OPTIMAL CHARGING COORDINATION OF PLUG-IN ELECTRIC VEHICLE INCORPORATING CAPACITOR AND OLTC OPERATION

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OPTIMAL CHARGING COORDINATION OF PLUG-IN ELECTRIC VEHICLE INCORPORATING CAPACITOR AND OLTC OPERATION

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OPTIMAL CHARGING COORDINATION OF PLUG-IN ELECTRIC VEHICLE INCORPORATING CAPACITOR AND OLTC OPERATION

ABSTRACT

Electric utilities are concern with the impacts of new generations of smart appliances such as Plug-in Electric Vehicles (PEVs) on the performances, efficiency, stability and reliability of the distribution systems. It is well known that random PEVs charging activities in distribution system largely deteriorates the performance of the distribution system as it increases power loss, voltage deviation and transformer overload. As a result, the overall operational cost is increased significantly. These issues can be overcome by scheduling the PEV charging activities that decides which PEV will take charge in what time. Many researches have been carried out to mitigate the stated issues of distribution system by scheduling the PEV charging. This research proposes an optimal PEV charging coordination incorporating capacitor switching and on-load tap changer (OLTC) adjustment. The main consideration in this research is to minimize the daily power loss and voltage deviation. The capacitor and OLTC operation is utilized here in order to further improvement of voltage profile. It is found that, the proposed method gives minimum power loss and voltage deviation during the PEV charging activities. To implement the proposed method, two meta heuristic optimizations- binary particle swarm optimization (BPSO) and binary grey wolf optimization (BGWO) are employed. Apart from that, time of use electrical tariff is considered to minimize the charging cost when the PEV charging coordination is made. The proposed approach is coded in MATLAB and tested on modified 449 nodes residential distribution system. It consists of 22 low voltage feeders and each feeder has 19 nodes which represent each residential household. For the wide range of feasibility of the proposed method, different PEV penetration levels (16%, 32%, 47%, 63%) are studied. The simulation results for optimal PEV charging coordination incorporating capacitor switching and OLTC adjustment showed that proposed method reduced the system stresses and enhanced the performances of PEV charging coordination.

Keywords: Plug-in Electric Vehicle, Coordination, Distribution system, Optimization, Charging cost.

PENYELARASAN PENGECASAN OPTIMUM KENDERAAN ELEKTRIK PALAM MASUK MENGGABUNGKAN KAPASITOR DAN OPERASI OLTC

ABSTRAK

Utiliti Elektrik prihatin dengan kesan peralatan pintar generasi baru seperti kenderaan elektrik (PEVs) jenis palam yang merangkumi isu prestasi, kecekapan, kestabilan dan kebolehpercayaan di dalam sistem pengagihan. Memang diketahui bahawa aktiviti mengecas PEVs yang berlaku secara rawak di dalam sistem pengagihan telah menyebabkan prestasi sistem pengagihan merosot kerana ia meningkatkan kehilangan kuasa, voltan sisihan dan beban lebih kepada alatubah. Hasilnya, kos keseluruhan operasi meningkat dengan ketara. Isu-isu ini dapat diatasi melalui penjadualan aktiviti mengecas PEV yang menentukan waktu mengecas bagi setiap PEV. Banyak penyelidikan telah dijalankan bagi menangani isu-isu yang dinyatakan dalam sistem pengagihan dengan menjadualkan pengecasan PEV. Kajian ini mencadangkan penyelarasan pengecasan PEV yang optima yang menggabungkan pensuisan kapasitor dan pelarasan OLTC. Pertimbangan utama dalam kajian ini adalah untuk meminimakan kerugian kuasa harian dan voltan sisihan. Kapasitor dan operasi OLTC digunakan bagi meningkatkan profil voltan. Kajian ini mendapati bahawa kaedah yang dicadangkan telah meminimakan kehilangan kuasa dan voltan sisihan semasa aktivit pengecasan PEV. Bagi melaksanakan kaedah yang dicadangkan, dua pengoptimuman meta heuristik (binary particle swarm optimization (BPSO) dan binary grey wolf optimization (BGWO) akan digunakan. Selain itu, masa penggunaan tarif elektrik juga diambil kira bagi meminimakan kos pengecasan apabila penyelarasan pengecasan PEV dilaksanakan. Pendekatan yang dicadangkan telah dikodkan dalam MATLAB dan diuji pada sistem pengagihan perumahan dengan 449 nod yang diubahsuai. Ia terdiri daripada 22 suapan voltan rendah dan setiap suapan mempunyai 19 nod yang mewakili rumah kediaman. Untuk pelbagai kemungkinan kaedah yang dicadangkan, pelbagai tahap penembusan PEV berbeza (16% 32% 47%, 63%) dikaji. Keputusan simulasi bagi koordinasi pengecasan PEV yang optima yang menggabungkan pensuisan kapasitor dan pelarasan OLTC menunjukkan bahawa kaedah cadangan ini telah mengurangkan tekanan sistem dan mempertingkatkan prestasi koordinasi pengecasan PEV.

Katakunci: Kenderaan elektrik pasang masuk, Koordinasi, Sistem Pengagihan, Pengoptimuman, Kos Pengecasan.

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LIST OF SYMBOLS AND ABBREVIATIONS

AI	:	Artificial intelligent
ACA	:	Ant colony algorithm
DSM	:	Demand side management
DG	:	Distributed generation
FACTS	:	Flexible AC transmission systems
G2V	:	Grid-to-vehicle charging
HV	:	High voltage
LV	:	Low voltage
IP	:	Internet protocol
OLTC	:	On-load tap changer
PEV	:	Plug-in electric vehicle
PSO	:	Particle swarm optimization
PHEV	:	Plug-in hybrid electric vehicle
PLC	:	Powerline communications
BPSO	:	Binary particle swarm optimization
RES	:	Renewable energy sources
SG	:	Smart grid
SOC	:	State of charge
V2G	:	Vehicle to grid charging

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CHAPTER 1:

INTRODUCTION

1.1 Overview

Plug-in Electric Vehicles (PEVs) -one of the most promising low emission vehicles- are getting popularities in recent years. The PEVs are propelled by an electric motor powered by the rechargeable battery, instead of internal combustion engine (ICE). Although, the electric vehicle has a much longer history, it was declined for more than a century. For a variety of reasons, including technological advances, environmental concerns, the market for electric vehicles is poised for a dramatic revival. Diminishing the natural sources of fuel oil and increasing the price of oil have driven the transportation sector to resume PEV market. Electric vehicles generate a range of short-term and long-term benefits such as innovation spillovers, and reduced reliance on oil. The electric vehicles are beneficial and cost effective to vehicle users and transportation sector. The lower charging and maintenance cost is another reason behind its huge popularity in current years (Clement-Nyns, Van Reusel, & Driesen, 2007).

From the technical point of view, electrification in the transportation system has opened a new era. Electric vehicles convert about 59-62% of the electrical energy form the grid to power at the wheels whereas conventional gasoline vehicles only convert about 17-21% of the energy stored in gasoline to power (Bansal, 2005). Electric motors often achieve 90% energy conversion efficiency over the full range of speeds and power output that can be precisely controlled. They can also be combined with regenerative braking systems that have the ability to convert movement energy back into stored electricity. This can be used to reduce the total energy requirement of a trip. From the environmental point of view, the dependency on fossil fuel is decreasing and there is no carbon dioxide, sound as well as heat emission from those vehicle (Raskin & Shah, 2006). These development guides the world to a modern and technologically sound human life. Many countries have already been initiated in order to reduce environmental pollution, which influence financial incentives on the sales of electric vehicles (Clement-Nyns, Haesen, & Driesen, 2009).

However, due to its various benefits on human life, the percentage of PEV integration on the transportation sector is dramatically increased. Many researchers are predicting the increment of PEV in next few years. As part of predicting future PEV uses, Pike Research (Adnan, Nordin, & Rahman, 2017) carried out a study about the adoption of PEV for thirty countries in the year 2012 and found incentives as a slightly positive as well as statistically influenced. According to new report from pike research, cumulative sales of PEV exceeded 1.4 million units in Asia Pacific region during the period from 2010 to 2015. It is found that the number of PEV is increasing dramatically particularly in China. The same increments are found in other Asia Pacific region countries. Moreover, around 18,967 units PEV were sold in Malaysia in 2013 whereas in Thailand, the ASEAN automotive market leader has sold 37,530 units PEV. On the other hand, the sale of PEV in the US hit around 88,000 units in the year 2014 (Segawa, Natsuda, & Thoburn, 2014). However, in recent years, the PEV has shown greater market success in western countries such as USA, UK, Netherland, Spain and so many.

