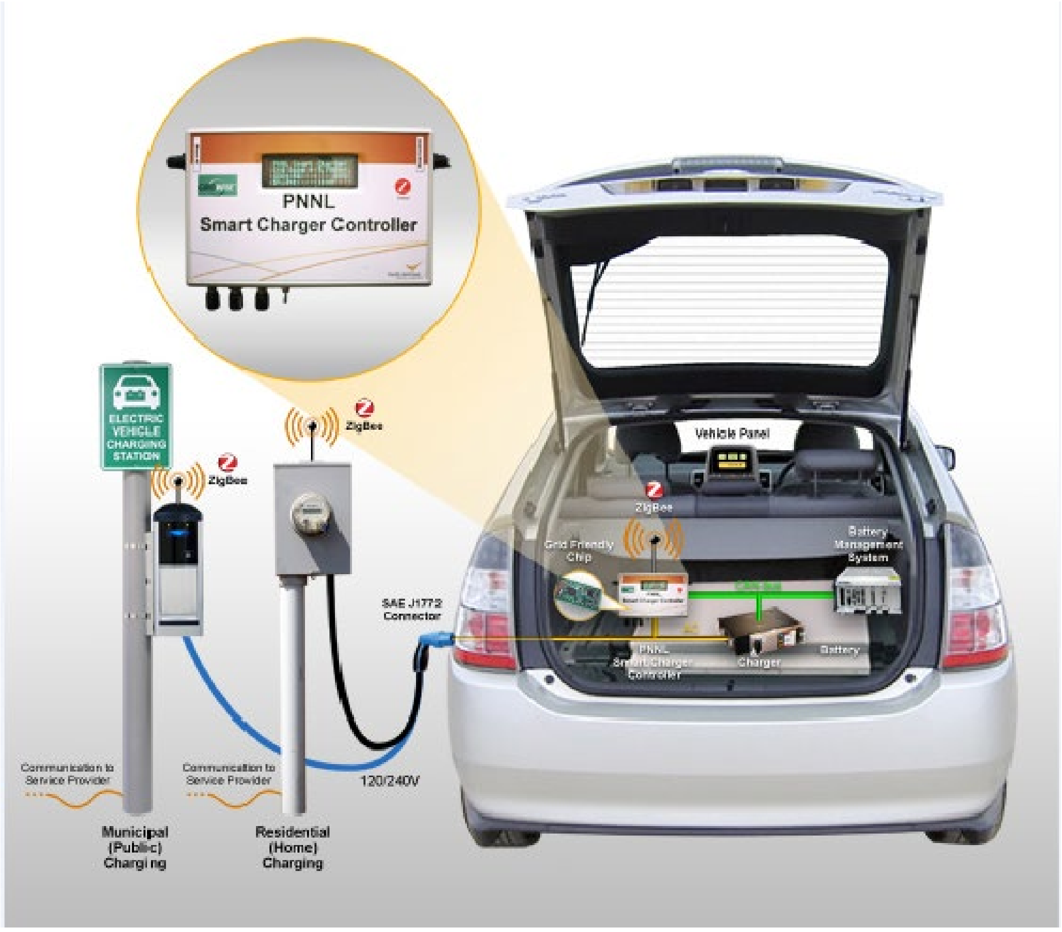


Figure 2.3. Proposed smart strategy of the concept of vehicle control and communication with residential/ charging station [38].

2.4 Impact of PEVs on Smart Grid

Consideration of market trend is essential to estimate and approximately evaluate the probability of impacts of PEVs on the smart grid. Figure 2.4 shows the projected PEV sales in the world market between 2017 and 2026 [39]. It means that, by 2026, the demand of PEVs will be increased by at least fivefold from today all around the world. It is difficult to estimate and track the number of home installations of slow charger by countries. However, according to the International Energy Agency (IEA), the slow charging infrastructures have been increasing intensely more than the fast charging stations [40]. Therefore, the increasing number of single phase chargers in LV distribution system and uncertainties associated with charging time and duration PEVs result in phase unbalance, which consequently will affect the consistency and standard of power supply. Expanding and organising the network for fast growth of the number of PEVs should be investigated by different controls and economy management studies. Therefore, it is essential to study the impacts of the high penetration of PEVs that become the source of severe detrimental problems in distribution systems. Some examples for these issues are phase unbalance, unacceptable power consumption rise, energy losses, line and distribution transformer overloading, high current in the neutral because of the phase unbalance, voltage drops, harmonics at the battery charger and circuit breaker and fuse blowout [41-44].

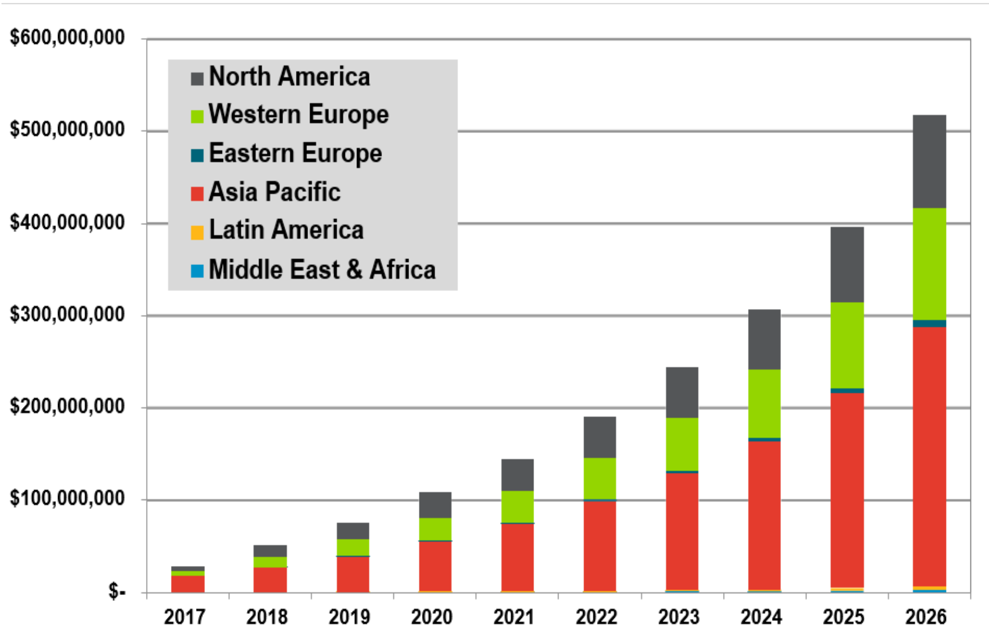


Figure 2.4. The projected PEV world market from 2017 to 2026 [39]

Typically, all phases of the three-phase distribution networks are loaded evenly by electrical utilities. However, at the usage point the loads can vary because of a number of impacts like unbalance impedance, uneven distribution of single-phase loads or high single-phase power consumptions such as vehicle charging activities (G2V) [5, 6]. Voltage unbalance (VU) problems caused by current variations need to be prevented in the network [45, 46].

Specifically, [47] has studied the effect of PEV charging and discharging as well as their impacts on network quality. Reference [34] investigated the implications of PEV medium and quick charging during the peak hours on a high-voltage distribution network to show the effects on power transformers. In [48], the starting time and charging durations for all PEVs are considered the same, while [49] and [50] studied the impacts when PEVs are charged at certain times and do not leave the grid till the batteries are fully charged. A methodology suggested in [51], for modelling the PEV charging at charging station.

In [52] and [53], a statistical procedure has been applied for charging model in the network. Research [54] studied the PEV charging and its effects on distribution transformer ageing and introduced a decentralized smart solution which could help to utilise the capacity of transformers more efficiently.

Converter based devices like PEV battery chargers used for converting low voltage AC power to DC can generate the high amount of current harmonics and voltage distortions, which will have negative impacts on power system in terms of neutral current and may cause transformer hot spots. Many studies such as [55] report the effects of harmonic distortion as a consequence of battery charger and how it causes suboptimal generation dispatch to serve the large number of PEVs charging.

2.5 PEV Charging Coordination

There is a large amount of literature on the distribution of PEVs in SG. One of the primary areas of them is related to PEV charging planning and power flow direction which can be categorized into charging only G2V and V2G/V2H (vehicle to grid or vehicle to home) scheduling. Besides, due to the possible challenges as a result of additional load of PEVs, the grid operators and planners have tried to find several solutions to adopt PEVs and alleviate their impacts appropriately. In the design stage, the growth to meet future demand and updating the network infrastructure need to be considered. Thus, for a long-term scope, items like load growth, PEV optimisation, advanced technologies, and economic efficiency should be studied [56].

According to [57], one of the effective ways to relieve charging many PEVs is shifting them to off-peak hours when there is more capacity in the feeder. In this method, the price of energy is the main factor to control charging. It is expected that a higher rate during peak hours could convince PEVs' owners to shift their charging time into lower demand hours such as nights, where the price is expected to be lower. As a result, this can prevent grid overloading in high demand periods. Although it seems to be a simple solution, finding out the effective shifting time and price setting has become a challenge for many researchers. It is vital to consider other aspects such as customer satisfaction and efficiency even for those who cannot go for off-peak hours. According to [57], the effectiveness of controlling PEV by price is related to regular electricity price and off-peak hours' tariff. It means that a reasonable price gap between peak and off-peak hours is needed to motivate the customer to charge during the low energy demand periods.

When high penetration of PEVs happens during the night time, upward pressure on distribution components may occur. So, there can be a conflict between the owner appropriate hour for charging the car and the utility partiality [9]. In addition, just out of system variables such as the price of electricity is highly focused on this method and there is less attention to the main system parameters. Thus, grid operators accomplish flexible charging scenarios noting the technical grid restrictions and satisfying vehicle owners concurrently. Several authors have expressed about price shift coordinated due to the straight forward and easily to manage strategy, considering different objective functions, such as considering vehicle owners profits or grid operational objectives [58]. These methods can be achieved by aggregators to gather data from PEVs and transfer it to the energy suppliers and the other way around. This communication can help smart grid by contributing ancillary services [59] [9].

Smart charging is a leading method not only for consider customer satisfaction but for grid control as well. It is not just about shifting vehicles' charging to off-peak but to include advanced control to meet vehicles owner demand on charging time, grid support by ancillary services and eliminating networks overload from simultaneous many vehicles' charging. [60]. It can control different charging parameters like charging time patterns and output power at various chargers. The control can be flexibly applied to a subset of the vehicles in different ways, but not necessarily to all vehicles in a similar way [57]. In this regard, reference [61] has presented the effect of smart charging on power losses and load factor for each PEV at residential outlets by using the quadratic programming technique (QP).

Centralized and decentralized architectures are the main control methods in smart charging. In the centralized architecture, an aggregator or fleet operator is receives information from PEVs and other individuals, applying the control limitations, transferring the final improved information and set points of each PEV by defined control procedure to vehicle owners [62].

The central operator defines the optimal charging patterns of PEVs using power flow studies. Features like energy price, PEV owner priority and distribution system condition are taken into account by the central controller. This results in discarding direct control by PEV users in this approach [7] [62]. Nevertheless, the decentralized control is dependent upon the local management of the charging procedure of the PEVs to meet the users' advantages and persuade them to participate in this scheme. In this way, the users retain the control of the charging progression of their PEVs. Additionally, the decentralized process presents several benefits such as "scalability" to adjust configurations and size to fit new conditions, "fault tolerance" operating as designed despite changes, "constant computational effort", fewer connection provisions and improved privacy for PEV users [62].

The impacts of coordinated charging have been described in various papers by considering different types of objective functions. Some articles have proposed quantitative methods such as minimization of power loss and charging cost or reduction of grid load factor in uncoordinated charging [20, 61, 63, 64], while some other studies have reported the impacts of uncoordinated PEV charging on the grid. The impact of fast PEV charging on distribution grids is analysed in [65] by integrating power flow, short circuit and protection studies. Reference [66] has proposed the demand response strategy when consumers can control their loads based on their preferences. In reference [68], a strategy is used to study a large scale distribution network and the impacts of several levels of PEV penetration on the distribution network and energy loss are simulated.

In addition, some researches have mentioned that PEV owners' preference during their charging process. For example, [69] has proposed a real-time load management method by minimizing the total system cost considering systems parameters like voltage deviation and grid losses. For customer charging, it allocates the different time of use energy tariffs. A sensitivity index at each step is responsible for identifying the most appropriate PEV to be charged. Another work [70], suggested a scenario based on which PEV owners, who are interested in paying more, can charge quicker than others. Research [71] considered hybrid overnight objective functions in day and night with the purpose of customer satisfaction.

While many research articles have investigated the impacts of PEVs on balanced systems, there are fewer studies for unbalanced networks. The articles [43] [43] proposed two different multi-objective functions for optimally charging PEVs. Each objective explains the "Greedy charging" and "Greedy charging with price" scenarios, with the conclusion that the optimization by greedy charging with price has a better result than others. However, the LV system has not been considered

2.6 Applications of V2G PEVs in Smart Grid

The idea of V2G was introduced by Willet Kempton in 1997 [72] with the aim of exploring the benefits of PEVs in economics and environment. The basic concept of V2G studies is mainly to find the benefits of PEVs in the product market. These days the subject of V2G is more common among researchers [60]. The Electric Power Research Institute (EPRI) has predicted that by 2050, V2G can produce 20% of grid consumption. In other words, it is 20% less dependence to central grid generation capacity [73] As the battery capacity of PEVs are limited (in the kW range), and grid power is on MW range, the role of the aggregator is very critical to collect energy from PEVs for supporting grid. In this regard, some researchers have studied the potential of PEVs functions in V2G operation which highlight new opportunities like reactive support, load balancing, peak load shaving, and harmonics filtering [74]. So, in most of this literature, the core V2G research area is the utility side profits such as balancing renewable sources, regulating grid and minimizing losses through voltage improvement.

The PEVs in V2G operation may be examined as a storage device and used for short time ancillary services because of faster response and lower cost in compare with standalone battery storages. Besides, the capability of ancillary services like frequency and voltage regulation and spinning/non-spinning reverses, the V2G can improve grid efficiency and credibility. [74]. With increasing installations of distributed PV sources, references [75]and [76] utilise the integrated battery storage (BS) and PV system to mitigate the variation of PV output, considering charging PEVs in industrial micro-grids systems. In reference [9], a smart management coordination is presented for PEVs charging in the future parking lots considering the electricity prices. Reference [77] reports that 43% of all PV generations in Australia are related to residential rooftop PVs, which can enhance the voltage regulation in locally. References [78, 79] [80] propose an integrated PV, energy storage (ES) and PEV systems for self-feeding houses.

For VUF improvement, recent researches have addressed some possible opportunities for coordinated charging and discharging of PEVs. Reference [81] highlights the importance of preventing VU conditions as a result of current variations [45]. According to [9], controlling PVs as charging capacitors can decrease the current unbalance. Authors in [82] studied a method for minimizing the current unbalance by managing reactive power of plug-in hybrid electric vehicles (PHEVs). In addition, using renewable energy sources or more PEVs penetration can improve voltage regulation that has addressed in some references [83]. Smart control on reactive power has also investigated by researchers as an efficient solution that can make better voltage profiles. Many investigators have examined reactive control based on centralized and decentralized approaches [77, 84]. In reference [85], independent inverters have been suggested to enhance voltage by using reactive power capability. This may decrease consumer advantage by affecting the active power. Moreover, reference [86] shows the reactive power control is less effective in low voltage networks in compare to medium and high voltage distribution networks. As a result, voltage maintenance in the end node/bus consumers or the rural areas with high length (R/X ratio) needs to be considered [46, 77].

Previously for voltage mitigations and unbalanced issues, traditional methods were used on system such as “online tap changer (OLTC), voltage regulators (VRs), fixed or switched shunt capacitors and energy storage devices” [88-90]. However, there are some problems with the traditional techniques that make them ineffective. Issues like an infrequent response to rapid fluctuation due to the mechanical limitation of OLTC, further failure points as a result of using a switched capacitor and high storage's price are among these uncommercial solutions [91]. Furthermore, reference [92] mentioned the configuration of distribution network would possibly be changed in the next years. Consequently, finding the optimal location of reactive power compensators in the network is a challenge. In addition, it is not beneficial for the utility to reimburse an extra cost for installation of new reactive power controllers. For voltage regulation, some researchers have developed the control method of current distribution generation (DG) by voltage management devices such as DSTATCOM or VR [93], However, Some others have researched to control the active and reactive power injection from DGs by using centralized /decentralized techniques [94, 95] to improve the voltage problems in systems [96].

Recently, some researches have investigated different types of control techniques that use bidirectional PEV's inverter as a distributed energy resource [97]. It has been displayed that the PEV's inverter for V2G operation can contribute to voltage profile regulation and reactive power compensation. This can be more efficient technically and economically. On the other hand, references [74] and [41, 98] have stated, though PEVs can perform as the energy storage in the electrical systems, the battery storage degradation is still an issue that needs to be considered. Reference [99] mentioned the voltage regulation in contrast to frequency regulation due to frequent charging and discharging of batteries cannot affect the battery's lifetime. These minimal effects motivate the users to make a profit of providing voltage regulation [97]. Reactive power compensation can support the grid to maintain power quality and reliability, and increase the active power transfer limits as well [99]. Reference [100] has investigated that the V2G reactive support in on-board chargers does not have any consequences on the battery's life cycle due to the structure of charger design.

In recent times, limited references such as [101] and [102] have investigated the possibility of PEVs as a source of reactive power in the reactive market by considering objective functions like minimizing total payment costs and losses in the network, while others have tried to use synchronous generator as the primary source for reactive power [103]. Reference [104] revealed that reactive power market is not attractive for the utility because the cost of it is much lower than energy production. However, the local sources and distributed generators (DG) can be contribute to voltage maintenance in the end node/bus users or the rural areas due to the high length (R/X ratio) in LV distribution networks. Hence, considering both PEV active and reactive power in the energy market could be more effective.

According to [100], reactive power losses are almost ten times or more in heavily loaded conditions than active power losses due to the nature of distribution lines, so they need to be placed close to the end users. Also, utilities provide customers with the required reactive power for their electrical apparatus such as washing machines, microwaves, and refrigerators at no charge. PEVs might readily supply these locally desired reactive power loads without the need for remote VAR transmission. By considering these local reactive power requirements and their essential role in network stability, it is possible to encourage the reactive power producers to maximize their profits and get benefits from the supply. In a fair market based on supply and demand, reactive power can be valued with appropriate incentives where it is not enough in the grid. Although recently some researchers have investigated the capability of PEV inverters as ancillary services for voltage regulation, still there are not many studies considering P and Q in optimal PEV scheduling based on price.

2.7 Mathematical Optimization

Mathematical optimization or mathematical programming is a method in which, by using a set of possible solutions, the best one can be found. These techniques are widely applied in engineering, manufacturing, and economic fields. In power systems, these methods can be used in applications like economy dispatch, power system planning, network reconfiguration, etc. [105]. One of the optimization methods is artificial intelligence (AI) which suggests several techniques for solving problems. AI methods are divided into three main categories – fuzzy logic (FL), neural network (ANN), and evolutionary computation (EC) [106]. Among these, EC strategies such as GA have drawn more attention due to their ability in solving complex real-world optimization problems [107]. Many investigators have shown GA as an acceptable method for optimal charging and discharging of PEVs in real systems. GA is based on natural evolution and was initially proposed by Goldberg [108] and then progressed by Holland [109] to make solutions for both constrained and unconstrained optimizations. GA starts with a random population as the set of feasible solutions. At each stage, a new generation of individuals with enhanced result will be created by using selection, mutation, and crossover procedures through the chromosomes of the old population. GA is extensively used in literature for coordinated charging and discharging PEVs. [107] applies GA optimization in the LV system for the load profile flatting and peak load shaving. [107] employs a GA combined with the method of power flow linearization to coordinate charging strategy for EV's batteries in charging station.

In this thesis, GA is selected in consequence of its flexibility to investigate multi-objective functions simultaneously with different constraints. The detailed process of GA optimization adopted in this study is described with parameters settings below:

- **Initialization:** An initial population with the size is randomly generated to improve the convergence rate to the global solution. Next, the unbalanced load flow is operated for each set of the population (chromosome) and each analyzed by objective function and constraints.
- **Selection:** Through the genetic operator in the reproduction process, the new combination of chromosomes (i.e. new population) is evolved by roulette method as a parent. Each with less value of objective function (due to the problem) effect on the grid has a higher probability of being chosen as parents.
- **Crossover:** Through the crossover operator, the offspring are generated by randomly mating two parents' chromosomes owing to the exchange information between chosen parent individuals from the selection process. In this study, a one-point cross over at the rate of 50% is selected.

- **Mutation:** To increase the diversity and the chance of global optimality, a mutation is applied among the parent individuals with a mutation rate of 5% considered in this study.

- **Stopping criteria:** In each iteration, the best population results against the objective function (in this study, the minimum of VUF) are saved. This procedure continues until the maximum number of 100 repeats is reached, or global optimality is located. All the GA based optimizations in this study are performed in MATLAB.

2.8 Summary

From the discussions in this Chapter, it can be concluded that the charging coordination of PEVs is one of the significant issues in integrating mass penetration of PEVs for the future smart grid. In this regard, firstly, the concept of the smart grid has been reviewed, and then two different aspects of PEVs deployments are discussed: (1) impact of high penetration of PEVs on network (2) capability of V2G into the smart grid. Moreover, different characteristics of PEVs including charger, communication, and battery modelling are discussed. In addition, the potential impacts of PEVs and various objectives, solutions and scenarios surrounding applications of PEVs have been reviewed. The last part of the Chapter provided general information regarding the optimization techniques selected in this thesis.

Chapter 3

Impact of PEV Charging in LV Distribution Networks on Voltage and Voltage Unbalance

3.1 Introduction

The next decade is likely to witness considerable growth in the application of plug-in electric vehicles (PEVs). However, uncoordinated PEV charging in low-voltage (LV) distribution networks may cause grid issues such as transformer overload, and voltage unbalance. With this background, this Chapter addresses the impacts of stochastic charging PEVs based on time, rating, and location of charging/discharging at residential houses on voltage and voltage unbalance factor (VUF). Additionally, the Monte Carlo Simulation (MCS) is applied to describe the stochastic behaviour of charging PEVs. Different aspects like penetration level, PEV charging rates and location of charging/discharging on the feeder are addressed to better understand the effects of PEVs on LV distribution network. This Chapter is organized as follow:

Sections 3.2 and 3.3 give a brief overview of VU definitions and limitations, Sections 3.4 to 3.7 analyse the main characteristics of real Western Australian (WA) distribution LV networks, PEV consumption model and load flow approach. The stochastically methodology and simulation results are presented in Sections 3.8, and 3.9, while Section 3.10 summarizes the findings and conclusions of this work.

3.2 Voltage Unbalance Definitions

In an electrical power system, VU is defined as any difference in a three-phase electric system in voltage magnitude and/or fundamental phase angle [7]. In a power system, unbalance is an important subject that needs to be reviewed. In this regard, standards were developed for the quality level assessment of voltage and current asymmetry for generation, transmission, distribution, and customer's load as well. For evaluation of the level of VU in the system there are different definitions [110, 111] including "the phase voltage unbalance rate" (PVUR) defined by IEEE (Institute of Electrical and Electronics Engineers), "the line voltage unbalance rate" (LVUR) stated by NEMA (National Equipment Manufacturer's Association), "the percentage voltage unbalance factor" (%VUF) explained by IEC (International Electrotechnical Commission) and VUF defined by CIGRE (International Council for Large Electric System). Different definitions of VU considering the effect of phase angle in their calculation are reported in [112] and [111]. For instance, NEMA, IEEE, IEC, and CIGRE suggest different techniques for VUF calculation. Using these various definitions, there is a concern for the level of asymmetric current and voltage amounts. That is the calculation excluding the phase angle results in an inaccurate formulation of the level of asymmetric current and voltage. The line-to-line voltage is considered for NEMA calculation, whereas IEEE uses phase voltage. Hence, in both definitions, the phase angle asymmetry is not considered. Nevertheless, in IEC definition both phase angle and RMS magnitude are used to calculate VUF [113]. In this thesis, based on IEC Std. 61000-3-13:2008 [114], the proper definition for VUF is determined as the ratio of the fundamental negative sequence voltage component (V^-) to the positive sequence voltage (V^+) in percentage. Therefore, % VUF is given by:

$$\%VUF = \left|\frac{V^-}{V^+}\right| . 100\ \% \tag{3.1}$$

where,

$$V^- = \frac{V_{ab}+a^2V_{bc}+aV_{ca}}{3}, V^+ = \frac{V_{ab}+aV_{bc}+a^2V_{ca}}{3}, a = e^{j120°} \tag{3.2}$$

This method uses symmetrical components, in which a three-phase unbalanced network is mathematically converted into three balance systems which are termed as zero, positive and negative sequences using Fortescue technique, given by [81, 115].

$$\begin{bmatrix} V_0 \\ V^+ \\ V^- \end{bmatrix} = [A]^{-1} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{3.3}$$

where $A = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$, V_0, V^+ and V^- are the zero, positive and negative sequence voltages whereas V_a, V_b and V_c are the phase voltages. Similar definition can also be used for the line-to-line voltages as well.

3.3 Voltage Magnitude and Voltage Unbalance Limitations

The supply voltages are different between regions, but nominally are 220-240V or 120V (US). The national standards state, depending on the countries, the nominal voltage range at the load needs to be in the range of ± 5 to ±10%. In this regard, according to Australian standard AS60038-2000, Australian LV network is 230 V with a tolerance between + 10% and – 6% [116].

According to [117], in LV networks, the acceptable limit for VUF is 2.0 %. Keeping the voltage unbalance within certain limits is an important issue that has been investigated by utilities. According to IEEE, a recommendation for the practice of an electric power system in commercial buildings [118], VU greater than 2-2.5%, where the voltage amounts overtake the limits, may cause issues on power electronics based equipment such as computers [118]. In addition, The “ANSI” standard for “Electric Power Systems and Equipment Voltage Ratings (60 Hertz)” mentioned that the maximum level of VU for electrical supply system should not exceed 3% when measured at no load condition at utility endpoints [119]. Due to the adverse effects of voltage and VUF issues on power quality and transformers' efficiency, keeping the voltage and VU within certain limits are an important subject that utilities have to be very careful about.

3.4 Network Structure based on Perth Solar City Project

Figures 3.1 and 3.2 explain the four-wire, three-phase distribution network, which is selected in this work for voltage deviations and VU investigations. The feeder model is based on the "Pavetta 1" within the Perth solar city high penetration PV trial by the regional network services provider, Western Power [120]. The 415/240 V network is supplied by a 200kVA, 22kV/415V distribution transformer and includes 74 nodes that feed 56 active residential customers. This is an unbalanced system with 11 houses connected to phase-a, 11 houses to phase-b and 12 houses to phase-c in addition to 22 three-phase customers. Of these, 34 consumers have single-phase rooftop PV systems with average ratings of 1.59kW, 1.88kW and 2kW etc. While the consumers have a mixture of single- and three-phase house connections, the loading is characteristically unbalanced. "The network under study is an aerial, 3-phase 4-wire construction with four equally sized conductors on a mixture of 0.9m and 1.2m cross arms. The consumer mains are 6mm^2 copper with R=3.7Ω/km and X=0.369Ω/km while the aerial mains are two seven strands, with aluminium conductor types":

7/4.50 AAC – R=0.316Ω/km; X=0.292Ω/km;
7/3.75 AAC – R=0.452Ω/km; X=0.304Ω/km.

Each house at the connection point to its switchboard has a meter. Therefore, there are 22 three-phase and 34 single-phase smart meters which record load data, including voltage and current in 15-minute intervals. The details of the "Pavetta 1" system in this thesis was obtained from[121,122], and the details of system characteristics can be found in the Appendix-B. Figure 3.1 gives an aerial view of the "Pavetta 1" system, while its physical layout is given in Figure 3.2.

Figure 3.1. Perth solar city high penetration feeder site, image obtained from Western Power [120,122]

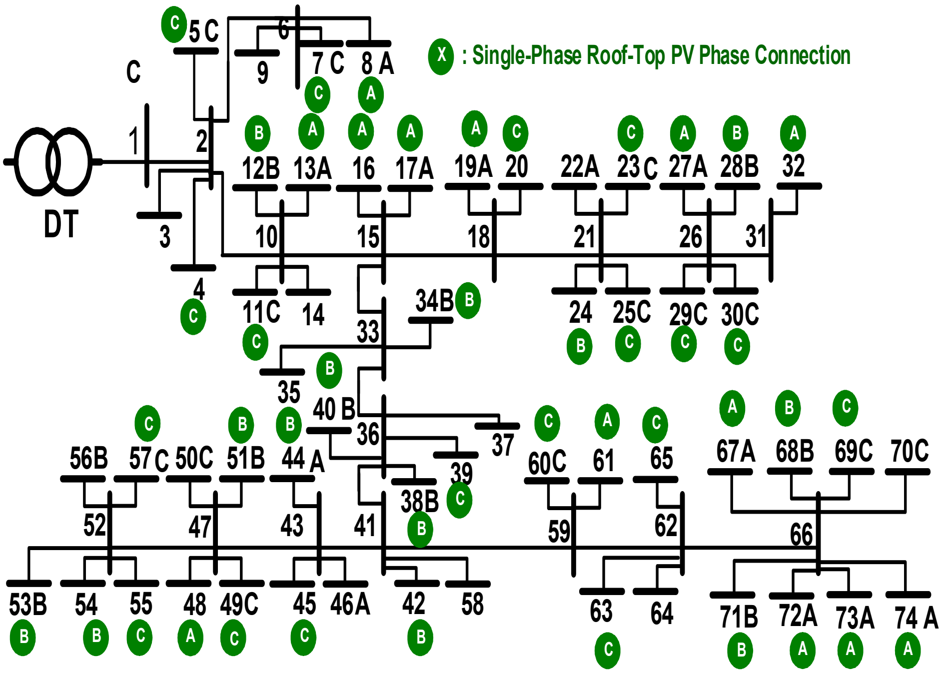


Figure 3.2. The diagram of "practical four-wire three-phase 74 nodes distribution system (Pavetta 1) in the Perth solar city, Western Australian" [120]. Single-phase nodes are shown with both node and phase number. The phases with the single-phase connections are represented with Letters A, B and C in the green circles.

3.5 System Modelling

In this research work, the system of Figure 3.2 is also connected with PEVs through the single and three-phase residential feeders. The generalised schematic diagram of a PEV and PV connection at Point of Common Coupling (PCC) of node 74A is shown in Figure 3.3. It is to be noted that a house may not have a PV or a PEV. In either case, the input power in case of PV or the output power in case of PEV are considered to be zero. The power at each node then can be represented by:

$$P(t,k) = P_{PV}(t,k) - P_{PEV}(t,k) - P_{Load}(t,k) \tag{3.4}$$

where k is the bus number, $P(t,k)$ is active power, $P_{PV}(t,k)$ is solar power, $P_{PEV}(t,k)$ is charging power consumed by PEVs and $P_{Load}(t,k)$ is residential demand at node k

at time t. Note that the values of $P(t,k)$ will be positive for exporting and negative for importing power, respectively.

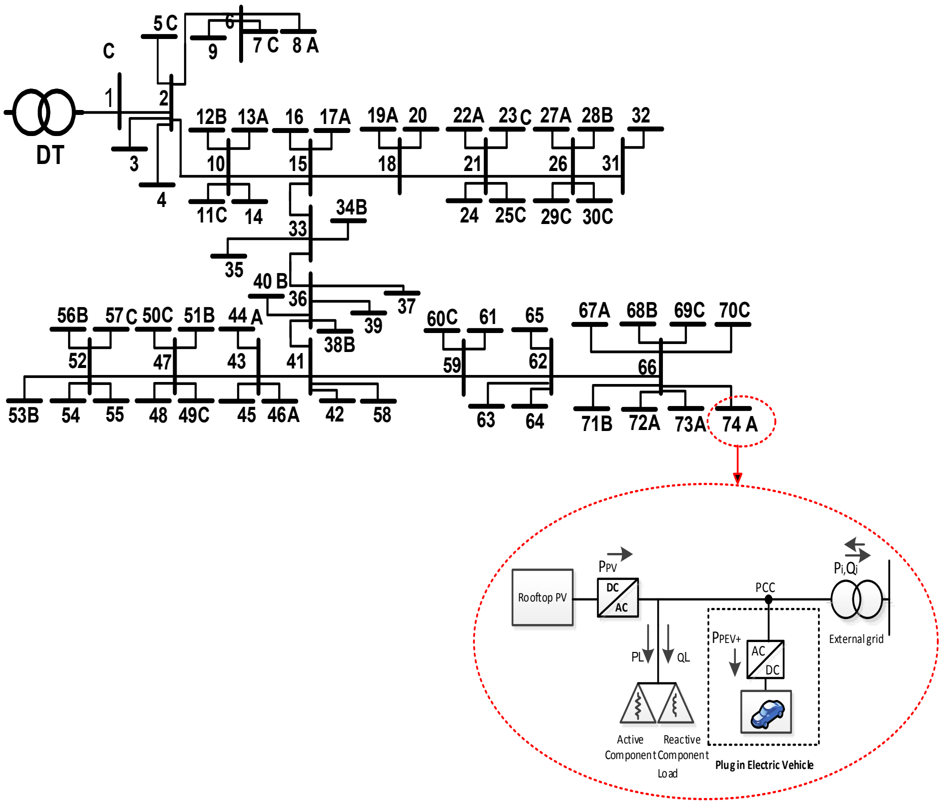


Figure 3.3. An example of connection a PEV and PV at PCC at "Pavetta 1" system

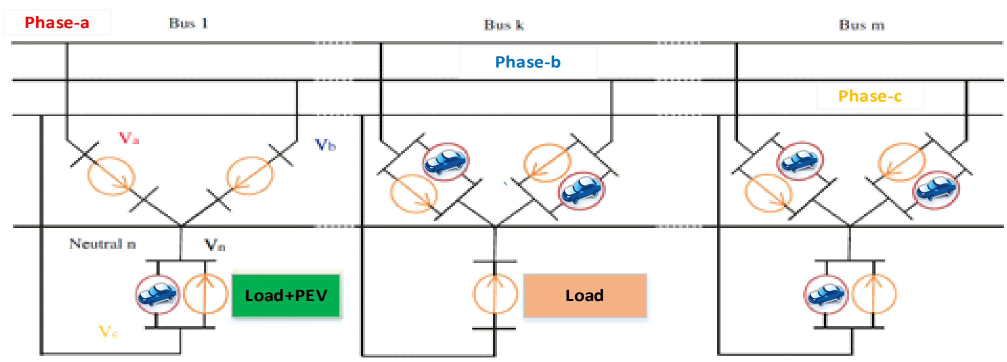


Figure 3.4. A node voltage at three-phase LV distribution system where the base loads are combined with PEVs. This figure is obtained from [7].

3.6 Stochastic Modelling of PEV

The battery charging of PEV represents a sizable load which can be influenced by driving behaviour and their travel patterns [123, 124]. Therefore, The PEV charging profile can be estimated by some uncertain variables, including the location of charging, start time, rate of charging, PEV model and energy requirements, which are defined below:

- **PEV Model:** The size of the battery and on-board power management considerably affect the PEV charging and vehicle cost. Besides, PEV charging will have to be rated high enough to charge batteries in reasonable time [125]. The list of recent PEV and EV models available in Australia is presented in [32]. In this thesis, the battery specification of all the PEVs is based on a Nissan Leaf battery pack (Bat_{cap}) with a capacity of 24 kWh.

- **PEV Charging Location:** In this research, it is assumed PEVs charged at home and the uncertainty of PEV location along the system is modelled by drawing a random number uniform distribution between 0 and 1. It is also assumed each of the 34 houses can have a PEV charger. This implies that each residential house has 1.7% probability of having a PEV charger.

- **Charging Power:** In this work, PEV charging rates based on Australian standard (10, 15, and 20 A single-phase outlets) are considered for different charging periods. These are sufficient to charge 24 kWh battery. In addition, to protect battery's life, 70% of rated battery capacity is considered usable resulting in 16.8 kWh capacity. The charging efficiency is assumed approximately 90%, such that 15 kWh energy is needed to charge a PEV from the grid [34]. It has been assumed that all PEVs work at unity power factor. For selecting these levels, a uniform random number [0 1] is used.

- **Energy Required:** The energy required $\left(Eng_{req}\right)$ to charge the PEV until it reaches the required state of charge by a user is calculated by (3.5)

$$\forall \text{PEV} : Eng_{req} = (SoC_{req}^{\%} - SoC_{ini}^{\%}) \times Bat_{cap}/(\eta \times 100) \quad (3.5)$$

where $SoC_{req}^{\%}$ and $SoC_{ini}^{\%}$ are the required and initial for the battery state-of-charge (*SoC*), respectively, and η is the charging efficiency that is considered as 90%.

- **Charging Duration:** Considering the PEV charging with constant power P with unity power factor, the time needed for complete charging is given by:

$$\forall \text{PEV: Time}_{\text{req}} = \frac{Eng_{req}}{P_{\text{PEV}}} \quad (3.6)$$

- **Start Charging Time:** As the PEVs are expected to start charging once their owners arrive home, knowing the PEVs arrival times is essential to determine the PEV charging profile. So, it is supposed the drivers plug in their vehicles between [4:00 PM and 7:00 PM] and the random number distributed generally with mean time of 4:45 PM and standard deviation 2.28 hr recommended in [124] by

$$\forall \text{PEV}: Time_{arrival} = GAUSS(\mu_{t_{arrival}}, \sigma_{t_{arrival}}^{2}) \quad (3.7)$$

3.7 Three Phase Load Flow Approach

The efficient load flow solution is essential for a large-scale distribution system. Distribution system usually consists of singe-/dual-/three-phase loads and four-wire cable/lines. Consequently, its power flow solution needs to consider unbalance with three-phase system modelling [126]. For distribution power flow, the system unbalance needs to be considered. For this, there are two approaches. One in which the neutral is not grounded and another in which the neutral is solidly grounded. In this thesis, the later approach is adopted such that the three phases can be treated independently. For this, the backward/forward sweep (BFS) load flow is one of the most appropriate approaches, especially for unbalanced systems because of its simplicity, better convergence and higher efficiency [126]. So, in this thesis, for analysing the VUF and voltage deviations in LV networks, the BFS method is used.

3.7.1 Backward-Forward Power Flow

The basic BFS includes two sweeps (i.e., forward sweep (FWS) and backward sweep (BWS)). Through this method, in an iterative procedure, the branches currents and bus voltages are updated by passing through the slack bus and end bus [126]. In this scheme, the distribution grid is similar to a tree by considering the slack bus as the root. Initially, the source bus and end buses are adjusted as a set point voltage. BWS starts from the end bus of the lateral and sum upstream line segment currents and shunts currents. It flows toward the supply bus based on the given active $P(t,k)$ and reactive $Q(t,k)$ consumption of residential load of each bus and the line impedance of each segment. FWS starts from the specific source bus voltage and the branch currents found from the previous BWS. This process will be repeated until the difference between resulting in the bus voltage and set point voltage to become within an acceptable tolerance.

Due to the tree shape structure of radial distribution network, the pattern of the deflection of buses and feeders makes the procedure more efficient and quicker for the load flow analysis. So, in this research work, all buses based on the model applied in reference [80] are numbered with an increasing path with considering reference bus as 1. The BWS starts at the furthest buses and sums all the currents at nodes moving along lateral or branch conductors in the direction of the supply bus. Considering in node k, a branch conductor splits into two sub-branches. The first sub-branch number begins from $n+1$ and continues to "m" to include remaining buses. Then the second sub-lateral bus number starts from "$m+1$," and all other buses will be identified in ascending order. Then BWS begins from the highest node number based on Table 3.1. Afterwards, three separate vectors by considering the total number of nodes are generated. In Table 3.1, $[Bustype]_k$ determines the bus type, which can be a slack/reference, PQ or load bus. The identification of each bus is based on Table 3.1. For example, if a PEV is connected to bus k without any rooftop PV the values of $[PEV]_k$ and $[PV]_k$ on that specific buses are 1 and 0 respectively. In order to analyse the steady-state performance of a distribution network, the consumer loads are supposed to be constant complex power components. This means load buses are designed as PQ specified buses. In the present study, 15-minute intervals are applied, thus a daily load curve is composed of 96 couples of time and demand values.

Table 3.1 Bus identification approach [80]

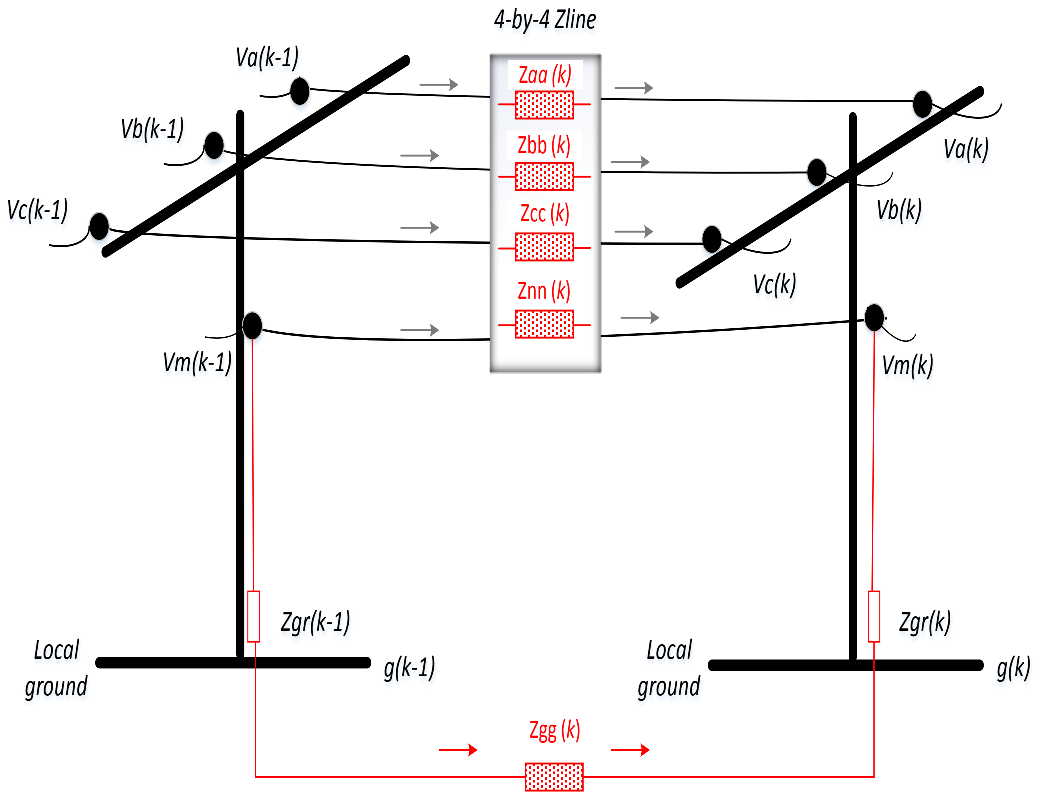
	$[Bustype]_k$	$[PV]_k$	$[PEV]_k$
Slack bus	1	0	0
Node bus	3	0	0
PQ bus	2	0	0
PV bus	2	0/1	0/1
PEV	2	0/1	0/1

After identification and numbering the bus feeders for unbalanced load flow calculation, Carson's line equation is applied to generate a series impedance matrix or "primitive impedance matrix" which comprises self and mutual impedance of a three-phase line segment as seen in (3.8).