Basically, PEV utilizes large battery capacity which require frequent charging to run high power rated motors (Clement-Nyns, Haesen, & Driesen, 2010). The batteries of PEV are charged at home or other commercial locations through the standard electrical power outlets. The PEVs load are considered as extra-large electrical consumption on distribution system. These PEV charging activities causes significant potential risk to the distribution system such as severe voltage fluctuations, excessive power loss and substation transformer overloading. Consequently, the overall performance of the system efficiency is degraded. Moreover, too large voltage deviation causes reliability problem which must be avoided to assure good operation of electric appliances. From the PEV owner point of view, the batteries of the PEV have to be charged overnight, so the driver can drive off in the morning with a fully charged battery. Though, overnight charging can also increase the loading of base power plants. In support of this PEV integration challenges on distribution system, two strategies of PEV charging in distribution system are proposed (García-Villalobos, Zamora, San Martín, Asensio, & Aperribay, 2014). The first strategy involves uncoordinated PEVs charging, which is possible via either upgrading the distribution system infrastructure or deploying Distributed Generation (DG) units to meet the excess power demand. However, the outcomes of this strategy are not effective for both PEV customer and utilities. The second strategy targets coordinated PEVs charging that relies on the availability of a two-way communication infrastructure under the smart grid paradigm. Coordinated PEV charging scheme are known to be more beneficial to the customers and distribution network operators (Hajforoosh, Masoum, & Islam, 2015). From the above study, it is found that the researchers have taken initiatives to develop PEV charging coordination in smart power grid infrastructure.

1.2 Problem Statement

PEVs charging impose new sizable loads to the distribution system compare to regular household electrical load. If the PEV charging activities are not managed appropriately, it may result potential risk such as increase in system stress and degrade the overall system performances. In uncoordinated charging scenario, PEVs arrives at charging point and starts charging without considering the system constraints. Consequently, it results power quality and reliability issues of the distribution system. Uncoordinated PEV charging raises load peaks or sometimes creates new load peaks that deteriorate the system efficiency and economy. High penetration of PEV charging causes severe voltage fluctuations and extreme power loss on the local distribution system. Moreover, transformer overload, fuse blowouts, system blackouts may happen frequently due to uncoordinated PEV charging.

To overcome these issues, some recent publications have studied the easy integration of PEV charging in the distribution system. In recent years, researches are continuing to enhance the distribution system performances during the PEV charging activities. From the previous studies, PEV charging coordination has been proposed in distribution system using different strategies and optimization methods. All the proposed strategies have been demonstrated to reduce the potential stress, improve the system performances and maximize the customer benefits.

From the preceding studies, in can be seen that few researches have been considered the minimization of daily power loss and voltage deviation together in the PEV charging coordination. All studies have considered the same charger capacity (4kW) and battery size (10kWh) in every node which is not feasible in practical scenario. Since the charger capacity and battery size are becoming larger to increase the mileage in recent years, higher PEV penetration with larger capacity of charger (such as 6.6kW, 7.2kW) in distribution system need to be studied. Moreover, different level of initial and required state of charges (SOCs) are have not been considered in previous studies.

Due to the larger capacity of PEV charger, the voltage profile at far node from the substation is lower. The stated studies have focused on PEV charge scheduling, however, the means of improving the voltage profile of distribution network during the PEV charge scheduling is yet to be explored. Therefore, it is important to improve the voltage profile in all low voltage feeders when the PEV charging coordination is made. Power system equipment's such as capacitor, on-load tap changer (OLTC) operation can be utilized in voltage profile improvement.

Apart from that, the computational effort to solve the PEV coordination problem increases with the penetration level of PEVs as well as the size to network. The PEV charging coordination is a dynamic and real time (Δt =5min interval) optimization problem which needs less computational time and faster convergence. As a consequence, it is challenging to solve the problem using classical optimization techniques. Therefore, meta-heuristic optimization algorithms are employed in PEV charging coordination as well as capacitor switching and OLTC adjustment in the residential distribution system.

Furthermore, there are few researches where energy generation cost is considered to minimize while the PEV charging coordination is made. None of them tried to consider PEV charging cost minimization for the benefit of PEV customer. It is imperative to develop a strategy along with PEV charging coordination to minimize the PEV charging cost. To address these stated gap, this research proposes a PEV charging coordination incorporating capacitor switching and OLTC adjustment using binary particle swarm optimization (BPSO) and binary grey wolf optimization (BGWO). The main consideration in the optimization process is to minimize the total power loss and voltage deviation in each bus. Moreover, time of use electrical tariff is included into the proposed method to make economic benefit for the PEV customer by minimizing charging cost.

1.3 Research Objectives

The aim of this research is to propose an optimal PEV charging coordination strategy considering capacitor switching and OLTC adjustment to minimize the power loss and voltage deviation. The objectives that need to be achieved are as following:

1. To propose optimal PEV charging coordination minimizing power loss and voltage deviation considering different capacity of charger and level of SOC using BPSO and BGWO.
2. To integrate capacitor switching and OLTC adjustment in the proposed PEV charging coordination to improve further the voltage profile of the network.
3. To consider time of use electrical tariff in determining PEV charging to minimize the charging cost.

1.4 Scope of Research

In this study, a PEV charging coordination is proposed to minimize the power loss and voltage deviation during the PEV charging activities. Capacitor switching and OLTC adjustment are considered and coordinated in the proposed method to improve the performance of distribution system particularly voltage profile. Moreover, time of use electrical tariff is included in the proposed PEV charging coordination to minimize the PEV charging cost. Throughout this study, all the system constraints are considered and PEV customer satisfactions are maintained. The proposed method in this research employs two meta-heuristic algorithms BPSO and BGWO which are recently introduced and widely used in power system research. A total five cases are carried out to demonstrate the performance of the proposed method.

1.5 Methodology of Research

The main contribution of this research is to propose a PEV charging coordination incorporating capacitor switching and OLTC adjustment. The switchable capacitor and OLTC are applied here so that the voltage can be improved in all buses during the PEV charging. In order to successfully carry out the proposed research objectives, the following methodologies are studied:

1) Journal review of previous researches related to PEV charging activities in distribution network. The researches on capacitor and OLTC operation are also studied
2) Model a distribution network consisting of PEV charging activities for different PEV penetration level.
3) Propose a PEV charging coordination method using meta-heuristic optimization considering different objective function.
4) Investigate the performances of proposed method as well as the distribution system for different objective function and select the best performed objective function.
5) Develop a method to incorporate the power system equipment's such as capacitor, OLTC into proposed PEV charging coordination.
6) Compare the performance of the method after and before adding the capacitor and OLTC operation.
7) Propose a method to include time of use electrical tariff for cost effective PEV charging in a day.

1.6 Dissertation Outline

This dissertation consists of six chapters, where every chapter has reported the related topic briefly.

Chapter 1 provides the background and motivation of the proposed research followed by problem statement. The objectives of study are presented followed by research scope. At the end, research methodology and research report outline are given.

Chapter 2: This chapter starts with general overview of smart grid and PEV. Two types of PEV charging coordination strategies are discussed here. The section of coordination technique for PEV charging involves strategy, optimization algorithm, methodology, system constraints, system priorities, objectives and solver or tools. Moreover, a comprehensive study is carried out regarding capacitor and OLTC operation in the distribution network.

Chapter 3: In this chapter, the methodology of the proposed PEV charging coordination is presented. In the start, the objective function with the considered constraints are presented. The explanation of proposed charging cost minimization strategy with the flowchart is presented. Then, the implementation BPSO and BGWO in the proposed are described in detail.

Chapter 4: The distribution system modelling consisting of PEV charging activities with PEV penetration level is done in this chapter. Moreover, several types of PEVs with charger and battery are described. Furthermore, the selection of capacitor and OLTC is carried out in this chapter.

Chapter 5: The simulation results are presented and the performance of the proposed method is analyzed. The analysis is focused on the minimization of power loss and voltage deviations employing meta-heuristic algorithm. The validation and robustness of the proposed method are highlighted at the end of this chapter.

Chapter 6: Finally, this chapter finalizes the summary of this work. The main contribution of this research work and recommendation for future work are discussed.

CHAPTER 2:

BACKGROUND AND LITERATURE REVIEW

2.1 Introduction

Due to the numerous aspects of green transportation, the existing smart grid is penetrated highly with the Pug-in Electric Vehicles (PEVs) charging activities. PEVs are driven by an electric motor powered by rechargeable battery packs which are the substitution of internal combustion engine vehicles (ICEVs). These batteries can be charged from any standard electric outlet at home, corporate or public car park. During the charging activities, it consumes large amount of electricity that entail potential risk to the distribution system, even with the low penetration of PEV. In addition, the PEV user's encouragement to use environment friendly transportation may no longer exist if they face difficulties in charging their vehicles during their demand. Therefore, the charging activities of PEVs in distribution system is a challenging demand side management from the utilities perspectives. Many research works have studied the integration of PEV charge activities in distribution system to improve the system performance. However, due to rapid growth of electricity demand, the distribution system is frequently operated under deficient performance. Hence, these bring the momentum for the researches to optimize the operation of additional power system equipment's such as capacitor and on-load tap changer (OLTC) to improve system performances during PEV charge activities.

In this chapter, different approaches and strategies of smart charging of PEVs are figured out. The chapter has been started with the brief introduction of smart grid infrastructure and PEVs specification as well as its operation in distribution system. Moreover, different strategies of capacitor and OLTC operation in distribution system have been described.

2.2 Smart Grid

The traditional AC power grid system is an electrical framework which is utilized to supply the electricity to a large number of users. Generally, the AC power grid consists of three important parts- generation, transmission and distribution. The modern smart grid is an improvement of twentieth century power grid. The modern smart grid is able to utilize two-way flows of electricity and information to develop an advanced electrical network. In contrast to the traditional power grid, the smart grid can be operated and controlled automatically. However, in recent years, the renewable energy resources such as wind, photovoltaic- are integrated to enhance the strength of smart grid. Moreover, modern power apparatus such as smart meters, state-of-the art real-time controllers, smart home appliances make concept of the smart grid more efficient. Therefore, smart grid is able to respond to wide ranging circumstances and events very fast (Gharavi & Ghafurian, 2011). Due to the emerging possibilities of improvement, capabilities and various upgraded functions for smart grid, the researchers focus on smart grid from different perspectives.

2.2.1 Smart Grid Infrastructure

The main components of smart grid infrastructure are energy, information and communication framework which provides two-way flows of electricity and information. The smart grid offers bi-directional electrical energy supply where the users can inject electric power to the grid as well. For instance, the end users may be able to produce electricity using solar system at home and deliver to the main grid. Moreover, electric vehicle is one of the extensive source of electricity which can be used to balance loads by peak shaving (return stored electricity to the grid to meet the high demand). However, the smart grid infrastructure is divided into three major subsection- smart energy subsection, information subsection and communication subsection (Fang, Misra, Xue, & Yang, 2012).

2.2.1.1 Smart Energy Subsection

In the smart energy subsection, advanced electricity generation, distribution and consumption are managed in efficiently. Electricity generation is the very first section of the smart grid and it has two-ways flow of electricity and information capability. Moreover, integration of renewable DGs to improve the power quality and reliability makes smart grid more adequate. The second section of smart grid is transmission system which is comprised by various innovative technologies, although its infrastructure is the main challenge. The last section of smart grid is distribution system where the electric energy is delivered to the end users. The main challenge in the distribution system is to maintain the power quality with the minimum power loss. However, in recent years, DGs are integrated in distribution system to overcome this challenge (Ruiz-Romero, Colmenar-Santos, Mur-Pérez, & López-Rey, 2014).

2.2.1.2 Smart Information Subsystem

The smart information section provides the smart metering, monitoring and management services in smart grid which established the smart grid as automated system. Many recent innovations in information technology can be addressed in smart grid automation. For example, interoperability of data exchanges and integration with existing and future devices, systems, and applications can be integrated to the smart grid (Fang et al., 2012). Hence, smart information section is one of the important part of smart grid to support information generation, modeling, integration, analysis, and optimization.

2.2.1.3 Smart Communication Subsystem

Different smart grid uses different types of communication technologies. The network structures and devices also depend on various aspects, although every smart grid phenomena are same. The smart communication subsection establishes the connectivity among the systems, devices, applications and shares the information in smart grid. In recent years, smart grid is becoming more flexible and automated after introducing wireless technologies in smart grid communication infrastructure (Gungor et al., 2011).

2.2.2 Smart Management System

The advanced smart grid utilizes the two-way flows of electricity and information which established the infrastructure to deal with different functions related to electrical energy. Currently, various emerging technologies are being adopted to improve the energy efficiency, reduce operational cost, control detrimental emission, balance the demand and supply. Due to the adoption of advanced technologies in smart grid, many management goals are achievable which were infeasible in traditional power grid. So far, the researchers have focused on increasing energy efficiency, improving demand profile, cost optimization, price stabilization and emission control. To obtain these goals, the researchers employ optimization, machine learning, game theory and auction as the main tools to determine different smart grid management issues (Fang et al., 2012). Figure 2.1 shows a simple electricity distribution system consisting PEV charging activities. A simple residential distribution system with PEV charging is presented in Figure 2.1.

Figure 2.1: Distribution system populated with Plug-in Electric vehicles

2.3 Plug-In Electric Vehicles (PEVs)

The global energy consumption is increasing very quickly, and greenhouse emission is becoming unavoidable treats to the human being and plants. Generally, a massive amount of fossil fuel (e.g. diesel, petrol) are burned in the transportation sector everyday which results substantial environment pollution. Moreover, fossil fuel-based electricity generation is another source of pollution. The residential houses also produce around 6% of total greenhouse gases (Tushar, Assi, Maier, & Uddin, 2014). However, substantial amount of electrical power loss is one of the major concern in electricity industry. Long distance of transmission and distribution networks are one of the reason of power losses and power outages (Clement-Nyns et al., 2010; Sortomme & El-Sharkawi, 2011; Tushar et al., 2014). Therefore, the smart grid is being upgraded utilizing smart technologies to overcome these stated issues. Additionally, Electric Vehicles (EV) like Plug-in Electric Vehicles (PEV) are introduced to overcome environment pollution and greenhouse emission issues.

PEVs are driven by an electric motor powered by rechargeable battery packs which are the substitution of internal combustion engine vehicles (ICEVs). In recent years, PEVs are getting more popularities due to the increasing cost of fossil fuels. Therefore, many prominent car manufacturers have taken step to introduce PEVs into the transportation sector. For example, Chevrolet Volt, Nissan Leaf, BMW i3, Toyota Prius, Ford Focus Electric Ford C-Max, Mitsubishi i-MiEV, Tesla ModelS, Holden Volt and Honda Fit EV, Mercedes B-Class, can be mentioned here.

2.3.1 Importance of PEVs

The PEV has brought enormous benefits including lower maintenance cost with no greenhouse emission. Moreover, some of the advantages of PEVs can be described as follow:

* **Lower Operational and Maintenance Cost:** The PEVs are considered as energy efficient transportation as its energy efficiency is 80%. On the other hand, the conventional engine using gasoline and diesel has 15% and 20% efficiency respectively. (Hawkins, Singh, Majeau-Bettez, & Strømman, 2013; Van Mierlo, Maggetto, & Lataire, 2006). Moreover, PEV does not consume energy in rest mode and some of the braking energy (around 20%) can be convertible through the regenerative braking. It has advantages of lower maintenance over internal combustion engine. PEV does not need oil changes and it last longer.
* **Negligible Greenhouse Gas Emissions:** Since the PEV uses electrical energy stored in rechargeable battery, it does not emit any harmful pollutions and greenhouse gases (Zielinska, Sagebiel, McDonald, Whitney, & Lawson, 2004). However, in one sense, PEVs are also responsible for environmental pollution as electric generation plants produce greenhouse gases. The benefits of PEV is that it saves the air in populated area.
* **Less dependence on Oil:** One of the great benefits of PEVs particularly reduces the dependency of oil. Due to the geographical location, PEVs have a new face to the transportation sector for oil importing countries. As a consequence of this, oil importing countries could improve economically and develop of their own sources of energy.
* **Noise reduction:** In contrast of conventional vehicles, PEV produce negligible roadway noise since it operates in lower speeds (Emadi, Lee, & Rajashekara, 2008). Although, this less noise produced vehicle has great advantages, but sometimes it could be harmful for the blind and visually defective people. Nevertheless, it can be solved utilizing the technological advancement.