Figure 3.5 (a) displays an impedance model of a typical three-phase four-wire line segment with self and mutual coupling effects. The sending end bus is *k-1* and receiving bus is *k*. It is assumed that the transformer has delta/wye-grounded design and the 4×4 matrix of (3.8) by applying "Kron reduction" which consider the effect of neutral through the phase impedances can be reformed to the 3×3 matrix as shown in (3.9).

$$[Z^{abcn}] = \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} & Z_{an} \\ Z_{ba} & Z_{bb} & Z_{bc} & Z_{bn} \\ Z_{ca} & Z_{cb} & Z_{cc} & Z_{cn} \\ Z_{na} & Z_{nb} & Z_{nc} & Z_{nn} \end{bmatrix} \tag{3.8}$$

$$[Z^{abc}] = \begin{bmatrix} Z_{aa-n} & Z_{ab-n} & Z_{ac-n} \\ Z_{ba-n} & Z_{bb-n} & Z_{bn-n} \\ Z_{ca-n} & Z_{cb-n} & Z_{cn-n} \end{bmatrix} \tag{3.9}$$



(a)

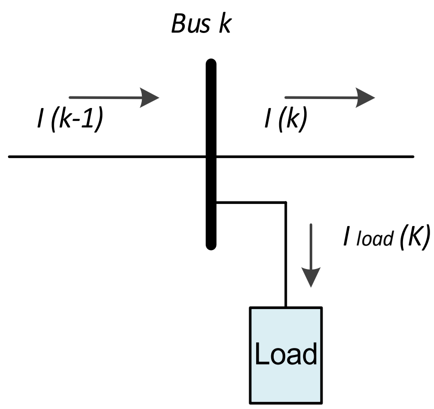


Figure 3.5. (a) Model of the three-phase, four wire multi-grounded line segment, supported by the scheme suggested in [126] (b) PQ bus model.

(b)

The overall algorithm for determining the FBS load flow method, which is applied in this thesis can be summarised as below:

- Step 1: applying efficient bus and branch numbering (based on Table 3.1**).**
- Step 2: reading input component data, based on a radial distribution network. including line/cable data, transformers model, load model and capacitor bank and DG as recommended by [126].
- Step 3: initializing the set value for voltage at the source and end buses for all phases using $V_{set=}\begin{bmatrix} 1 \\ 1 < -120 \\ 1 < 120 \end{bmatrix}$ (backward path).
- Step 4: setting iteration count n=1 and Ɛ=0.0001.
- Step 5: calculating the load current, based on voltage starting at the end bus by using $[I_{load}]_k = ([P]_k - j[Q]_k)/conj([V]_k)$ for all nodes at n iteration. Where $[V]_k$and $[I]_k$ are the bus voltage and equivalent current injection of bus *k*, $[P]_k\ and\ [Q]_k$ are active and reactive power consumption of residential load at each bus.
- Step 6: calculating the current between two adjacent buses using $[I]_k = [I]_{k-1} - [I_{load}]_k$ to add the branch currents connected to the bus downstream from end branch based on Figure 3. 5 (b).
- Step 7: calculating the node voltage from $[V]_k = A * [V]_{k-1} - [Z^{abc}][I]_k$ in the FWS; where $A = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$.
- Step 8: checking convergence for each of the bus voltage magnitudes by specified tolerance. If the *ΔV* in two consecutive iterations is less than Ɛ then go to step 7, else set *n=n+1* and go to step 4.
- Step 9: calculating power flow.

3.8 Stochastic Analysis

Monte Carlo Simulation (MCS) is a method where statistical sampling from system inputs is used to get a large dataset of the probable approximation. This method is commonly used in power system calculation, including uncertainties [127]. As a consequence of the inherent typical of LV distribution system with random variation of customer load over 24 hours and PEVs demand at different time, an MC as a stochastic method is used. Base on the recommendations on research [124], a large number of simulations is considered (MCmax=3000) to achieve an accurate approximation model. In this study, the implemented approach includes the following steps:

- Step 1: the first step is initialization for the parameters. This information consists of the “Pavetta 1” network characteristic (e.g. distribution conductor parameter, load type, and transformer). In addition, the number of trials needs to be initialized in this step.
- Step 2: in this step, a random variable sample of PEVs demand is generated considering PEVs arrival time, location of charging and different charging rates as explained above using distribution in Figure 3.6.
- Step 3: the three-phase unbalanced power flow is applied (Sub-Section 3.7.1) to calculate the voltage of each customer and the VUF to assess the corresponding impacts.
- Step 4: simulation results are saved, and steps 1 to 5 repeated until the last iteration for each penetration level is reached.
- Step 5: once the iterations have finished, calculate the probability distribution function (pdf).

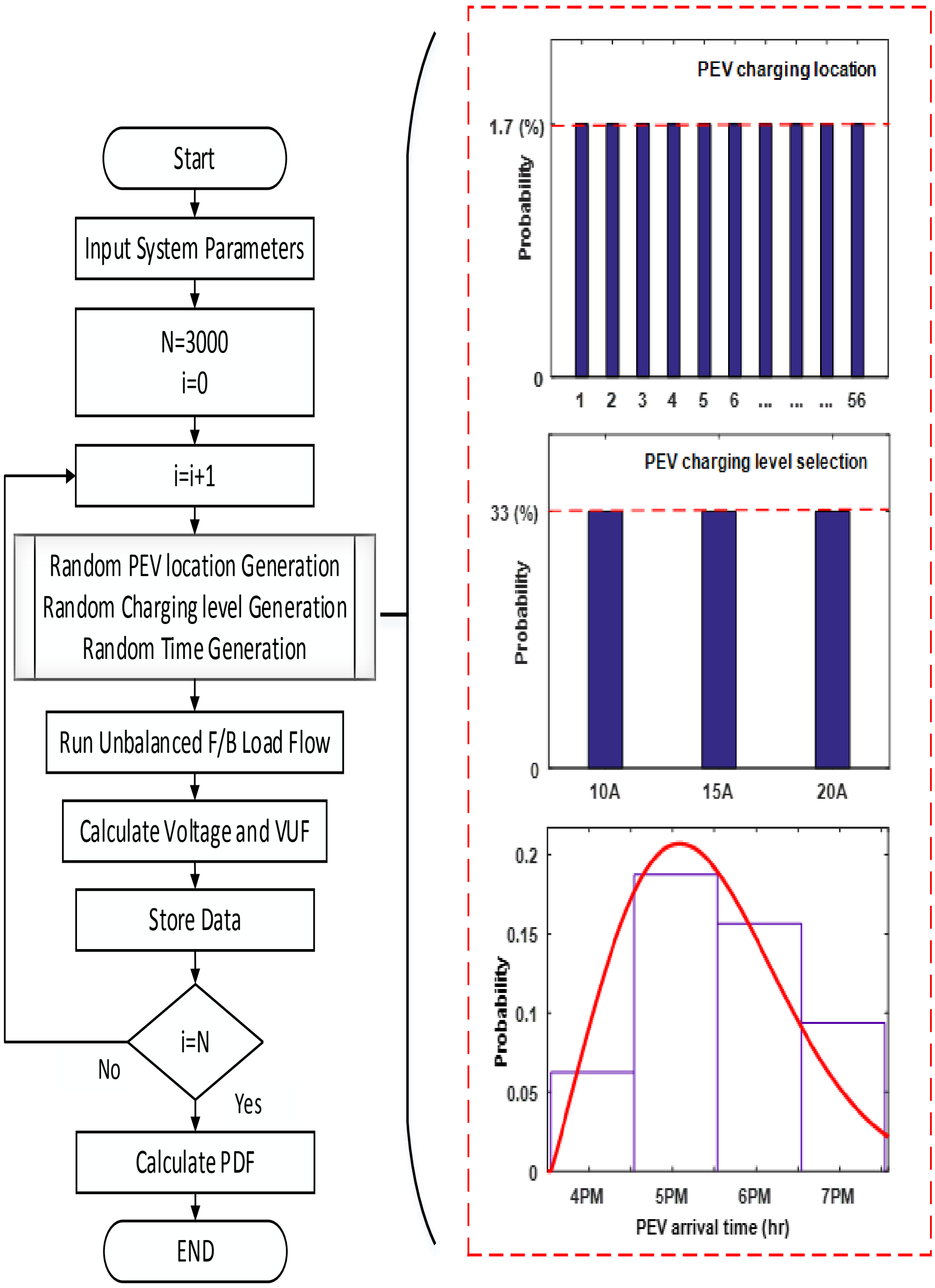


Figure 3.6. Flowchart of the stochastic framework

3.9 Simulation Results and Discussion

In this section, simulations are performed considering three PEV charging scenarios (cases A, B and C) for the system of Figure 3.3 which are discussed as below:

3.9.1 Case A: Main System with No PEVs

Figure 3.7 shows the power demand of the 74 buses unbalanced LV residential feeder without any PEVs in different phases (a, b, and c) which are indicated in black, red and green, respectively. Each residential load is made of local load and consumer installed PV systems. Import and export power are defined as negative and positive power. The peak demand is between 5:00 PM and 7:00 PM during the evening hours, which is approximate -30 kW. In the real network, even in the most severe condition, the voltage and VUF are still in acceptable limitations. However, as per the Australian Electric Vehicle Market Study [128], the sales of PEVs are expected to reach 400k annually by 2027. The growth rate will proceed to hit 1890k PEVs per annum by 2040. Moreover, statistics show most PEV drivers (approximately 78%) prefer to charge their vehicles at home instead of public areas. These results show the voltage and VUF issues can occur in Australia network in future.

For the purpose of this study in this thesis, in order to increase the level of VU, the penetration of rooftop PVs and the domestic load demands on phase-a, phase-b and phase-c are changed. According to [8], the VU measurement typically is conducted at the beginning of the feeder by utilities. Therefore, there is a low chance to have a voltage unbalance more than the limitation at this point. As power consumption is different, the voltage deviation along the feeder is changed. As a result, higher VU can be uniformly expected, especially at the end of the feeder. As mentioned in Chapter 2, the utilities try to keep the voltage amount along the feeder within limits by different strategies. However, VU is still higher at the end of the feeder. This can cause problems in some situations such as PEV charging by random at the end of the feeder. For instance, in the system under study, the voltage amplitude and VUF at the beginning and end of the feeder are given in Table 3.2. These values of voltage are decreased to 0.937, 0.97, and 0.94 pu at the end of the feeder. Meanwhile, the VUF has been increased from 0.2% at the beginning to 1.12% at the end, as shown in Figure 3.8.

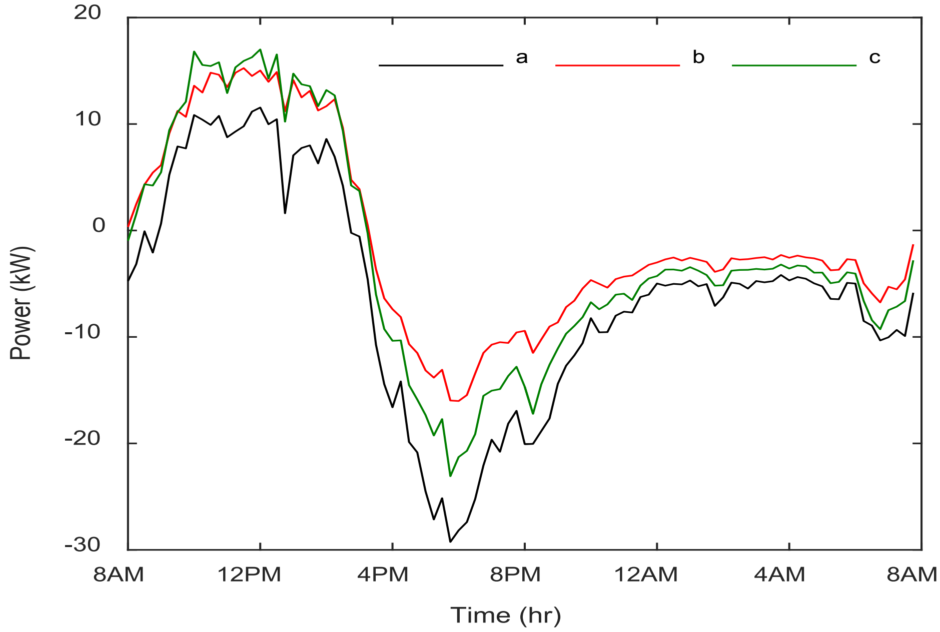


Figure 3.7. The three-phase distribution transformer loading without PEV charging

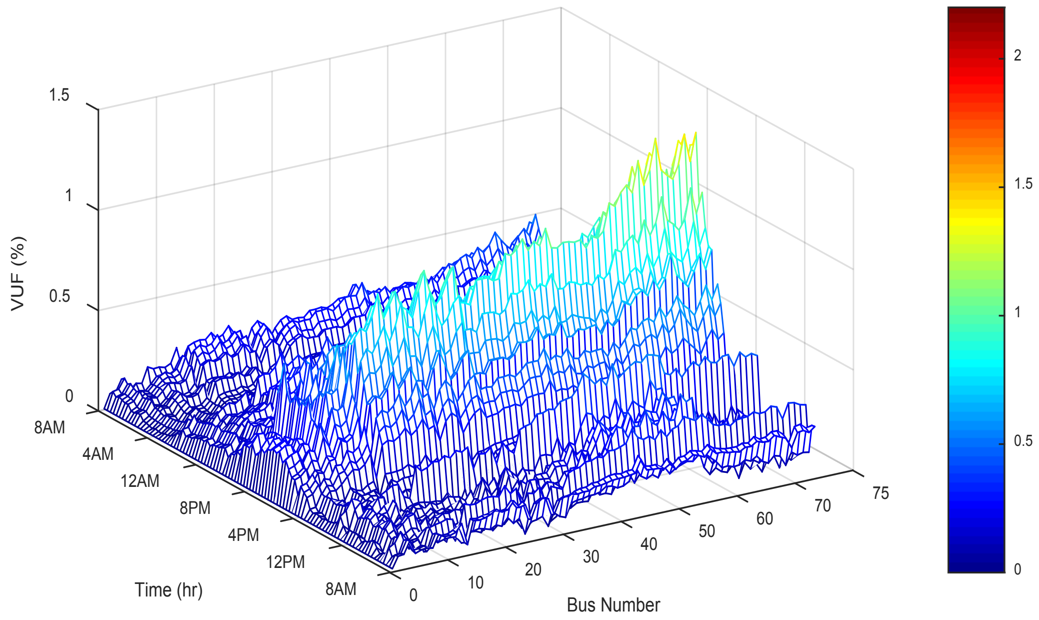


Figure 3.8. Voltage unbalance for the main system over 24 hours versus the location

Table 3.2 Main system

Main System	Voltage (p.u)			VUF (%)
	a	b	c	
Beginning of the feeder	0.985	0.995	0.99	0.22
End of the feeder	0.937	0.97	0.94	1.12

3.9.2 Case B: Impacts of Number of PEVs on Voltage and VUF

B1: Charging PEVs (G2V)

For PEV charging in the unbalanced system, one of the factors that affect voltage and VUF is the phase connection (high load phase, low load phase). It is expected that the VUF will increase if PEVs connected to high load phase (phase-a in this research) and will decrease when connected to a low load phase (phase-b). Thus, in the first case study, at the initial step, the assumption is 11 PEVs connected to only one phase of the system, which can be charged with 240V/20A home charger at the peak load periods with normal distribution between 4:00 PM and 7:00 PM.

Figure 3.9 shows the comparison with the average VUF when 11 PEVs connected on phase-a, and phase-b. It can be observed that when PEVs are connected to low load phase, the VUF is still in the acceptable limit or even less than the VUF for main system value on that time while the connection of PEVs on high load phase causes VUF deviation to increase.

The location of PEVs charging (beginning of the feeder or end of the feeder) and the charging rates of PEVs are two effective factors on voltage profile and VUF. Figures 3.10 and 3.11 show the voltage profile and VUF on phase-a (where the PEVs are connected) both at the beginning and end of the feeder. As expected, the voltage drops and VUF increases more at the end of the feeder in compare to the begging of the feeder or the higher rate of PEVs charging. While a higher rate of charging from a low load phase (phase-b) decreases the VUF due to the deviation reduction between the phases. It means the VUF will be improved by plugging to the lower load phase in an unbalanced network. In Figure 3.12, the VUF versus location and rating of PEVs charging in low load phase (phase-b) is shown.

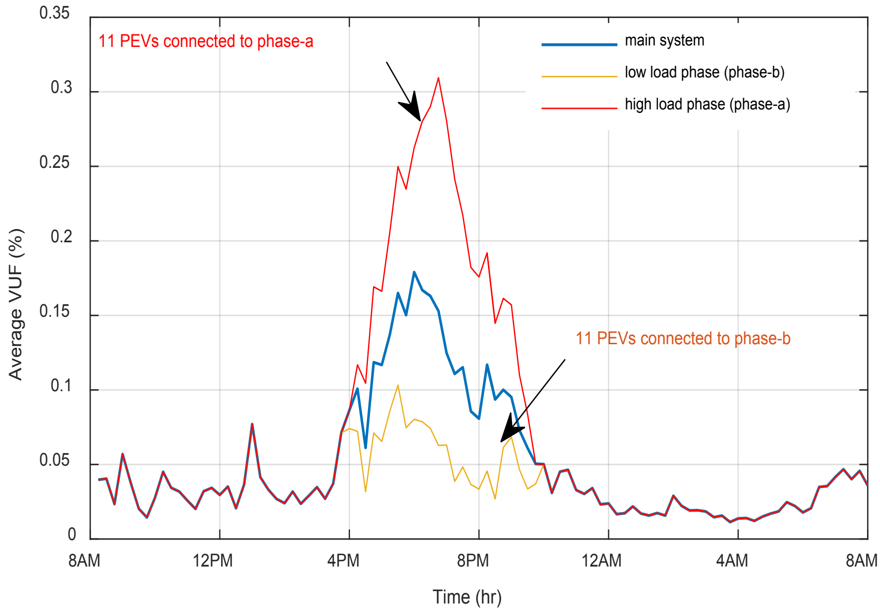


Figure 3.9. Comparison with the average VUF over 24 hours versus location, when connected to high load phase (phase-a), and low load phase (phase-b).

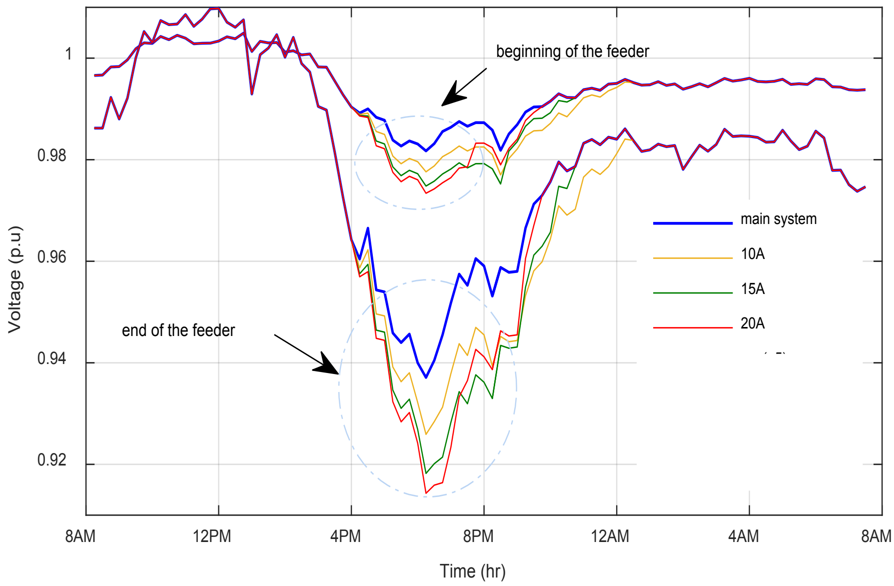


Figure 3.10. Variation of phase-a voltage versus different charging level and the location (G2V mode).

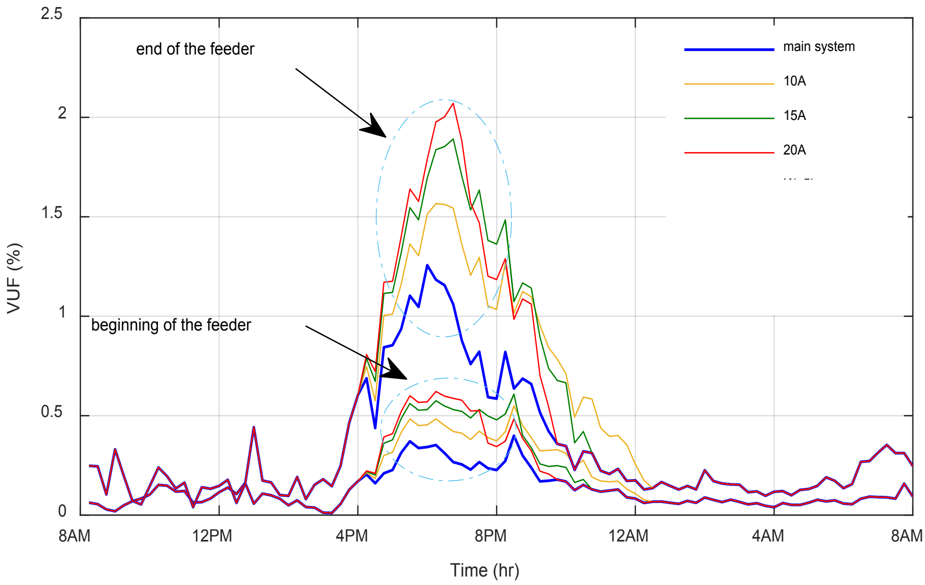


Figure 3.11. VUF when PEVs are connected to high load phase (phase-a) versus different charging level and the location (G2V mode).

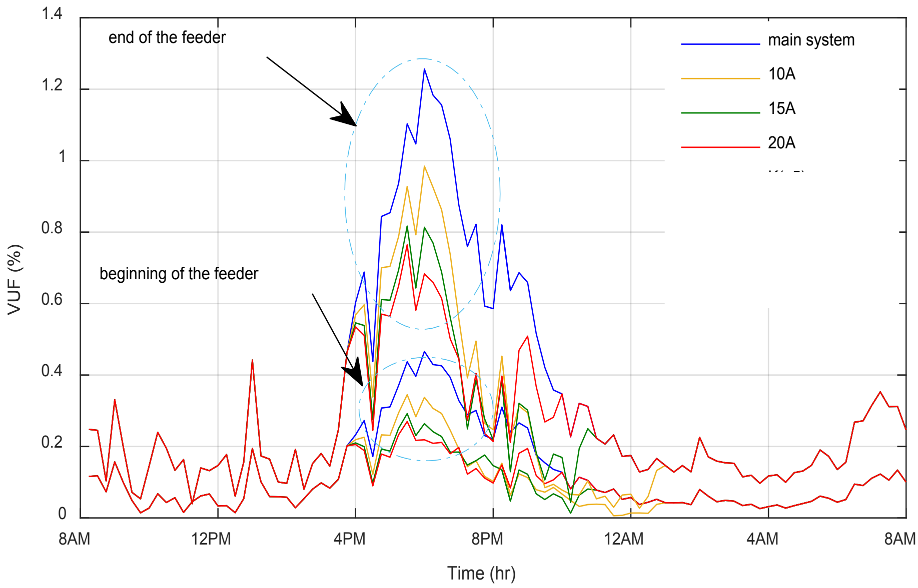


Figure 3.12. VUF when PEVs are connected to low load phase (phase-b) versus different charging level and the location (G2V mode).

After checking the effects of PEVs on high load phase and low load phase separately, to check the impact of several PEVs on voltage and VUF, 11 PEVs are added to the two other feeders, respectively. Table 3.3 demonstrates the results for the scenario when, at first 11 PEVs are only plugged into one phase (phase-a), and then the PEVs are added in other phases (phase-c and phase-b), respectively. It is assumed that a number of PEVs and charging capacities are the same. From Table 3.3 can be seen that the maximum VUF and voltage drop increases when the PEVs are connected to phase-a. However, adding PEVs to another phase (phase-c) causes voltage drops on that phase (phase-c). It does not cause a significant rise in the voltage drops on phase-a. In addition, it can be found that the VUF at the end of the feeder increases with charging rates of PEVs. By adding PEVs to the third feeder (phase-b), the voltage variation is decreased due to the PEVs charging in all three phases, On the other hand, the total VUF decreases, causing voltage difference reduction between the phases.

Table 3.3 VUF and voltage values at the beginning and end of feeders for several cases when PEVs are connected (G2V) to only phase-a (high load phase), phases-(a, and c), and phases-(a, b, and c)

Operation Condition						**Comparison of Simulation Results**				
Charging Rates	**Charging Periods**	**Number of PEVs**				**Worst VUF (%)**		**Worst Voltage (p.u)**		
		a	**b**	**c**	**3ph**	**Feeder Beginning**	**Feeder End**	**a**	**b**	**c**
High Load phase (phase-a)										
10 A	4PM-7PM	11	0	0	0	0.31	1.42	**0.925**	0.973	0.94
15 A	4PM-7PM	11	0	0	0	0.39	1.74	**0.920**	0.975	0.935
20 A	4PM-7PM	11	0	0	0	0.43	2	**0.915**	0.973	0.935
Two-phase (phase-a, and phase-c)										
10 A	4PM-7PM	11	0	11	0	0.32	1.45	**0.93**	0.972	**0.93**
15 A	4PM-7PM	11	0	11	0	0.41	1.8	**0.926**	0.971	**0.92**
20 A	4PM-7PM	11	0	11	0	0.45	1.94	**0.92**	0.972	**0.917**
All Single phases (phase-a, phase-b, and phase-c)										
10 A	4PM-7PM	11	11	11	0	0.27	1.21	**0.930**	0.955	**0.935**
15 A	4PM-7PM	11	11	11	0	0.3	1.33	**0.920**	0.945	**0.93**
20 A	4PM-7PM	11	11	11	0	0.31	1.4	**0.916**	0.945	**0.920**

Table 3.4 illustrates the results of a scenario when PEVs are initially charged from the low load phase (phase-b) and then similar to the previous case added to the other phases in the same manner. From the results, it can be found that the VUF decreases significantly as the PEVs are connected to phase-b. However, adding PEVs in the other two phases causes the VUF increase, especially at the end of the feeder. Although the VUF at the end of the feeder is not significant, the voltage drops can be seen in all conditions

Table 3.4 VUF and voltage values at the beginning and end of feeders for several cases when PEVs are connected (G2V) to only phase-b (low load phase), phases-(b, and c), and phases-(a, b, and c)

Operation Condition						**Comparison of Simulation Results**				
Charging Rates	**Charging Periods**	**Number of PEVs**				**Worst VUF (%)**		**Worst Voltage (p.u)**		
		a	**b**	**c**	**3ph**	**Feeder Beginning**	**Feeder End**	**a**	**b**	**c**
Low Load Phase (phase-b)										
10 A	4PM-7PM	0	11	0	0	0.21	0.89	0.937	0.953	0.945
15 A	4PM-7PM	0	11	0	0	0.18	0.71	**0.936**	0.951	0.95
20 A	4PM-7PM	0	11	0	0	0.17	0.66	**0.934**	0.950	0.95
Two-phase (phase-b, and phase-c)										
10 A	4PM-7PM	0	11	11	0	0.21	0.9	0.939	0.95	0.937
15 A	4PM-7PM	0	11	11	0	0.18	0.77	0.939	0.94	**0.933**
20 A	4PM-7PM	0	11	11	0	0.17	0.73	0.94	0.947	**0.930**
All Single phases (phase-a, phase-b, and phase-c)										
10 A	4PM-7PM	11	11	11	0	0.27	1.71	**0.930**	0.955	**0.935**
15 A	4PM-7PM	11	11	11	0	0.3	1.33	**0.920**	0.945	**0.93**
20 A	4PM-7PM	11	11	11	0	0.31	1.4	**0.916**	0.945	**0.920**

B2: Fast Charging

Another case study is carried out to determine the consequences of the number of PEVs randomly connected to three phase buses in the network, as shown in Table 3.5. The results indicate that the voltage deviation and VUF in the feeder is increased by charging PEVs from the three-phase customer (fast charging).

Table 3.5 VUF and voltage values at the beginning and end of feeders for PEVs which are connected (G2V) to the three-phase customer

Operation Condition						**Comparison of Simulation Results**				
Charging Rates	**Charging Periods**	**Number of PEVs**				**Worst VUF (%)**		**Worst Voltage (p.u)**		
		a	**b**	**c**	**3ph**	**Feeder Beginning**	**Feeder End**	**a**	**b**	**c**
20 A	4PM-7PM	0	0	0	11	0.3	1.8	**0.935**	0.950	**0.89**

B3: Discharging PEVs (V2G)

The similar studies for G2V are repeated for V2G condition. In this mode, the discharge capacity of PEVs is assumed the constant output power of 3, 4, and 5 kW. For V2G way, it is expected that when the 11 PEVs connected to the high load phase (phase-a) due to the reducing of the voltage differences between phases, the VUF is decreased. There is more reduction if PEVs connected to the end of the feeder or with higher discharging power. Figure 3.13 shows the VUF versus the location and rating of PEVs discharging from phase-a (high load phase). It can be found that VUF rapidly decreases when PEVs discharge from high load phase. This effect is more at the end of the feeder or where the higher rate of battery discharging happens. While discharging from the phase-b (low load phase) leads to increasing VUF and it is getting worse by increasing the rate of discharging as well (in Figure 3.14).

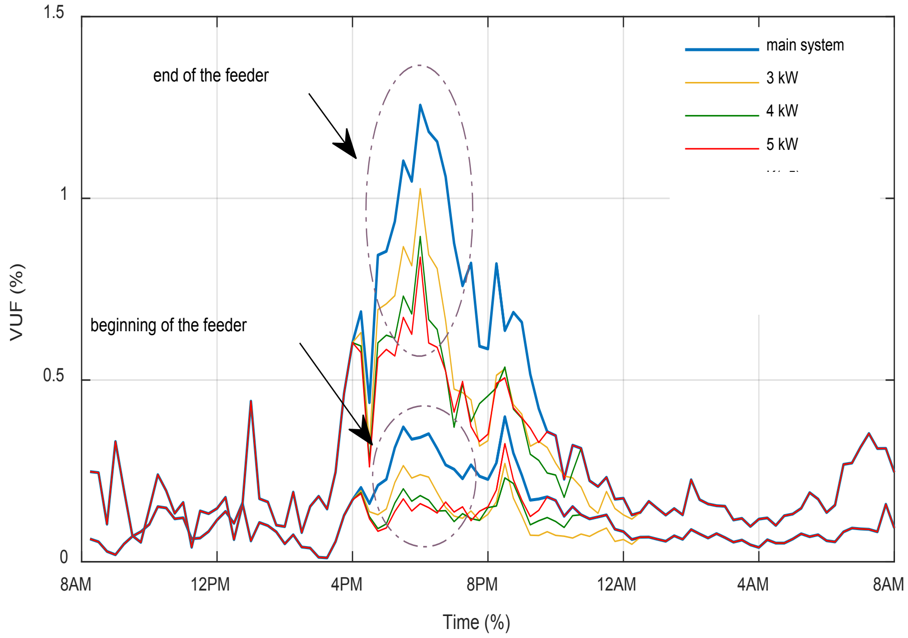


Figure 3.13. VUF when PEVs are connected to high load phase (phase-a) versus different output power and the location (V2G mode).

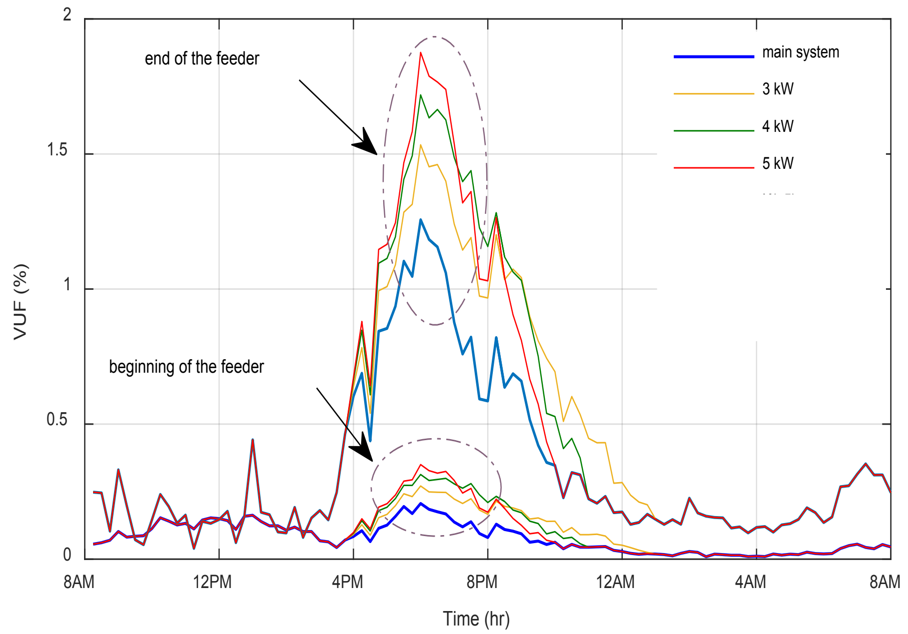


Figure 3.14. VUF when PEVs are connected to low load phase (phase-b) versus different output power and the location (V2G mode).

In the next stage, the numbers of PEV are increased by adding PEVs to the two other feeders to increase the PEVs penetrations. Table 3.6 demonstrates the results of the scenario when firstly PEVs discharge from high load phase (phase-a). It can be found that by adding PEVs for discharging to the second phase (phase-c), the VUF is decreased. This reduction is more for PEVs with higher output power. However, discharging PEVs from the third phase also leads to increasing VUF through the feeder. In all these scenarios for discharging modes, the voltage is within the permissible tolerance.

Table 3.6 VUF and voltage values at the beginning and end of feeders for several cases when PEVs are discharged (V2G) from only phase-a (high load phase), phases-(a, and c), and phases-(a, b and c)

Operation Condition						**Comparison of Simulation Results**				
Power Rates	**Discharging Periods**	**Number of PEVs**				**Worst VUF (%)**		**Worst Voltage (p.u)**		
		a	**b**	**c**	**3ph**	**Feeder Beginning**	**Feeder End**	**a**	**b**	**c**
High Load phase (phase-a)										
3 kW	4PM-7PM	11	0	0	0	0.19	1	0.947	0.967	0.942
4 kW	4PM-7PM	11	0	0	0	0.16	0.86	0.952	0.969	0.943
5 KW	4PM-7PM	11	0	0	0	0.14	0.81	0.95	0.96	0.940
Two-phases (phase-a, and phase-c)										
3 kW	4PM-7PM	11	0	11	0	0.137	0.84	0.943	0.970	0.950
4 kW	4PM-7PM	11	0	11	0	0.13	0.67	0.946	0.968	0.958
5 KW	4PM-7PM	11	0	11	0	0.12	0.59	0.948	0.968	0.958
All Single phases (phase-a, phase-b, and phase-c)										
3 kW	4PM-7PM	11	11	11	0	0.20	0.94	0.951	0.955	0.952
4 kW	4PM-7PM	11	11	11	0	0.20	0.97	0.949	0.975	0.95
5 KW	4PM-7PM	11	11	11	0	0.22	1.02	0.945	0.974	0.947

The next study is performed for the scenario where PEVs at first connected to the low phase (phase-b). The results are given in Table 3.7. From this table, it can be found that the VUF increased at the end of the feeder by increasing the rate of power when discharging from the low load phase. However, adding PEVs for discharging in the other two phases causes the VUF reduction, especially at the end of the feeder. It can also be observed that the results of discharging PEVs from all the phases in terms of voltage deviation are better than the other two cases.

Table 3.7 VUF and voltage values at the beginning and end of feeders for several cases when PEVs are discharged (V2G) from only phase-b (low load phase), phases-(b, and c), and phase-(a, b and c)

Operation Condition						**Comparison of Simulation Results**				
Power Rates	**Discharging Periods**	**Number of PEVs**				**Worst VUF (%)**		**Worst Voltage (p.u)**		
		a	**b**	**c**	**3ph**	**Feeder Beginning**	**Feeder End**	**a**	**b**	**c**
Low Load phase (phase-b)										
3 kW	4PM-7PM	0	11	0	0	0.29	1.5	0.94	0.978	**0.936**
4 kW	4PM-7PM	0	11	0	0	0.33	1.58	0.942	0.982	**0.932**
5 KW	4PM-7PM	0	11	0	0	0.36	1.74	0.944	0.984	**0.93**
Two-phases (phase-b, and phase-c)										
3 kW	4PM-7PM	0	11	11	0	0.29	1.35	**0.935**	0.98	0.943
4 kW	4PM-7PM	0	11	11	0	0.3	1.51	**0.934**	0.985	0.945
5 KW	4PM-7PM	0	11	11	0	0.33	1.6	**0.934**	0.988	0.942
All Single phases (phase-a , phase-b, and phase-c)										
3 kW	4PM-7PM	11	11	11	0	0.20	0.94	0.951	0.955	0.952
4 kW	4PM-7PM	11	11	11	0	0.20	0.97	0.949	0.975	0.95
5 KW	4PM-7PM	11	11	11	0	0.22	1.02	0.945	0.974	0.947

3.9.3 Case C: Stochastically Assessment for PEVs Impacts on Voltage and VUF

The PEV penetration level is defined as the percentage of PEV number on total residential nodes, which is considered from 10% to 100% in this research work. The test system is repeated for different charging level (10A, 15A, and 20A), separately.

As explained in Section 3.8, each penetration runs several times. Table 3.8 indicates the probability of PEV owners with voltage issues versus different PEV penetrations and charging rates. The Probability voltage deviation column, which is considered for the three different charging level, indicates the PEV penetration level in which customers have voltage issues. From Table 3.8, it can be observed that by increasing the penetration level and the rates in all cases, the voltage drops are increased. For example, for a 40% penetration level of PEVs, the probability of customers with voltage issues is about 50% when vehicles are being charged with 20A. Charging with 20A needs more power during shorter periods than 10A and 15A, which means the impact of PEV on voltage, is more significant by increasing the rates. A complete visualisation of MC regarding voltage deviation is shown in Figure 3.15. This figure indicates the percentage of customers [%] with voltage issues in different charging rates and the corresponding frequency in the simulations.

The maximum VUF for this feeder for different PEVs penetration at the end of the feeder in G2V mode are shown in Table 3. 9. From this table, it can be found that there is no direct relation between the maximum VUF values at different penetrations. For example, when the PEV penetration level increases from 10% to 100%, the probability of the maximum VUF value has not increased (at the same rate). The connection phase of PEVs charging (phases) is more effective than the penetration level. However, it is not any guarantee the voltage remained in the standard limitation. For example, at 60% penetration, the maximum VUF has its lowest value due to the balanced PEV charging from all phases; however, 66% of nodes are under the voltage set value.