2.3.2 Energy consumption by PEVs charger

The energy consumption by the PEV charger depends on the battery size and its SOC. Therefore, it is important to consider the battery capacities to develop the realistic model of PEV charging loads. Generally, different PEV manufacturers use different capacities of battery range from a few kWh to around 50kWh (Deilami, Masoum, Moses, & Masoum, 2011). Generally, the depth of discharge (DOD) of deep cycle batteries in PEV is assumed 70% of the rated battery life. Hence, from a PEV 10kWh battery, 7kWh is useable energy that must be charged by the charger. Since, the battery charger efficiency is not 100% and it has some losses in AC to DC conversion, the actual power consumption from the grid is higher than the stated battery capacity. Conventionally, the efficiency of a battery charger is assumed 88%, which requires a total 8kWh of energy to charge a simple PEV battery (Duvall, Knipping, Alexander, Tonachel, & Clark, 2007).

In the practical scenarios, the PEV batteries must be charged in acceptable time designated by the PEV users. Therefore, the battery charger is always rated high enough in delivering the power to the battery very fast. However, it is important to maintain the household wiring in safe operation. A typical 1-phase 240V electric outlet can deliver maximum 2.4kW. Some 15A and 20A outlets (1-phase and 3-phase) are also exists which can deliver generally 4kW and 14.4kW respectively (Alonso, Amaris, Germain, & Galan, 2014). In this research, three different capacities of chargers (3.3kW, 6.6kW and 7.2kW) are considered, since these chargers are relatively common in the recent PEV's market. Moreover, these chargers are adaptable in residential distribution system without reinforcing the electrical outlets.

2.3.3 Impacts of PEVs Charging on Smart Grid

The PEVs are propelled by electrical energy stored in rechargeable battery which are charged from any standard electric outlet at home or any commercial parking space.

However, this PEV charger is considered as a sizable load compare to the residential demand and could significantly stress the distribution network. The higher PEV penetration causes transformer and cable overloading, degradation of the system performances as well. These sorts of conditions lead the distribution system to lower reliability, higher blackout and operational costs. Since the PEV is driven fully by electrical power, it needs frequent charges from the distribution system. The charger capacity is also relative higher as the battery size is large enough to drive the vehicle at certain millage. Therefore, the PEV charger loads impose extra peak demand into predictable daily residential demand. In addition, the time and duration of PEV charger activities in distribution system are unpredictable since it depends on the PEV users only. Furthermore, in recent years, the PEV penetration in the distribution system is rapidly increasing due to its numerous advantages. However, it can be presumed that most of the PEVs arrive at the charging point in the evening during the peak demand of residential load.

The adverse impacts of PEV charging activities with higher penetration level on residential distribution network are yet to be explored. However, the researchers have found some of the unavoidable impacts of PEV charging activities in the distribution system as follows:

- Distribution transformer as well as feeder overloads may lead to power blackouts due to unacceptable PEV charge integration.
- Extreme and undesirable surge in daily power loss during the peak loads.
- Substantial PEV load on distribution system can cause a large voltage deviation.
- Excessive power loss during the PEV charging at peak consumption hour is an economic concern for utilities perspective.

- Poor voltage profile, mainly at the peak hour in a certain node is a power quality concern for distribution system.

2.4 Review on PEV Charge Coordination Strategy

To overcome the impacts of PEV on distribution network and to smoothen the PEV charging activities, many coordination strategies are proposed and implemented. However, PEV charging coordination offers technical and economic benefits for both PEV customer and utilities by scheduling the PEVs charging. This type of charging strategy is called simply active control of loads (García-Villalobos et al., 2014). The optimization or heuristic optimization is applied to achieve certain objectives, such as- avoid transformer overloading, minimize generation cost, prevent excessive power loss and reduce voltage sag etc. In order to implement the technical and economic management of PEV charging schedule, the existence of an aggregator is required. The aggregator builds the bridge between the PEVs of a certain region with the respective distribution system. All the PEV's chargers within a region are monitored and controlled through the aggregator (Bessa & Matos, 2012). The goal of that research is to develop a practical implementation of PEVs into electricity market. From the previous studies regarding PEV charging control in distribution system, two main control architectures are found. Generally, centralized and decentralized control architectures are used in PEV charging coordination.

2.4.1 Decentralized coordination

Decentralized control architecture does not rely on a central control unit. Here, each PEV owner is responsible to select its own charging timeslot. Although the decision of "when and how much charge" is taken by the PEV users, these decisions can be influenced by some ways. In this case, the aggregator can send price and control signals to each PEV maintaining the system constraints. Then, each PEV can chose the time and required energy to optimize the cost autonomously. The PEV owner be motivated to response to virtual price signal offered by the utility side. However, there are various decentralized PEV charging coordination methods have been proposed considering different objectives, strategies and tools.

To minimize the PEV charging cost and reduce the load fluctuation using a non-cooperative game approach for a building, a decentralized control has been proposed in (Nguyen & Song, 2012). In this solution, the building controller sends the total load data of the building to each PEV customer. Then the PEV customer select the charging timeslot and charge amount in order to pay as less as possible. This procedure is done in rounds and repeated until convergence is reached. Similarly, to fill the maximum demand at the off-peak hours optimally, (Gan, Topcu, & Low, 2013) proposes an iterative algorithm. In each iteration, PEVs update their charging profile and control signal is updated the algorithm converges. To implement this solution, the customer preferences are considered and the algorithm is adapted for real time operation.

A game theoretic approach algorithm has applied in (Sheikhi, Bahrami, Ranjbar, & Oraee, 2013) to minimize the overall charging cost for all PEVs. In this research, the PEV owners driving pattern has been considered. Moreover, a multi-level optimization is adapted in (K. Zhang et al., 2014) to achieve valley-filling effect using price signals scheme. In this technique, the objective at distribution level is minimizing overall generating costs while at user level is minimize the charging cost. However, this control scheme, aimed at cost minimization through price signals, has the drawback as congestion of lines and transformers. Furthermore, a decentralized approach is proposed in (Ma, Zou, Ran, Shi, & Hiskens, 2016) to minimize the charging cost considering local grid and battery effects. This strategy facilitates the tradeoff between total generation cost and the local cost to solve large scale optimization problem.

A multi-agent system was introduced by (McArthur et al., 2007) to implement and organize of decentralized coordination. The system is a set of two or more agents where intelligence is distributed in PEVs. Then, (Karfopoulos & Hatziargyriou, 2013) has proposed and implemented PEV charge coordination based on multi-agent system. Here, each PEV tries to minimize the charging cost employing hybrid PSO technique. At the same time, transformer agent can vary price signals of PEV agents to avoid transformer overloading. However, a real time multi agent system is carried out as decentralized coordination and practically implemented in (Unda et al., 2014). In this research, the authors defined four numbers of different agents and showed that multi-agent system can manage PEVs charging task avoiding transformer overloading.

Moreover, an agent based approach has been proposed to postpone the PEVs charging activities in balancing the fluctuations of renewable energy sources (Dallinger & Wietschel, 2012). In addition, vehicle to grid (V2G) and price signals are considered to enhance the performances of the proposed strategy. Graph search algorithm is used to minimize the charging cost contemplating electricity prices, state of charge (SOC), substation transformer capacity, charging power and battery degradation. On the other hand, avalanche effects occur caused by sudden increases of load demand or generation in decentralized price signal approaches. Therefore, a mechanism to avoid avalanche effects is also proposed in (Dallinger & Wietschel, 2012).