Table 3.8 PEV penetration leading to voltage deviation

Number of PEVs	**PEV Penetration [%]**	**Probability of Voltage Deviation (V< set value)**		
		10 A	**15 A**	**20 A**
6	10	13 %	17 %	18 %
11	20	19 %	28 %	30 %
17	30	25 %	33 %	36 %
22	40	31 %	40 %	50 %
28	50	35 %	46 %	62 %
33	60	36 %	54 %	66 %
40	70	39 %	60 %	70 %
45	80	42 %	67 %	73 %
50	90	45 %	70 %	77 %
56	100	47 %	73 %	79 %

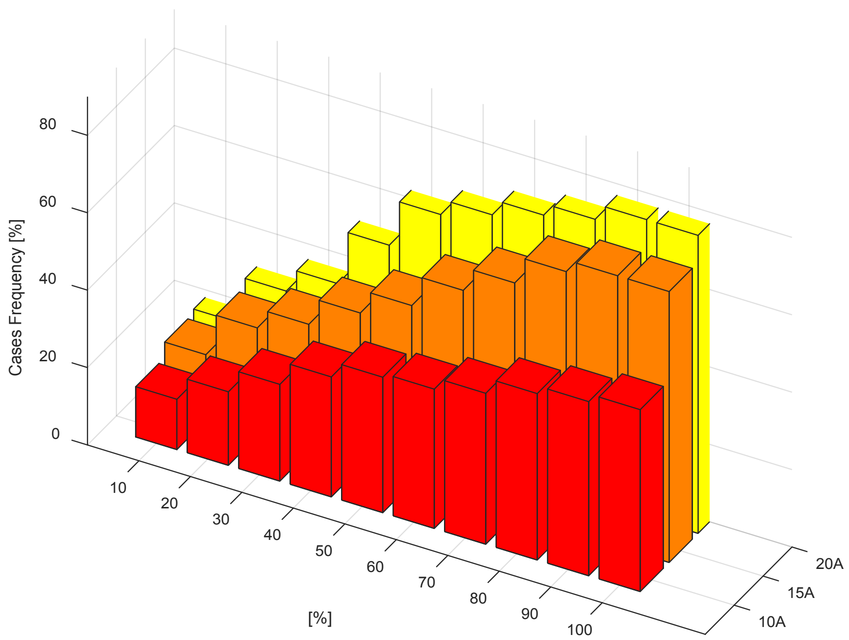


Figure 3.15. Percentage of customers with voltage issues at each rate

Table 3.9 PEV penetration leading to maximum VUF

Number of PEVs	PEV Penetration [%]	Maximum VUF
6	10	1.78 %
11	20	2.02 %
17	30	1.94 %
22	40	2.04 %
28	50	1.72 %
33	60	1.68 %
40	70	1.91 %
45	80	1.92 %
50	90	2.01 %
56	100	2.05 %

3.10 Summary

This Chapter discusses the background information relevant to the remaining Chapters. Besides, the effect of PEVs demand on voltage and voltage unbalance on three phases four-wire distribution LV network has been analysed. The Monte Carlo Simulation method is used to consider uncertainties related to the charging different penetration of PEVs based on time, rating, and location of charging at residential houses. The various aspects are analysed as follow:

- The research demonstrated that depending on the phase of the PEVs connection (high load phase or low load phase), and the rating of the charge/discharge voltage deviation and VUF will be decreased or increased.
- It has been shown that the voltage issues and VUF would increase at the end of the feeder due to the charging/discharging PEVs and sometimes even above the desired limit. However, these effects are minor at the beginning of the feeder.
- For PEV charging, the place at which the PEV is connected is more important than their rate of charging. For example, if PEVs are placed in the lowest loaded phase,

then the VUF may reduce. On the other hand, completely opposite results can be observed if they are placed in either high or medium loaded phases.

Chapter 4

Online Coordinated Charging PEVs in Unbalanced Smart Grid

4.1 Introduction

Based on the results from Chapter 3, it can be concluded that uncoordinated charging PEVs poses a risk for voltage drops and VUF deviations from the designed limitations.

In addition, several factors like location of the PEVs connection (beginning of the feeder or end of the feeder), phase connection (high load phase, low load phase), rate of charge and number of PEVs can impact the voltage deviations and VUF. The PEV placement at the beginning of the feeder has less impact on the grid problem in most of the cases. However, they can have a severe impact when placed towards the end of the feeder. Therefore, to assist the adoption of PEVs charging and remedy these problems, this Chapter proposes the online coordinated charging PEVs based on GA optimization aiming to improve smart grid performance by considering the network constraints in unbalanced LV distribution network. Using this background, two case studies with different objective functions are proposed to find the effect of PEVs on the system: The first objective function is based on cost optimization (by considering intelligent variable tariff contracting between owner and aggregator) and charging all PEVs at low-cost period. The second one is established upon fixed price optimization (by considering regular constant price) which allows the PEVs to charge their preferences when the network allows.

The proposed solution addresses the drawbacks cited in Chapter 3 by considering the uncertainty regarding PEV specification (e.g. rates, location, and time). This Chapter begins by explaining the schematic of the problem and proposed objective functions in Section 4.2. It then goes on to the proposed constraints in Sections 4.3. The next two sections present the proposed method and the simulation results. Finally, the conclusion in Section 4.6 gives a summary of the findings.

(*) Note: Some parts of this Chapter were published and presented as a conference paper [46] and a journal paper [87] (Appendix B1 and B2).

4.2 Smart Charging Scheme: Problem Formulation

A large and growing body of literature has investigated the smart charging schemes, as mentioned above in the previous Chapter. Generally, the goal of selecting the objective function for charging PEVs control varies depends on the viewpoint considered by a scheduler. For example, from the owner's standpoint, the objective function may be a demand satisfaction such as achieving the PEVs charging before their deadline, reducing the cost of charging or maximizing profits like selling power to the grid. Nevertheless, the objective of the utility can be cost minimization, frequency/voltage regulation, and peak shaving. Typically, the selected objective functions for scheduling charging PEVs are based on cost minimization and several attempts such as the researches [69] and [129] have been made in this area to shift PEVs during off-peak hours and reducing cost. Despite these strategies to increase efficiency and network utilization, they suffer from several significant drawbacks:

For example, by increasing the number of PEVs and charging PEVs during off-peak hours, upward pressure will exist on the distribution network. In addition, an ideal time for the PEV owner and the utility could be conflicted. From all the above, the variable price contract has still not been approved in many countries. Hence, the grid operators need to find a smart strategy, which simultaneously accommodates the grid's technical limitations, and satisfies vehicle owners as well. This section aims to investigate the difference between the two viewpoints. It explains two possible objective functions for smart charging PEVs to identify the impacts on voltage, VUF and load profile as follows:

4.2.1 Objective Function for PEV Charging Coordination based on Optimal Variable Price

The selected objective function of (4.1) for centralized online PEV coordination in the unbalanced system is the minimization of total costs associated with system losses ($Fcost{-}Loss$) and energy costs related to active power generation ($Fcost{-}gen$). It is possible to purchase or generate energy for charging vehicles over the 24-hour period by selecting the PEVs to connect per phase at each time interval t, to reduce the total cost as well as considering constraints.

$$min \;\; F_{Cost-G2V} = \{F_{cost-Loss}(t) + F_{cost-gen}(t)\}; \qquad (4.1)$$
$$for\ t = \;\; 0, \Delta t, 2\Delta t \ldots 24h$$

where,

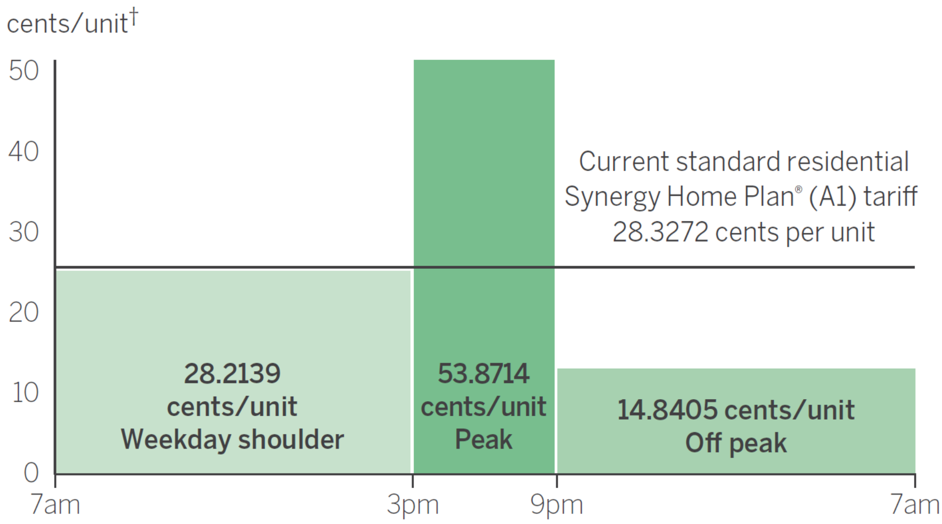
$$F_{cost-Loss}(t) = \sum_{a,b,c} \sum_{k=1}^{N_{node}} K_E P_{loss}(t,k) \qquad (4.2)$$

$$= \sum_{a,b,c} \sum_{k=1}^{N_{node}} K_E R(k,k+1)(V(t,k+1) - V(t,k)||Y(k,k+1))^2$$

$$F_{cost-gen}(t) = \sum_{a,b,c} \sum_{k=1}^{N_{node}} K_{Variable}(t) P(t,k); \quad if \;\; P(t) < 0 \qquad (4.3)$$

where Δt is the time interval and set to 15 min in this study, k is the node number and N_{node} is the total number of nodes; a, b, and c are phase numbers, K_E is the cost per kWh of losses [130, 131]; while $R(k,k+1)$ and $Y(k,k+1)$ are the resistance and admittance of line between nodes k and k + 1; $K_{Variable}(t)$ is the cost per kWh of imported energy generation based on variable price “Synergy’s smart home plan” contract (Table 4.1) [133].

Table 4.1 Time of use tariffs for "smart home plan" in WA from [133]



In the context of this thesis, the optimisation based on variable price is defined as "optimal price."

4.2.2 Objective Function for PEV Charging Coordination based on Optimal Fixed Price

The second objective function, which is referred as optimal fixed price in this research work is designed to minimize the total VUF in the unbalanced distribution network by choosing the PEVs to connect per phase at each time slot Δt , in order to manage voltage unbalance efficiently and not to exceed the system's limitations. In this method, it has been assumed that the PEV owners unlike the first objective function (4.1) have not any contracts regarding their charging time with aggregators so they can charge their vehicles by a constant rate of electricity (like the current situation in many countries such as Australia). It means the customers do not have any financial incentives to charge during off-peak hours. Therefore, the total objective function consists of daily operating cost due to the energy required to charge PEVs with constant rate and minimization of voltage unbalance deviation at pole buses.

$$min \;\; F_{Cost-G2V} = \{F_{cost-gen}(t) + F_{cost-VUF}(t)\}; \quad for\ t = \;\; 0, \Delta t, 2\Delta t \ldots 24h \tag{4.4}$$

where,

$$F_{cost-gen}(t) = \sum_{a,b,c} \sum_{k=1}^{N_{node}} K_{Constant}(t) P(t,k); \quad if \;\; P(t) < 0 \tag{4.5}$$

$$F_{cost-VUF}(t) = \sum_{k=1}^{N_{node}} K_{VUF}(t) \left| \frac{V^-(t,k)}{V^+(t,k)} \right| \tag{4.6}$$

where $K_{Constant}(t)$ is the cost per kWh of imported energy generation based on constant price from "Residential electricity price trends WA" which is considered (28.32 cents/kWh) [133], $K_{VUF}(t)$ is the penalty for sequence voltage deviation of VUF from their optimal value, to coordinate voltage magnitude and balance profile improvements at time *t*.

4.3 Constraints

The objective functions (4.1) and (4. 4) are subject to the following constraints:

- Power Demand Constraints:

$$\sum_{k=1}^{N_{node}} [P_{Load}(t,k) + P_{PEV}(t,k) - P_{PV}(t,k)] \;\le P_{max}(t) \tag{4.7}$$

where,

$$P_{max}(t) = \sum_{k=1}^{N_{node}} max\{P_{Load}(t,k)\} \tag{4.8}$$

$P_{load}(\mathrm{t},k)$ and $P_{PEV}(\mathrm{t},k)$ are the real power of load and PEV charging at node k at each time interval Δt respectively. $P_{Load}(\mathrm{t},k)$ is determined from the daily load curve.

- Bus Voltage Constraints:

$$V_{min} \leq V(\mathrm{t}, k) \leq V_{max}, \qquad for\ k \ = 1, \ldots, N_{node} \tag{4.9}$$

where, V_{min} and V_{max} are minimum and maximum limits respectively typically set by the utility, as explained in the previous Chapter.

- Decision Constraints:

The decision variable PEV being a binary variable means it is valid only if PEV is connected to the grid at the corresponding time step while the consumed active power $PEV(\mathrm{t}, k)$ is zero, as expressed by (4.10).

$$\begin{cases} PEV(t,k) = 0, & is\ not\ connected \\ PEV(t,k) = 1, & is\ connected \end{cases} \tag{4.10}$$

- Battery State of Charge Constraints:

$$SoC_{min}(k) \leq SoC_{req(t,k)} \leq SoC_{max}\,(k), \qquad for\ k \ = 1, \ldots, N_{node} \tag{4.11}$$

where $SoC_{min}(k)$, $SoC_{req(t,k)}$, and $SoC_{max}\,(k)$ are the minimum, requested and maximum battery SoCs of PEVs at time t, respectively. SOC_{min} is limited by the Depth of discharge (DoD).

- Charging Deadline Constraints:

Each PEV guarantee is finishing the charging task by the requested time to the required level.

$$E_{PEV}(t,k) = \sum_{t_{k,Plug-in}}^{t_{k,requested}} P_{PEV}(t,k)\,, \qquad for\ k \ = 1, \ldots, N_{node} \tag{4.12}$$

where $t_{k,Plug-in}$ is the random plug-in time of PEV number at node k and $E_{PEV}(t,k)$ is the requested total battery energy to be received by the requested time the $t_{k,Plug-in}$.

Assumption and Definitions:

- According to residential electricity price report from [131], the $rloss$ cost consists of four main components; retail, wholesale, regulated networks (transmission and distribution) and environmental policies costs. Out of this, wholesale energy and regulated networks costs cover about 80% of the total value. Other elements on electricity price consist of retail and environmental policies such as upgrades, O&M, and reinforcements driven by voltage and thermal limit violations as well as recovery costs of incentive schemes and carbon costs.
- The transmission cost is not included in the cost analysis as it is only about 10% ~15% of the total regulated network cost (the rest is related to the distribution cost in this category).
- $K_{VUF}(t)$ is the penalty for sequence voltage deviation of VUF from their optimal value, to coordinate voltage magnitude and balance profile improvements at time t. In this thesis, the rate of VUF deviation is assumed similar to the rate of voltage violation due to the peak generation which is given by K_{VUF}=14.2c/kWh [134] [80].
- The PEVs are not available from 8:00 AM to 4:00 PM. It is assumed that most people are not at home during that period. So, all the PEVs are randomly plugged into the residential load between 4:00 PM and 7:00 PM.
- In this Chapter, no reactive power is injected by PEVs, so just active power control is considered which will be referred to P-control strategy in this thesis.

4.4 Proposed Online PEVs Charging Coordination (P-Control Strategy)

This method is based on the conventional P-Control strategy (OL-C-TP) without any PEV reactive power injections. The idea is making smart PEV battery charging decisions to prevent line/transformer overloading (due to the extreme PEV charging) and under-voltage (during peak-load hours) conditions while it also reduces generation cost and controls VUF. The active power balance at each PCC node k can be calculated by

$P(t,k) = P_{PV}(t,k) - P_{PEV}(t,k) - P_{Load}(t,k)$ as demonstrated in Chapter 3.

Usually, the reactive power does not have significant impacts on the performance of distribution networks due to the high R/X ratio. Thus, most attention is managing *P* rather than Q. Therefore, generally the intention is to attain a near-unity power factor [80]. For the OL-C-TP strategy, which is considered in this Chapter, the power factor of PEV inverter is assumed to be unity; consequently, no absorption or injection of reactive power occurs.

4.4.1 GA Applied at Each Time Slot (Δt)

To solve the PEV charging problem, GA optimization is selected to consider multi-objective functions with several constraints simultaneously [107]. The flowchart of the proposed online optimal PEV charging is shown in Figure 4.1. It consists of the following three steps:

- Step 1: The required input information including daily load curve, PV status, PEV data (e.g., arrival and departure time, location, charging duration and battery size), and the market energy prices of *P* are provided.

- Step 2: Based on Step 1, GA optimization is then started: The large random initial population is created to increase the convergence rate to the global solution. Then, the unbalanced load flow by BFS is run for each set of population (chromosome) and each individual evaluated by the objective function, and constraints. Figure 4.2 shows the configuration of the GA chromosomes in this study. Based on the objective functions described in this Chapter which are minimizing the total system cost and reducing voltage deviation in the unbalance network, the control variables in this optimization are the positions (status) of all PEVs. The number “0” displays a PEV that has not been charged yet or already finished whereas number “1” indicates the PEV is being charged. For tracing each PEV’s status including their plugged in and plugged out times, initial and requested SoCs as well as battery sizes, a queue table (Q-table) is generated as shown in Figure 4.3 after plugging a new $P_{PEV}(\mathrm{t}, k)$, the Q-table will be updated by performing GA optimization.

- Step 3: After the GA process is being completed and the maximum iteration achieved, the result shows the optimal status of PEV charging/discharging at the first time slot, so the information of PEV Q-table and daily load curve with optimized solution will be updated and moved to the next time slot which is ($\Delta t = \Delta t + 15$ min).

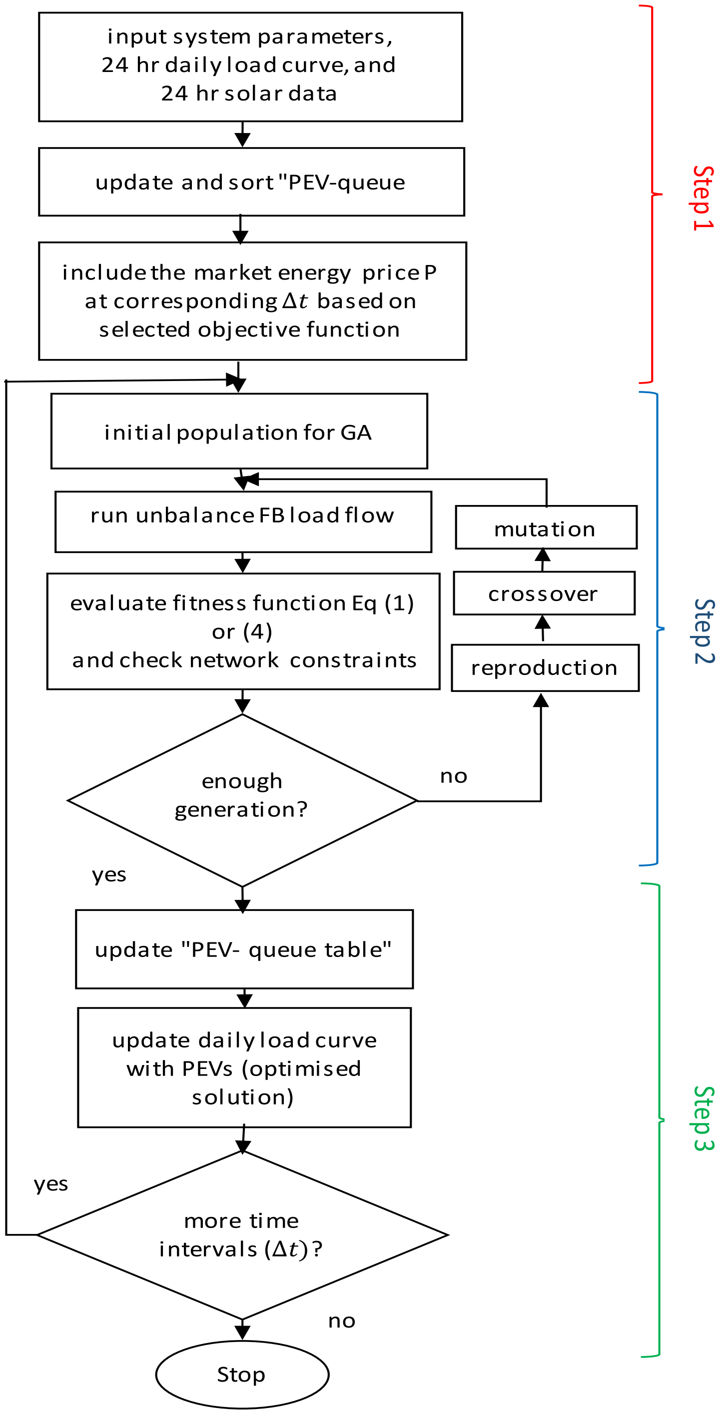


Figure 4.1. Flowchart of the proposed PEV charging by GA at each time slot

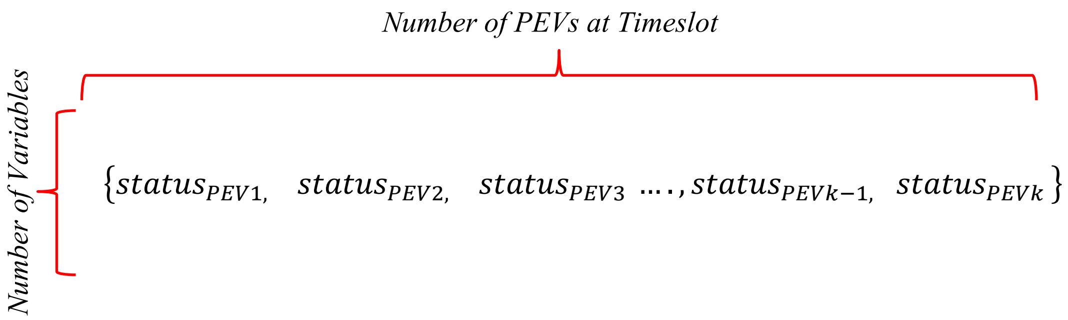


Figure 4.2. Proposed GA structure of variables (chromosomes)

4.4.2 Online GA Optimization Process Over 24 Hours

Through the online PEV charging issue as considered in this dissertation, it is assumed that the scheduler just accesses the information revealed so far. For example, a charging facility is only aware of the charging outline for the PEV just arrived, load demand, and DG in the network till the present time. Figure 4.3 demonstrates the proposed GA optimization schematic for charging/discharging PEVs in the unbalanced system during 24 hrs (96-time slots). t shows the time steps through the optimization based on 15 minutes while k shows the different number of buses connected to the PEVs. For example, in the first time step Δt_1, t_1 shows the optimized time and start time for charging/discharging a PEV connected to bus *k1* while t_{12} displays the finishing time of PEV charging with 3 hr charging duration considered in this thesis (12 slots).

The details of each time step of optimization are applied through sub-section 4.4.1. As time passes on, the algorithm updates the information and prepares to schedule the next time step. Figure 4.3 shows that even though schedules are prepared for several time steps (24 hr = 96-time slots), charging/discharging decisions are planned in the current 15 minutes time step. In Figure 4.3, the red colour shows the present time step while grey and black colours represent the previous and future steps which have not yet been carried out through the process.

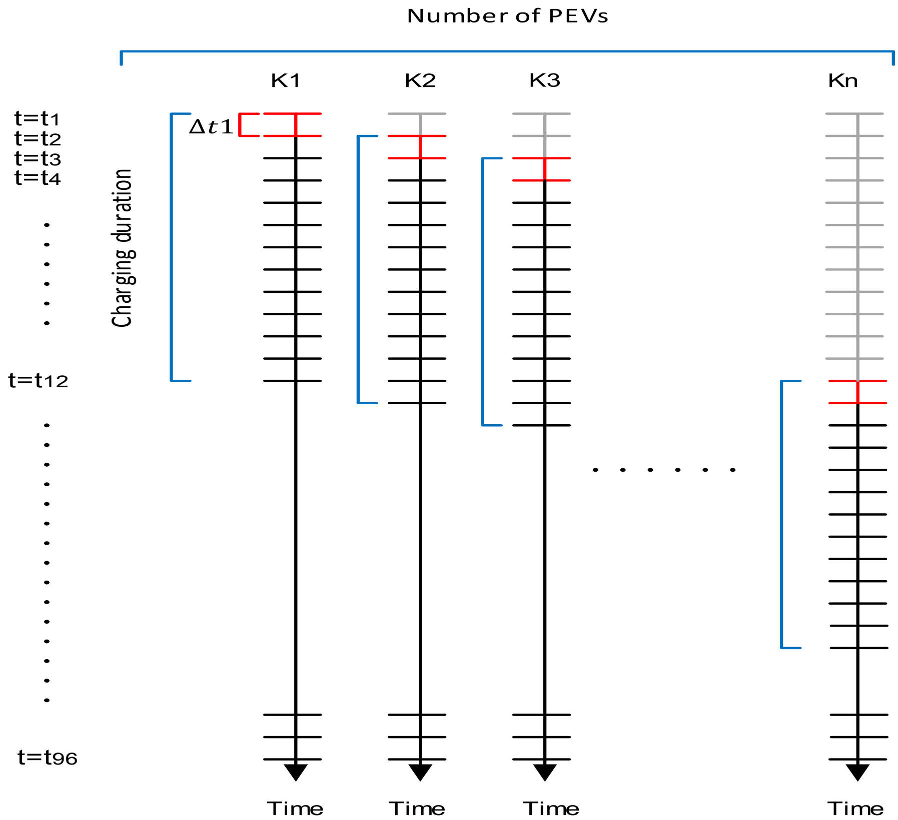


Figure 4.3. GA optimization scheme for the proposed PEV charging over 24 hours

4.5 Simulated Case Studies and Analysis

The simulation results are carried out for two different simulation cases in Table 4.2 as discussed in section 4.2. Case C shows the optimized results based on variable price. In case D the optimized results based on fixed price are analysed. To observe the impacts and better illustrate the effectiveness of PEVs control charging in both cases, four different unbalance scenarios have been created.

- Scenario 1 is designed when all PEVs are connected to high load phase (phase-a) through the three-phase LV unbalance network. According to Figure 4.4, it means all green circles plug into the grid, which is 20% of all houses.
- Scenario 2 is related to the lowest load phase (phase-b). All houses connected to this phase have a PEV. Red colour (Figure 4.4) represents the PEVs also connected to phase-b and represents the next 20% of all homes.

- Scenario 3 shows the number of PEVs increased by 40% penetration when connected to both of the highest load phases (phase-a, and phase-c).

- Scenario 4 is designed to show the highest number of PEVs connected to the single-phase houses, which is about 60%. Figure 4.4 indicates this scenario with PEVs colored in green, red, and blue circles, respectively.

Table 4.2 Simulated PEV charging cases

Case	Coordination Strategy	Simulation Results
Case C	Coordinated charging based on variable price	Figures 4.5 (a-c); 4.6 (a-c); 4.7 (a-c)
Case D	Coordinated charging based on fixed price	Figures 4.8 (a-c); 4.9 (a-c); 4.10 (a-c)

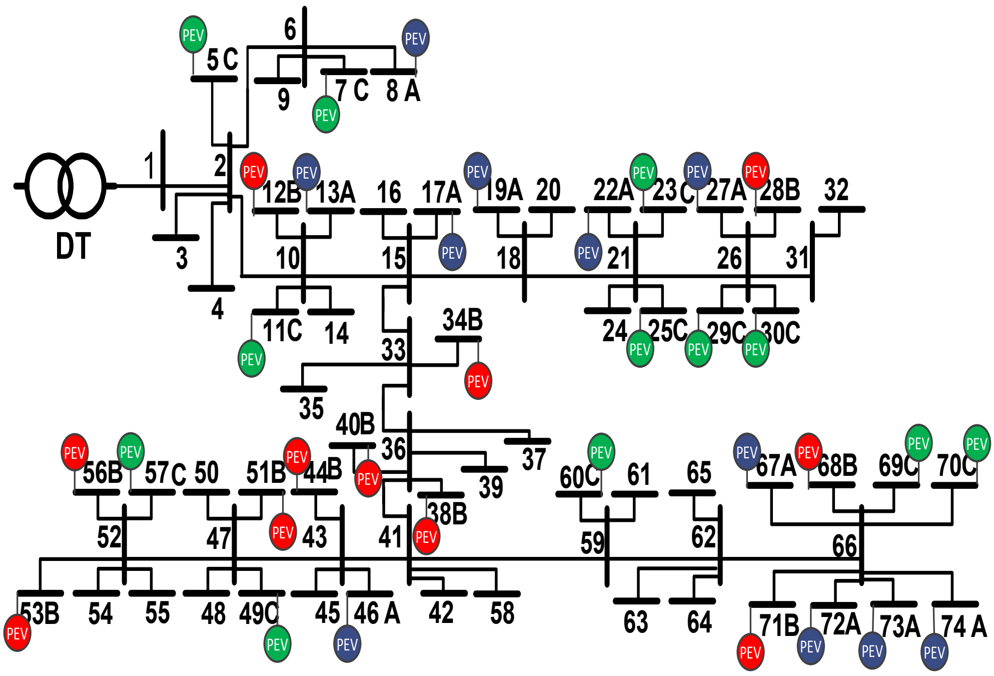


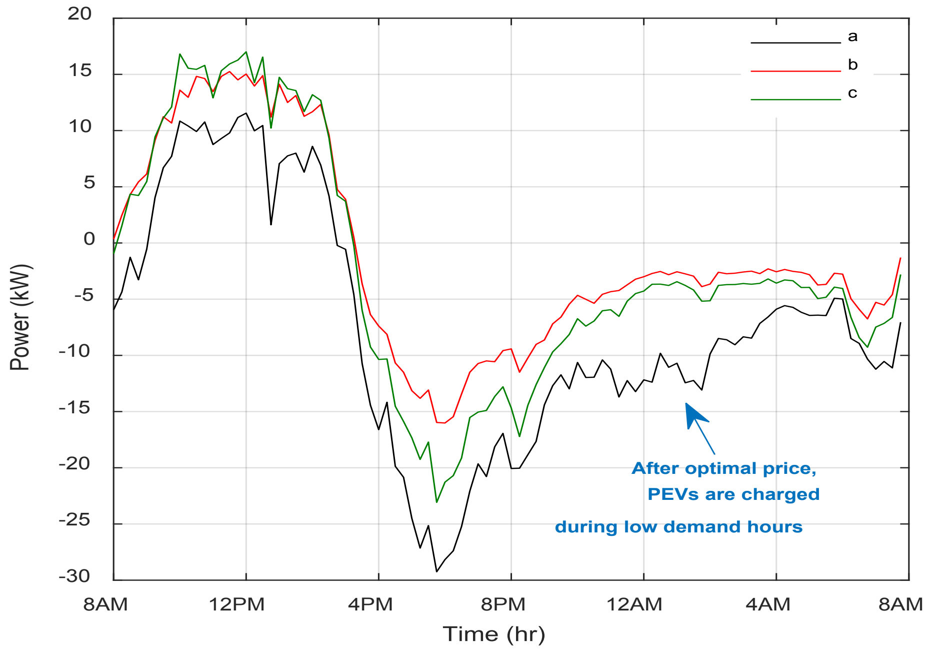
Figure 4.4. The practical test distribution system with PEVs which demonstrate the scenarios by colours; For example, scenario 1 and scenario 2 are highlighted in blue and red colours respectively. Blue, red, and green colours represent scenario 4.

4.5.1 Case C: Coordinated Charging PEVs based on Variable Price

In this scenario, the coordination strategy in sub-section 4.2.1 is used to solve the optimization problem of 4.1 by considering a smart contract between owners and aggregator. The idea is to coordinate PEV charging at each time interval Δt to improve the overall system and reduce the cost of network generation by considering the constraints of (4.7-4.12). It means the consumer has the possibility to know the real-time electricity price before using smart meters. In this part "Synergy smart home plan time off use tariff" [133] is applied, which means the cost rate applied based on the time of the day when using electricity. Consequently, this method is designed to shift PEVs charging during off-peak (valley areas) hours in order to reduce charging cost and improve system performance. The real-time price typically points to the total demand of the network. Accordingly, when the price is at high levels means the aggregate demand is high. Figures 4.5 - 4.7 show the total demand, VUF, and voltage on different phases for scenarios 1, 2, and 4, respectively. In addition, the system performances for case C for all scenarios (C1-C4) are shown in Table 4.4.

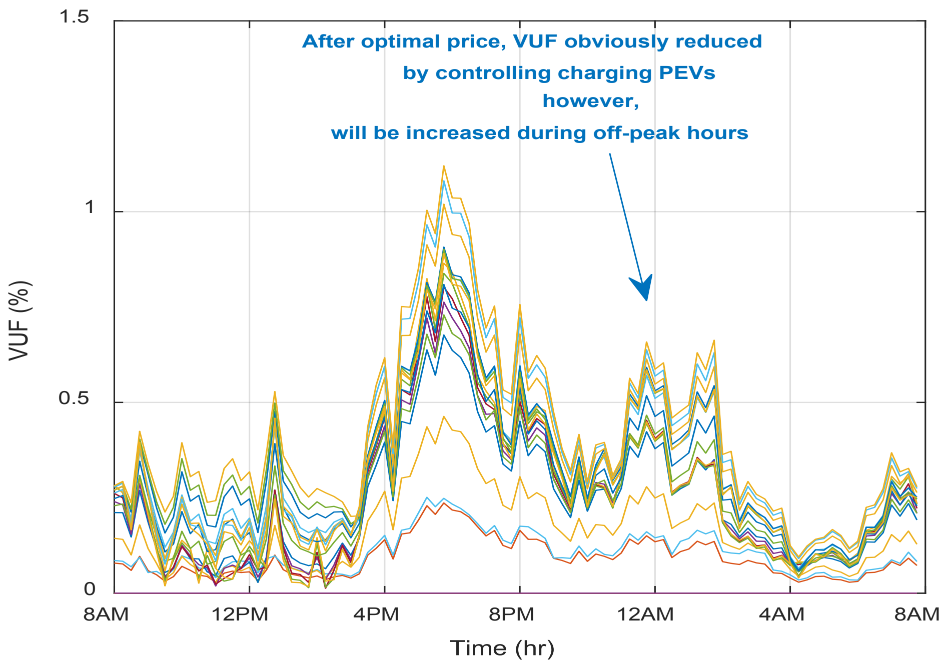
According to Figure 4.5 (a), Figure 4.6 (a) and Figure 4. 7 (a) in terms of total demand in different phases in scenarios (1, 2, and 4), the objective functions allocate charging in the low spots' price, off-peak hours. Therefore, the overall system peak demands decreases during peak hours.

The VUFs in scenarios 1, 2, and 4, according to Figures 4.5 (b), 4.6 (b) and 4.7 (b) are significantly improved compared to uncoordinated charging. It can be observed that the VUF peaks are shifted during early morning and late-night hours. Figures 4.5 (c), 4.6 (c) and 4.7 (c) show the effect of PEV's demand on the voltage on phase-a, phase-b (due to charge PEVs from this phase) and phase-a, respectively. From these figures, all voltages are within the limitation and charged successfully during low electricity price hours.



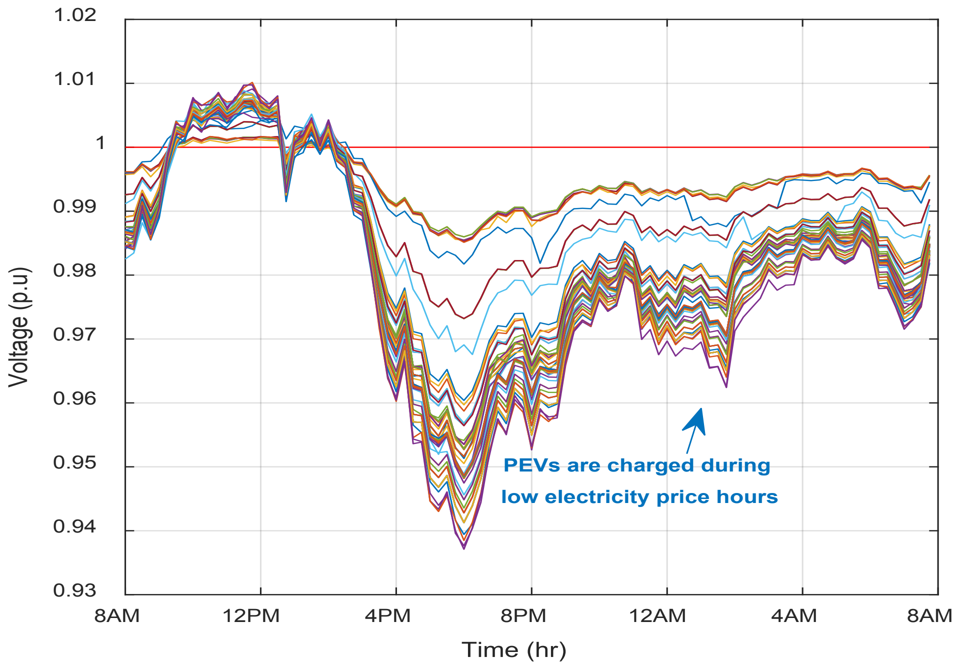
a
b
c
After optimal price,
PEVs are charged
during low demand hours
Power (kW)
Time (hr)
20
15
10
5
0
-5
-10
-15
-20
-25
-30
8AM
12PM
4PM
8PM
12AM
4AM
8AM

(a)



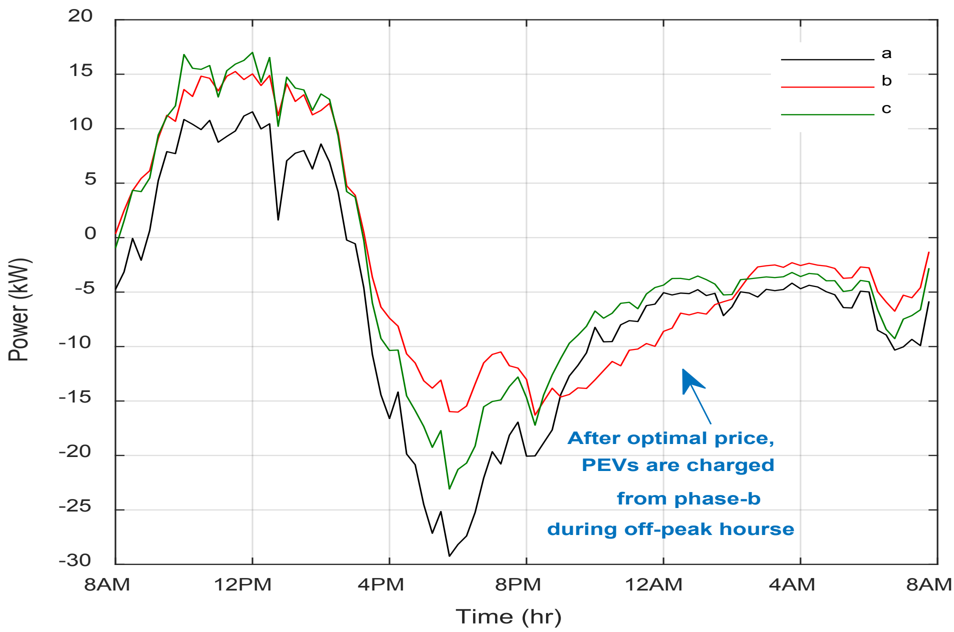
After optimal price, VUF obviously reduced
by controlling charging PEVs
however,
will be increased during off-peak hours
VUF (%)
Time (hr)
1.5
1
0.5
0
8AM
12PM
4PM
8PM
12AM
4AM
8AM

(b)

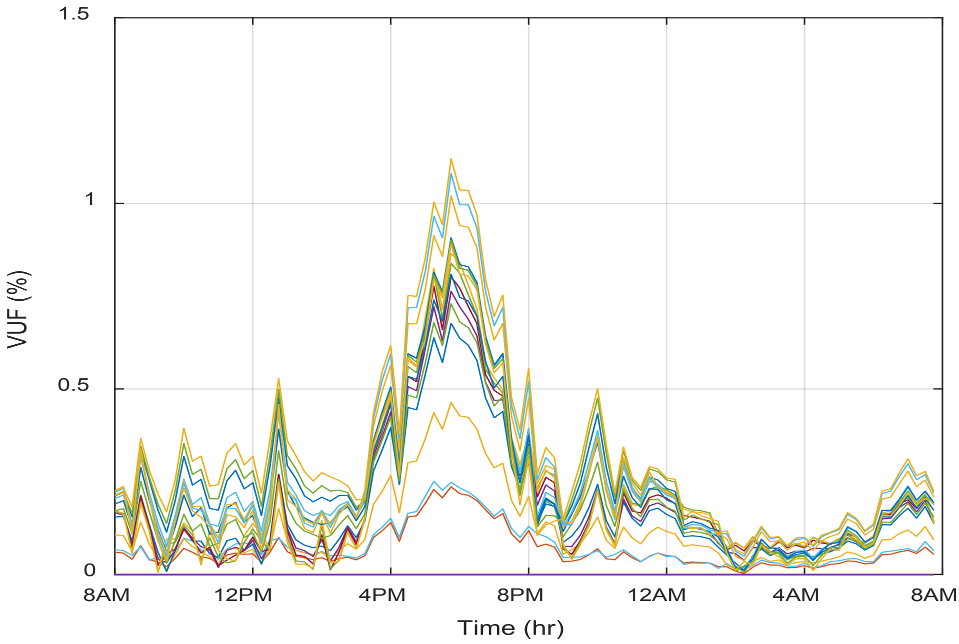


(c)

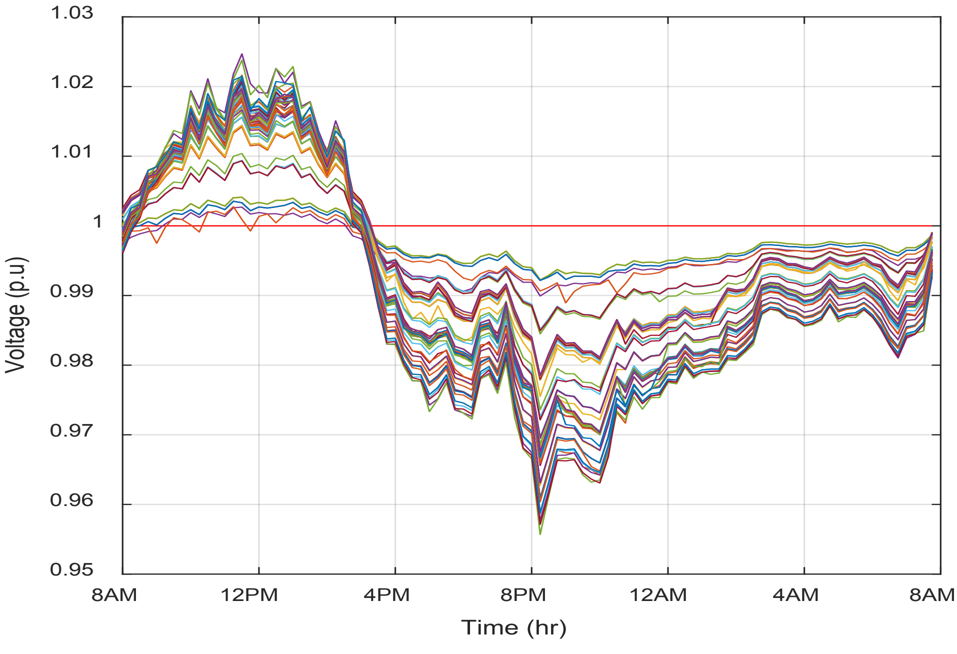
Figure 4.5. Case C1: Impact of variable price coordinated charging PEV (optimal price) on (a) system demand, (b) VUF, and (c) voltages phases-a profile.