To develop a PEV charge coordination along with the distributed demand response in a residential distribution network, a congestion pricing approach was proposed in (Luo, Xia, & Chan, 2014),(Fan, 2012). In this study, PEV customer preference was considered, such as charging tariff in a certain period of time. Thereby, those PEV will receive faster charging who are willing to pay more. Moreover, a random access framework to schedule the PEV charging is presented in (Zhou & Cai, 2014) to avoid network congestion and voltage drops problems. The control center will monitor load, voltage of buses and agent will schedule the PEV charging based on stochastic probabilities. The stochastic process is also used in (Iversen, Morales, & Madsen, 2014) to schedule PEV charging and model use driving patterns. However, Figure 2.2 shows a simple decentralized architecture of PEV charging coordination.

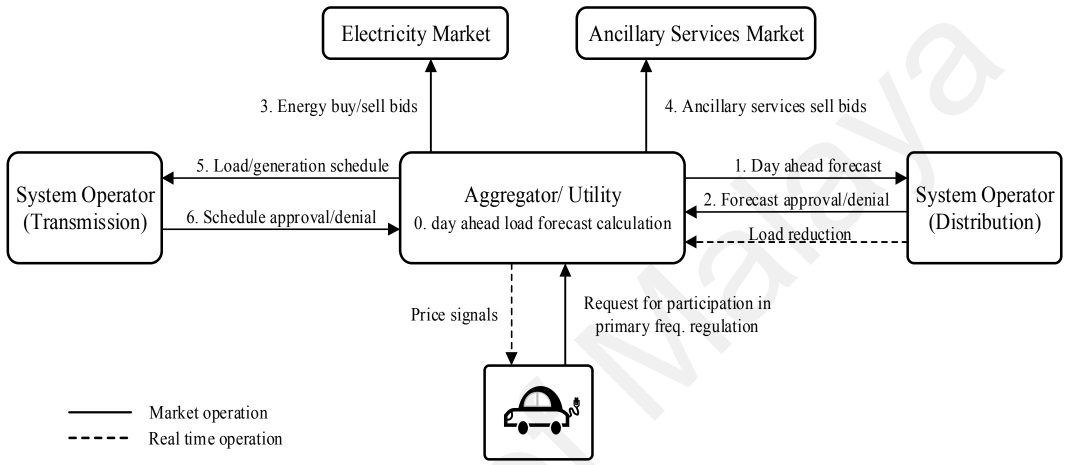


Figure 2.2: Decentralized control architecture presented in (Galus, Vayá, Krause, & Andersson, 2013)

From the above discussion regarding decentralized PEV charging coordination, it is found that there is a hardware base system called agent, which process the necessary data. This agent also works for residential energy management which has all the information and intelligence for PEV charging coordination. Since the PEVs are movable load in distribution network, hence the roaming concept is introduced to ensure the quality of services and features of the coordination.

However, the outcome of decentralized coordination may or may not be optimal, since this coordination depends on local information and signals. In the decentralized coordination, the optimal scheduling for PEV charging can be achieved by sending price or control signal through aggregator. However, the final decision is always taken by the

PEV user, which never guarantee the optimal solution. In addition, simultaneous reactions may occur when substantial number of PEV try to minimize the charging cost by changing their charge rate at the same time. Moreover, limited ancillary services provision and forecasting the reaction of consumers are some drawbacks for decentralized coordination (García-Villalobos et al., 2014).

2.4.2 Centralized coordination

In centralized PEV coordination, the utility is responsible to coordinate vehicle charging by directly considering grid performance improvements while also looking after PEV owners` benefits by postponing vehicle charging to off-peak hours with inexpensive electricity prices. The centralized coordination is also known as direct control where the aggregator manages the charging decision for each PEV within its region. Through the coordination process, the aggregator performs demand forecasts based on previous days data and PEV user's driving behavior. Then, the distribution system operator (DSO) investigates the demand profile for the safe operation of distribution system. However, when the distribution system operates in unusual condition, the aggregator will attempt to resolve the situation to ensure the safe operation of the distribution system.

Since the PEV charging coordination is a real-time operation, the aggregator must need the necessary data such as PEV identification, charger capacity, battery size, initial and required state of charge of battery from each PEV. Hence, the aggregator collects data from each PEV through the communication framework. Then, based on this PEVs information, the aggregator will execute algorithms to achieve certain objectives and fulfils PEV customer's preferences. Figure 2.3 shows a simple centralized architecture of PEV charging coordination

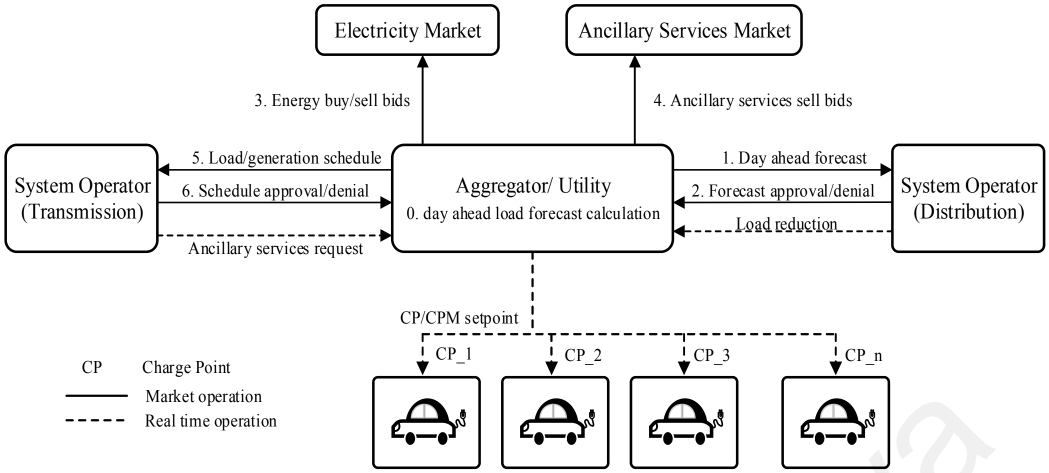


Figure 2.3: Centralized control architecture presented in (Galus et al., 2013)

There are many studies regarding centralized PEV charging coordination with different objectives, constraints and strategies. In addition, many proposed algorithms are found to achieve certain objectives. As a part of this, three different charging algorithms are compared in (Sortomme & El-Sharkawi, 2011) to maximize aggregator profits. Each algorithm focuses to minimize the PEV charging cost for the customer and reduce grid impacts considering electricity prices, PEV load and additional services prices. In order to minimize the difference between demand profile and power demand created by the PEV charging activities, (Soares, Almeida, & Lopes, 2014) proposes a linear optimal solution based on convex optimization. Moreover, this research paper presents a heuristic algorithm to identify the abnormal conditioned feeders and buses. Through this strategy, lines overloading, voltage limitation problems could be solved. An intelligent charging algorithm based on meta-heuristic method is proposed in (Valentine, Temple, & Zhang, 2011) to minimize generation costs. An optimal PEV charge scheduling is developed to minimize the operational cost in (Vayá & Andersson, 2012). Here, each network node consisting PEVs are aggregated into virtual storage resource and then, a multi-period optimal power flow (OPF) is carried out to schedule PEV charging. Total operational cost and CO_2 emissions have been reduced using convex optimization to solve large scale problem in (Zakariazadeh, Jadid, & Siano, 2014). Furthermore, this paper applied fuzzy solution approach to enhance these two objective functions. A heuristic method is proposed in (Lopes, Soares, & Almeida, 2011) to curtail the lines overloading and transformers overloading and improve the voltage profile. This algorithm executes load flow and investigates whether the distribution system is in good operational condition. The algorithm continuously monitors the voltage deviation of the node and system overloading elements. When any of these problems occurs, immediately this algorithm proceeds to stop the charging or adding those PEV to a waiting list. Artificial Immune Systems (AIS) is integrated with a heuristic method to minimize the total power loss considering network constraints. Here, the function of heuristic method is to avoid overloads and voltage limits violations (Oliveira, de Souza, & Delboni, 2013). The same network constraints are taken into account in (Deilami et al., 2011) to minimize the generation cost associated power loss and voltage deviation. In this paper, maximum sensitivities selection (MSS) originated from the combination of heuristic method and objective function is employed. MSS optimization is employed to investigate the impact of PEV charging on distribution network and then a charge scheduling is prepared for each PEV. Three simultaneous PEV charging algorithms are proposed and investigate the better performances in (Sortomme, Hindi, MacPherson, & Venkata, 2011). In the first algorithm, minimization of power loss is considered in PEV charging coordination. Then, minimization of load variance during the PEV charging is considered in the second algorithm. Finally, load factor maximization is studied in third algorithm. Among these three algorithms, the second algorithm based on minimization of load variance is found satisfactory performance since it does not depend on the network topology. On the other hand, third algorithm provides better solution in terms of computation time since computation time is one of the main parameter in real time solutions. To overcome the complexity of computational time, a double layer optimal charging strategy is proposed in (Jian, Zhu, Shao, Niu, & Chan, 2014; Nguyen & Song, 2012).