(a)

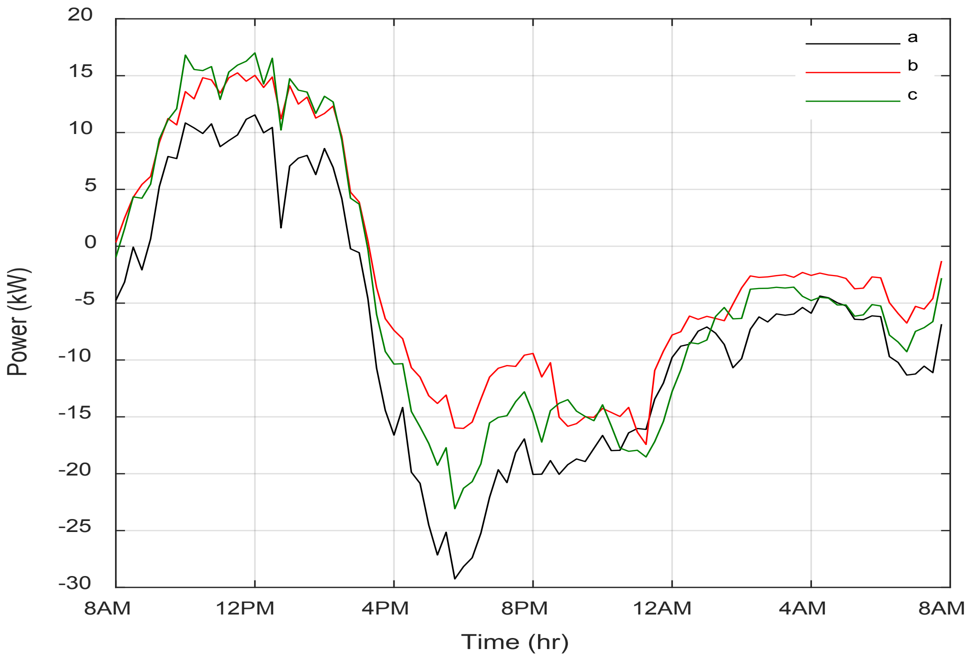


(b)



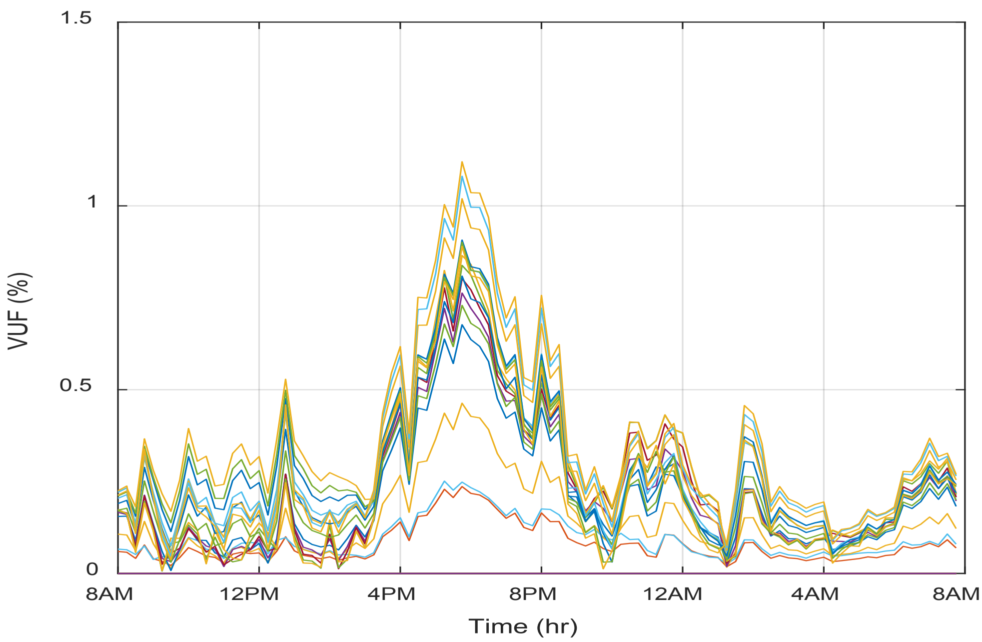
(c)

Figure 4.6. Case C2: Impact of variable price coordinated charging PEV (optimal price) on (a) system demand, (b) VUF, and (c) voltages phases-b profile.



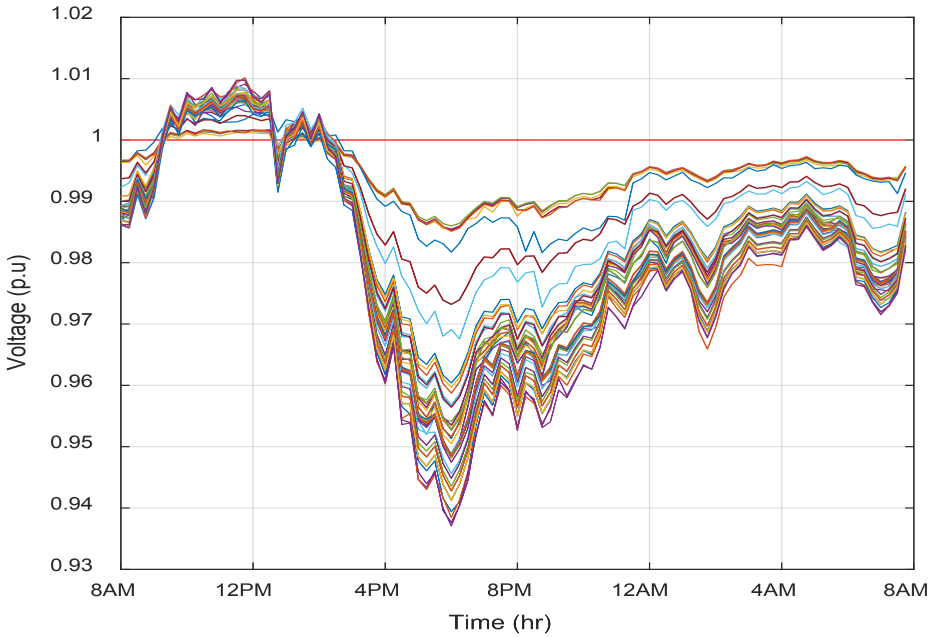
Power (kW)
Time (hr)
a
b
c
20
15
10
5
0
-5
-10
-15
-20
-25
-30
8AM
12PM
4PM
8PM
12AM
4AM
8AM

(a)

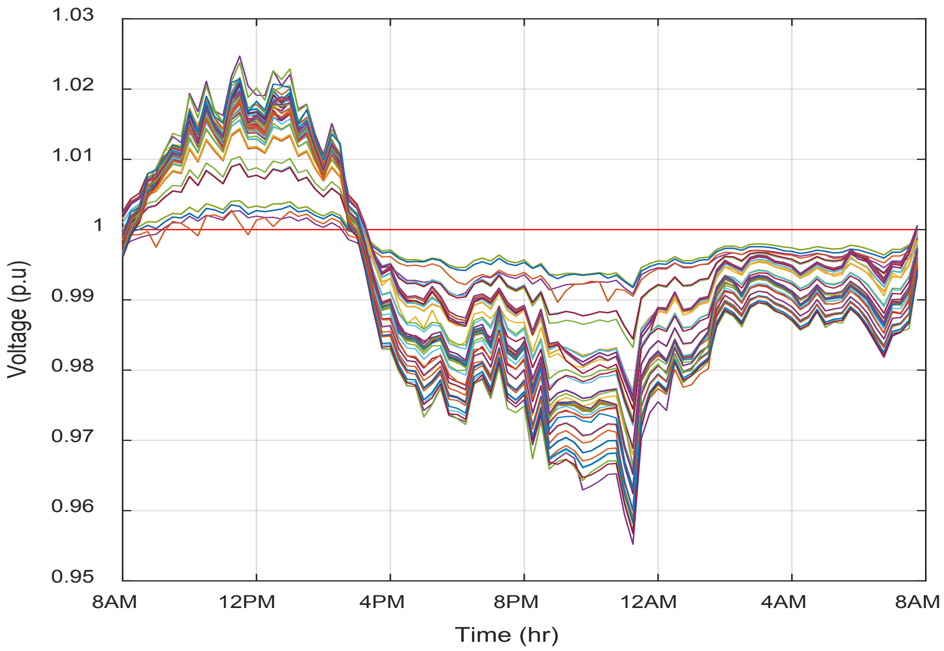


VUF (%)
Time (hr)
1.5
1
0.5
0
8AM
12PM
4PM
8PM
12AM
4AM
8AM

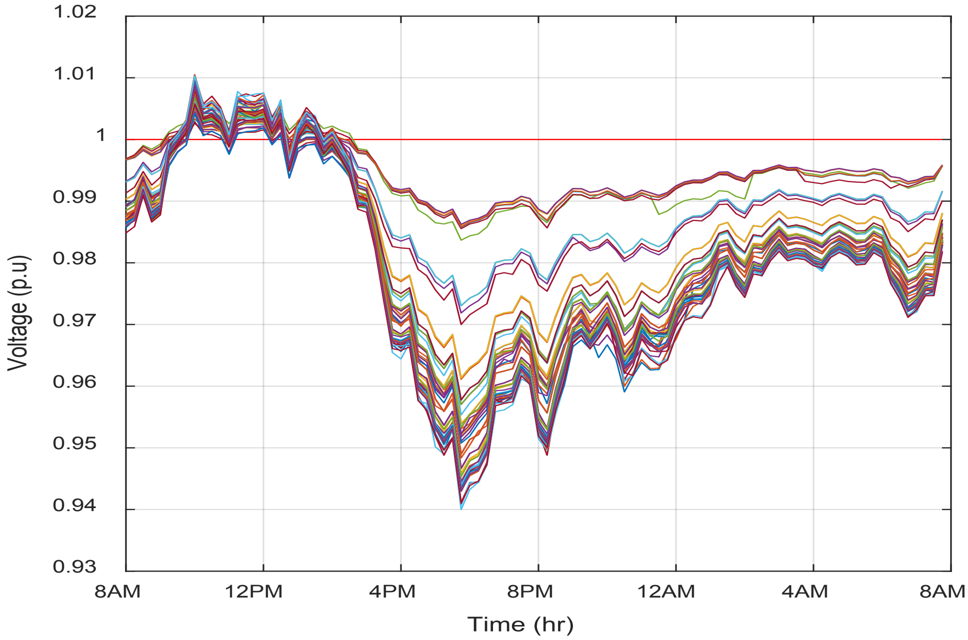
(b)


1.02
1.01
1
0.99
0.98
0.97
0.96
0.95
0.94
0.93
Voltage (p.u)
8AM
12PM
4PM
8PM
12AM
4AM
8AM
Time (hr)

(c)


1.03
1.02
1.01
1
0.99
0.98
0.97
0.96
0.95
Voltage (p.u)
8AM
12PM
4PM
8PM
12AM
4AM
8AM
Time (hr)

(d)



(e)

Figure 4.7. Case C4: Impact of variable price coordinated charging PEV (optimal price) on (a) system demand, (b) VUF, and (c)-(e) voltages phases-a, b and c profile

The results obtained from the analysis of case C are summarised in Table 4.3 show the effectiveness of the price based optimization. In comparison with case B, general improvements in terms of system performance and operational cost are observed. For example, scenario 4 (case C4) has the highest total payment comparing with other cases due to the higher number of PEVs. The cost is $93.36 per day, which consists of four components, as explained in section 4.4, which is $91.61 for active power generation, and the rest is for power losses. Compared to case B4, it is certainly offering a better solution in terms of grid operation and consumer as well. Moreover, the voltage at all buses kept within system limit (Figures. 4.7 (c), (d) and (e)), and VUFs have also reduced Figure 4.7(b).

Table 4.3 Comparison of optimization results for all scenarios based on variable price

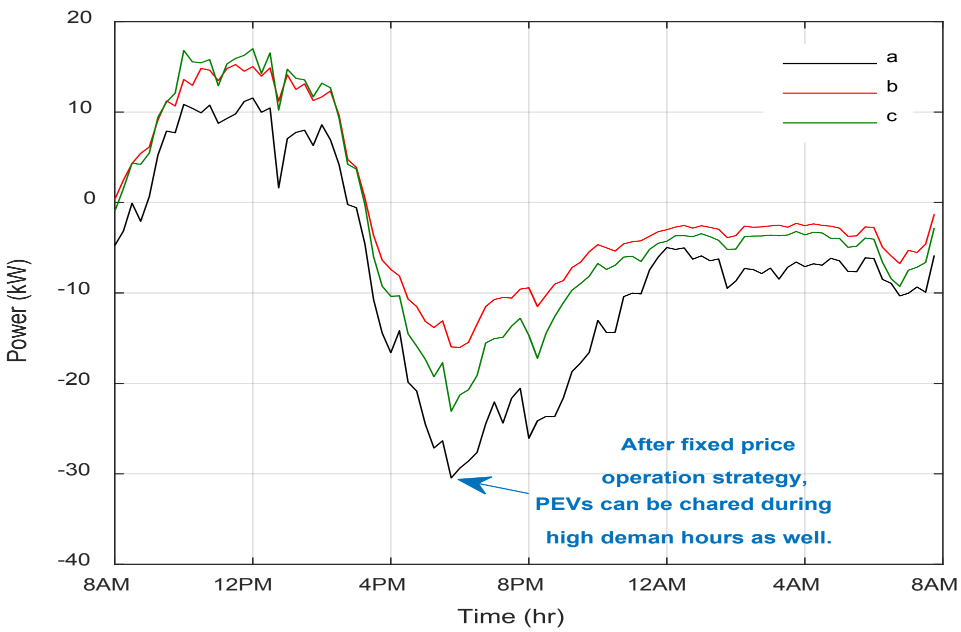
	Generation Cost [$/Day]	Total Cost [$/Day]
	Case A	
	73.4	75.01
Scenario 1 (high load phase)	**Case B1**	
	92.5	94.09
	Case C1	
	79.2	81.6
Scenario 2 (low load phase)	**Case B2**	
	91.85	93.6
	Case C2	
	81.06	82.7
Scenario 3 (two phases)	**Case B3**	
	113.035	114.78
	Case C3	
	86.09	87.85
Scenario 4 (all single phases)	**Case B4**	
	132.39	134.15
	Case C4	
	91.61	93.36

4.5.2 Case D: Coordinated Charging PEVs based on Fixed Price

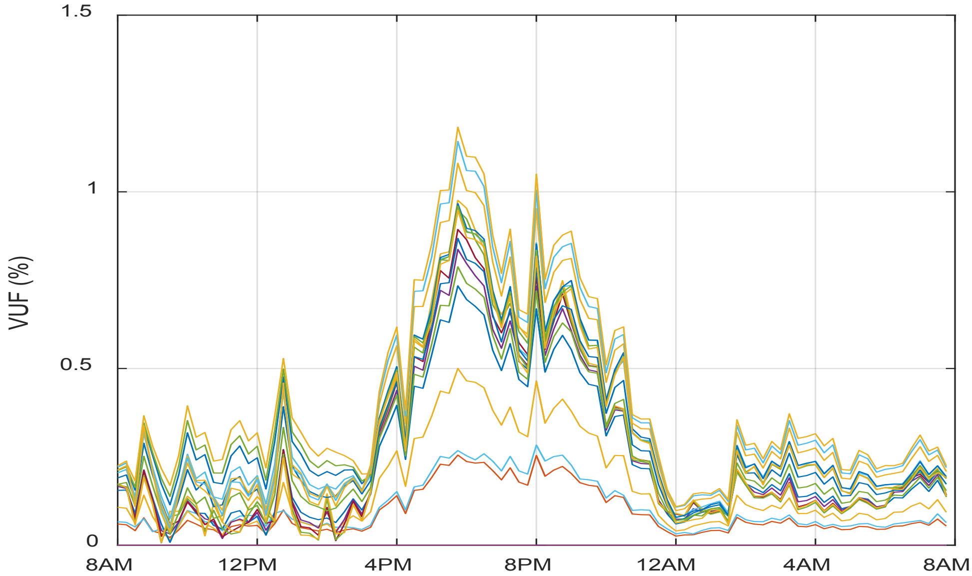
In this case study, the PEVs are allowed to charge based on the optimal fixed price strategy of section 4.2.2. The goal of this case study is coordinated charging based on the fixed price of electricity during a day that can adjust PEV charging at each time interval Δt and improve the overall VUF of the system by considering the overload and voltage quality constraints. In addition, at the same time, this method has the benefit of giving the opportunity to the owners to charge their vehicles as soon as possible while network operation criteria are considered. The results of implementing this strategy by considering the constant rate electricity price are shown in Figures 4.8 - 4.10 and the system performance for case D (D1-D4) are listed in Table 4.4., When compared to case B, general improvements in terms of system performance are observed.

In terms of power demand from Figures 4.8 (a), 4.9 (a) and 4.10 (a), it can be found that this strategy resulted in charging PEVs during high peak loads and as expected reach to the lowest level of network limits (network capacity). For VUF, Simulation results indicate that the VUF of the network for all scenarios is significantly improved and limited to 1.2% during the evening peak hours as shown in Figures 4.8 (b), 4.9 (b) and 4.10 (b).

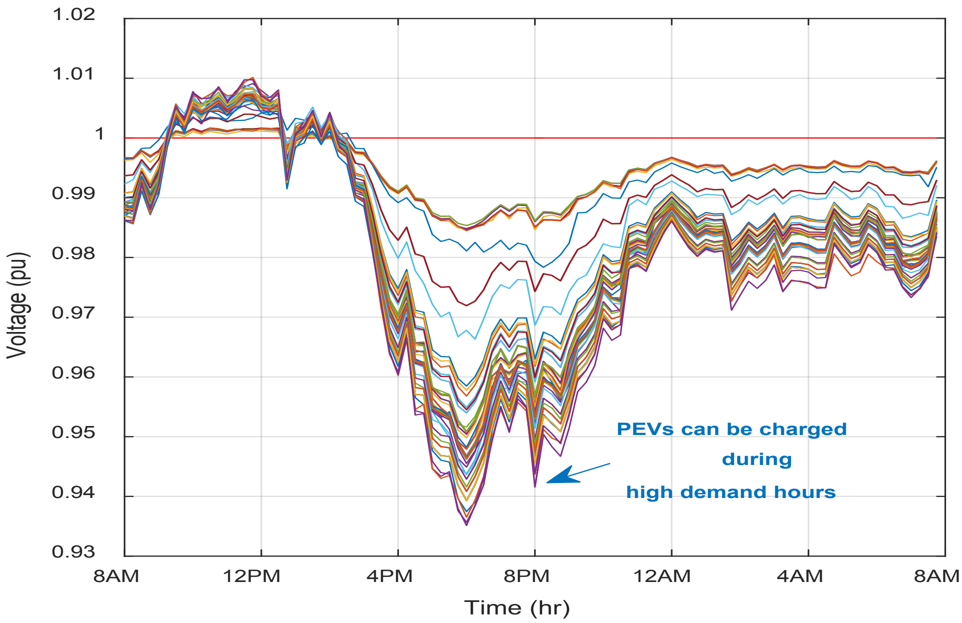
However, the voltage profiles on three different phases for all scenarios are not in the grid limitation. For example, in scenario 4, Figures 4.10 (c) and 4.10 (e) show the voltage profile of phase-b and phase-c, respectively. It can be seen hat during the peak load periods the voltage magnitudes of some nodes have reached 0. 935 pu. Therefore, this case may not be justified for downstream consumers in the network.



(a)

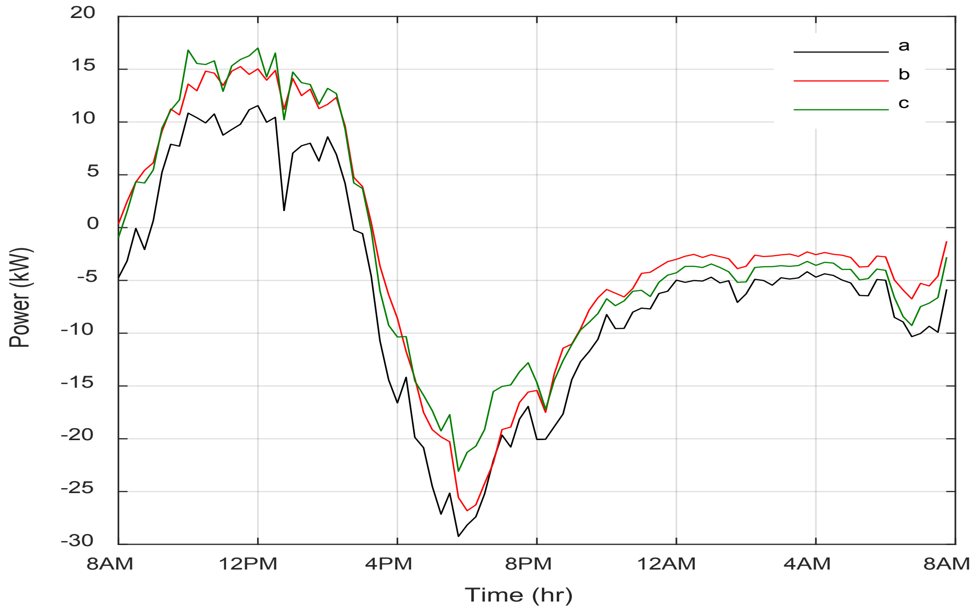


(b)



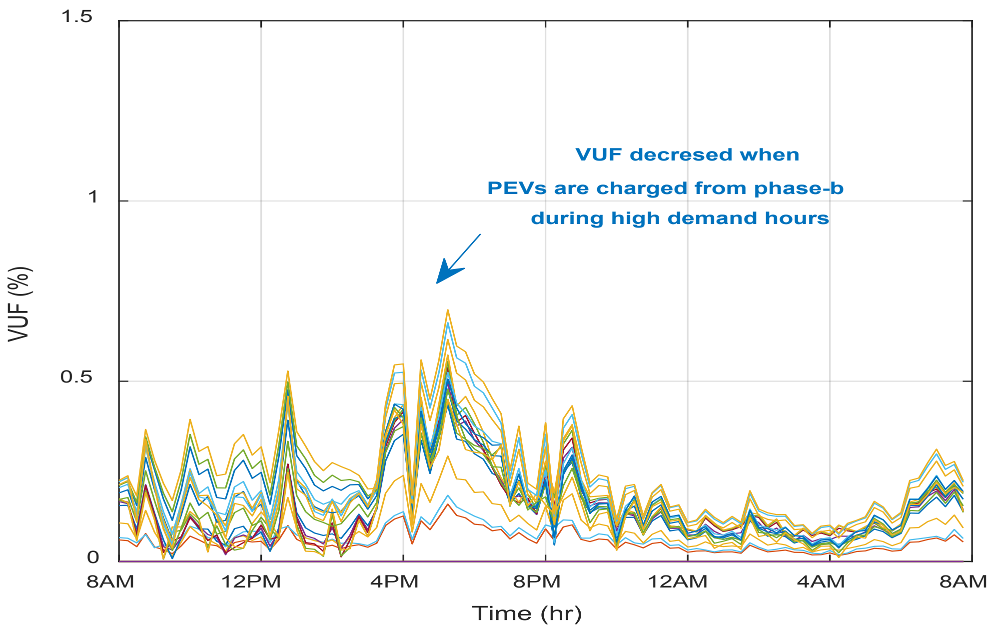
(c)

Figure 4.8. Case D1: Impact of fixed price coordinated charging PEV on (a) system demand, (b) VUF, and (c) voltages phases-a profile.



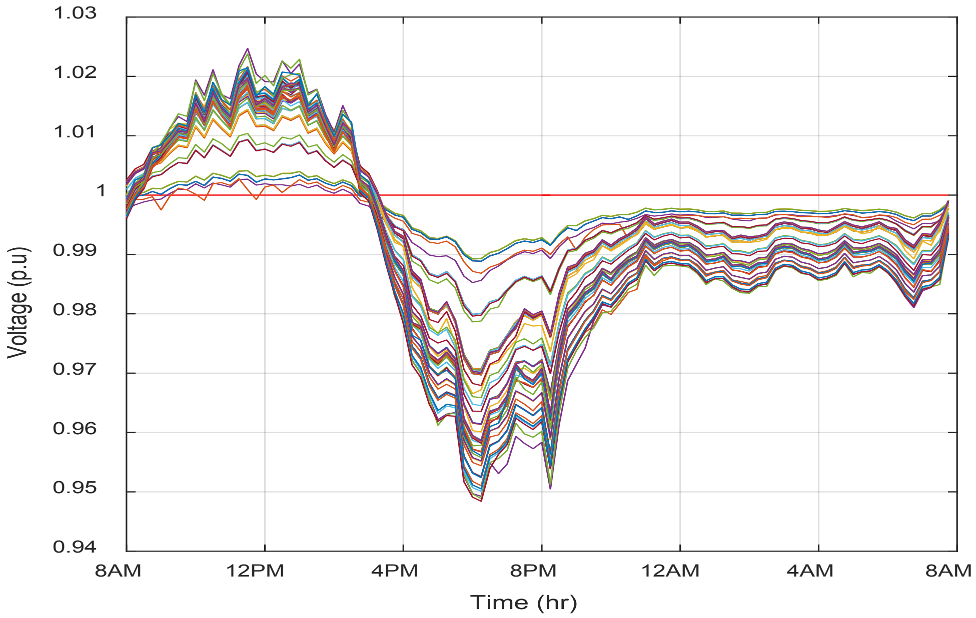
20
15
10
5
0
-5
-10
-15
-20
-25
-30
Power (kW)
a
b
c
8AM
12PM
4PM
8PM
12AM
4AM
8AM
Time (hr)

(a)



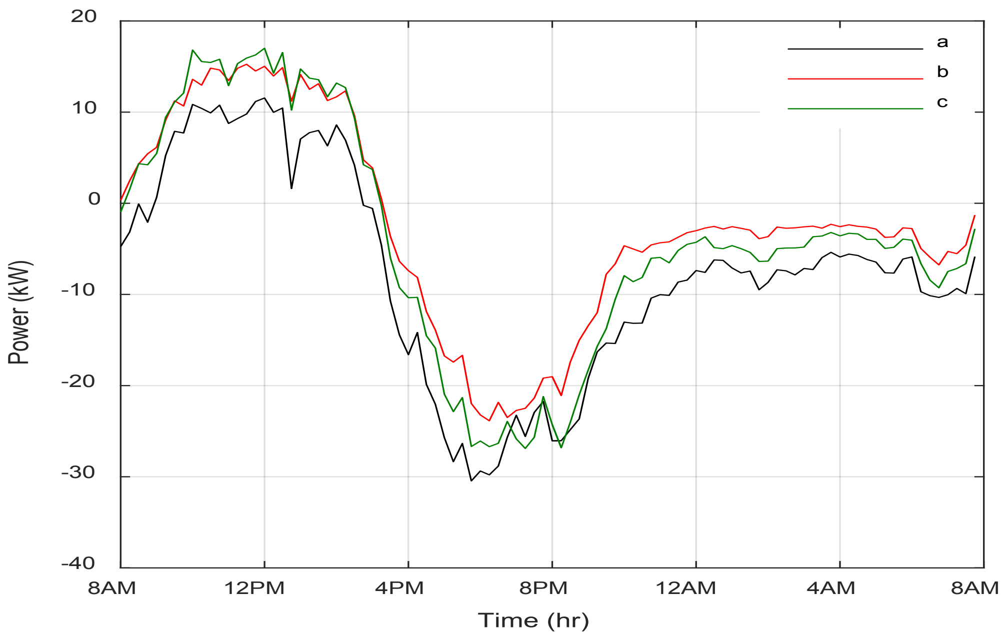
1.5
1
0.5
0
VUF (%)
VUF decresed when
PEVs are charged from phase-b
during high demand hours
8AM
12PM
4PM
8PM
12AM
4AM
8AM
Time (hr)

(b)

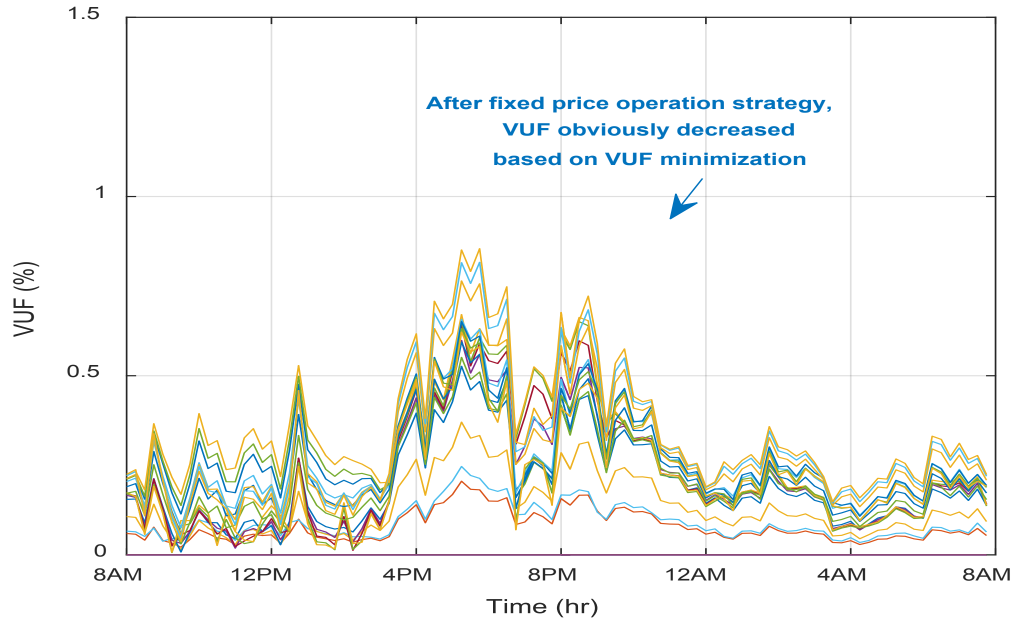


(c)

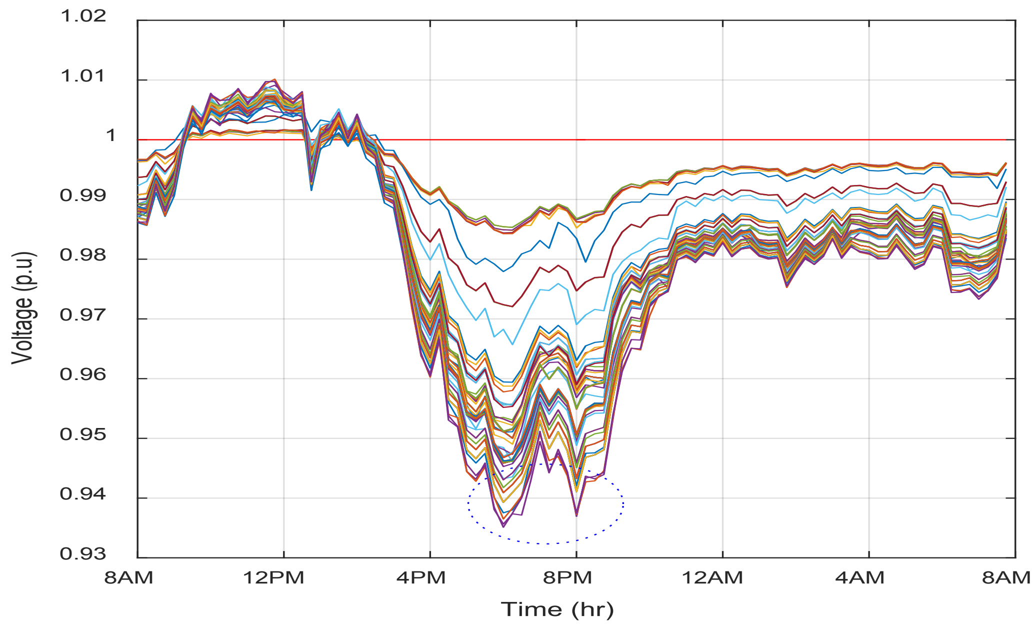
Figure 4.9. Case D2: Impact of fixed price coordinated charging PEV on (a) system demand, (b) VUF, and (c) voltages phases-b profile.



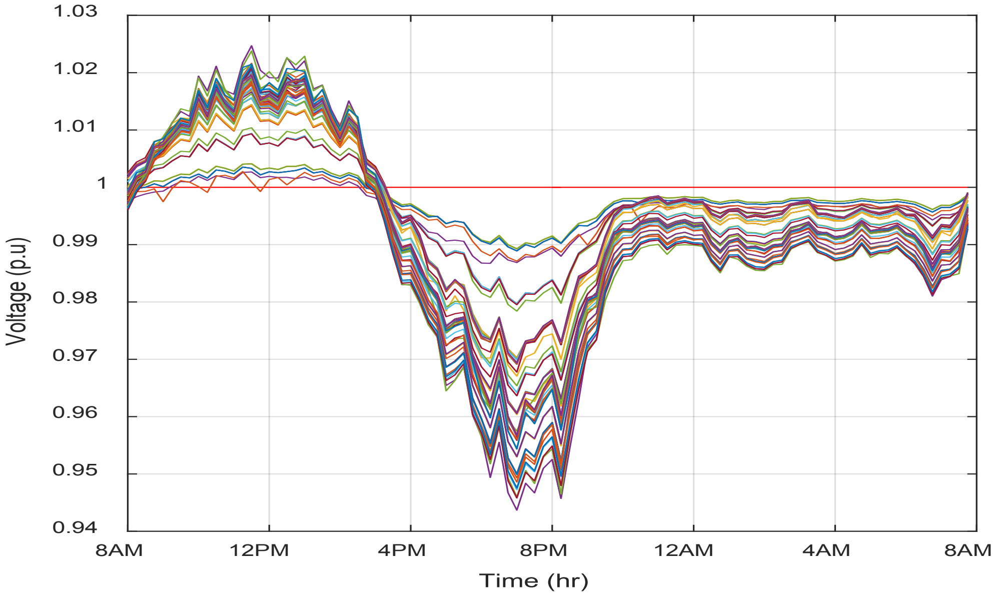
(a)


1.5
1
0.5
0
VUF (%)
After fixed price operation strategy,
VUF obviously decreased
based on VUF minimization
8AM
12PM
4PM
8PM
12AM
4AM
8AM
Time (hr)

(b)


1.02
1.01
1
0.99
0.98
0.97
0.96
0.95
0.94
0.93
Voltage (p.u)
8AM
12PM
4PM
8PM
12AM
4AM
8AM
Time (hr)

(c)



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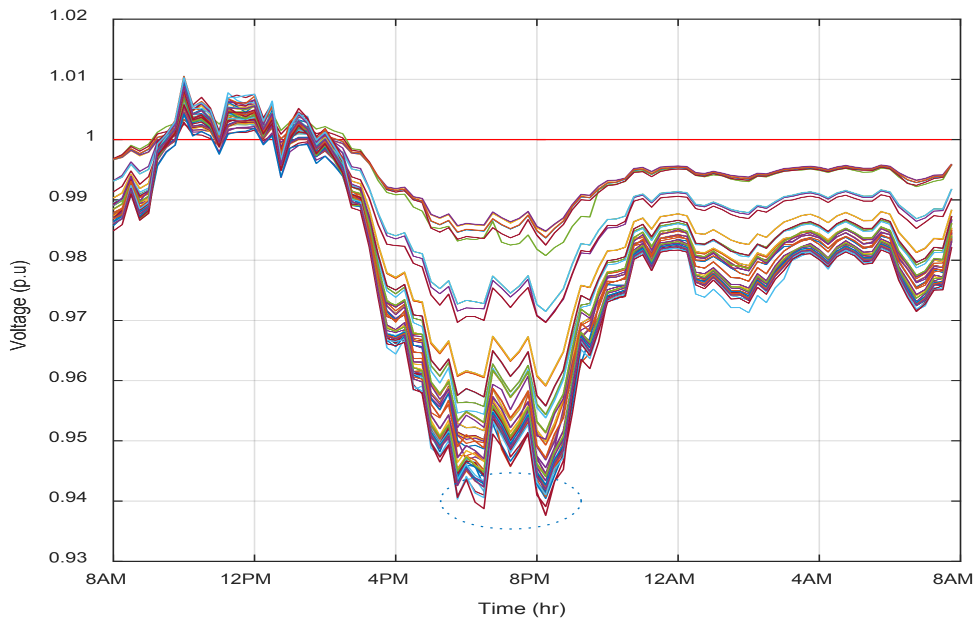


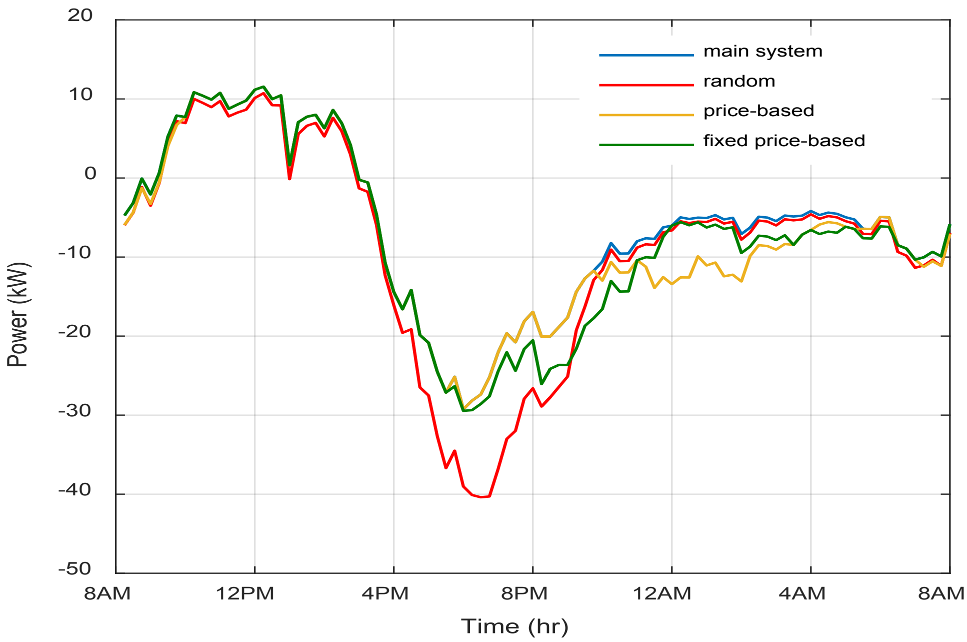
(e)

Figure 4.10. Case D4: Impact of fixed price coordinated charging PEV on (a) system demand, (b) VUF, and (c)-(e) voltages phases-a, b and c profile.

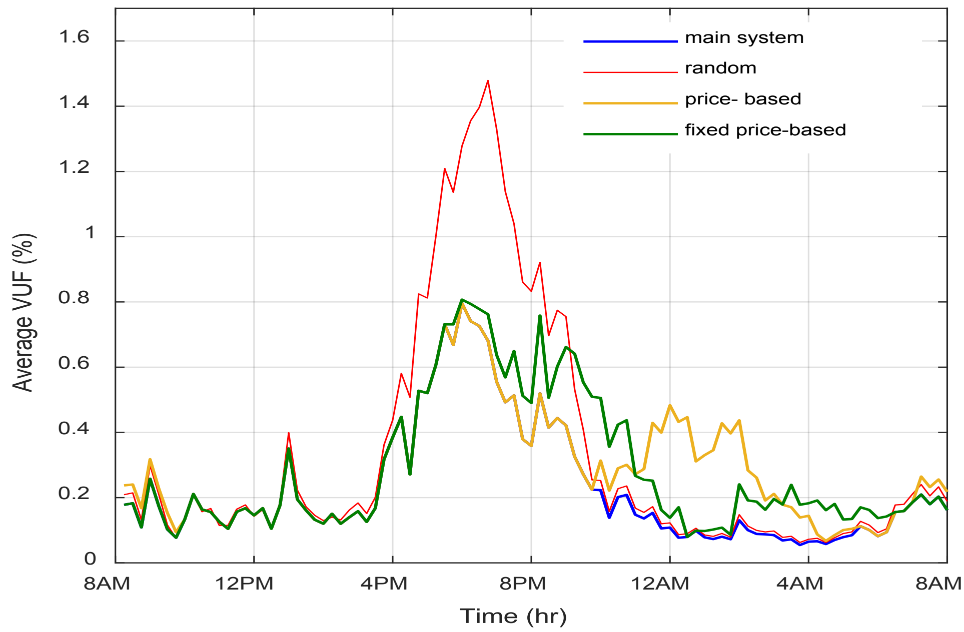
4.5.3 Comparison of Smart Charging Cases

In this sub-section study, the coordinated charging PEVs for all cases (random, based on fixed and variable price) are analysed for different scenarios to show the effectiveness of each method.

- **Scenario 1:** A comparison of total power energy drawn from the utility for scenario 1 (PEVs on phase-a) is presented in Figure 4. 11 (a). This figure shows the highest import (negative) power obtained in the random case (-40.1 kW) is more than price based and fixed price cases (-29.2 kW, -29.8 kW, respectively). It means approximately 36% improvement in maximum power consumption for both cases. Compared with fixed price based schedule; it is clear that charging loads in all price based methods are located at the periods when the prices are low. However, none of the PEVs starts to charge before 9:00 PM and waits in the Q-table. According to Table 4.4, most of the PEVs could charge quickly and smoothly in fixed price based method before midnight. In addition, the total VUF is improved from 2% to 1.12% as well. However, the 2.7% of buses (2 buses) are under the voltage limitation in operation method, so implying that the network capacity is not enough to charge even for 20% of PEVs. The average VUFs of all cases over 24 hours are shown and compared in Figure 4.11 (b). The maximum values for random, variable price and fixed price based are 1.5%, 0.80%, and 0.81 %, respectively. In the price based case due to the charging during off-peak hours the VUF increases at night and reaches to 0.4% however in the fixed price based case exactly during that time the system reaches the minimum value of VUF which is 0.1%. This means the peak average VUF value for each scenario depends on the time of the charging which is variable. However, in both methods, the total VUFs are improved.



(a)



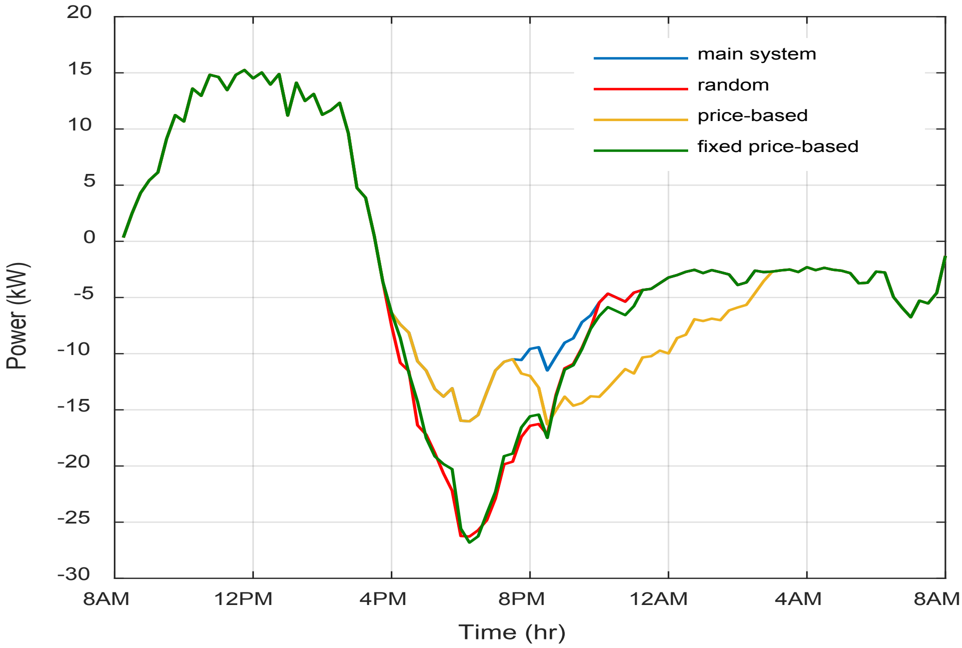
(b)

Figure 4.11 Comparison of simulation cases for scenario 1 (PEVs are connected to phase-a) on (a) system demand on phase-a, and (b) average VUF over 24 hours.

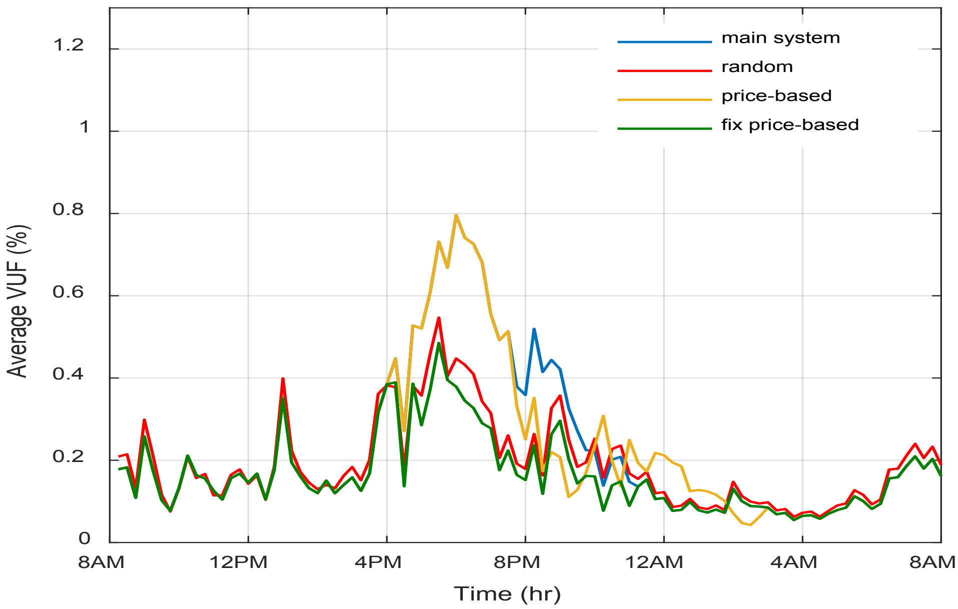
- **Scenario 2:** In this scenario, as PEVs are connected to phase-b (low load phase), the average of system demand over 24 hours on that phase-b is considered in Figure 4.12 (a). It can be found that in price based method, charging of PEVs are occurring during low load time due to the price facilities. However, in a fixed price based method because of the availability of the system capacity and constraints, owners could charge their PEVs during high peak as well. So, all PEVs could charge before 11:00 PM. Furthermore, by comparing of average VUF for scenario 2, VUF in the fixed price case is less than the other one which is 0.5% at the peak house as shown in Figure 4.12 (b).

As discussed in the previous Chapter, charging in low load phase reduces the difference between phases and leads to decreasing VUF. Although the optimal fixed price based method leads to more effective VUF (one of the primary concerns in this thesis), the voltage, especially at the end of the feeder is reduced and reached to its limitation.

- **Scenario 3:** In this scenario, PEVs are connected to phase-a and phase-c as the two highest load phases. It is expected that like the previous cases in price based, PEVs shift during the night and all PEVs charge till 8:00 AM. However, in fixed price based, some PEVs are charged during peak load and some off-peak hours. Consequently, The VUF will be increased during those charging times.

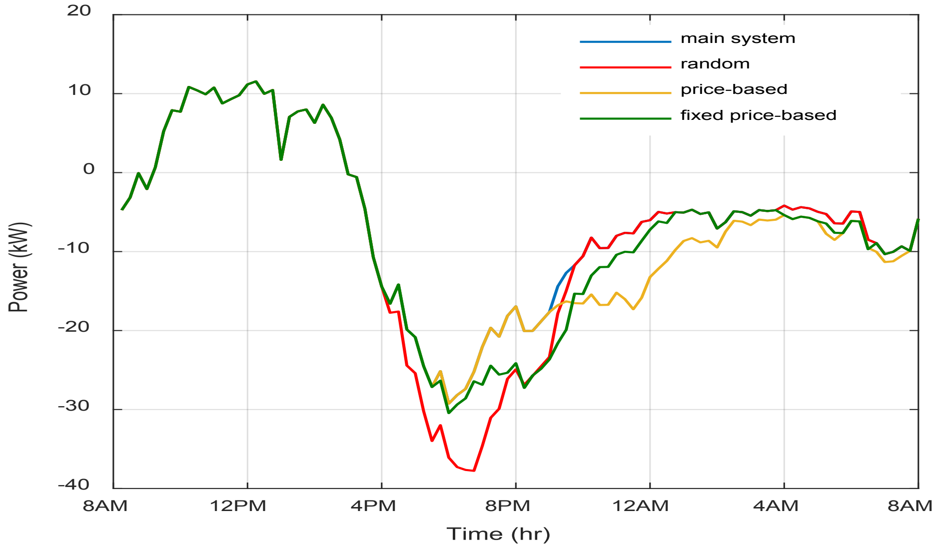


(a)

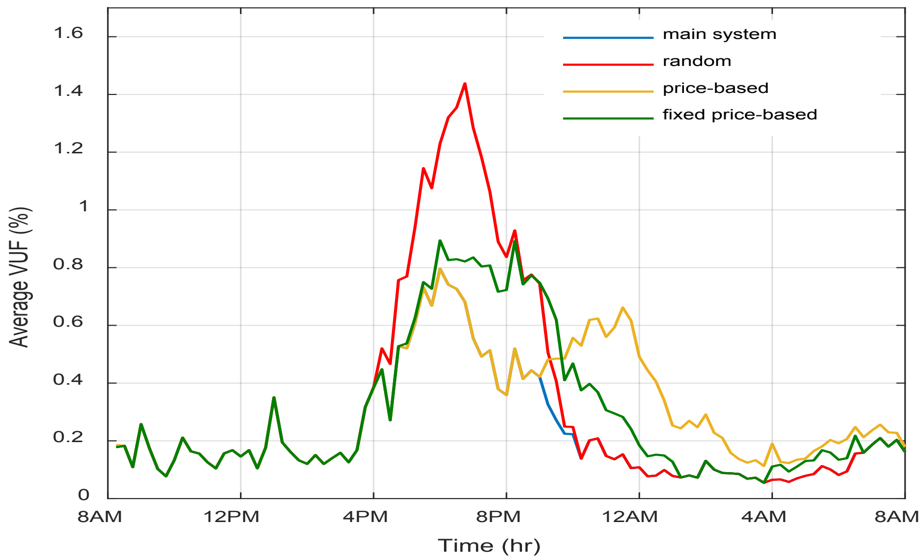


(b)

Figure 4.12 Comparison of simulation cases for scenario 2 (PEVs are connected to phase-b) on (a) system demand on phase-b, and (b) average VUF over 24 hours.



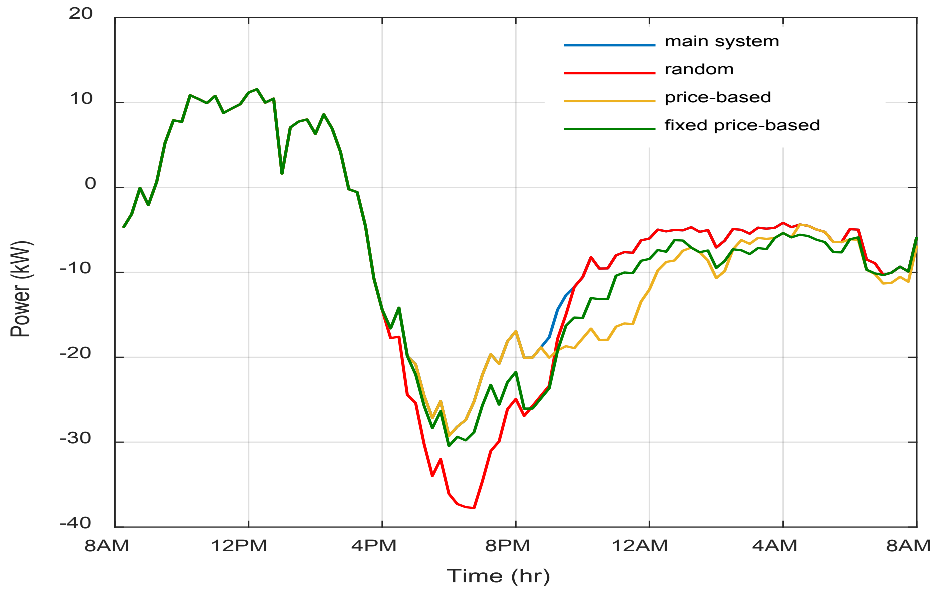
(a)



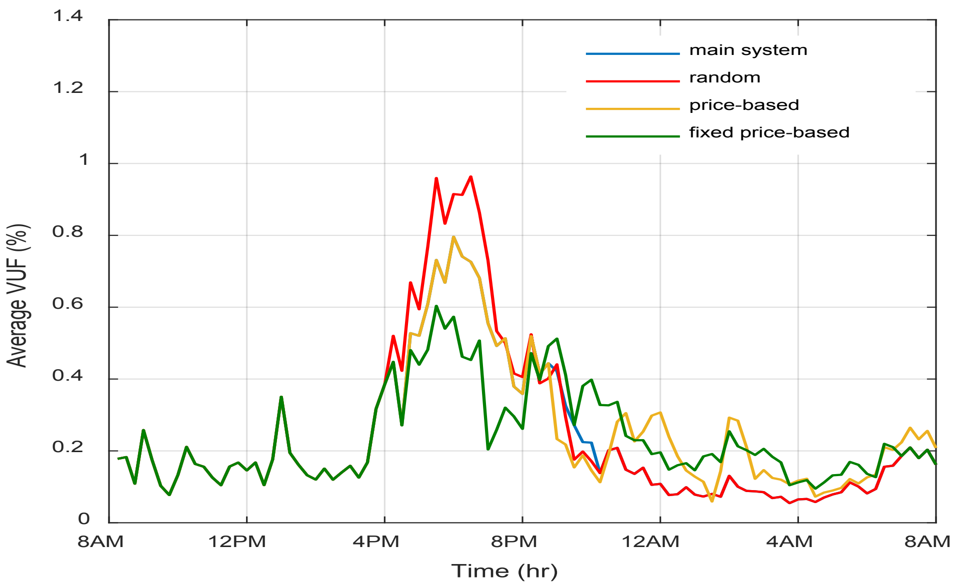
(b)

Figure 4.13. Comparison of simulation cases for scenario 3 (PEVs are connected to phase-a, and c) on (a) system demand on phase-a, and (b) average VUF over 24 hours.

- **Scenario 4:** In this scenario, all single-phase houses (phase-a, b, and c) have a PEV. Figures 4.14 (a) and 4.14 (b) present the variation of total power demand on phase-a for all cases and average total VUF over 24 hours. From the results, the total power is improved by approximately 20% for both fixed price, and variable price based cases comparing to the random ones. Although the total VUF 4.14 (b) is improved in all optimization objectives, in optimal fixed price strategy due to the charging of the PEVs during high demand time and reducing the difference of voltage phases or voltage variation from PEVs, the VUF is more improved in compare with the other cases.



(a)



(b)

Figure 4.14. Comparison of simulation cases for scenario 4 (PEVs are connected to phase-a, b, and c) on (a) The average system demand on phase-a, and (b) average VUF over 24 hours.

According to Table 4.4 when evaluating cases C and D for all scenarios, it is observed that the maximum power demand for all phases (a, b, and c) is obtained in case D due to the charging of most of the PEVs during high peak loads. Both cases charge all PEVs successfully; however, in case D, there are some problems on buses at the end of the feeder.

Table 4.4 Comparison of optimization results for different charging methods

	Operation Condition				**Comparison of Simulation Results**									
	PEV [%]	**Number of PEVs**			**Maximum Demand (kW)**			**Worst Voltage (p.u)**			**Worst VUF (p.u)**	**Buses under Voltage [%]**		
		a	**b**	**c**	**a**	**b**	**c**	**a**	**b**	**c**	**Feeder End**	**a**	**b**	**c**
Base	0	Case A Base Case without any PEVs												
		0	0	0	30	23.1	15.9	0.937	0.97	0.94	1.12	0	0	0
Scenario 1	20	Case B1: Uncoordinated PEVs												
		11	0	0	40	162	23.1	**0.908**	0.97	**0.933**	2	38	0	0
		Case C1: Optimal online charge control based on the optimal price												
		11	0	0	29.2	16	23.1	0.937	0.97	0.94	1.13	0	0	0
		Case D1: Optimal online charge control based on optimal fixed price												
		11	0	0	29.8	16	23.1	**0.935**	0.969	0.94	1.12	2.7	0	0
Scenario 2	20	Case B2: Uncoordinated PEVs												
		0	11	0	29.2	26.2	23.1	**0.930**	0.948	0.949	0.68	12	0	0
			Case C2: Optimal online charge control based on the optimal price											
		0	11	0	29	17.3	23.1	0.937	0.957	0.94	1.12	0	0	0
		Case D2: Optimal online charge control based on optimal fixed price												
		0	11	0	28.2	26.3	23.1	**0.930**	0.949	0.95	0.7	12	0	0
Scenario 3	40	Case B3: Uncoordinated PEVs												
		11	0	12	37.7	16	32.7	**0.924**	0.97	**0.916**	2	32.4	0	56
		Case C3: Optimal online charge control based on the optimal price												
		11	0	12	29.2	16	23.1	0.937	0.967	0.941	1.12	0	0	0
		Case D3: Optimal online charge control based on optimal fixed price												
		11	0	12	31.6	15.5	24.8	**0.936**	0.969	**0.934**	1.2	4	0	12
Scenario 4	60	Case B4: Uncoordinated PEVs												
		11	11	12	37.6	34.8	32.1	**0.914**	0.947	**0.923**	1.4	50	0	50
		Case C4: Optimal online charge control based on the optimal price												
		11	11	12	30	17.4	23.1	0.937	0.955	0.941	1.1	0	0	0
		Case D4: Optimal online charge control based on optimal fixed price												
		11	11	12	30.4	23.9	26.3	**0.935**	0.943	**0.939**	0.85	5	0	4

It is needed to note that, the results of the main system case A and uncoordinated case B for all scenarios as mentioned above are presented in Chapter 2, and the details are repeated in Table 4.4 as well.

4.6 Summary

In this Chapter, optimal online charge control based on genetic algorithm (OL-C-TP) for G2V coordination in an unbalanced grid is discussed. The main aims are minimization of the voltage deviation and VUF. Two different multi-objective PEVs coordination strategies are discussed – priced based and fixed price based. The results indicate that the effect (advantages and disadvantages) of each scheme on the network.

Detailed simulation results are presented and compared for the unbalanced Western Australian Distribution network of Figure 4.4. The main conclusions are:

- The online centralized genetic PEV coordination based on optimal cost strategy are shown in Figures 4.5 - 4.7. Using the proposed method reduces the total cost for the consumer and improves system performance. However, the opportunity of PEV charging at high energy demand time is not considered.
- The online centralized genetic PEV coordination based on fixed price operating strategy with the target of minimizing VUF and PEV charging at peak hours are shown in Figures 4.8- 4.10. This is done by quick charging as many vehicles as possible by considering constant electricity price while keeping the remaining vehicles in a PEV-Queue table and serving them during the off-peak load hours. Although this method satisfies the vehicle owners, the voltage limits are violated in some of the buses.
- Summarizing these results, it can be concluded that the network operators must consider smart charging scenarios that accommodate the technical limits of the network and also customer satisfaction at the same time. To successfully integrate these kinds of strategies, the next Chapters will propose coordinated charging and discharging simultaneously to mitigate the voltage regulation issues.

Chapter 5

Coordinate Charging through both Real and Reactive Power Control

5.1 Introduction

In this Chapter, the methodology proposed in Chapter 4 is developed for real and reactive power flow management in three-phase four-wire low voltage unbalanced distribution networks with high penetrations of PVs. It presents a hybrid strategy of centralized GA-based PEV charging and decentralized PEV var discharging for biased distribution networks. It aims to minimize VUF by making smart PEV charging/discharging decisions simultaneously. Besides the online centralized PEV charging coordination (OL-C-TP) of Chapter 4, the proposed strategy also relies on decentralized discharging to provide PEV inverter reactive support at selected nodes based on droop control, to further locally improve the voltage profile and reduce the overall network VUF. The approach is tested on existing real modified Australian LV distribution system with considerable rooftop PVs. So, the facilities that PEV owners could charge during the morning from PV (8:00 AM-11:00 AM) is also considered.

This Chapter is an effort to highlight the reactive power capability of PEV inverters to keep the acceptable voltage limit of the specific houses with PEV in an LV residential distribution system for voltage regulation. The decentralized droop controller is applied through the proposed strategy for the PEV owners. In this regard, an algorithm to use this capability is presented and discussed. This Chapter is organized as follow:

Section 5.2 briefly mentions the problem formulation, including objective function and constraints of the system. Section 5.3 introduces the proposed method for utilising reactive power of PEV for regulation voltage. This section first explains the concept of the capability of PEV inverter for voltage regulation, then introduced the system modelling and the possibility of two battery inverter control used in this Chapter. The flowchart of the procedure and detailed MATLAB simulations of real 74 nodes unbalanced distribution network are discussed in Sections 5.4 and 5.5, respectively. Finally, the conclusion is summarized in Section 5.6.

(*) Note: The main parts of this Chapter were accepted as a journal paper with the title of, "Online Centralized Charging Coordination of PEVs with Decentralized Var Discharging for Mitigation of Voltage Unbalance" (Appendix B3).

5.2 Problem Formulation

5.2.1 Objective Function

The problem formulation in (4.4.2) and GA optimization of section 4.4 are used to perform online coordination of PEV charging/discharging problem which is subject to the minimization of total VUF for ancillary voltage support by choosing the PEVs to connect per phase at each time slot Δt, to efficiently manage VU within the selected upper and lower voltage ranges.

5.2.2 Objective Function Constraints

The inequality constraints defined in Chapter 3 are implemented in this Chapter. Furthermore, to evaluate the performance of the proposed PEV charging and discharging coordination and its impacts on the "Pavetta 1" system, the following assumptions are considered:

- Total of 24 hours with time intervals of Δt = 15 minutes.

- S_{PEV}=24kWh denotes the total battery capacity per PEV with charging period of 3 hours.
- PEVs are randomly plugged into residential nodes between [8:00 AM – 11:00 AM], and [4:00 PM – 7:00 PM].
- The lower and upper limits for the battery state-of-charge (SoC) are 20% and 90%, respectively.
- The voltage limitation set to $\pm$ 10% in this Chapter.

5.3 Proposed Online PEV Coordination Strategies for Ancillary Voltage Support

5.3.1 Voltage Regulation by Reactive Power Capability of PEVs

The ability of directional power transfer of PEV inverter can be applied for voltage control. According to [135], transferring the reactive power is difficult over a long distance due to the high losses on the wires. Therefore, it is more effective than the supplier of reactive power to be close to the local area where needed. If the apparent power and real power from a PEV inverter are S_{PEV} and P_{PEV} respectively the capability of PEV inverter is calculated by:

$$|Q_{PEV}| \leq \sqrt{{S_{PEV}}^2 - {P_{PEV}}^2} \tag{5.1}$$

In this Chapter, the PEV inverter is managed for suppling reactive power during peak hours to diminish voltage deviation. PEV owners by using droop controller theory, which can be, decided the amount of the reactive power based on the droop characteristics of the voltage variation have the ability to automatically self-corresponding to voltage violation.

It is needed to highlight that this method can be succeeded by the availability of smarts meters and controllers. After plugged-in vehicles and start to charge based on conventional optimization at every 15 minutes, the central control communicates with smart meter at each house with PEV to regulate the needed reactive power to be supplied from PEV inverter.

5.3.2 System Modelling for Coordinated Charging/Discharging PEVs

This Chapter presents an online strategy for optimal coordination of PEVs charging and discharging that performs voltage regulation during morning and evening hours considering high penetration of distributed PVs. Each residential node with PEV and rooftop PV is connected at PCC through the network, as shown in Figure 5.1.

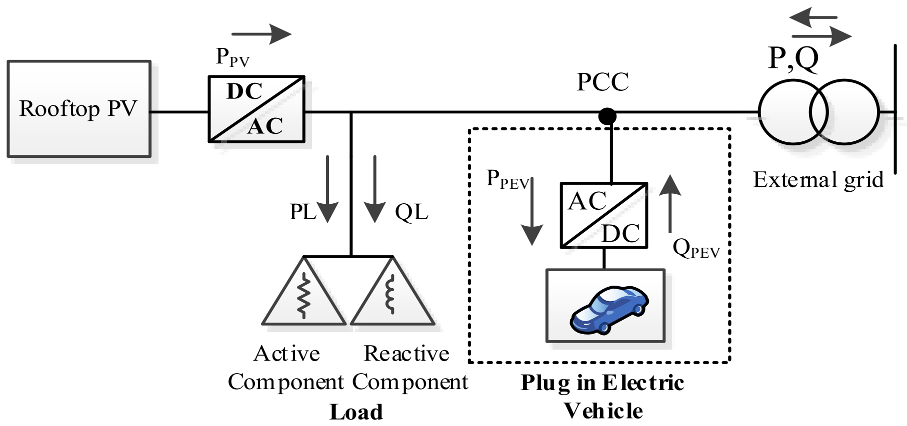


Figure 5.1. Connection of residential node with PV and PEV to the grid

Typically, the invert of PEVs is designed to operate both active and reactive power modes. However, according to AS/NZS 4777.2, the reactive power capability is not activated by default. The existing practice is to operate the inverter at unity power factor (PF), therefore cannot contribute for injecting or absorbing reactive power. Consequently, voltage regulation was not allowed [136] [137]. However, when the PEVs quantity with high penetration of PVs are increased, over-voltage and under-voltage conditions in radial distribution network can occur particularly at the end nodes as a consequence of the higher resistive specification. Therefore, to sort out this problem the regulation of PEV inverter is applied. In this regard, the possibility of using the reactive power capability of inverters for voltage regulation have been studied [77, 138]. In this Chapter, online PEV coordination is performed using the following two battery inverter controls:

- P-Control Strategy- Only active power charging.
- PQ-Control Strategy- Both active power charging and reactive power discharging.

The first control methods, based upon the conventional centralize online PEV charging (OL-C-TP) is completely explained in Chapter 4 to reduce the total system VUF. In the second control method, due to the voltage regulation and VUF issues at some of the buses, each of the PEV inverters is allowed to participate in local (decentralized) voltage regulation by injecting reactive power at selected nodes based on droop voltage control. For the OL-C-TP strategy, the power factor of PEV inverter is assumed to be unity. Consequently, no absorption or injection of reactive power has happened while it is actively controlled for the PQ-Control strategy, as explained in the next sub-section.

5.3.3 Optimal Online Charging/Discharging Coordination (PQ-Control Strategy) based on Droop Voltage Control

While the centralized P-Control strategy of section 4.4 considers node voltage regulation as the optimization constraint which is mentioned in the previous Chapter, single phase and relatively high PEV active power charging can cause voltage unbalance issues, especially at the end feeder locations. In this regards, a second centralized PEV coordination method that relies on the *P/Q* consumption/injection control is proposed and investigated. This approach also performs local (decentralized) voltage quality improvements by discharging PEV batteries at selected single-phase residential houses. This method can be more useful for the end users of the network. The new ideas are:

- Perform the conventional centralized coordinated PEV charging of Chapter 4 (P-Control). This is needed to highlight that, the optimization method of Chapter 4 is developed by considering high penetrations of rooftop PVs to analyse the impact of load unbalance and rooftop photovoltaic (PV) on the system.

- Allow decentralized/local PEV discharging (PQ-Control) for reactive power injection at selected nodes for further voltage regulation and VUF reduction. The PEV discharging at selected nodes is locally managed by automatically controlling voltage variation by the amount of injected reactive power based on the corresponding droop characteristics [77].

Figure 5.2 shows the characteristic of the droop voltage control for each consumer with PEV. Equation (5.1) can be used to calculate the amount of export/import (injected/consumed)) PEV inverter reactive power at each node based on its droop characteristics for ancillary voltage support to prevent under-voltage and over-voltage conditions, respectively.

$$\Delta V(t,k) = V(t,k) - V_{ref} \tag{5.2}$$

$$Q_{PEV}(t,k) = \Delta Q(t,k) = \frac{1}{\alpha}\Delta V(t,k) \tag{5.3}$$

where $\Delta V(t,k)$ different voltage, V_{ref} is the reference value of voltage, α is the slope of the droop controller (Figure 5.2) and the value of $V(t,k)$ is the voltage at node k at time t and updated at each time interval $\Delta t = 15$ minutes by the BF load flow algorithm of Chapter 3 (section 3.7). The sign of $\Delta V(t,k)$ will determine the reactive power will be injected or absorbed. It means the negative sign shows the situation when the house voltage $V(t,k) \geq 1.01\,pu$, so it is needed to absorb Q. on the other hand, the positive sign indicates $V(t,k) \leq 0.90\,pu$ need to inject (supplied) the reactive power. In this paper, $V_{ref} = 1.0$ pu while the maximum PEV injected reactive power (at the minimum voltage of $V_m = 0.8$ pu) is assumed to be $Q_m = 0.7$ kVar. Therefore, $\alpha = (0.8 - 1.0)/(0.7) = -0.29$.

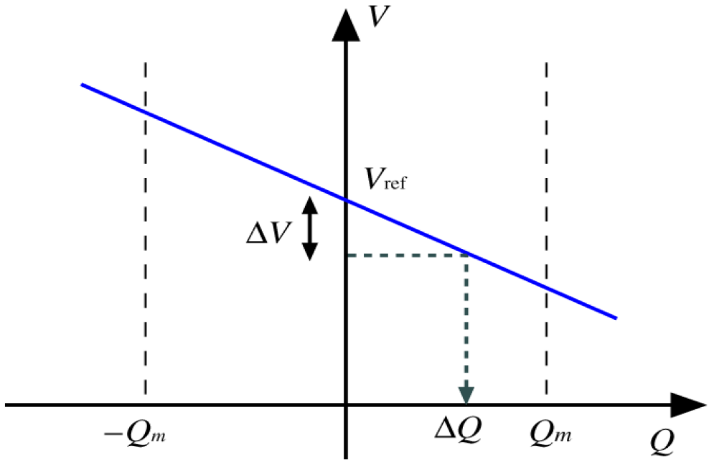


Figure 5.2. The droop voltage control characteristic for each consumer with PEV [138]

5.4 Flow Chart of Proposed PEV Charging / local Discharging Approach

The flowchart of proposed online PEV coordination based on the above strategies is shown in Figure 5. 3 and consists of the following steps:

- Step 1: In this step, optimizer requires the input information, including daily load curve, PV status, and PEV data, same as (4.4.1).
- Step 2: The centralized GA-based PEV coordination without any Q injection is performed (P-Control), and the voltage of all nodes are recorded.
- Step 3: If the voltage deviation of a house with PEV is not within the designated constraint of section 4.3, the voltage difference is calculated by 5.2 then the droop control approach of (5.3) is used to inject or absorb reactive power to regulate the node voltage.
- Step 4: After inject/absorb reactive power for all houses with PEV, the house voltages again are updated by running load flow by the central controller and move to the next time step.

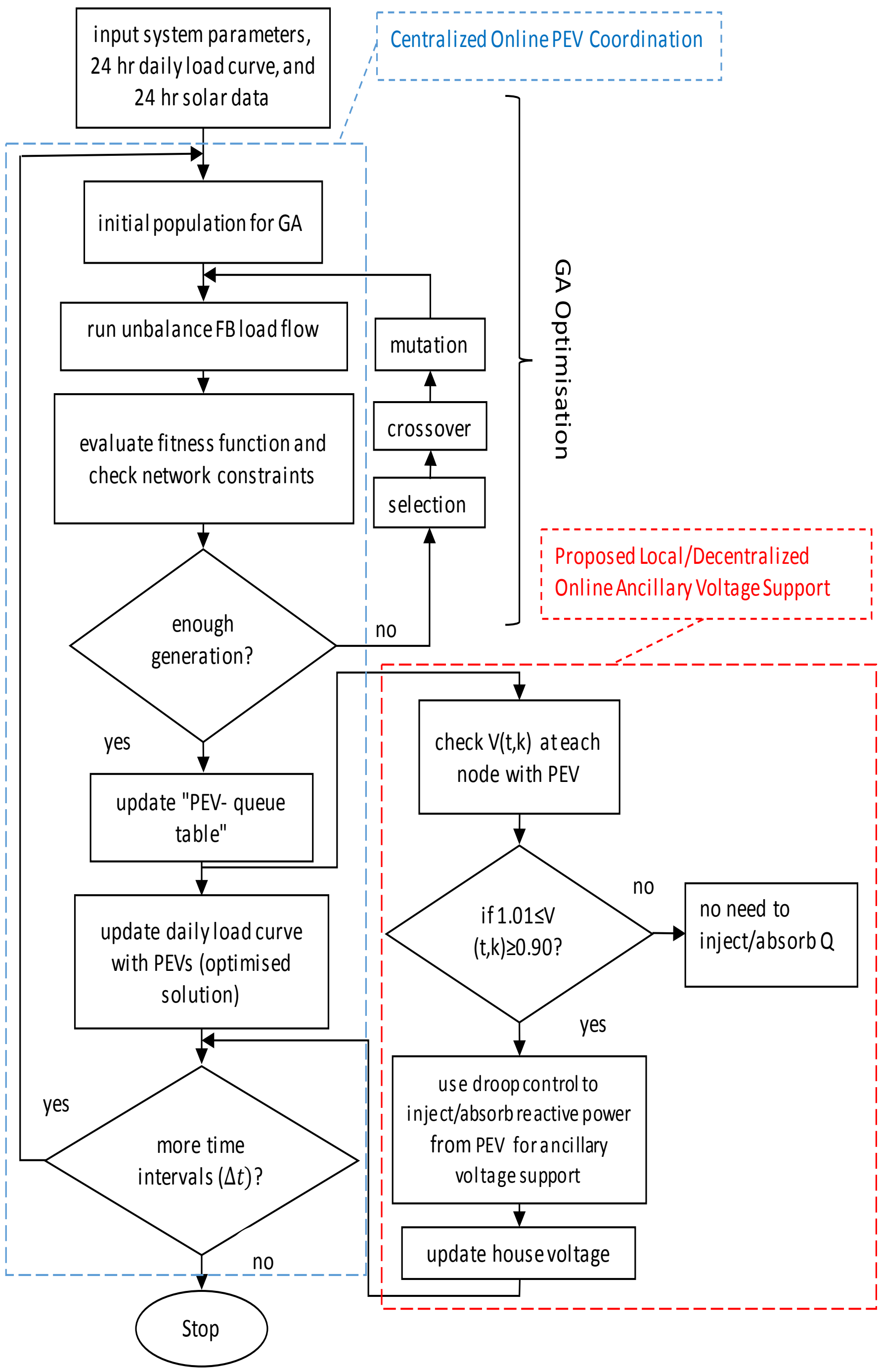


Figure 5.3. Proposed optimization approach for central coordination of PEV charging with local (decentralized) reactive power injection for ancillary voltage support.

5.5 Simulation Results and Analysis

5.5.1 LV Distribution Test System with Rooftop PVs

The simulations of this section are performed using the real network LV distribution model presented in Chapter 3. This system has a number of installed rooftop solar panels, so it has enabled the study of the impact of PV generation on unbalancing the system. As mentioned, unbalanced loads are one of the main reason for unbalancing voltage on the feeder. So, to increase the level of voltage unbalance, in this Chapter the penetration of rooftop PVs and the domestic load demands are reduced by 27% in one of the phases of the network (phase-c) as demonstrated in Figure 5.4 (a). The PV generation is assumed to have a normal distribution in a typical winter day and starts from 8:30 AM at reach peak of -11 kW,-11 kW and -8 kW at noon for each phase-a, b, and c, respectively and then gradually decrease at 3:30 PM.

Therefore, in this Chapter, The load level in compare to the previous Chapter is changed. In addition, it is supposed that customers will charge their PEVs in the morning hours (between 8:00 AM-11:00 AM) as well. The simulations are performed for the four cases studies (cases A, B, C, and D) of Table 5.1. Case A presents the base scenario without any PEVs (Figure 5.4). Case B reveals the uncoordinated PEVs charging during the morning (8:00 AM-11:00 AM) and evening (4:00 PM-7:00 PM) with a time step of $\Delta t = 15$ minutes over the 24h period (Figures 5.5 (a-b) and 5.6 (a-b)). Case C presents the optimized results based on online coordination of PEV charging by controlling the charge of PEVs in different phases (Figures 5.7(a-b) and 5.8 (a-b)). The decentralized voltage upgrading by PEVs var discharging is studied in case D (Figures 5.9 (a-b), and Figures 5.10 (a-c)).

Two different unbalance scenarios for each case (A, B, C, and D) to demonstrate the effectiveness of proposed PEVs control charging/discharging are considered as follows:

- Scenario 1: All PEVs are connected to high load phase (phase-a) during 8:00AM-11:00AM and 4:00AM-7:00PM.

- Scenario 2: All single-phase (phase-a,b,and c) houses have PEVs during 8:00AM-11:00AM and 4:00AM-7:00PM.

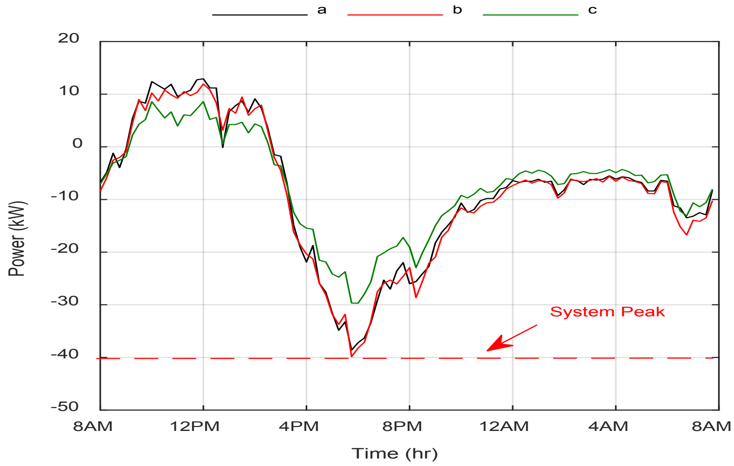
Table 5.1 Simulated PEV charging cases studies

Case	Coordination Strategy	Simulation Results
Case A	Base case without PEVs	Figures 5.4 (a-b)
Case B	Uncoordinated PEVs charging (8:00-11:00AM) and (4:00-7:00 PM)	Figures 5.5 (a-c); 5.6 (a-b)
Case C	Centralized online PEV charge coordination (P-Control Stratesgy)	Figures 5.7 (a-c); 5.8 (a-b)
Case D	Centralized online PEV charge coordination with decentralized/local ancillary voltage support (PQ-Control stratesgy of 5.3.3)	Figures 5.9 (a-c); 5.10 (a-b)

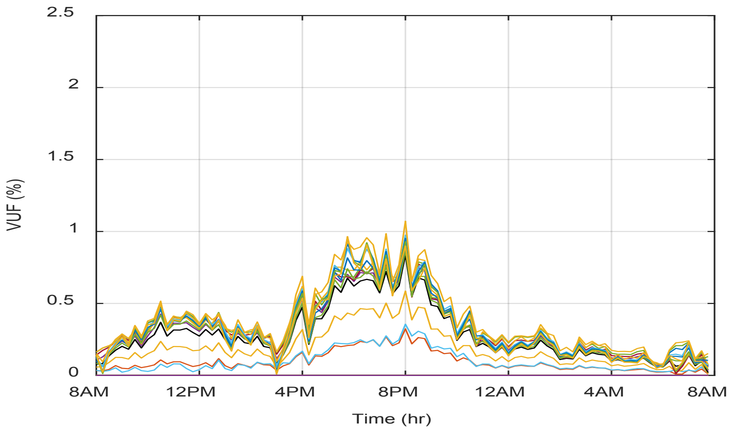
5.5.2 Case A: Main System with Demand Reduction on Phase-c

Figures 5.4 (a), and (b) show the power demand for the unbalanced (74 nodes) LV residential feeder with PVs without any PEV loads with 27% demand reduction on phase-c. It is apparent the red, and black phases (phase-b and phase-a) are the most heavily loaded phase, while the green phase (phase-c) is the least loaded phase. Furthermore, the lowest amount of solar PV system generation occurs on the green phase. Note that, for visibility reasons, these colour phases are chosen in this thesis.

The peak demand and the maximum VUF of the network are between 5:00 PM and 7:00 PM, at -40 kW and 0.8%, respectively. Whereas, the maximum VUF during peak PV generation hours is 0.4936% due to the reverse power flow. The voltages of each phase are revealed in Table 5.2.



(a)



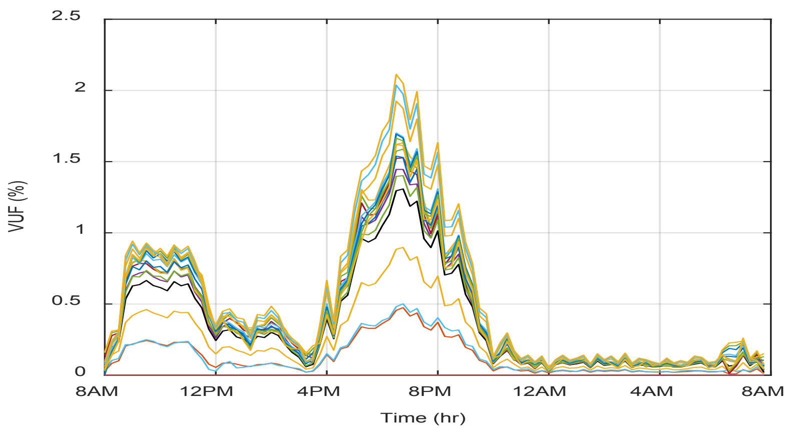
(b)

Figure 5.4. Case A: (a) The three-phase distribution transformer (DT) loading with 27% demand reduction on phase-c (b) VUF.

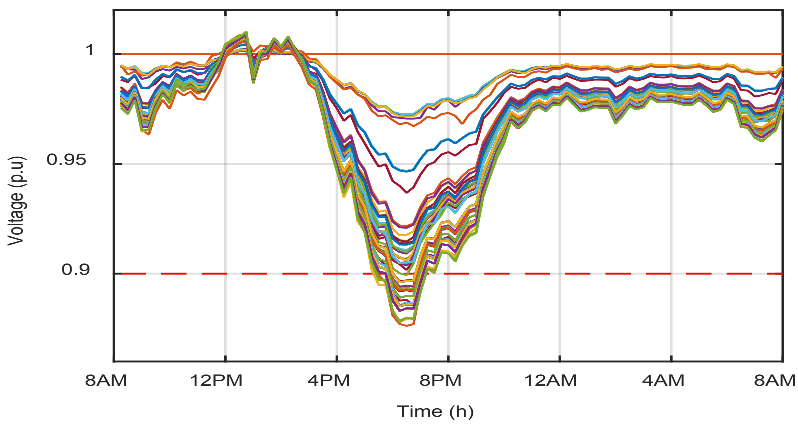
5.5.3 Case B: Uncoordinated G2V during Morning and Evening

In this case, as mentioned in Chapter 3, it is supposed that in uncoordinated charging customers will quickly charge their PEVs when they arrive home in the morning and afternoon hours. In this case, PEVs are allowed to be charged as soon as possible during morning and evening without considering any system constraints. Consequently, vehicle charging mainly happens at the peak demand periods that can result in transformer overloading, high VUFs, and poor voltage profiles.