In centralized PEV charging approach, convex optimization is utilized to carry out the algorithm while quadratic and dynamic programming are used to minimize the total power loss and voltage deviation (Clement-Nyns et al., 2010). Only heuristic methods are used in (Kang, Duncan, & Mavris, 2013; Subramanian et al., 2012) for real time control of PEV charging. However, it is well known that the X/R ratio in low voltage distribution network is low and reactive power control strategy is ineffective to resolve the voltage disturbances. Therefore, active power imposed by PEVs on the low voltage network can be controlled efficiently to improve the voltage profile. This control strategy becomes complex when user's preferences are considered. Since the coordination postpone the charging in off-peak hour and may cause delays for the full charge. Regarding this problem, fuzzy logic strategy is employed in (Singh, Kumar, & Kar, 2012) to control energy flow between the grid and PEVs. By employing this active power control approach, voltage stability of the distribution system is improved and can be easily implemented in a real-time scenario.

A PEV charging and discharging coordination architecture is proposed in (Shaaban, Ismail, El-Saadany, & Zhuang, 2014) that is capable of dynamically managing PEV charger's energy consumption. The architecture comprises prediction and optimization units. In the prediction unit, the PEV arrival and departure information is made and based on these parameters, optimization unit decides the charging schedule for each timeslot. Due to the prediction errors in the optimization parameters, sometimes the output decision of optimization may not be optimal. However, the arbitrary nature of PEV arrival opens the face for mathematical model based on Tabu Search (TS) and Greedy Randomized Adaptive Search procedure (GRASP) (Arias, Franco, Lavorato, & Romero, 2017). The objective is chosen to minimize the total operational costs of the distribution system during the PEV charging activities.

Nevertheless, all the previous PEV charging coordination strategies have considered the same charger size for all the PEV's and the capacity of charger is small (4kW). The battery size, initial state of charge and final state of charge are also same for all PEVs which is not feasible in practical scenario. Different battery sizes and charger types are considered in PEV charging coordination to minimize energy generation cost and power loss in (Hajforoosh et al., 2015). The hybrid fuzzy discrete particle swarm optimization is used to solve the problem. The proposed algorithm failed to address the PEV customer satisfaction. However, a coordinated aggregated particle swarm optimization has been adopted to introduce the variable charge coordination in PEV charging to maintain PEV customer satisfaction in (Hajforoosh, Masoum, & Islam, 2016).

Form the above studies, some of the proposed solutions are failed to address coordinated PEV charging in practical scenario. Based on the recent literature, the different sizes of batteries and chargers are considered in this research which is available in the PEV market. However, the charger capacity has significant impact on the PEV charging coordination as the same capacity of charger from different location gives different power loss. The voltage deviations in the low voltage nodes are increasing which stops the algorithm in non-optimal solutions. As a consequence, the algorithm fails to coordinate the PEV charging due to the voltage constraints and some PEVs are left to be full charged as required. Furthermore, no previous research has introduced the additional power system equipment such as capacitor and OLTC to improve the voltage in low voltage nodes. Therefore, this research integrated capacitor switching and OLTC operation during the PEV charging coordination. The literature review for capacitor switching in distribution system and OLTC operation is described here.

2.5 Capacitor switching

The capacitor in the distribution system is consider an important compensator to improve the security, reliability and power quality of distribution system. In addition, the capacitive compensators can improve the loadability of the line by controlling the reactive power flow (Sallam, Desouky, & Desouky, 1994). To minimize the total loss in every feeder, an optimal capacitor dispatching schedule is presented (Y-Y Hsu & Kuo, 1993) based on a dynamic programming approach. The maximum allowable number of switching operations in a day for each capacitor and the voltage limits on the feeder are considered as constraints to solve the problem. Similarly, a genetic algorithm is employed for optimal selection of capacitor to minimize the peak power loss and energy loss of a distribution system. Moreover, a sensitivity analysis based method is used to select the candidate locations for the capacitors (Sundhararajan & Pahwa, 1994).

2.6 Tap changer adjustment

The voltage of the distribution feeder is controlled by using on-load tap changer (OLTC) and capacitor. An OLTC provides a voltage regulation range from -10% to 10% using 32 steps (Short, 2014) or -5% to +5% using 16 steps (Azimi & Esmaeili, 2013). The process of changing the position of OLTC is called tap changer adjustment. Practically, the voltage of the distribution feeder decreases towards the end of the network. Tap changer adjustment is performed to ensure that the voltage at the feeder end is higher than the minimum allowable limit and the sending end voltage is lower than the maximum allowable limit. Hence, this will solve the voltage drop problem in distribution system.

Many researches on OLTC have been carried out. For instance, a multi-objective optimum dispatch schedules with OLTC adjustment at substations and capacitor based on day ahead load forecast using binary ant colony optimization was proposed in (Azimi

& Esmaeili, 2013). The voltage deviation on the secondary bus of the distribution system, total power loss, number of OLTC's and capacitor operation and voltage fluctuations were minimized. However, tap changer adjustment plays important role in distribution system. Few researches employed tap changer adjustment into distribution system to reduce power loss (Azimi & Esmaeili, 2013; Hu, Wang, Chen, & Taylor, 2003). In addition, some approaches (Feng-Chang Lu & Hsu, 1997) have been reported to solve the reactive power/voltage control problem in a distribution system.

However, the dispatching schedule of capacitor and OLTC is determined in (Yuan-Yih Hsu & Lu, 1998) to minimize the power loss as well as reduce the reactive power flow through the main transformer. Furthermore, optimal dispatch of capacitor and OLTC is demonstrated using a fuzzy optimization approach in (Liang, Chen, & Chen, 2011) to solve the Volt/Var control problem. From the literature review, a study on combination of capacitor switching and OLTC in distribution system considering PEV charging has not been investigated. So far, there is no research that utilizes optimal dispatch of capacitor and OLTC to reduce power loss and voltage deviation during the PEV charge coordination. Therefore, in this research, PEV charge coordination, capacitor switching and tap changer adjustment using BPSO is proposed in distribution system for power loss and voltage deviation reduction.

2.7 Summary

This chapter has described the fundamental PEV charging on distribution system and reviews on the emerging smart grid, PEV specifications and different charge coordination strategies. For the literature review, it concedes some important points-

- Uncoordinated and random PEV charging on distribution system leads extreme power loss and voltage deviation.

- The PEV charge coordination strategy can reduce the power loss of distribution system effectively.
- Only few researches have been considered PEV customer satisfaction during the coordination process.
- Many different methodologies have been proposed and applied to secure the distribution system from the unacceptable impacts of the PEV charging. However, capacitor and OLTC switching have not been applied to improve the network performances during the PEV charge coordination.
- Most of the researches have considered lower capacity of charger (4kW), which is not feasible in practical scenario. From the literature review, different capacity of chargers (3.3kW, 6.6kW, 7.2kW) are found in distribution system.