Figures 5.5 (a) and 5.6 (a) show the phase unbalances for both scenarios (1 and 2) where each line displays the VUF at one of the poles in the system. According to 5.5 (a) regarding the scenario 1 the entire network is fairly unbalanced at morning and peak hours, and it can even reach to higher unbalances of over 0.8% and 2% respectively. The individual voltages at the PCCs of all houses on phase-a are shown in Figure 5.5 (b) and Figure 5.6 (b). In both scenarios, it can be seen that during the peak time, the voltages of some nodes fall below the designated minimum threshold of 0.87 p.u. Due to vehicle demand. However, during the morning time, it caused the reduction of voltage on the phases with PEVs and might solve the upper voltage problems. Figures 5.5 (c), and 5.6 (c) present the power demands for different phases for both scenarios. As expected during high peak hours, the power demands are an under-designed limitation.



(a)



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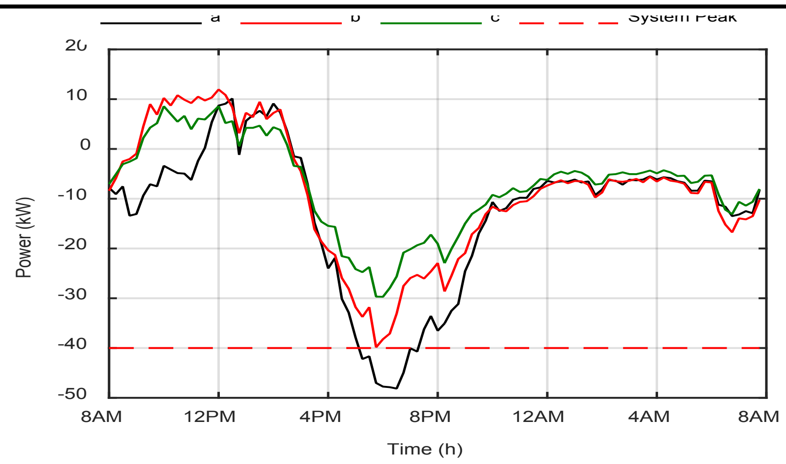
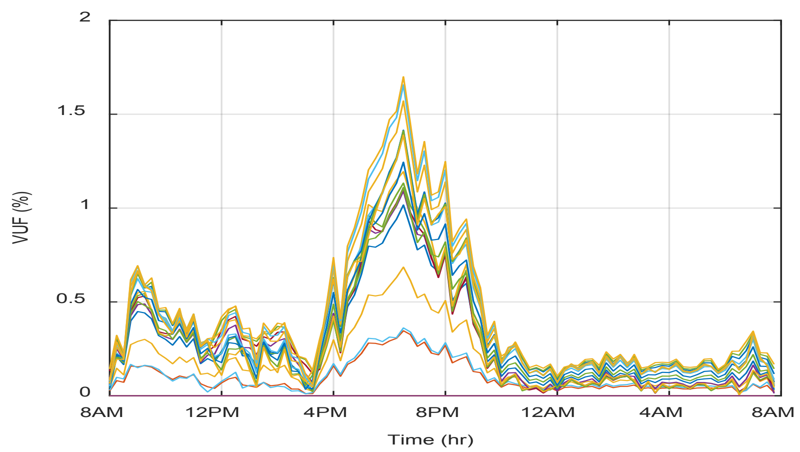
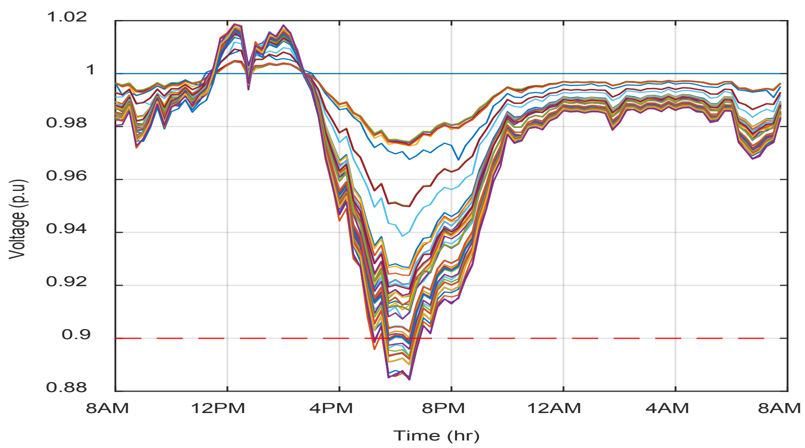


(c)

Figure 5.5. Case B1: Impact of random uncoordinated PEV charging within 8:00AM-11:00AM and 4:00PM-7:00PM on (a) VUF (b) voltage phase-a profile, and (c) system demand.



(a)



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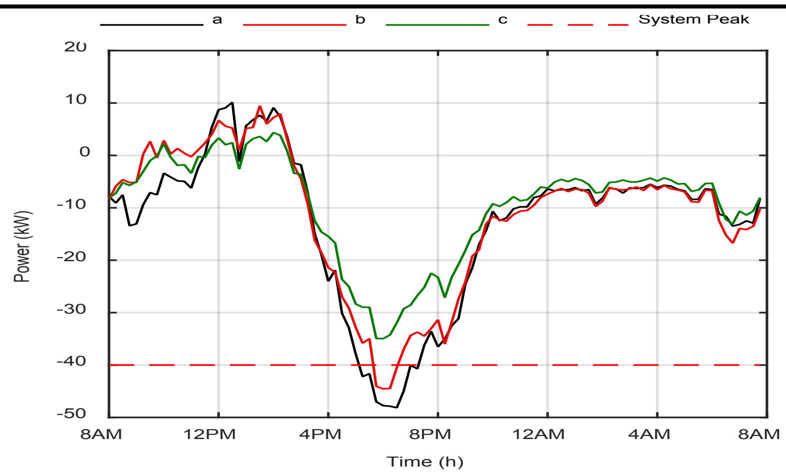


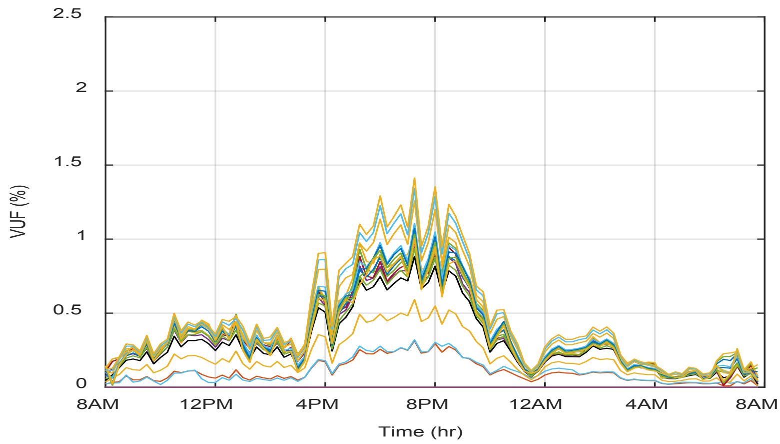
(c)

Figure 5.6.Case B2: Impact of random uncoordinated PEV charging within 8:00AM-11:00AM and 4:00PM-7:00PM on (a) VUF (b) voltage phase-a profile, and (c) system demand.

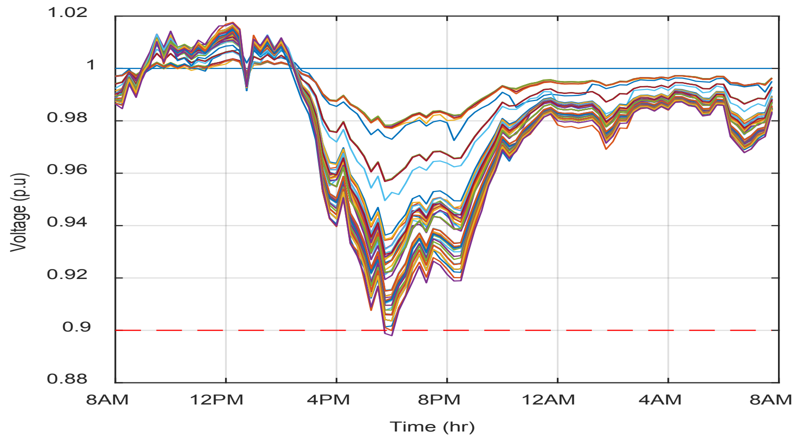
5.5.4 Case C: P-Control

In this scenario, the formulation and GA of Chapter 4 along with the coordination strategy of section 5.2 are used to solve the optimization problem of (4.4) by considering the overloading and voltage quality constraints of (4.7-4.12). Simulation results indicate that the VUF at all nodes is improved and limited to 0.5% and 1.37% during the morning and evening peak hours as shown in Figure 5.7 (a) for the first scenario and reach to 0.4% and 1% in the second scenario. It is also can be considered that some PEVs still wait in the queue till the aggregator coordinates their charging during the off-peak hour to minimize VUF on the system.

The voltage profile of phase-a for each scenario are shown in Figures 5.7 (b), and 5.8 (b). Note that during the peak load periods; although the significant improvement can be seen for VUF during morning and evening, however, the voltage magnitudes of some nodes have reached the minimum threshold of 0.90 p.u on the peak load hours. During the high peak, the power demands are still high as can be observed in Figures 5.7 (c) and 5.8 (c).



(a)



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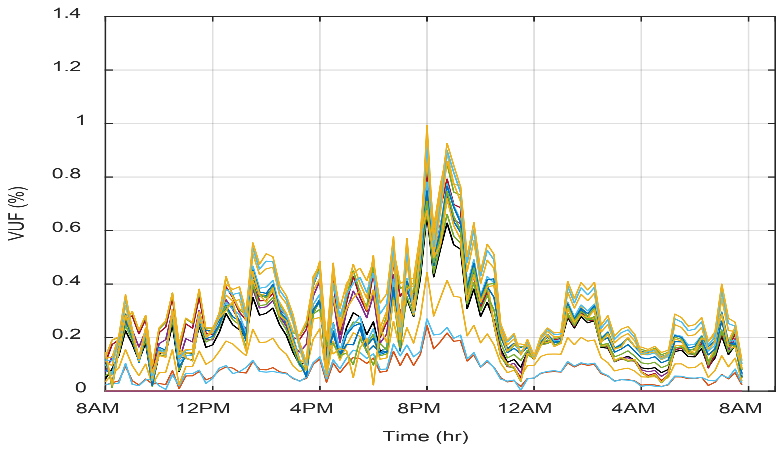
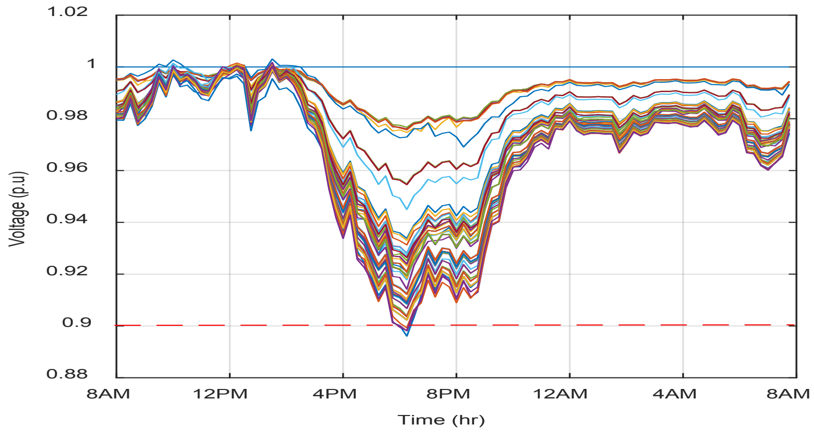


(c)

Figure 5.7. Case C1: Impact of coordinated PEVs charging (OL-C-TP) on (a) VUF (b) voltage phase-a profile, and (c) system demand.



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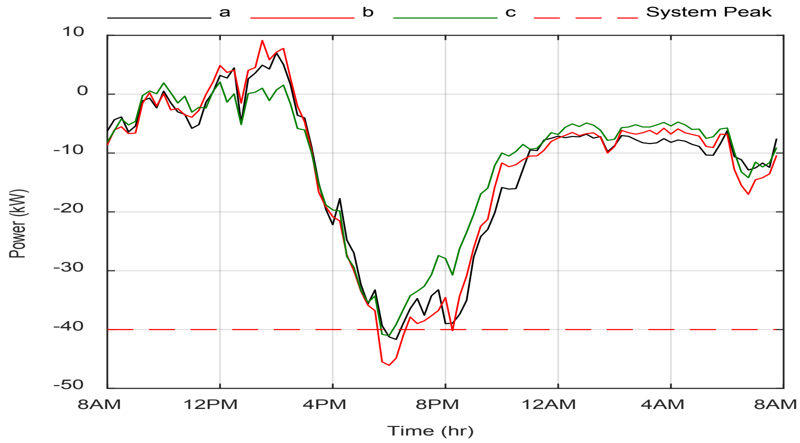


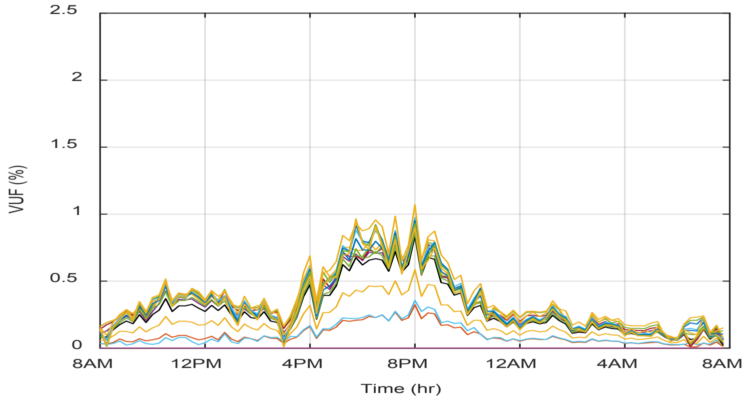
(c)

Figure 5.8. Case C2: Impact of coordinated PEVs charging (OL-C-TP) on (a) VUF (b) voltage phase-a profile, and (c) system demand.

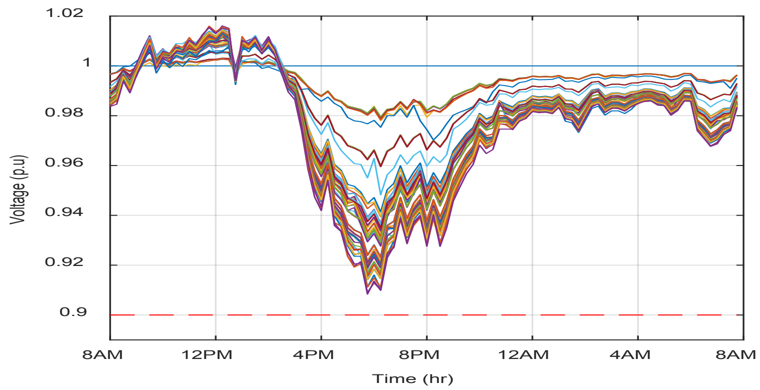
5.5.5 Case D: PQ-Control

This case study is similar to Cases C; however, some of the PEV inverters are allowed to inject reactive power based on the PQ-Control strategy of section 5.3 for further improvements in voltage regulation and more reduction of VUFs.

Figures 5.9 (a), (b), and (c) show the VUF, phase-a voltage and power demand, respectively. Simulation results are summarized in Table 5.2. From this table, the maximum VUF is 1% at the peak hours and only 0.32% in the morning in the first scenario. In comparison with case C1, the maximum VUF and the worst voltage are significantly improved. The VUF values for all poles (three-phase nodes) are depicted in Figure 5.9 (a) besides, the VUF improvement and desirable voltage profile on phase-a and b can be seen in the second scenario in Figure 5.10 (a) – 5.10 (c)- and Table 5.2.



(a)



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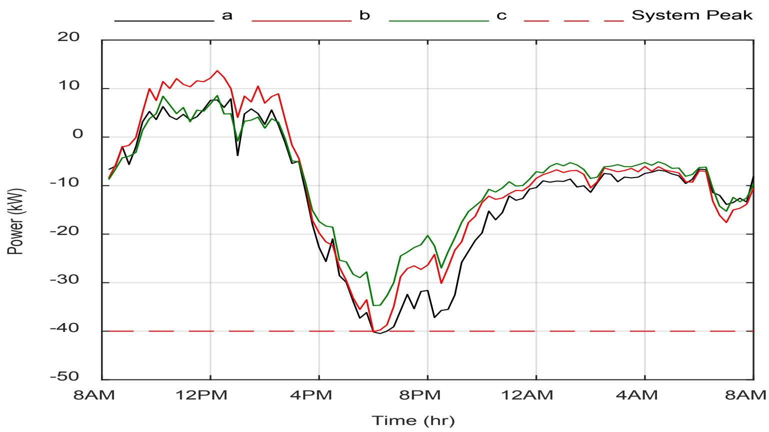
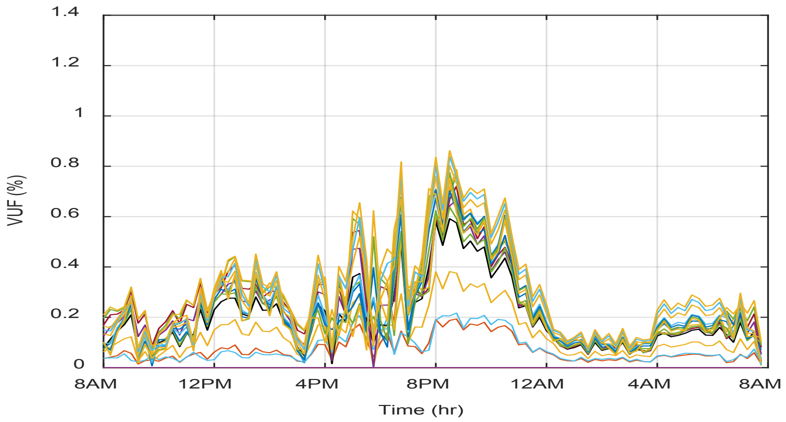
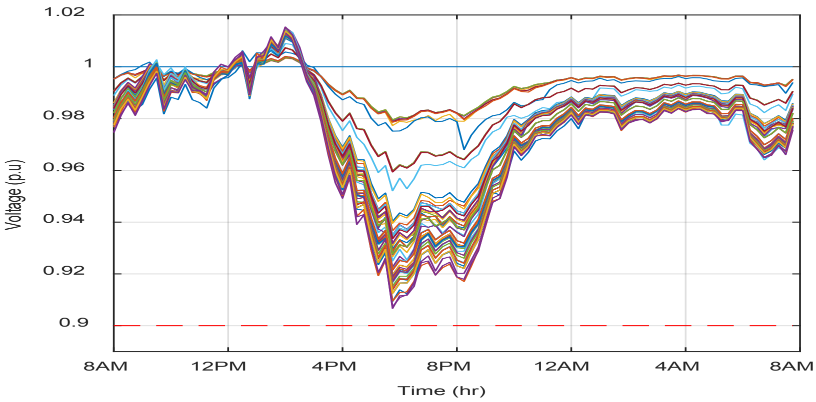


(c)

Figure 5.9. Case D1: Impact of coordinated PEVs charging/discharging (OL-CD-TPQ) on (a) VUF (b) voltage phase-a profile, and (c) voltage phase-b profile.



(a)



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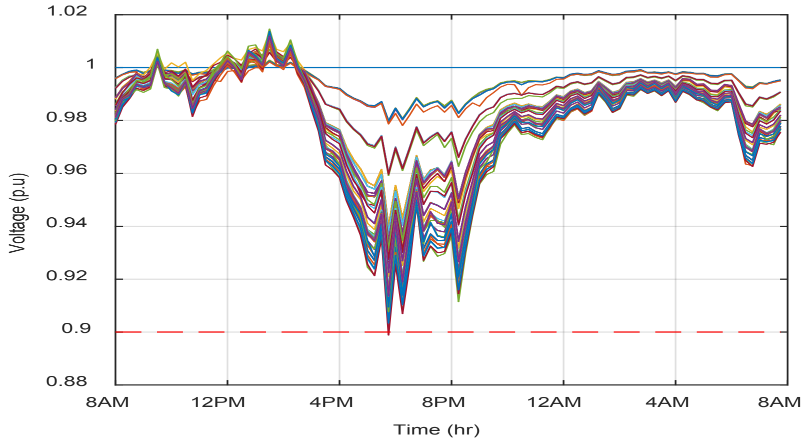


(c)

Figure 5.10. Case D2: Impact of coordinated PEVs charging/discharging (OL-CD-TPQ) on (a) VUF (b) voltage phase-a profile, and (c) voltage phase-b profile.

Table 5.2 Summary of results for test OL-CD-TPQ based on droop controller for scenarios 1 and 2

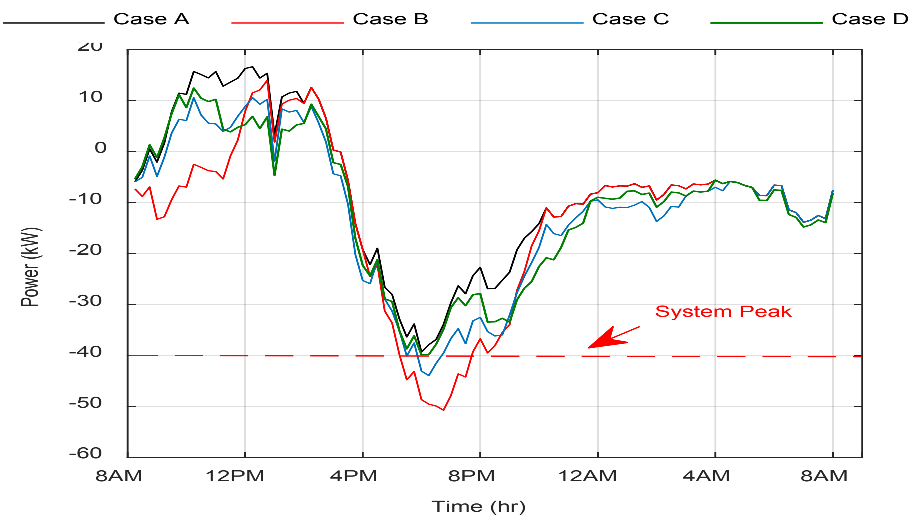
	Operation Condition							Comparison of Simulation Results			
	Time of the Day	Number of PEVs			PV (%)			Worst VUF (p.u)	Worst Voltage (p.u)		
		a	b	c	a	b	c		a	b	c
Main System	Case A: Main System without any PEVs; Figs 5.4 (a-b)										
	Morning 8AM-11AM	0	0	0	45.2	43.4	27	0.53	1.017	1.006	1.005
	Evening 4PM-7PM	0	0	0				0.8	0.908	0.91	0.94
Scenario 1	Case B1: Uncoordinated PEVs ; Figs 5.5 (a-c)										
	Morning 8AM-11AM	11	0	0	45.2	43.4	27	0.94	0.99	1.02	1
	Evening 4PM-7PM	11	0	0				2.14	0.868	0.92	0.94
	Case C1: GA-Online coordinated of PEVs charging; Figs 5.7 (a-c)										
	Morning 8AM-11AM	11	0	0	45.2	43.4	27	0.5	1.001	1.018	0.99
	Evening 4PM-7PM	11	0	0				1.41	0.8930	0.91	0.94
	Case D1: GA-Online coordinated of PEVs charging/discharging; Figs 5.9 (a-c)										
	Morning 8AM-11AM	11	0	0	45.2	43.4	27	0.49	1.001	1.013	0.99
	Evening 4PM-7PM	11	0	0				1.1	0.910	0.915	0.94
Scenario 2	Case B2: Uncoordinated PEVs ; Figs 5.6 (a-c)										
	Morning 8AM-11AM	11	11	12	45.2	43.4	27	0.7	0.97	1.008	1
	Evening 4PM-7PM	11	11	12				1.69	0.886	0.890	0.93
	Case C2: GA-Online coordinated of PEVs charging; Figs 5.8 (a-c)										
	Morning 8AM-11AM	11	11	12	45.2	43.4	27	0.49	1.001	1.007	0.99
	Evening 4PM-7PM	11	11	12				1.04	0.904	0.893	0.93
	Case D2: GA-Online coordinated of PEVs charging/discharging; Figs 5.10 (a-c)										
	Morning 8AM-11AM	11	11	12	45.2	43.4	27	0.32	0.98	0.98	0.987
	Evening 4PM-7PM	11	11	12				0.81	0.91	0.90	0.92

5.5.6 Analysis and Comparison of Results

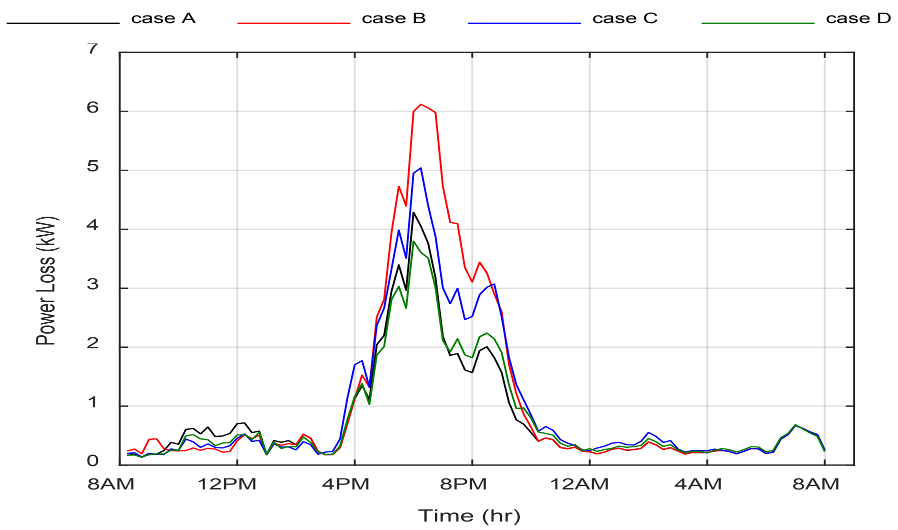
In this sub-section, to show the effects of the proposed method OL-CD-TPQ on the system performance for both scenarios (1 and 2), all cases (A, B, C, and D) are analysed.

- **Scenario 1:** The total system demand on phase-a, power losses of phase-a, and the average VUFs for all cases in scenario 1 over 24 hours are shown, and the results are compared in Figures 5.11 (a-c).

  Figure 5.11 (a) shows the peak (negative) power obtained in the random case B1 (-50 kW) is more than C1 and D1 cases (-42.2 kW, -40 kW respectively). It means approximately 20% improvement in maximum power consumption for case D1 and around 15% for case C1. The demand is improved in the P-control schedule due to the way the consumers charged their PEVs. According to these figures, offering voltage regulation by consumers in case D can lead to better results of the whole system performance. In addition, Compared with case B; the power losses are reduced by 31% and 34% in cases C and D, respectively, as shown in Figure 5.11 (b). Figure 5.11 (c) displays the average total VUF during 24 hours. From this figure, it can be found that the level of average VUF achieved in case C and case D modes are matched during high peak hours.



(a)



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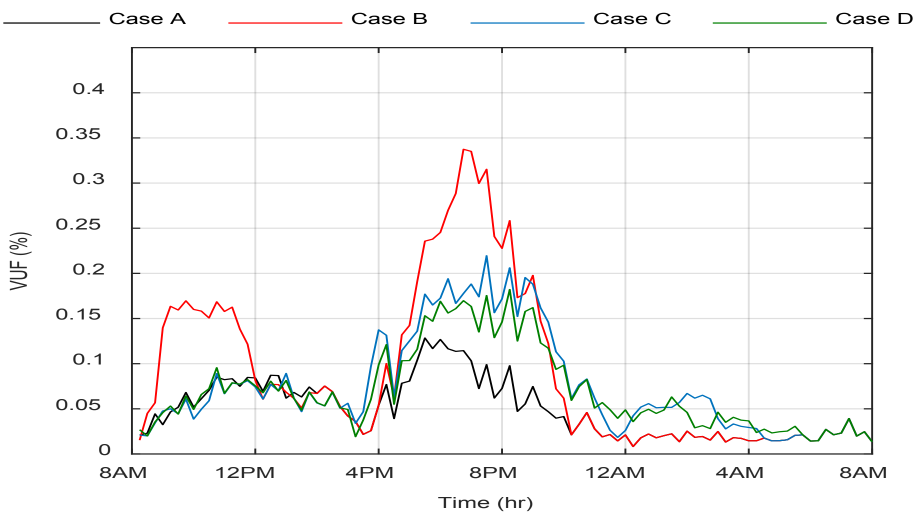
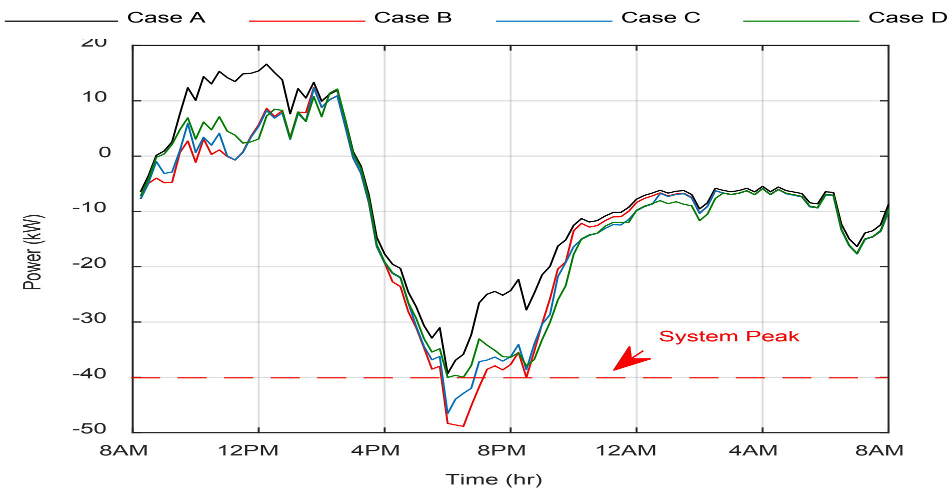


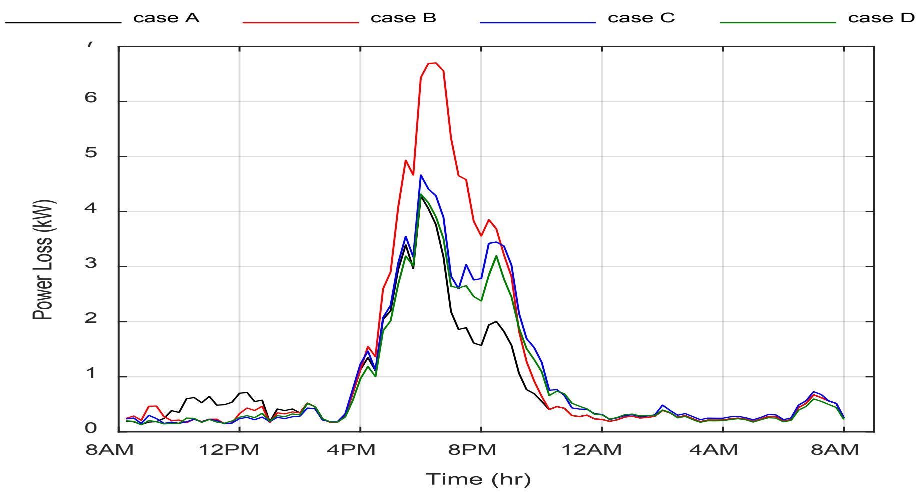
(c)

Figure 5.11. Comparison of different cases for scenario 1(high load phase) on (a) system demand on phase-a (b) total system power losses on phase-a, and (c) average VUF over 24 hours.

- **Scenario 2:** In this scenario, all single-phase houses (phase-a, b, and c) have PEVs. Figures 5.12 (a), (b), and (c) presents the variation of total power demand for all cases, power losses and average total VUF over 24 hours. As seen in Figure 5.12 (a), case D has a peak value of -40 kW during peak hours, and it is about 20% and 4.7% improvement on the maximum power consumption in compare to case B (uncoordinated) and case C (only active power), respectively. The variations of total energy losses for all cases are shown in Figure 5.12 (b). In case D, the maximum power loss amount is 3.8kW during the high demand hours due to the operation of injecting reactive power from PEVs. This has decreased by 38% in compare to the case B (6.1kW) and 4.8% to the case A (4.1kW). The reason for the loss reduction in case D is reactive power injections that accordingly cause reducing reactive load consumption. The average VUFs of all cases when PEVs connected to the high load phase (first scenario) over 24 hours are shown and compared in Figure 5.12 (c). The maximum values for case B, C and D are 0.34%, 0.21% and 0.17% respectively.



(a)



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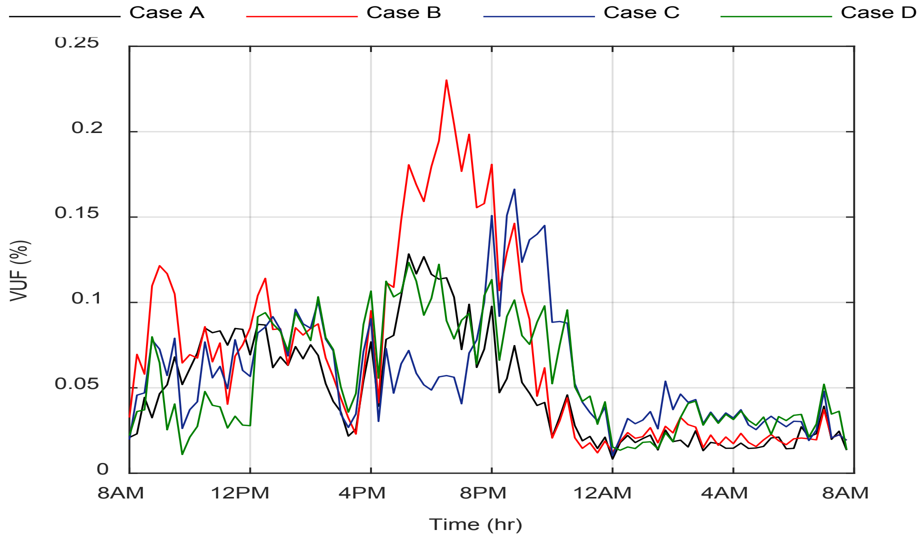


(c)

Figure 5.12. Comparison of different cases for scenario 2 (all single-phase) on (a) system demand on phase-a (b) total system power losses on phase-a and (c) average VUF over 24 hours.

To show the effectiveness of the proposed mothed the convergence characteristic plot of scenario 1; case D1 for 15 minutes during 6:00-6:15 PM is presented in Figure 5.13. It demonstrates the convergence of the best value and means the value of fitness function with a maximum of 100 generations. It can be found that from convergence plots for the interval, the fitness value did not improve any more after the average generation of 10. In addition, to show the robust convergence of the proposed optimization, Figure 5.14 depicts the density function for the same time point above (6-6:15 PM) which demonstrate converge the same solution in almost the results. In this analysis, the computing time for solving the problem for 24 hours is approximately 8 minutes (490 seconds) on a computer with Intel Core i7 processor @2.60GHz. The input system parameters in this test system are measured every 15 minutes by smart meter through the network. So, the consumption time of optimization for the proposed method is less than the record data in the interval and the proposed method can well support online applications.

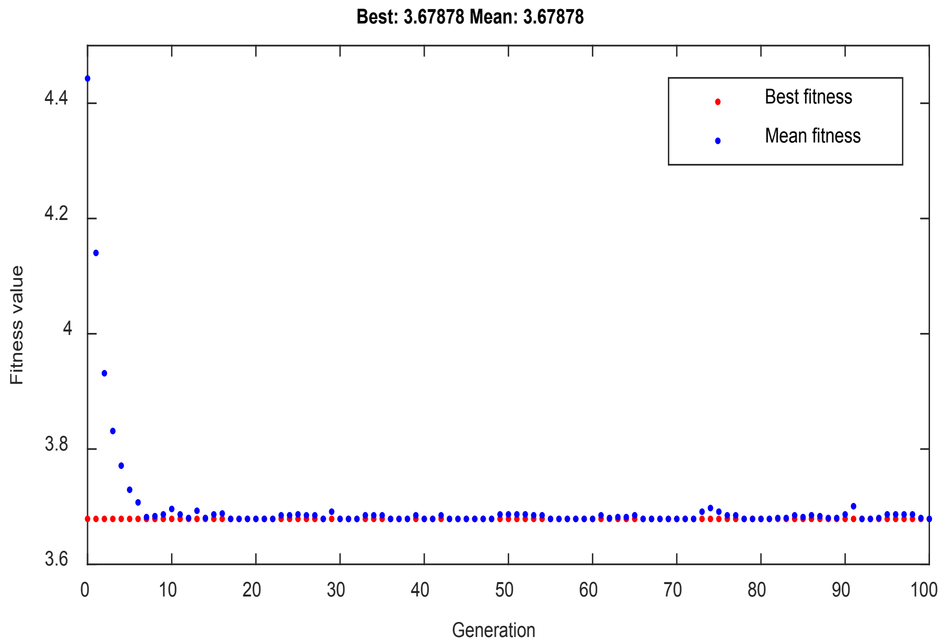


Figure 5.13. Case D1: Convergence characteristic of the proposed method at 6:00-6:15 PM

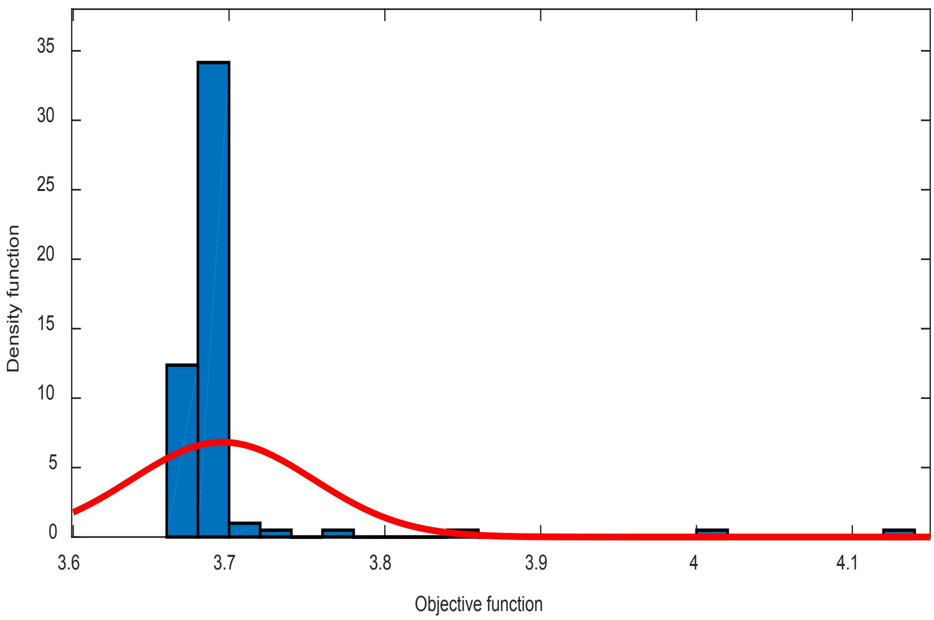


Figure 5.14. Case D1: The density function of the objective function at 6:00-6:15 PM

5.6 Summary

This chapter presents an online PEV charge/discharge coordination strategy using genetic algorithm optimization to minimize the VUF considering individual node voltage regulations. The available inverter reactive power is used to perform voltage regulation at the nodes with poor voltage profiles. In this regard two different coordination schemes (centralized and local/decentralized) are considered in LV network, two different unbalance scenarios for each case (A, B, C, and D) are regarded as detailed simulation results are presented The main conclusions are:

- An uncontrolled PEV charging strategy will have negative impacts on VUF and voltage profile of the distribution network as shown in 5.5 (a-c) and 5.6 (a-c). For both scenarios, extreme voltage variations are observed for phase-a of the simulated system in the evening especially during the peak hours while the VUF of some poles (three-phase nodes) is higher than the designated upper limit of 1.5.
- The online centralized genetic PEV coordination (P-Control) strategy in conjunction with overloading and voltage quality constraints minimizes the VUF and limits the voltage fluctuations as shown in Figures 5.7 (a-c) and 5.8 (a-c). This is done by quickly charging as many vehicles as possible while keeping the remaining vehicles in a PEV-Queue table and serving them during the off-peak load hours. The shifted PEVs are successfully charged while the VUF peaks are limited to the designated value of 1.5. In this Chapter is strategy is applied during morning and evening.
- The online centralized genetic PEV coordination (PQ-Control) strategy in conjunction with the proposed centralized/local droop-based voltage regulation also minimizes the VUF and voltage fluctuations as shown in Figures 5.9 (a-c) and 5.10 (a-c). This is done by decentralized discharging and Q-injection of selected PEV inverters that are connected to nodes with poor voltage profiles. The proposed decentralized PQ-Control strategy results in better voltage regulations and further

VUF reductions. The voltage deviations are kept above 0.91pu and below 1.01pu during the evening and morning hours while the maximum VUFs of all poles are below 1.0%.

It should be noted that to apply the proposed charging control, policies, and price-based incentives like demand-side response should be presented to form a supporting market environment. In addition, the current restriction to mitigate voltage unbalance is only from the perspective of utilities; future work can be carried out to fully consider the changing expectations of customers and achieve a win-win solution between the utility and customers. In this regard, the next chapter will apply central charge/discharge by considering reactive market to motivation customer for ancillary support.