CHAPTER 3:

RESEARCH METHODOLOGY

3.1 Introduction

In this research, a PEV charging coordination is proposed incorporating capacitor switching and OLTC voltage adjustment. Binary Particle Swarm Optimization (BPSO) and Binary Grey Wolf Optimization (BGWO) are employed in coordination to reduce the power loss and voltage deviation. The proposed method for PEV charging scheduling is analyzed with the dynamic residential load. Moreover, the PEV customer satisfaction is considered in different PEV penetration levels in the network. However, the aim of this research is to develop an optimal PEV charging coordination during the capacitor and OLTC operation. Therefore, a nonlinear objective function has been constructed and adopted to the optimization techniques to determine the PEV charge coordination as well as capacitor switching and OLTC adjustment. A series of constraints are considered to ensure the safe operation of distribution network. Furthermore, a method is included to minimize the cost effective PEV charging activities.

3.2 Problem Formulation

The PEV charging coordination in a distribution system is considered as a real-time optimization problem. The PEV charging coordination in the presence of switching capacitors and OLTC are determined based on minimum system power loss and voltage deviation over 24 hours, while considering maximum demand of the system. The PEV coordination is divided into 288 timeslots of 5min interval. Integration of capacitor switching and OLTC adjustment during the PEV charging coordination splits the proposed method into two parts. One is PEV charging coordination and another is optimal capacitor switching and OLTC adjustment. Moreover, a set of constraints are taken into account to obtain the objective function. The objective function can be formulated as equation (3.1).

$$\min f = \sum_{h}^{24}(P_{loss}^{c} + V_{d}) \tag{3.1}$$

As the objective function has the different units, the final power loss P_{loss}^{c} is calculated as the ratio of total system power loss after P_{loss}^{coord} and before coordination $P_{loss}^{uncoord}$.

$$P_{loss}^{c} = \frac{P_{loss}^{coord}}{P_{loss}^{uncoord}} \tag{3.2}$$

The power loss equation for the distribution system is presented by-

$$P_{loss}^{c} = \sum_{t=1}^{timeslot}(I_{b,t}^{2} \times R_{b}) \tag{3.3}$$

Voltage deviation (V_d) can be defined as the difference between the nominal voltage and the actual voltage. The smaller the deviation of bus voltage from the nominal voltage, the better the voltage condition of the system.

$$V_{d} = Max_{i=2}^{m}\left(\frac{V_{rated} - V_{i}}{V_{rated}}\right) \tag{3.4}$$

V_{rated} is the nominal voltage of the system that is 1.0p.u. and V_i is the voltage at the i^{th} node. *m* is the total number of nodes of the system.

However, in this research, a series of constraints have to be satisfied to achieve the objective function. The constraints are described below:

Maximum demand constraint

$$P_{demand}^{\max} \geq \sum_{i=2}^{n} \left(P_{load} + P_{PEV} \right)_i \tag{3.5}$$

Here, n is the number of branches, $P_{load,i}$ refers to the residential load and $P_{PEV,i}$ denotes the PEV load on i^{th} node and $P_{demand}^{\max}$ is the maximum demand from the substation transformer of the system within 24 hours.

Bus voltage constraint

$$V_{\max} \leq V_i \leq V_{\min} \tag{3.6}$$

$V_{\min}$ and $V_{\max}$ stand for minimum and maximum allowable voltage range respectively. In this work, the voltage limits are specified to ±10% (considered 0.9 pu to 1.1 pu for this distribution system).

State of charge (SOC) constraint

$$SOC_{\text{int}} \leq SOC_{curr} \leq SOC_{req} \tag{3.7}$$

Here, SOC_{int} is the initial state of charge when the battery is plugged-in, SOC_{req} is the requested maximum charge set by the customer and SOC_{curr} is the state of charge after each Δt timeslot.

Operation number for capacitor constraint

Although, capacitors along with the feeder are allowed to switch on and off once a day, the switching of capacitor at secondary bus can occur more than once. It is worthy to mention that, the maximum allowable number of capacitor at secondary bus is perceived as constrained (Hu et al., 2003). The daily number of switching operation for capacitor is enclosed by equation

$$\sum_{h=1}^{24}\left(C_{s,h} \otimes C_{s,h-1}\right) \leq C_{sm} \tag{3.8}$$

Where, $C_{s,h}$ is the status of the capacitor '*s*' at hour '*h*' and C_{sm} is the maximum allowable switching number for capacitor's in a day.

Daily switching number of OLTC constraint

On-load tap changer (OLTC) cannot be switched frequently due to higher maintenance cost and reduction of life expectancy. Therefore, the daily number of switching operation is limited by a constraint.

$$\sum_{h=1}^{L} |Tap_h - Tap_{h-1}| \leq Tap_{\max} \tag{3.9}$$

Here, L is the number of load level in a day. The maximum number of allowable switching operations of OLTC is 30 times a day (Liang & Cheng, 2001).

The tap changer has to have 17 tap positions (-8,-7, … 0, 1, 2, …,8) (Azimi & Esmaeili, 2013) and the voltage can be changed from -5% to +5%. Therefore, the lower and upper voltage limits for the tap changer are 0.95 per unit and 1.05 per unit respectively. Throughout the optimization process, the tap changer adjustment is functioning in terms of its corresponding voltage that corresponds to the tap changer position as shown in Table 3.1.

Table 3.1: Tap changer position and its corresponding voltage

Tap changer position	**Voltage value that represents the tap changer position (p.u.)**	**Voltage range of tap changer position, V_{tap}**
-8	0.95000	$0.95000 \leq V_{tap} < 0.95313$
-7	0.95625	$0.95313 \leq V_{tap} < 0.95938$
-6	0.96250	$0.95938 \leq V_{tap} < 0.96563$
-5	0.96875	$0.96563 \leq V_{tap} < 0.97188$
-4	0.97500	$0.97188 \leq V_{tap} < 0.97813$
-3	0.98125	$0.97813 \leq V_{tap} < 0.98438$
-2	0.98750	$0.98438 \leq V_{tap} < 0.99063$
-1	0.99375	$0.99063 \leq V_{tap} < 0.99688$
0	1.00000	$0.99688 \leq V_{tap} < 1.00313$
1	1.00625	$1.00313 \leq V_{tap} < 1.00938$
2	1.01250	$1.00938 \leq V_{tap} < 1.01563$
3	1.01875	$1.01563 \leq V_{tap} < 1.02188$
4	1.02500	$1.02188 \leq V_{tap} < 1.02813$
5	1.03125	$1.02813 \leq V_{tap} < 1.03438$
6	1.03750	$1.03438 \leq V_{tap} < 1.04063$
7	1.04375	$1.04063 \leq V_{tap} < 1.04688$
8	1.05000	$1.04688 \leq V_{tap} < 1.05000$

3.3 Proposed PEV charging coordination, capacitor switching and OLTC adjustment using Binary Particle Swarm Optimization (BPSO)

The BPSO is first proposed by (James Kennedy & Eberhart, 1997) is a swarm intelligence technique, which was inspired by the social behavior of bird flocking and fish schooling. However, BPSO is introduced to allow the conventional particle swarm optimization (PSO) algorithm (James Kennedy & Eberhart, 1995) to operate in binary problem spaces. In BPSO, the search space is considered as a hypercube shape where particles move to nearer and further edge of the hypercube. The movement of particles is done by flipping of the bits. The movement of the particle is defined as the velocity and it is adjusted stochastically based on previous best position for the particle itself. In the same time, the neighborhood best position is also considered in the particle movement. The moving velocity is defined in terms of changes of probabilities that a bit will be in one state or the other. Therefore, a particle moves in a state space between '0' and '1' in each dimension. The particle best and neighborhood best are determined based on the selected objective function (J Kennedy, Eberhart, & Shi, 2001). The nature of the particle movement in BPSO is generally emerged to an optimal or near-optimal solution. Therefore, BPSO can be employed in wide range of optimization problems in power system application. So far, many researches are found in past few years that focused on the application of BPSO in power system (Chang & Lu, 2002; Park, Lee, Shin, & Lee, 2005; W. Zhang, Liu, & Clerc, 2003).

In this research, BPSO has been chosen as optimization technique because of the nature of required solution. The solution of BPSO comes in binary form as "1" and "0", which indicate the status of all PEVs charging directly. Moreover, the BPSO offers a suitable solution to the selected objective function and constraints. It is proven that BPSO offers better optimal solution compared to the other optimization and there are only very few parameters to be adjusted (Ramadan, Bendary, & Nagy, 2017).