Chapter 6

Coordinated Charging/Discharging Strategy of PEVs with Ancillary Reactive Service in Energy Market

6.1 Introduction

As addressing, the minimizing of VUF and voltage violation problems is the critical focus in this research work in this Chapter, like the previous chapter the capability of PEV inverter to regulate the voltage profile and improve the voltage unbalance factor is investigated for ancillary voltage support. However, based on the integration of PEVs as active and reactive power providers in the market, this Chapter presents an online GA-based centralized PEV coordination charging/discharging strategy for an unbalanced three-phase four-wire LV distribution network. The main contributions of the paper are summarized below:

- A simple, practical PEV-controlled strategy for ancillary voltage support. This online approach aims to minimize the cost and provide ancillary voltage support by making optimal charging/discharging decisions.
- Customer satisfaction and overall network VUF reduction. Different from the conventional centralized online PEV battery charging technology, the proposed approach relies on centralized PEV charging and discharging, by providing PEV inverter reactive power injections at selected nodes based on variable

pricing/contract scenarios for selling reactive power to improve node voltage profiles, reduce the overall network VUF and the total system cost.

- Solution Justification. Detailed MATLAB simulations were performed for a real 74 node unbalanced Western Australian distribution network to show the impacts of uncoordinated and the proposed GA coordinated PEV charging/discharging strategy on the individual nodes and the overall network over 24 hours. The validity of the proposed approach is proved and presented in the Results section of the Chapter.

This Chapter is organized as follows: Section 6.2 explains system modelling and proposed strategies, Section 6.3 focuses on problem formulation and explains the multi objective functions when inverted interface PEV operates in active/reactive power mode (OL-C-TPQ), respectively. Section 6.4 explains all the steps of the proposed method. The test system, simulation results, discussion, and conclusions are presented in Sections 6.5 and 6.6, respectively.

(*) Note: The contents of this Chapter have been mainly extracted from [87] as a journal paper (Appendix B2).

6.2 Proposed Strategy for Auxiliary Voltage Support in Energy Market

6.2.1 Overview of PEV Capability Analysis as Reactive Power Providers in Market

Generally, when discussing electricity price and energy market, the reactive power market is not being considered. However, PEV inverters with the ability of bidirectional power transfer can produce active and reactive power. So, there is an opportunity to participate in reactive power in the energy market [102]. Many studies like [139] and [140] have been investigated for coordinating PEVs to charge during off-peak hours to prevent overloading distribution transformer and reduce electricity bill. However, there has not been much focus on PEV reactive power market for reactive compensation. Reactive power plays an effective role to ensure secure and reliable power system operation. It helps to improve the voltage regulation and the transfer power without battery degradation. According to [135], transferring the reactive power is demanding over a long distance due to the high losses on the wires. As a consequent, it is more effective than the supplier of reactive power to be close to the local area where needed. This availability issue limits the number of suppliers in the market. An instructive solution to ensure the availability of sufficient reactive power generators in different areas and periods is considering the pricing for reactive power. This can encourage the customers to enter the market and contribute to the voltage control in the network. Also, it can increase the reliability and efficiency of the grid [135] and has more profits for consumers with PEV. There are limited researches like [99] focusing on the day ahead reactive pricing power based on contacts between grid and commercial reactive power compensators. This reference shows the small reactive power providers like PEVs can follow the commercial contracts which can be obtained using historical data, to provide ancillary services.

6.2.2 Optimal Centralized OL-CD-TPQ Coordination based on Reactive Service in Energy Market

As discussed in Chapter 5, the common centralized P control (OL-C-TP) by considering constraints in the network can improve the system by naturally shifting the charging time of PEVs to lower prices. However, due to the distributed single-phase and relatively high PEV active power consumptions, the voltage fluctuation and unbalance problems, especially at the end-feeder locations occur. In this regard, a second centralized PEV coordination method that relies on the *P/Q* consumption/injection control is proposed and investigated. This approach also performs centrally voltage quality improvement by reactive discharging of PEV batteries at selected single-phase residential houses based on day-ahead reactive power price signal for offering voltage regulation. This method is more effective, especially for the end users of the network:

- Performing centralized and coordinated PEV charging/discharging (OL-CD-TPQ) for active/reactive power consumption/injection at selected nodes for further voltage regulation and VUF reduction based on energy prices for both active and reactive power.
- Selling reactive power using the PEV discharging at the selected centrally managed nodes by motivating consumers to enter the market and cooperate with the utility.

In this scenario, the active power and reactive power outputs for PEV inverter can be calculated by (6.1) and (6.2). The equation (6.3) states the reactive power balance at node k at the PCC, and the active power balance can be calculated by (5.2) as explained in the previous chapter $P(t,k)$, the $Q(t,k)$ will be positive when power is being exported or negative for being imported.

$$P_{PEV}(t,k) = S_{PEV}(t,k).cos\theta \tag{6.1}$$

$$Q_{PEV}(t,k) = S_{PEV}(t,k).sin\theta \tag{6.2}$$

$$Q(t,k) = Q_{PEV}(t,k) - Q_L(t,k) \tag{6.3}$$

where $S_{PEV}(t,k), \theta\ and\ Q_L(t,k)$ are the apparent power for PEV, power factor angel and load reactive power requirements respectively, at each node k at time *t*.

6.3 Problem Formulation

6.3.1 Multi-Objective Function for OL-CD-TPQ with Cost Minimization and Ancillary Support

To manage multiple PEVs charging and discharging activities in the unbalanced distribution network, in this part, the objective function has been defined based on day-ahead price signals for offering voltage regulation services. To achieve the best system performance, the objective function of (4.4) for centralized online PEV coordination in the unbalanced system is updated to participate in the energy market effectively and consists of minimizing of daily operating cost due to power losses ($F_{cost-Loss}$), energy generation to charge PEVs ($F_{cost-gen}$) and voltage unbalance ($F_{cost-VUF}$) at pole buses and maximizing of reactive power consumption($F_{cost-Q,V2G}$). Accordingly, the cost function is defined as:

$$min\, F_{Cost-G2V/V2G} = \left\{ F_{cost-Loss}(t) + F_{cost-gen}(t) + F_{cost-VUF}(t) - F_{cost-Q,V2G}(t) \right\};\ \text{for } t = 0, \Delta t, 2\Delta t \ldots 24 \text{ h} \tag{6.4}$$

$$F_{cost-gen}(t) = \sum_{a,b,c} \sum_{k=1}^{N_{node}} \left\{ \begin{matrix} K_P(t)P(t,k)\ if\ P(t) \geq 0 \\ K_S(t)P(t,k)\ if\ P(t) < 0 \end{matrix} \right\} \tag{6.5}$$

$$\begin{aligned} F_{cost-Q,V2G}(t) &= \sum_{a,b,c} \sum_{k=1}^{N_{node}} K_Q(t) Q_i(t,k) \\ &= \sum_{a,b,c} \sum_{k=1}^{N_{node}} K_Q(t)[Q_{PEV}(t,k) - Q_L(t,k)] \end{aligned} \tag{6.6}$$

Where $F_{cost-Loss}$ and $F_{cost-VUF}$ are defined in Chapter 4 (Equation (4.4)), $K_P(t) = 40\text{c/kWh}$ and $K_S(t)$ are the costs per kWh of imported energy generation based on renewable energy buyback rate and variable tariffs (Peak 7:00AM–11:00AM and 5:00PM-9:00PM, 53.37c/kWh; Shoulder 11:00AM-5:00PM, 26.64c/kWh and Off-peak all other times 13.86c/kWh)[132, 133]), and exported from solar from [81] respectively. $K_V(t)$, and $V(t,k)$ are the costs corresponding to deviations of voltage and the magnitudes of instantaneous at the voltage of node k at t to effectively minimize the voltage deviation and improve VUF. $K_Q(t)$, is the cost per cent/kvarh of reactive power export at time *t*. As the author could not access any real price format for reactive power in the market, in this thesis , 10 % of the active power price is used an assumption (Peak time 7:00AM–11:00AM and 5PM-9PM, 5.3 c/kWh; 11:00AM-5:00PM, 2.6 c/kWh and Off-peak time and all other times 1.3 c/kWh). Negative sign '-' in (6.4) corresponds to exporting reactive power.

The inequality constraints demarcated in Chapter 4 are applied in this Chapter as well.

6.4 Summary of Proposed Centralized OL-CD-TPQ Method

This Chapter uses the central PQ inverter control approach online optimal PEV charging/discharging. It is considered that the inverter can participate for both *P* and *Q*. It means the central aggregator optimize the charging and var discharging of all vehicles. Besides, it allows PEV as a source of active and reactive power to participate in the energy market based on different prices during the day, without any degradation. The following procedure is adopted for online optimal PEV charging/discharging and participate.

- Step 1: Input information including daily load curve, PV status, and PEV data (e.g. arrival and departure time, location, charging duration and battery size same as (4.4.1), as well as the market energy prices of *P* and *Q)*.
- Step 2: Based on step 1, GA optimization is then started and the Cost function is evaluated based on multi objection function at each selected bus at one time.
- Step 3: then optimization return

i) The value of cost function

ii) The optimal bus where the cost function is optimal or (the position (status) of all PEVs). The number “0” displays a PEV has not been charged yet or already finished whereas number “1” indicates the PEVs are being charged.

- Step 4: After the GA process, when the maximum iteration is achieved, the result shows the optimal status of PEV charging/discharging at the first time slot. So, the information of PEV Q-table and daily load curve with the optimized solution will be updated and move to the next time slot, which is ($\Delta t = \Delta t + 15\text{min}$).

6.5 Implementation and Results

In this Chapter, the proposed procedure was applied to an exciting LV residential distribution network in WA, as explained in the previous Chapters. Like Chapter 5, the load on phase-c is assumed to reduce by 27% to effectively present the unbalance system and different case study.

The optimization results are summarized in Table 6.1 with two different cases (case C and D). In addition, for proving efficiency the proposed scheme, two scenarios were studied for 30% and 60% PEVs penetration, which can be seen in Figure 6.1the details of simulation results of for both cases can be seen in Table 6.2.

Case D represents the main part of this Chapter which aims in upgrading the voltage by selling reactive power from PEVs as shown in (Figures 6.2 (a-d) and 6.3 (a, b)).

Table 6.1 Simulated cases

Case	Coordination Strategy	Simulation Results
Case C	Coordinated based on OL-C-TP (without considering Q)	Table 6.2
Case D	Coordinated based on OL-CD-TPQ (by considering Q injection)	Figures 6.2 (a-d) and 6.3 (a, b)

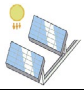
<table>
<tr><th>Penetration (%)</th><th></th><th></th></tr>
<tr><td>30%</td><td>3-8-13-17-19-
27-48-67-72-73
74-16-22-61-64
32</td><td rowspan="2">5-7-8-11-
12-13-16-
17-19-20-
23-24-27-
28-30-32-
34-35-38-
39-40-42-
45-48-49-
51-53-54-
55-57-60-
61-63-65-</td></tr>
<tr><td>60%</td><td>3-5-7-8-12-13-
17-19-23-27-28
30-34-38-49-40
51-53-57-60-67
68-69-71-72-73
74-16-22-32-48
61-65</td></tr>
</table>

Figure 6.1. Illustration of buses which have rooftop PV systems or PEVs through the system.

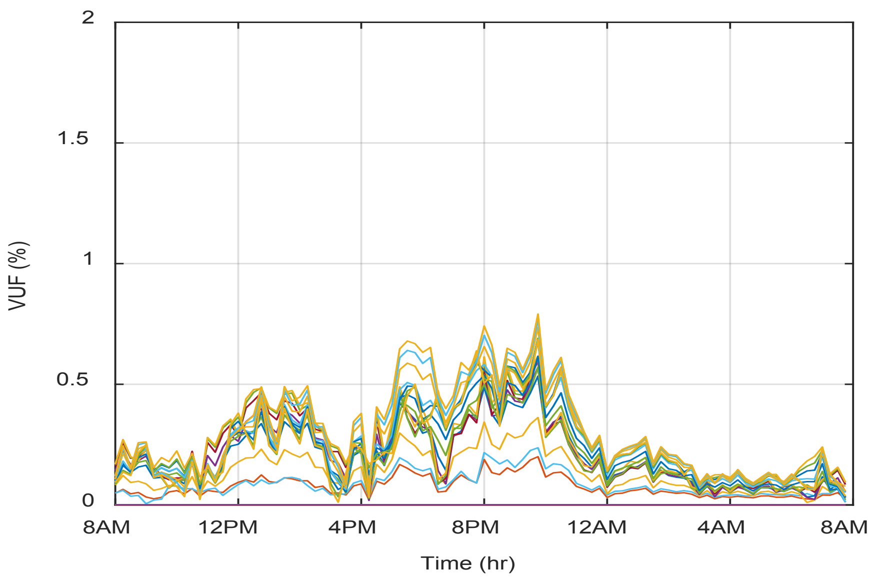
According to Table 6.2, the system power consumption increases during the peak hours and causes significantly higher peaks in the three phases. In addition, as the rooftop PVs are connected to some of the residential houses, the whole network is fairly unbalanced at morning and evening peak hours. During the peak time, the voltages of some nodes fall below the designated minimum threshold of 0.87, due to the vehicle demand. As a result, in all uncoordinated conditions, high generation cost and energy losses happen as well. The daily energy cost can be calculated by:

$$Daily\ Cost\ of\ Generation = \sum_{m=1}^{96} generation\ Cost\ (m\Delta t) \tag{6.7}$$

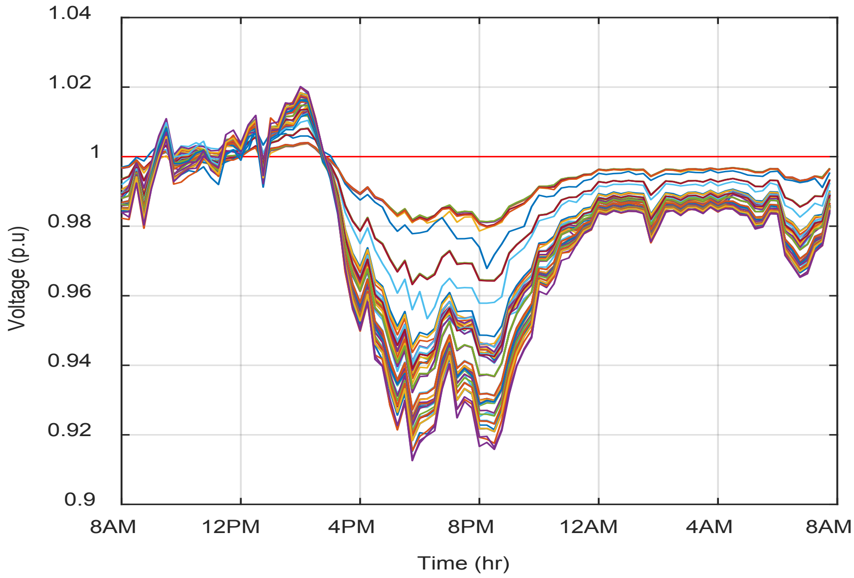
In scenario C, the coordination strategy of OL-C-TP proposed in previous Chapter 4 is used to solve the optimization problem as mentioned before. In comparison with case B, general improvement in terms of system performance and operational cost is observed in Table 6.2.

In the case of D, the PEV inverters are allowed to absorb/inject active and reactive power simultaneously based on the proposed OL-CD-TPQ strategy of sub-section 6.2.3. It means each PEV has an ability to share its capacity to charge *P* and discharge *Q* at the same time based on price signals for minimizing the cost operation and further improvement of voltage regulation and more reduction of VUF. According to Table 6.2, scenario 1; the total cost of charging PEVs and generation is \$115.5 per day which consists of four components, i.e., \$118.0 for active power generation, \$−3.03 per day for reactive generation from PEVs and the rest for losses and VUF penalties. Compared with case C1, it certainly offers a better solution in terms of both grid operation and for consumers with the total payment reduced from \$126.9 to \$115.5. Furthermore, the voltages at all buses kept within the system limit (Figures 6.2 (b)-(c)), the peak power consumption is above the limit (Figure 6.2 (d)) and VUF has also been reduced Figure 6.2 (a). From Table 6.2, the maximum VUF is 0.8% at peak hours and 0.6% in the morning. In comparison with case C1, the maximum VUF and the worst voltage are significantly improved. Furthermore, from Figures 6.3 (a)-(b) the voltage improvements and VUF reduction can be observed for scenario 2.

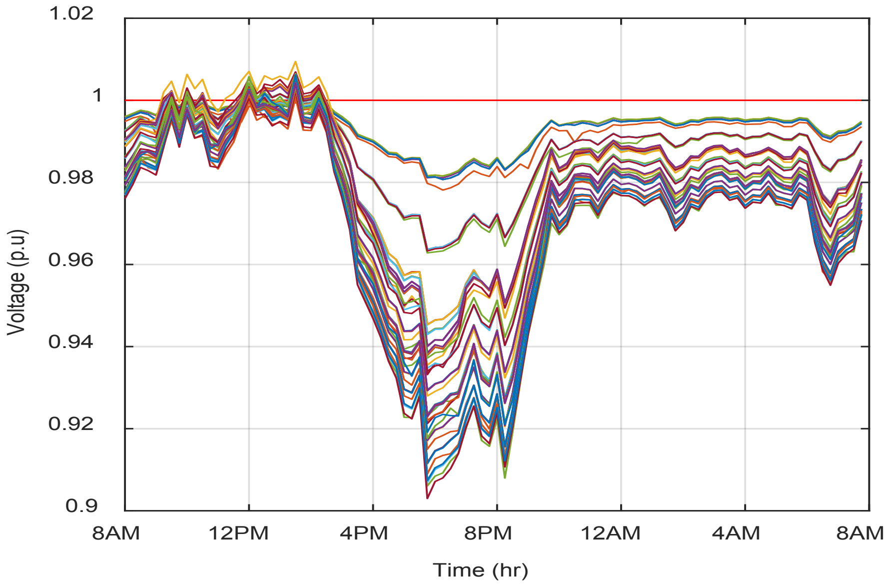
To show the effectiveness of the proposed mothed the convergence characteristic plot of case D1 for three separate 15 min are presented in Figures 6.4 (a–c) between 5:15 PM.–6:00 PM. These figures demonstrate the convergence of the best value and mean value of fitness function with a maximum of 50 generations.



(a)

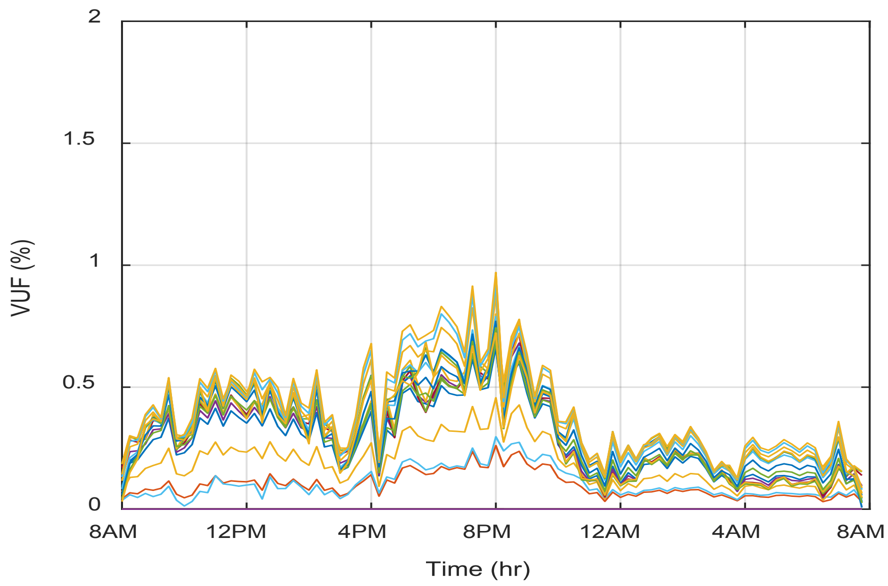


(b)

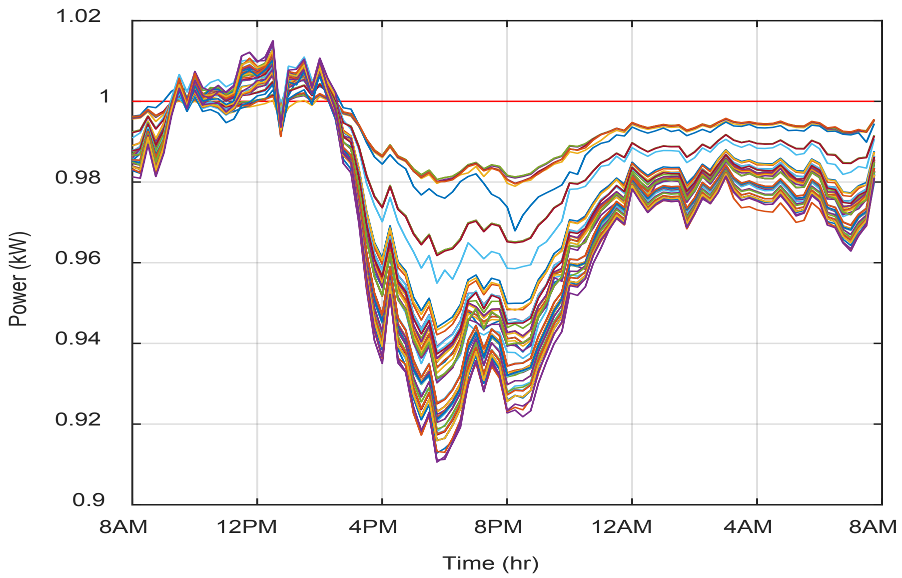


(c)

Figure 6.2. Case D1: Impact of online coordinated PEVs charging/ var discharging (OL-CD-PTQ) on (a) VUF, and (b) phase-a voltage profile, and (c) phase-b voltage profile.

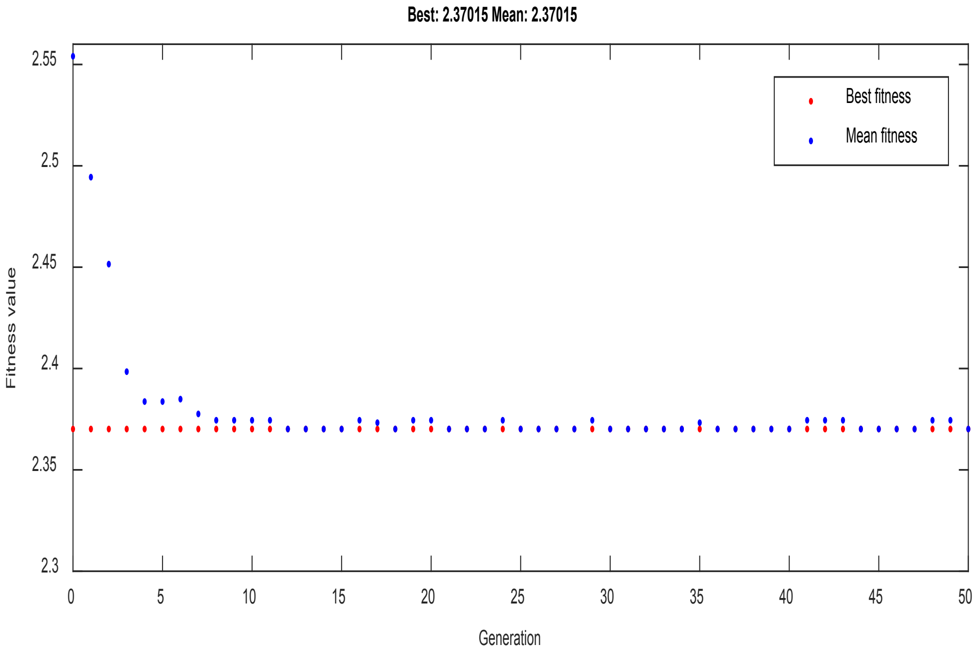


(a)

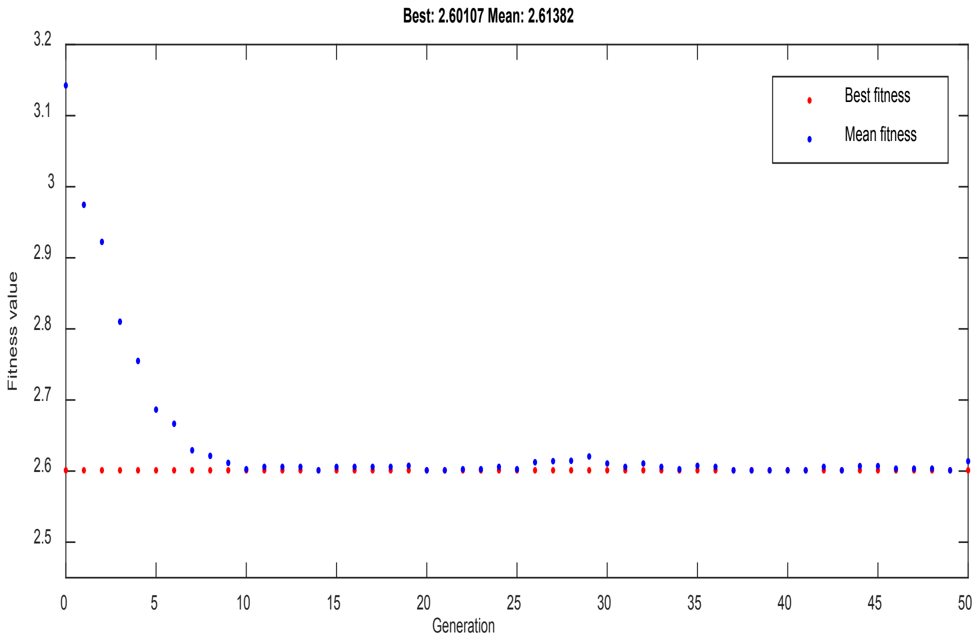


(b)

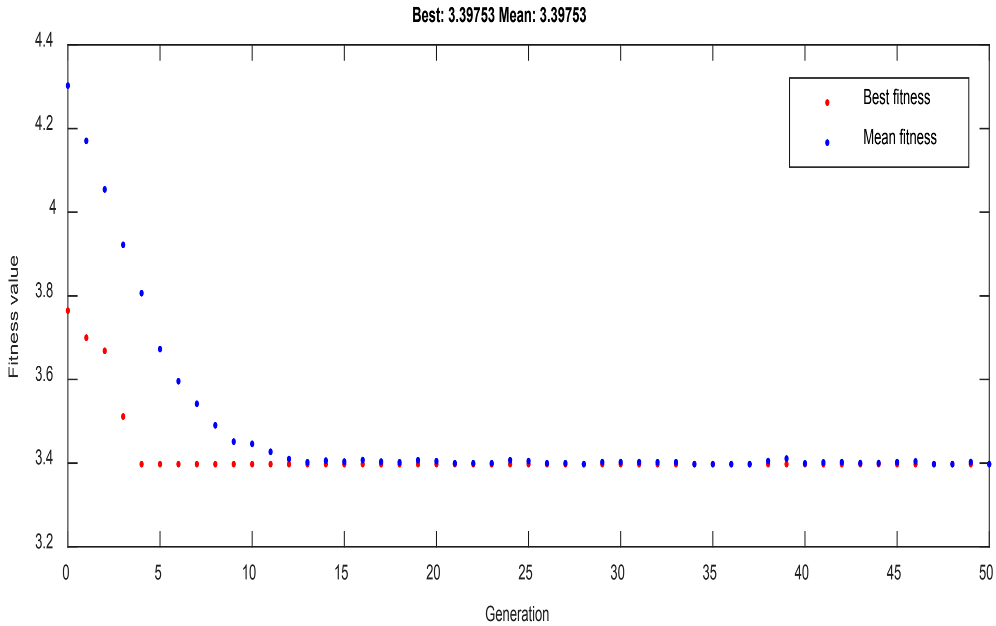
Figure 6.3. Case D2: Impact of online coordinated PEVs charging/ var discharging (OL-CD-PTQ) on (a) VUF, and (b) phase-a voltage profile.


Best: 2.37015 Mean: 2.37015
Best fitness
Mean fitness
Fitness value
Generation
2.55
2.5
2.45
2.4
2.35
2.3
0
5
10
15
20
25
30
35
40
45
50

(a)


Best: 2.60107 Mean: 2.61382
Best fitness
Mean fitness
Fitness value
Generation
3.2
3.1
3
2.9
2.8
2.7
2.6
2.5
0
5
10
15
20
25
30
35
40
45
50

(b)



(c)

Figure 6.4. Case D1: Convergence characteristics of proposed method (OL-CD-TPQ) at each time interval between 5:15 p.m.–6:00 PM: (a) 5:15–5:30 PM; (b) 5:30–5:45 PM; (c) 5:45–6:00 PM.

Table 6.2 Summary of optimization results for OL-CD-TPQ based on energy market for scenarios 1 and 2

	Operation Condition								**Comparison of Simulation Results**						
	Time of the Day	**Number of PEVs**				**PV [%]**			**Worst VUF [%]**	**Worst Voltage (p.u)**			**Generation Cost ($/Day)**	**Q Generation ($/Day)**	**Total Cost ($/Day)**
		a	b	c	3ph	a	b	c		a	b	c			
Base case	Base Case A without any PEVs														
	Morning 8AM-11AM	0	0	0	0	45	43	27	0.63	1.1	1	1	87.7	0	88.78
	Evening 4PM-7PM	0	0	0	0				0.78	0.9	0.9	1			
Scenario 1 (60% PEVs penetration)	Case B1: Uncoordinated PEVs														
	Morning 8AM-11AM	11	11	12	0	45	43	27	0.7	1	1	1	136.2	0	137.4
	Evening 4PM-7PM	11	11	12	0				1.69	0.9	0.9	1			
	Case C1: Optimal online charge control based on P-Control Strategy (OL-C-TP)														
	Morning 8AM-11AM	11	11	12	0	45	43	27	0.56	1	1	1	125.8	0	126.9
	Evening 4PM-7PM	11	11	12	0				1.03	0.9	0.9	1			
	Case D1: Optimal online charge/discharge control based on PQ-Control Strategy (OL-CD-TPQ); Figures 6.2 (a-c)														
	Morning 8AM-11AM	11	11	12	0	45	43	27	0.61	1	1	1	118	−3.038	115.5
	Evening 4PM-7PM	11	11	12	0				0.8	0.9	0.9	1			
Scenario 2 (30% PEVs penetration)	Case B2: Uncoordinated PEVs														
	Morning 8AM-11AM	11	0	0	5	45	43	27	0.96	1	1	1	268.2	0	283.1
	Evening 4PM-7PM	11	0	0	5				2.14	0.9	0.9	1			
	Case C2: Optimal online charge control based on P-Control Strategy (OL-C-TP)														
	Morning 8AM-11AM	11	0	0	5	45	43	27	0.54	1	1	1	234	0	256.2
	Evening 4PM-7PM	11	0	0	5				1.41	0.9	0.9	1			
	Case D2: Optimal online charge/discharge control based on PQ-Control Strategy (OL-CD-TPQ); Figures 6.3 (a) and (b)														
	Morning 8AM-11AM	11	0	0	5	45	43	27	0.6	1	1	1	230.5	−9.5	224
	Evening 4PM-7PM	11	0	0	5				0.96	0.9	0.9	1			

6.6 Summary

This Chapter has developed an online and coordinated PEV charging/var discharging strategy based GA optimization to minimize the total cost of generation, energy losses and to improve the performance of unbalanced four-wire LV system with high PV penetrations. The proposed method allows PEV owners to generate reactive power for ancillary voltage service and participate in the energy market. The benefits and improvement of proposed strategy versus uncontrolled PEV charging and OL-C-TP are compared and demonstrated through extensive simulations results for the WA Distribution network. The online PEV coordination is charging/discharging (OL-CD-TPQ) strategy also minimizes the VUF and voltage fluctuations, as shown in Figures 6.2 (a-c) and 6.3 (a-b). Based on the proposed method, the total cost decreases for consumers (i.e., customer benefits) and the system performance is improved (i.e., utility preference) with the objective function lower than the OL-C-TP strategy. It verifies the feasibility of PEVs to participate in the energy market and provide ancillary service

Chapter 7

Online Centralized Coordination through Feeder Switching

7.1 Introduction

In the previous two Chapters, particular focus has been set in utilising the reactive power capability of PEV inverter for ancillary voltage support. In this regard, two different studies were investigated, such as Decentralized (Chapter 5) and Centralized (Chapter 6). However, there are some limitations related to the capability of injection reactive power, as has been discussed in the literature. Therefore, it is essential to consider a more suitable methodology of voltage regulation for the consumers placed at the end of the feeder when the network is predominantly resistive. Recently, open tie switches are applied for reconfiguration of medium voltage distribution systems. According to [36] there are some advantages of using this technique such as minimizing the power loss, integrating higher penetration of DG, enhancing power quality and quicker restoration service due to the fault [141-143]. This Chapter investigates the capability of dynamic only PEV load transfer within the three-phase system to propose a new hybrid PEV coordination approach. This approach uses GA optimization to perform online centralized battery charging and var discharging. It also applies local voltage improvement by switching PEV at selected single-phase residential houses with a voltage problem among the other two phases.

In Sections 7.2 and 7.3, the problem formulation including the objective function, constraints and requirements for modelling the proposed strategy are explained. The online coordinated control algorithm of PEVs and switching ability for voltage regulation and VUF improvement are discussed in Section 7.4. In Section 7.5, the efficacy of the proposed scheme is tested on a real 74 node unbalanced Western Australian distribution network. Finally, the Chapter summary is presented in Section 7.6.

7.2 Problem Formulation

Single-phase residential charging can initiate or contribute to unbalance voltage conditions in the distribution feeder. This can be severe at the end of the feeder as has been explained in the previous Chapters. Thus, aggregators based on consumer preference and grid configuration and energy price need to consider the coordination solution for both peak and off-peak charging hours. Reference [85] has recommended independent inverters for voltage enhancement by reactive power capability. This may affect the active power, so the profit of consumer will be reduced. Moreover, reference [86] shows that the reactive power control in medium and high voltage is more effective than LV distribution systems. Thus, voltage maintenance in the end node/bus customers or the rural areas needs to be investigated because of high length (R/X ratio) [77]. This Chapter presents a hybrid online algorithm for optimal coordination of PEVs. It targets to improve VUF and also performs voltage regulation during high peak hours by switching PEVs among the three-phases of the feeder.

In this scheme, it is assumed that the PEV owners have agreed to a contract with the aggregator, whereby their PEVs can be shifted from one phase to the other. When the PEVs are plugged-in, all PEV information like driver's charging manner, mobility behaviour, and PEV penetration are sent and saved in a central controller. The aggregator processes this data by considering a grid interface and offers a suitable optimized charge option to each owner based on the objective function. However, this communication has some potential issues as follows:

- The PEVs owners' try to fully charge their battery by receiving the signal from the central controller. In online optimization with constant power charging, there is no guarantee the charging duration to be kept in limit constraints.

- Voltage deviation and VUF problem will increase at the end of the feeder, which always cannot be solved by conventional online PEV optimization.

To fix these issues, the online PEV switching phase control method is proposed. In this method, in addition to having smart meters, all PEV owners are assumed to have smart switches that can switch the PEV connection from one phase to the others. Obviously, the smart meter will send the power consumption of each house to the central controller at some discrete time intervals. The central controller analyses the voltage deviation between three-phase systems and selects the PEVs that need to be switched from the connected phase to another one, when required. A command is issued to the smart PEV switches to initiate phase switching. For reducing the switching process, the voltage band limit (0.94) has been put on the system.

7.2.1 Objective Function

The multi-objective function in (6.4) is updated to include a voltage violation penalty ($F_{cost-V}(t)$) (as explained in Chapter 4) to effectively minimize impacts of voltage deviation:

$$min\, F_{Cost-G2V/V2G} = \{\, F_{cost-Loss}(t) + F_{cost-gen}(t) + F_{cost-VUF}(t) + F_{cost-V}(t)\};$$
$$for\ t = 0, \Delta t, 2\Delta t \dots 24\ h \qquad (7.1)$$

where

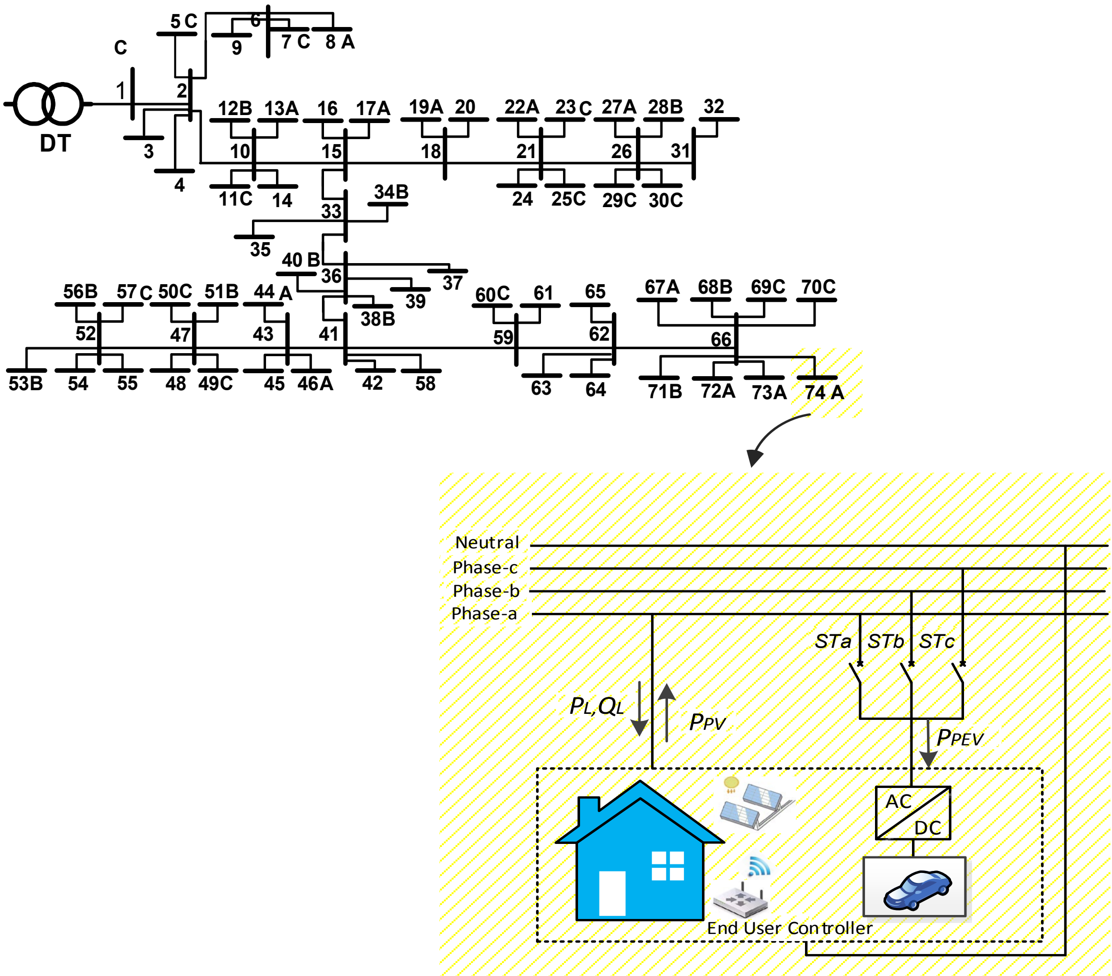
$$F_{cost-V}(t) = \sum_{a,b,c} \sum_{k=1}^{N_{node}} K_v(t)|V(t,k) - 1| \qquad (7.2)$$

The inequality constraints defined in Sub-section 4.3 are used in this chapter, as well.

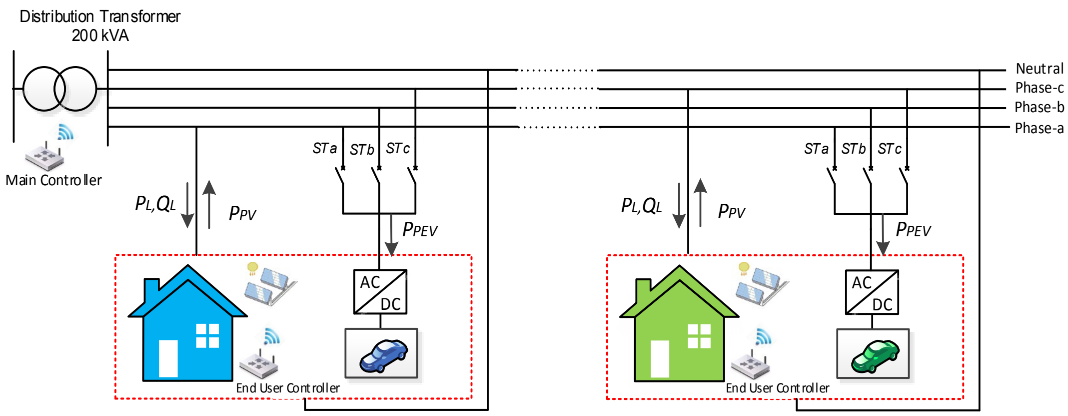
7.3 Proposed Strategy

7.3.1 System Modeling and PEV Coordination Strategies

Figure 7.1 (a) presents an example of the proposed schematic connection of a single phase customer (node) with a rooftop PV and PEV connected to phase-a of a distribution network (node 74 A) and the proposed scheme for single phase residential customers is shown in Figure 7.1 (b).



(a)



(b)

Figure 7.1. (a) Schematic of the proposed connection of node 74 A with a PV and PEV to the grid. (b) Schematic diagram of LV feeder with the proposed scheme for single phase residential customers.

The proposed phase unbalance reduction method in this work is based on the following detailed assumptions:

7.3.2 Restructure System's Wiring

In a radial distribution system, there are a large number of single-phase loads connected to the network. Generally, the single phase load in the distribution network is connected to phase-a, b or c at the time of installation. In this proposed method, according to [144], it is needed to modify the wiring structure to switch PEV phases from one to another, as shown in Figures 7.1. At the preliminary stage of this method, the utility should be aware of the phase connection of each PEV. So, in this work, the initial phase is the phase each home connected.

7.3.3 Load Characteristics

According to [144], all the single-phase loads can be divided into static loads or variable loads. The static load cannot switch between phases which means directly connected to phase-a, b or c. However, the loads will change depending on the time of the use. In this work, it has been assumed that all the household loads are static, while the PEV loads are dynamic or variable. It is to be noted here that the static load does not mean that the load is constant, it is just connected to a designated phase.

7.3.4 Smart Operation of the Switching Controller

To perform this operation, the following devices are assumed to be presented at the premises of the customers who own PEVs.

- **Smart meters:** In this method, a smart meter is required to record the power consumption of residential loads. So, all houses with PEVs are equipped with this electronic device that can communicate the information every 15 minutes to the central controller.

- **Controllers:** This is installed in the premises of the customers that have PEVs. The aggregator control centre determines the VUF and the power mismatch between phases. It then selects the candidate PEV, which needs to be switched from one phase to another. Upon receiving this command from the control centre, the controller activates the switching action.

Note that the switch structure reported by [36] has been assumed here. However other viable switching structures are also possible. Since the aim is to generate a scenario where switching PEVs between phases can alleviate VUF and voltage limit violation through an optimisation procedure, the functioning of the switch is not the main concern. Power electronics based switches can automatically shift phases almost instantaneously, as has been discussed in [36].

According to Figure 7.1, the grid side of the switch is connected to all three phases. However, the PEV side has only one connection to PEV. It is obvious from this figure, each switch in one side is connected to one of the phases of a, b, or c and their output connected to the PEVs. If the $ST_{a,k}$ is closed means PEV connected to phase-a. Exactly the same procedure can happen for phase-b and phase-c. For example, if the PEV is connected to either phase a or b or c at node k, it will be defined in the following form (7.3).

$$\begin{cases} ST(\Delta t,k) = ST_{a,k}\overline{ST}_{b,k}\overline{ST}_{c,k} \text{ ; for phase a connection} \\ ST(\Delta t,k) = \overline{ST}_{a,k}ST_{b,k}\overline{ST}_{c,k} \text{ ; for phase b connection} \\ ST(\Delta t,k) = \overline{ST}_{a,k}\overline{ST}_{b,k}ST_{c,k} \text{ ; for phase c connection} \\ ST(\Delta t,k) = \overline{ST}_{a,k}\overline{ST}_{b,k}\overline{ST}_{c,k} \text{ ; for no PEV connection} \end{cases} \quad (7.3)$$

7.4 Hybrid PEV Coordination for Ancillary Voltage Support

While the centralized OL-CD-TPQ strategy of the previous Chapter considered voltage regulation due to the capability of PEV's inverter for Q injection, the distributed single-phase and relatively high PEV active power consumptions can cause voltage and voltage unbalance issues, especially at the end feeder locations. The VUF issue is related to the voltage magnitudes difference through the three phases on that bus. In this regard, the idea of an online PEVs charging coordination with local ancillary voltage support by dynamic switching of PEVs is performed. This approach consists of two stages as below:

- Stage 1: Perform the centralized coordinated PEV charging/discharging (OL-CD-TPQ)
- In this stage, the centralized online PEV charging/ var discharging is performed to regulate voltage profile, reduce total system VUF and losses by applying the smart charging decision.
- Stage 2: Allow local switching phase at selected nodes with PEV for further voltage regulation and VUF reduction. This can be done by choosing the most suitable phase connection for each PEV in every 15 minutes.
- This stage performs local voltage improvement by switching from one phase to another at selected single phase residential houses with PEV with voltage problem within the three phase system.

Combining two stages can be more effective for the end consumers of the network as well as consumers which can charge during on-demand hours by considering constraints on the network. Instead of load switching that some researches work on [36], in this strategy, only the PEV can switch between phases for voltage improvement. It means switches can be active only during voltage deviation time. So, it results in dynamic issue reduction by minimizing the number of switching.

An overview of the proposed strategy is presented in Figure 7.2 and brief description at each time interval (15 minutes) are given as below:

Necessary input information including daily load curve, PV status, and PEV data (e.g. arrival and departure time, location, charging duration and battery size) are collected by the central controller from an individual smart meter in each residential house.

The centralized GA-based PEV coordination is performed and Optimization returned the optimal bus where the fitness function is optimal (Stage1).

Load flow is run and checked the new voltage with PEV on that time by a controller; if the voltage deviation of a house with PEV is not within the set value ($0.94\, pu \leq V(t,k) \leq 1.06\, pu$) then the maximum and minimum index voltages for each node with PEV and their phase connection are observed.

If the selected PEV is connected to low phase voltage, the switch is applied to transfer PEV load from high load phase to the minimum phase through the three-phase unbalance, otherwise no need to transfer the PEV's load.

The new voltage V*(t, k) is checked to be less than the old ones. Then the selected phases are saved and updated the new phase PEV is connected and made ready for the next step.

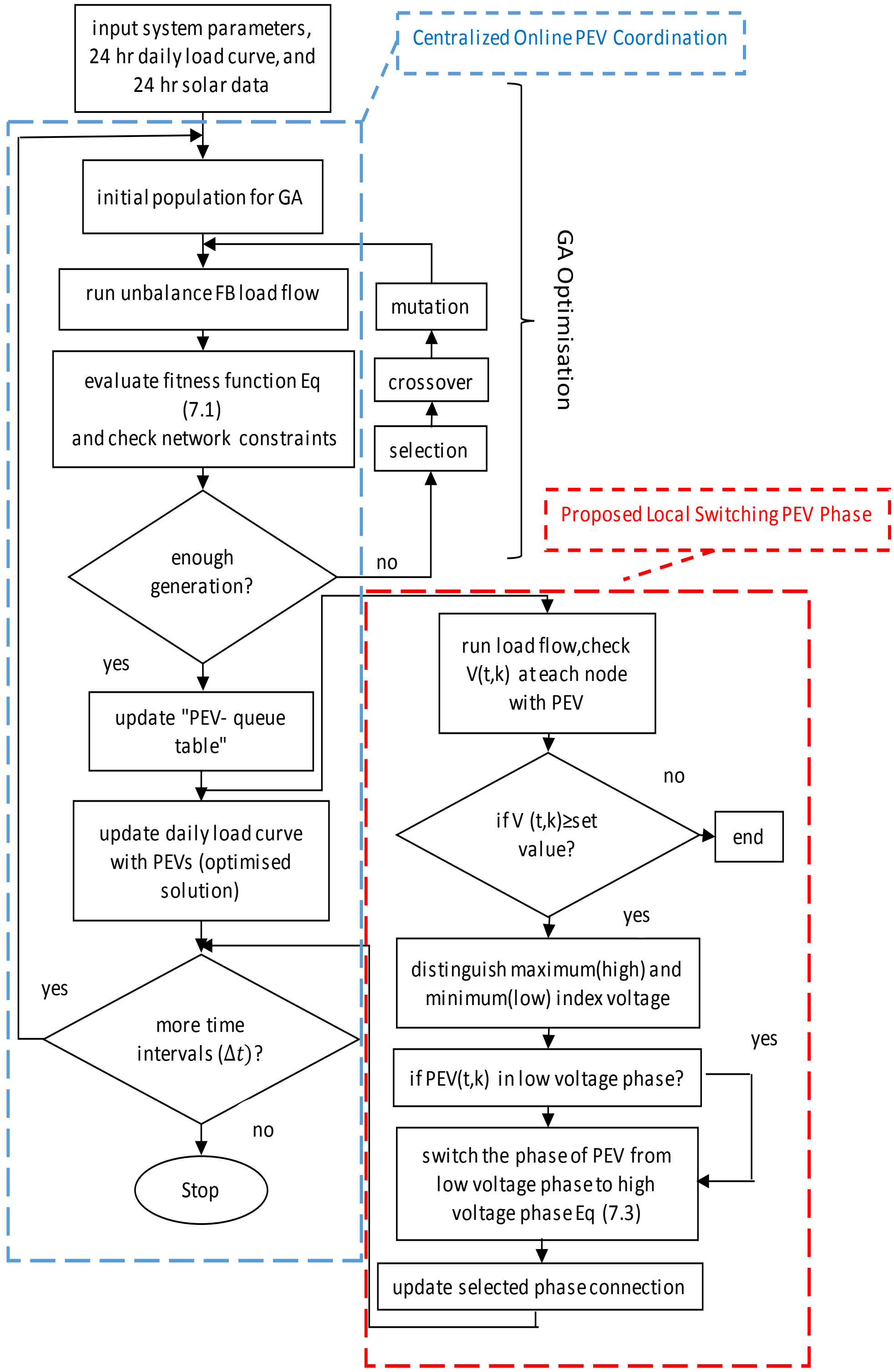


Figure 7.2. Proposed switch phase flowchart

7.5 Simulation Results and Discussion

The Proposed approached for hybrid online PEVs charging coordination is tested on the LV distribution model of Figure 7.1 (a). Analysis of the proposed approach was carried out for two different case studies (cases C and D). Case C presents the optimized results with PQ control (PEV charging and var discharging). Case D shows the results of the proposed hybrid control method. For each case, two different unbalance scenarios have been generated as below:

- Scenario 1 is designed when all PEVs are connected to high load phase (phase-a) through the three-phase LV unbalance network, which is 20% of all houses.
- Scenario 4 is designed to show the highest number of PEVs connected into the single-phase houses through the system, which is about 60%.

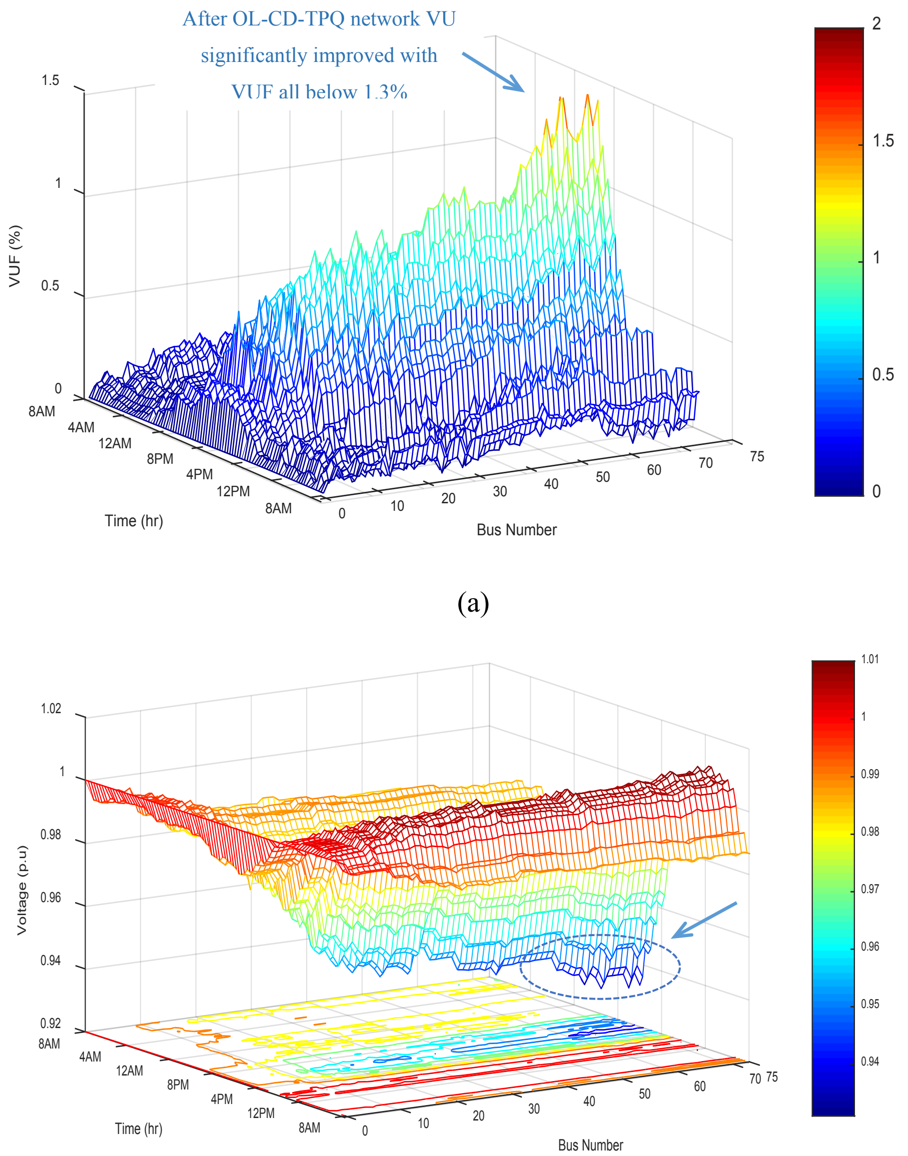
The details for all cases and scenarios are shown in Table 7.1.

7.5.1 Case C: with Centralized OL-CD-TPQ Control Only

In this case, the coordination strategy proposed in Chapter 6 (OL-CD-TPQ) is used to solve the optimization problem of (7.1). The VUF and the system voltage profile after PQ control are illustrated in the 3D form in Figures 7. 3 (a), and 7.3 (b).

Figure 7.3 (a) indicates the VUF for all nodes when all the PEVs connected to the high load phase on the system (phase-a). It can be observed that VUF is improved and reached a maximum value of 1.3% during the evening peak hours. As can be seen in Figure 7.3 (b) the voltage level on phase-a (main phase in this case study) is improved by PQ control strategy in comparison with uncoordinated ones (case B). However, during the peak load periods, the voltage magnitudes of some nodes are out of the under assume limit. The details of the simulation results can be seen in Table 7.1.

According to Table 7.1, in scenario 1, the peak power is reduced for all the phases due to coordination charging PEVs, and the power losses are enhanced from 171.3 kW to 136.7 kW. Although this method achieves an important reduction in terms of voltage deviation and VUF, using PEV inverter *Q* capability can be more useful for low PEV penetration charging during demand hours and for the residential placed at the beginning of the feeder. So, compensation maybe not enough in all conditions, and additional technology is needed to investigate a plan to mitigate voltage deviations and reduce VUF especial at the end of the unbalanced feeder. In this regard, coordinated PEV charging with local ancillary voltage support is applied to reach this objective in the next case study (case D).



(a)

(b)

Figure 7.3. Case C1: Impact of coordinated (OL-CD-TPQ) PEV charging (high load phase) on (a) VUF, and (b) phase-a voltage profile

7.5.2 Case D: with Centralized OL-CD-TPQ and Local Ancillary Voltage Support by PEVs Switching

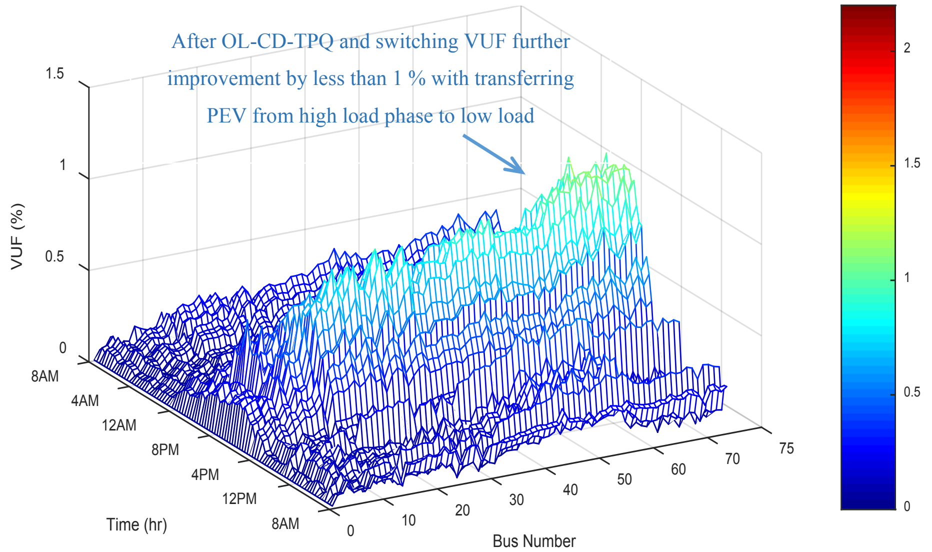
This case study is similar to case C; however, some PEVs are allowed to switch their loads between phases based on the proposed switch phase strategy of Section 7.3 for further improvements in voltage regulation and more reduction of VUF.

As switching in any bus will affect the voltages for all buses and phases, the proposed algorithm can improve the total system's performance, as shown in Table 7-1. According to Figure 7.4 (a), by applying the switching action, further reduction of VUF is achieved and reached the desirable limitation of constraint. It can be seen that in comparison with case C, the maximum VUF is significantly improved from 1.3% to 1% after switching, which results in better coordination through all phases.

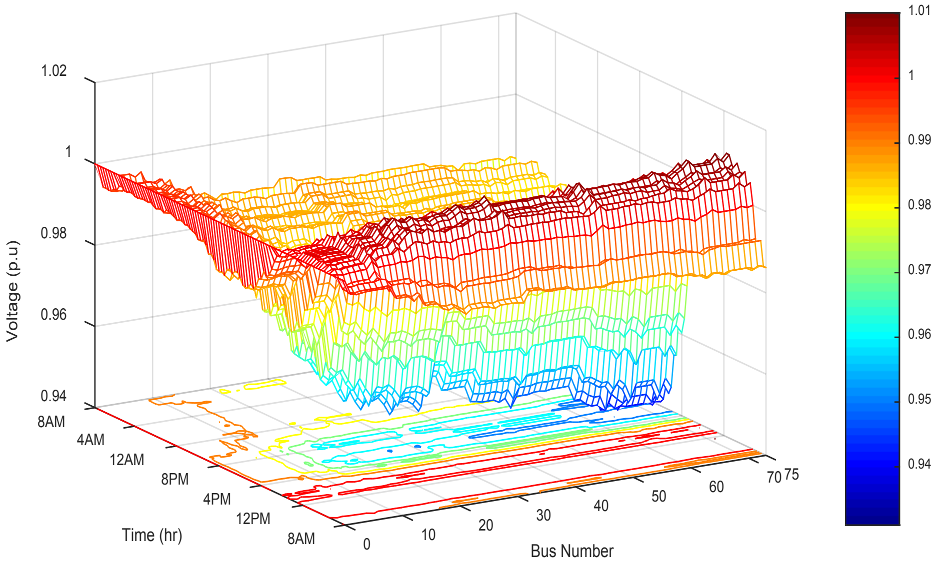
The minimum voltage along the feeder on phase-a (high load phase) and phase-b (low load phase) after applying the proposed switching method are shown in Figures 7.4 (b) and 7.4 (c). In this process; at each time step after applying OL-CD-TPQ, when the voltage is more than the limitation (>-6%), PEV on that specific phase switches from high load phase to low load. According to the Figures during peak-hours, some PEVs on their charging time (3hrs) switch to phase-b for reducing the voltage deviation and smoothing VUF. In this research, the set value of the voltage is assumed by 0.945p.u. The reason to use this value is reducing the number of switching and regulating voltage and VUF improvement into the desired value. However, by changing the limitation (for example 0.97), it is clear that the number of switching is increased. From Figure 7.4 (b) and 7.4 (c), it can be seen that the voltage on phase-a in some nodes increased from 0.932 p.u to 0.94 p.u and precisely on that time phase-b reduced from above 0.973 p.u to lower than 0.96 p.u. By this process, It can be observed that the value in phase-a, as well as VUF, are improved after switching.

Figure 7.5 demonstrates the phase connection of PEVs for scenario 1 for both cases C and D. The figure on the top shows the results of coordinated with PQ control (case C) which shows 11 PEVs are charged from phase-a (initial phase) at an optimal time. The figure on the below shows, the phase connection results of case D.

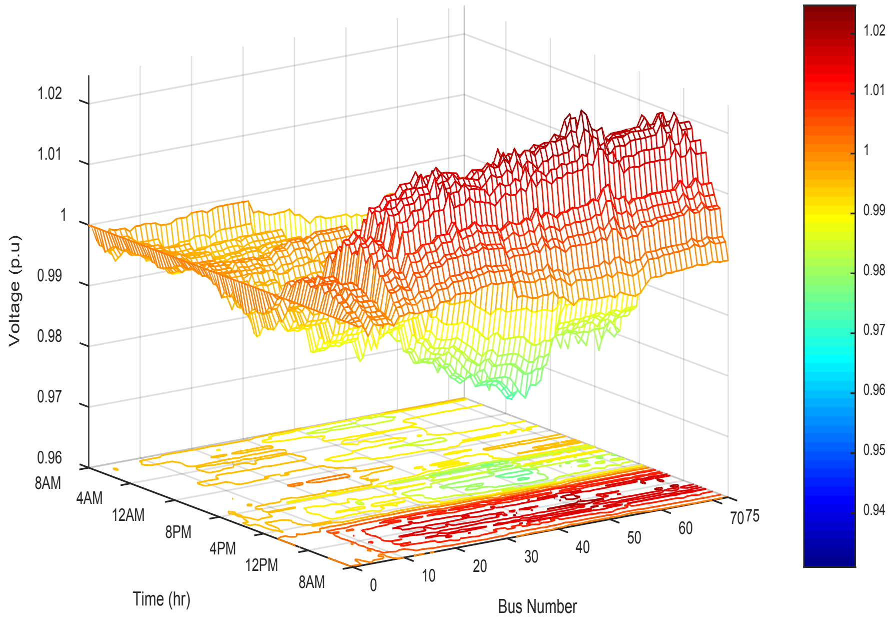
According to this figure some PEVs during their charging periods based on flowchart 7.2 are switched to phase-b (low load phase) and charged from that phase.



(a)

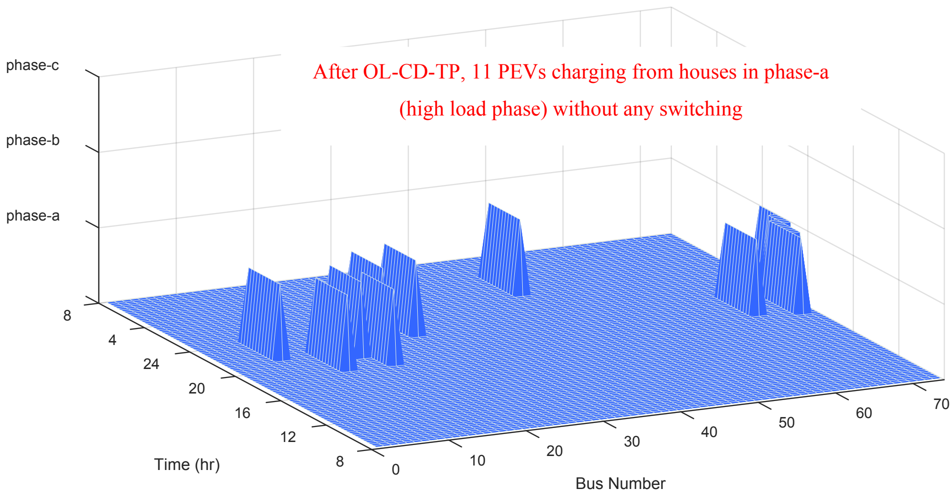


(b)

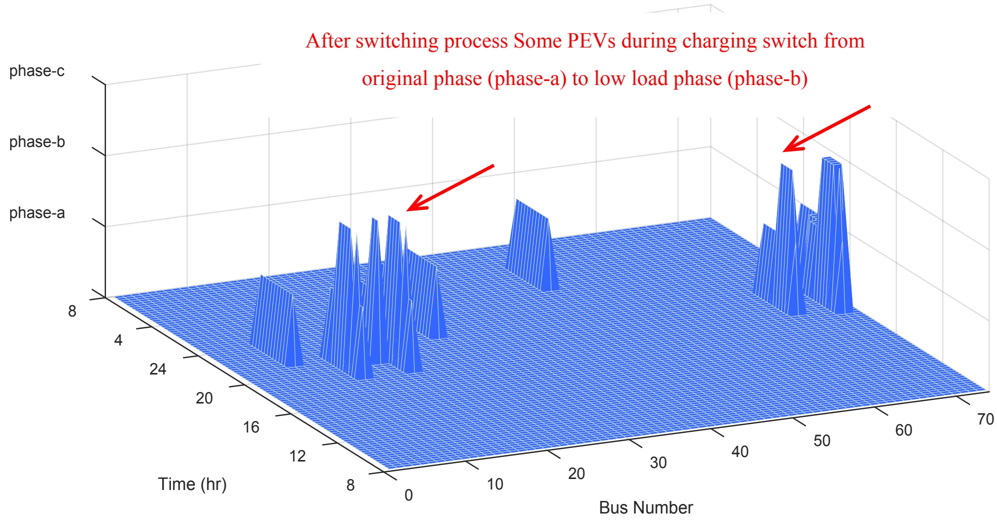


(c)

Figure 7.4. Case D1: Impact of hybrid coordinated PEVs charging (high load phase) on (a) VUF, (b) phase-a voltage profile and, (c) phase-b voltage profile. Note that switching PEV maintains all voltages within regulation.



(a)



(b)

Figure 7.5. Demonstration of phase connection of each PEV (a) Case C1 (OL-CD-TPQ) (b) Case D1 (after switching)

To observe the performance of the proposed scheme, Figure 7.6 demonstrates a comparison of three-phase voltage profile of node 72A between case C and case D. It can be observed that after switching, the voltage on phase-a is reduced to the limited value by transferring the PEV loads on that time to phase-b as a low load phase. So, it causes a reduction in the gap between three-phase voltages and regulates voltage profile.

By applying the proposed method, it can be seen that every PEV is charged without exceeding the limitations during a day. It leads to power improvement at each phase, VUF reduction, and voltage deviates mitigation through the feeder in both scenarios. However, it does not modify the previous results in terms of power losses. It means the most reduction of losses was related to the optimization process. The power losses on phase-a of all cases over 24 hours are shown and compared in Figure 7. 7. The maximum values for cases B, C, and D, are 3.2kW, 2.1kW and 1.9 kW, respectively.

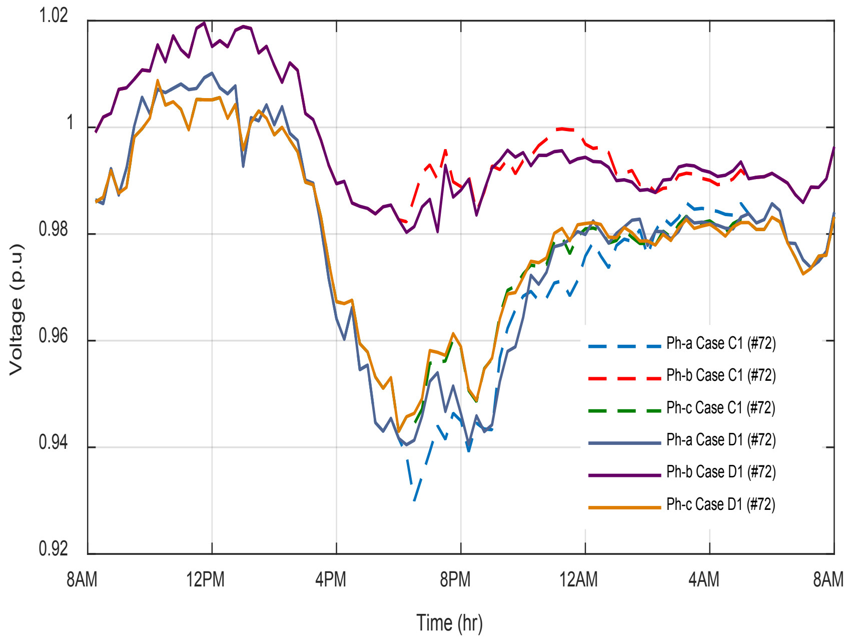


Figure 7.6. Three-phase voltage profile of node 72 A (worst affected node) for Case C1 (OL-CD-TPQ) and D1 (hybrid coordinated PEVs charging).

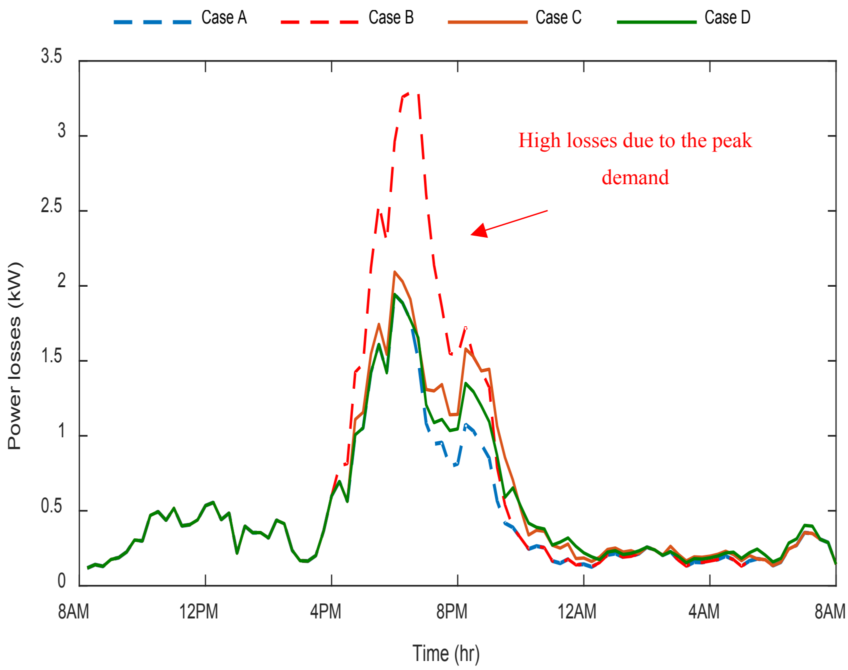


Figure 7.7. Variation of total system power losses on phase-a over 24 hours for all Cases.

Table 7.1 Summary of optimization results for hybrid online PEVs charging coordination test for scenarios 1 and 2

	Operation Condition				**Comparison of Simulation Results**										
	PEV [%]	**Number of PEVs**			**Maximum Demand (kW)**			**Worst Voltage (p.u)**			**Worst VUF [%]**	**Maximum Losses (kW)**			
		a	**b**	**c**	**a**	**b**	**c**	**a**	**b**	**c**	**Feeder End**	**a**	**b**	**c**	**Total**
Scenario 1 (high load phase)	20	Case B1: Uncoordinated PEVs													
		11	0	0	40	15.97	23.1	**0.908**	0.98	**0.936**	2	3.2	1.39	1.7	171.3
		Case C1: Online Coordinated Charging (OL-CD-TPQ)													
		11	0	0	30.2	15.97	23.1	**0.93**	0.974	0.94	1.3	2.1	1.18	1.6	136.8
		Case D1: Hybrid Online Coordinated charging/discharging with Switching ability													
		11	0	0	29.2	16.02	23.1	0.94	0.96	0.94	1	1.9	1.15	1.5	137
Scenario 2 (All single phase)	60	Case B2: Uncoordinated PEVs													
		11	11	12	37.7	24.84	32.1	**0.914**	0.947	**0.92**	1.4	3.35	2.19	2.8	176.6
		Case C2: Online Coordinated Charging (OL-CD-TPQ)													
		11	11	12	31.6	23.86	28.7	**0.934**	0.945	**0.94**	0.85	2.29	1.84	2.1	159.7
		Case D2: Hybrid Online Coordinated charging/discharging with Switching ability													
		11	11	12	29.2	24	25.5	0.94	0.94	0.94	0.76	2	1.76	1.9	157.6

7.6 Summary

This Chapter presented a hybrid online PEV charging coordination strategy using genetic algorithm optimization to minimize the VUF and power losses considering individual node voltage regulations. Additionally, a new approach to mitigate voltage deviation and reduce VUF, especially at the end of the feeder and during peak demand hours has been developed based on smart PEV switching structure. In this regard, two different case studies (with PQ control and hybrid control) are considered. The main conclusions are:

- The online centralized genetic PEV coordination (OL-CD-TPQ) strategy as explained in the previous chapter is repeated on the system in Chapter 4 (it means the amount of the load for each phase is similar) and demonstrated in Figures 7.3 (a) and 7.3 (b).

- The hybrid online centralized genetic PEV coordination strategy in combination with the proposed local switching phase based voltage regulation also minimizes the VUF and voltage fluctuations as shown in Figures 7.4 (a),7.4 (b), and 7.4 (c). This is done by a central controller and three transfer switches that are connected to the selected house with PEVs. The proposed hybrid strategy results in better voltage regulations and further VUF reductions. The voltage deviations are kept above 0.94pu and below 1.02pu during the evening and morning hours while the maximum VUFs of all nodes are below 1.0.

- The reactive capability of PEV inverters alone may be sufficient to improve the voltage profile in low penetration. However, local voltage improvement with PEV inverters is required in the end feeder cases which have a higher R/X ratio as well as charging PEVs during high peak hour's cases. If switching is used alone for the voltage improvement, a more significant number of switching time is required. In this regard, the hybrid scheme is considered in this section.

- The hybrid proposed method is shown to be beneficial in reducing the VUF and voltage deviation through the feeder on unbalanced network by applying optimization and switching procedure. The PEVs could easily be coordinated by online optimization and if required switch between high load and low load phases. However, this method is more effective on high unbalance system with unequal distributed loads between three phases.

Chapter 8

Conclusions and Recommendations

In this chapter, the general conclusions of the thesis and possible future research directions are presented.

8.1 Conclusions

The main conclusions of this thesis are summarized as below:

- Increasing number of PEVs can deteriorate voltage profile and increase voltage unbalance in LV distribution grid due to the different ratings and random locations of PEVs that are plugged in different phases of a three-phase system.

- Several factors such as location of the PEVs (beginning of the feeder or end of the feeder), phase connection (high load phase, low load phase), rate of charge and number of PEVs can cause voltage deviations and increase VUF. As has been shown in Chapter 3, the effect of PEVs on voltage profile and VUF at the end of the feeder is much higher than the beginning of the feeder and sometimes they can be more than the desired limits.

- For PEV charging, the place at which the PEV connected is more important than the rate of charging or the ratings of the PEVs. If PEVs are connected in the lowest loaded phase, then the VUF may reduce. Conversely, exactly opposite results can be observed if they are connected in either high or medium loaded phases.

- In Chapter 4, two different strategies are considered – charging based on optimal/variable price and fixed price. The proposed optimal/variable price method reduces the total cost for consumers and improves system performance. However, the opportunity of PEV charging at high-energy demand time is not considered. For the proposed fixed price operating strategy, while minimizing VUF, PEV charging at peak hours could satisfies vehicle owners by quick charging of as many vehicles as possible. Considering constant electricity price, the voltage limits are violated in some of the buses.

- The inclusion of distributed PV and daytime PEV charging option, PEV owners have a chance to charge their vehicles from rooftop PVs. In such cases, the PEVs charge from PVs during the sunlight hours without any voltage profile problems in the network.
- The OL-CD-TPQ, based on droop control, performs centralized active power control and decentralized reactive power control. This proposed strategy results in better voltage regulations and further VUF reductions compared in OL-C-TP due to the use of the reactive power capability of PEVs inverter.
- The optimal online centralized charge/discharge control algorithm (called OL-CD-TPQ) allows the PEV owners to generate reactive power for ancillary voltage service and participate in the energy market based. The total cost decreases for the consumers, and the system performance improves compared to the OL-C-TP strategy. Thus, the PEV owners can participate in the energy market and provide ancillary support.
- The proposed hybrid strategy is a combination of centralized PEV coordination strategy and PEV switching between phases. This results in better voltage regulations and VUF reductions.

8.2 Recommendation for Future Research Scope

This research work could be extended in further by considering the following recommendations:

- In this research considers a typical Australian network for voltage profile and VUF studies. However, the network layouts are different in Australia that those in the US or Canada. Therefore, it is difficult to make a general conclusion. Yet the work can be extended considering larger networks to study the cumulative effects of VUF on transmission networks.

- The model used in this research can be enhanced to include distributed storages such as battery packs and investigate the effect of combination of PEVs, renewable sources and battery storages on the network. Next step is to consider appropriate ESS selection, smart ESS charging and discharging, ESS sizing, placement and operation, power quality issues, optimisation techniques, social impacts and energy security.

- Charging PEVs in the future will not be limited to homes. So, the methodology in this research can be extended to optimize charging vehicles at the public parking lots or charging stations. In addition, the system could be improved by considering the ability of communication between PVs and charging station or public parking with the target of providing low cost PEV charging in the future.

- The possibility of the discharging of multiple batteries per parking session and the impacts of battery degradation could be explored through the implementation of further mathematical modelling of economics and incentives.

- This work assumes that PEV can work in V2G mode and can also support voltage through reactive power injection. However, the cost-benefit analysis needs to be performed in terms of the size and lifetime of the batteries and the size of the inverters.

- Exploitation of PEV as a storage unit with bi-directional power flow can be investigated to mitigate solar and wind power generation fluctuations. Real time data from distribution network can be used for case study to demonstrate PEV utilization for grid ancillary support.

- Applying both, for example combined frequency and voltage regulation by PEVs. In this regard, it is needed to investigate a set of constraints that essential to be taken into account on PEVs' active and reactive power flow to offer ancillary services.
- A number of performance assessment methods could be developed in order to create guidelines for the future regulation of Smart Grids. These performance assessment factors would reflect the success of the aggregator with respect to different perspectives: The owners, The utilities, and Aggregator fairness/economy.

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Appendix A

Publications Included in This Thesis

The main content of the thesis is based on the following articles:

1) **N. Jabalameli**, M. A. S. Masoum, and S. Deilami, "Optimal online charging of electric vehicles considering voltage unbalance factor," in IEEE Power and Energy Society General Meeting (PES), 2017 Chicago, Illinois, USA, 2017.
Partially incorporated as Chapters 2, and 4

2) **N. Jabalameli**, X. Su, and S. Deilami, "An Online Coordinated Charging/Discharging Strategy of Plug-in Electric Vehicles in Unbalanced Active Distribution Networks with Ancillary Reactive Service in the Energy Market," Energies, vol. 12, no. 7, p. 1350, 2019. Partially incorporated as Chapters 2, 4 and 6.

3) **N. Jabalameli**, X. Su, and A. Ghosh, "Online Centralized Charging Coordination of PEVs with Decentralized Var Discharging for Mitigation of Voltage Unbalance," Accepted on IEEE Power and Energy Technology Systems Journal. Partially incorporated as Chapters 2, 4 and 5.

4) **N. Jabalameli**, X. Su, and A. Ghosh, "Stochastic Assessment of Plug-in Electric Vehicles Charging in LV Distribution Network on Voltage Unbalance," Accepted for presentation in 9th International Conference on Power and Energy Systems 2019. Partially incorporated in Chapters 2 and 3.

Appendix B

B1. Australian LV Aerial Network

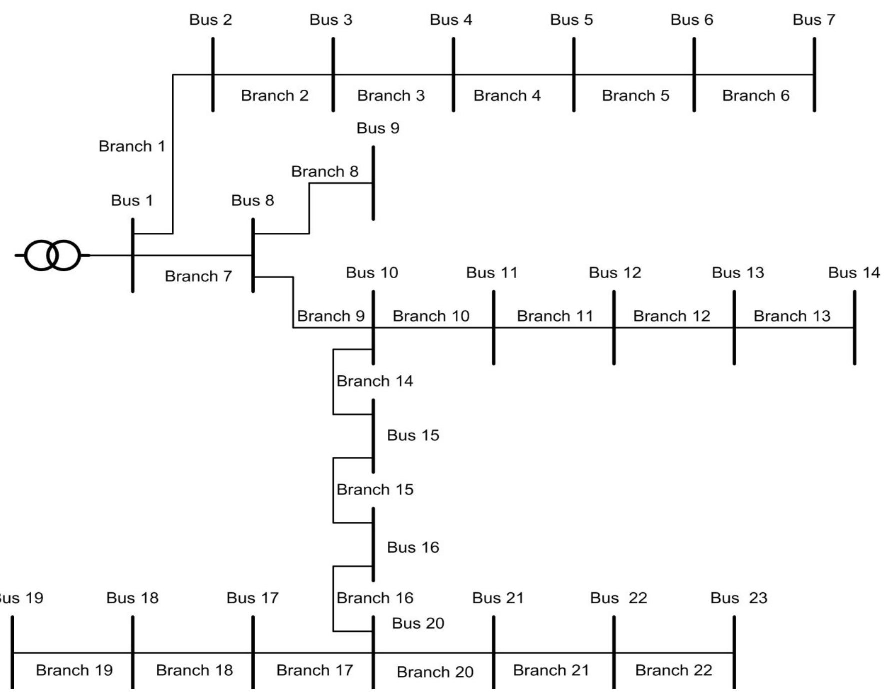

Table B-1 Australian overhead cable parameters

Cable Type	Impedance at 45°C
4x7/3.75 AAC (Mars)	0.452+ 0.304j ohm/km
4x7/4.5 AAC (Moon)	0.316+ 0.292j ohm/km
6 sq mm (Service line)	3.700+ 0.369j ohm/km

Table B-2 Australian overhead system connectivity

From Bus	To Bus	Cable Type	Length (meter)	From Bus	To Bus	Cable Type	Length (meter)
1	**2**	Mars	46	**12**	**13**	Mars	45
2	**3**	Mars	45	**13**	**14**	Mars	45
3	**4**	Mars	42	**10**	**15**	Moon	30
4	**5**	Mars	42	**15**	**16**	Moon	35
5	**6**	Mars	42	**16**	**20**	Moon	35
6	**7**	Mars	39	**20**	**17**	Moon	45
1	**8**	Mars	44	**17**	**18**	Moon	45
8	**9**	Mars	45	**18**	**19**	Moon	45
8	**10**	Mars	44	**20**	**21**	Moon	43
10	**11**	Mars	46	**21**	**22**	Moon	25
11	**12**	Mars	44	**22**	**23**	Moon	23