3.3.1 Proposed PEV charging coordination using BPSO

Input data and parameters: At the beginning of algorithm, all the input data are inserted in the program. This include network data, bus data, line data, residential load data and a set of PEV data. The PEV data consists of the arrival time to the charging point with charger capacity, battery size, battery initial state of charge (SOC), requested SOC by the user's. However, the load curve of residential load over 24 hours is considered. There are some parameters are needed to be set in BPSO such as number of population, social and cognitive coefficients (C_1 , C_2), initial velocity and maximum and minimum weight ($W_{\max}$, $W_{\min}$).

Initial random particle: The initial population is determined by selecting the random PEV charger to be turn on. In this case, only the arrived PEVs at the charging point are considered. Each particle of the population represents the status of PEV charger where digit "1" corresponds to a PEV being charged while digit "0" indicates the charging has not been started or already finished. However, the maximum power demand constraint is taken into account in initializing the random population. Initial population structure is-

$$\begin{pmatrix} Status_{PEV\_11} & Status_{PEV\_12} & \cdots & Status_{PEV\_1n} \\ Status_{PEV\_21} & Status_{PEV\_22} & \cdots & Status_{PEV\_2n} \\ \vdots & \vdots & \vdots & \vdots \\ Status_{PEV\_m1} & Status_{PEV\_m21} & \cdots & Status_{PEV\_mn} \end{pmatrix} \tag{3.10}$$

Where, *m* indicates the number of population and *n* is the number of PEVs in a single time slot (Δt = 5min interval). Each population is a set of status of each particle. Hence, the solution of the algorithm will be the combination of particle status.

Evaluate fitness: In every iteration, the fitness function is calculated based on Equation 3.1. Once the initial particle status is generated, the PEV load is updated in the bus data. The power loss and voltage deviation is calculated using the Backward Forward load flow.

Selection of P_{best} and G_{best} : The two best values are recorded in each iteration process. Each particle keeps track of its coordinate in the solution space that is associated with the best solution it has reached so far. The switching combination of PEV charger for which the fitness is minimum, is considered as the P_{best}. The best switching combination of PEV compare to the other combination is defined as G_{best}. The initial P_{best} and G_{best} will be updated in every iteration.

Particle inertia weight: The inertia weight determines the contribution rate of a particle's previous velocity to its velocity at the current time step. The inertia weight concept is first introduced by (Shi & Eberhart, 1998). It is well known that a large inertia weight facilitates a global search while a small inertia weight facilitates a local search. Based on inertia weight linearly decreasing strategy in (Shi & Eberhart, 1998), the inertia weight factor *w* is typically set according to the following equation:

$$w^{ite} = w_{\max} - \frac{w_{\max} - w_{\min}}{ite_{\max}} \times ite \qquad (3.11)$$

In this research, the $w_{\max}$ and $w_{\min}$ inertia weight is selected to be 0.9 and 0.4 respectively during the iterative process for better exploration and exploitation of global search.

Update particle velocity: A restriction is needed to limit the acceleration of each particle velocity. Hence, all the particles move in the search space within a certain acceleration. This restriction is used to put the control on particle so that no particle can accelerate uncontrollably within the search space. Therefore, a velocity range [$V_{\max}$, $V_{\max}$] is defined to clamp those particles which exceeds the range. The value of $V_{\max}$ is needed to be set precisely. However, bigger value in the positive direction of *Vmax* causes more probability of "1" and increasing in the negative direction causes probability of "0" for the particle position. In addition, if the $V_{\max}$ is chosen too small, the solution search space will be very small. As a result, the algorithm might be trapped in local optimum or will take more iteration to reach in global solution. Therefore, in this research, the maximum value of *Vmax* is set to [-4, +4] to ensure the probability of "1" and "0" as required.

$$v_{i,d}^{t+1} = w^t v_{i,d}^t + c_1 r_1 [pbest_{i,d}^t - x_{i,d}^t] + c_2 r_2 [gbest_{i,d}^t - x_{i,d}^t] \quad (3.12)$$

Here $v_{i,d}^t$ and $x_{i,d}^t$ is the velocity vector and position vector of particle *i* in dimension *d* at time *t* respectively. r_1 and r_2 are two random numbers from uniform distribution at time *t*. The value of c_1 (cognitive component) and c_2 (social component) is set to 1.4 and 1.8 respectively. It is proven that too large or too small value of these coefficients may affects the performance of the optimization (Del Valle, Venayagamoorthy, Mohagheghi, Hernandez, & Harley, 2008).

Position update and Sigmoid function: Although, the concept of continuous PSO and BPSO are same, it has a difference in particle position change. Generally, in BPSO the particle does not use information from its current position. Particularly, it can be said that the new position of particle in BPSO is influenced by the velocity of the particle instead of current position. This suggests that it is not important to know the particles' current position. Therefore, the velocity and the position of the BPSO be taken as a particle and a solution transformed by the sigmoid function, respectively. The sigmoid function determines the position of a particle whether it is one or zero based on the concept of velocity as a probability. However, Equation 3.12 remains unchanged for the velocity change but the updating position is as follows:

$$x_{i,d}(t+1) = \begin{cases} 0 & rand() \geq sig(v_{i,d}) \\ 1 & rand() < sig(v_{i,d}) \end{cases} \quad (3.13)$$

Here, $sig(v_{i,d})$ is the sigmoid function for transforming the velocity to the probability as the following expression:

$$sig(v_{i,d}) = \frac{1}{1+e^{-v_{i,d}}} \tag{3.14}$$

$rand()$ is arbitrary random number generated from a uniform distribution over [0.0, 1.0].

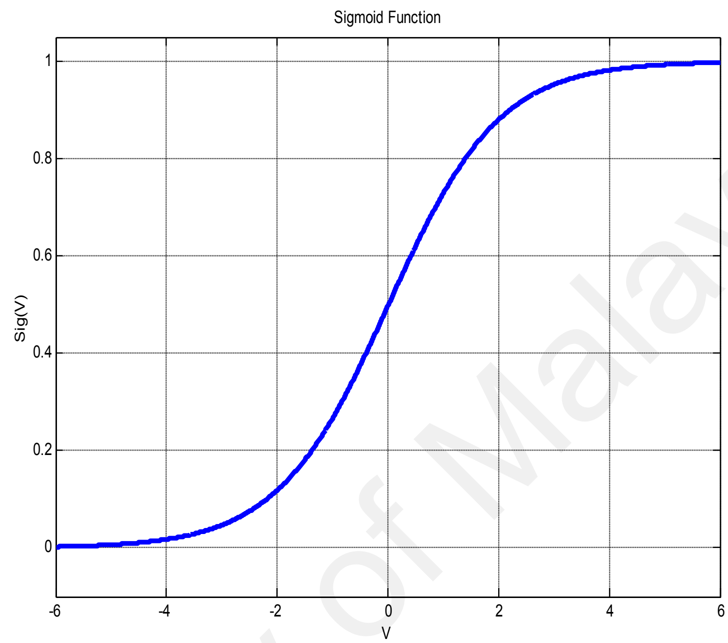


Figure 3.1: Sigmoid function

It is found that BPSO is affected by the saturation of sigmoid function. When the velocity of the particles is too large or too small, the probability of changing the particles position by sigmoid function is zero. For example, if the velocity of the particle is zero, the probability of changing the position of particle is 50%.

Evaluation of new fitness, P_{best} and G_{best}: After the velocity and position update process, a new switching combination of PEV charger is prepared. This combination is examined by all the network constraints. However, in the BPSO algorithm process the new P_{best} and G_{best} are generating from the updated switching combination. Then based on the new fitness function the G_{best} is updated if the fitness is found less compare to the previous iteration fitness.

Stopping criterion: The algorithm is terminated if the convergence happens or reaches to maximum iteration number.

Check full charged and new arrival PEV: In each t time slot, the algorithm takes the input of new arrival PEV to the charging point. The algorithm always checks the full charged PEV and eliminates from the queue. Only the new arrival PEV and those PEV are left to be charged are considered in optimization process.

Figure 3.2 shows the flow chart of the proposed BPSO algorithm for PEV charging coordination.

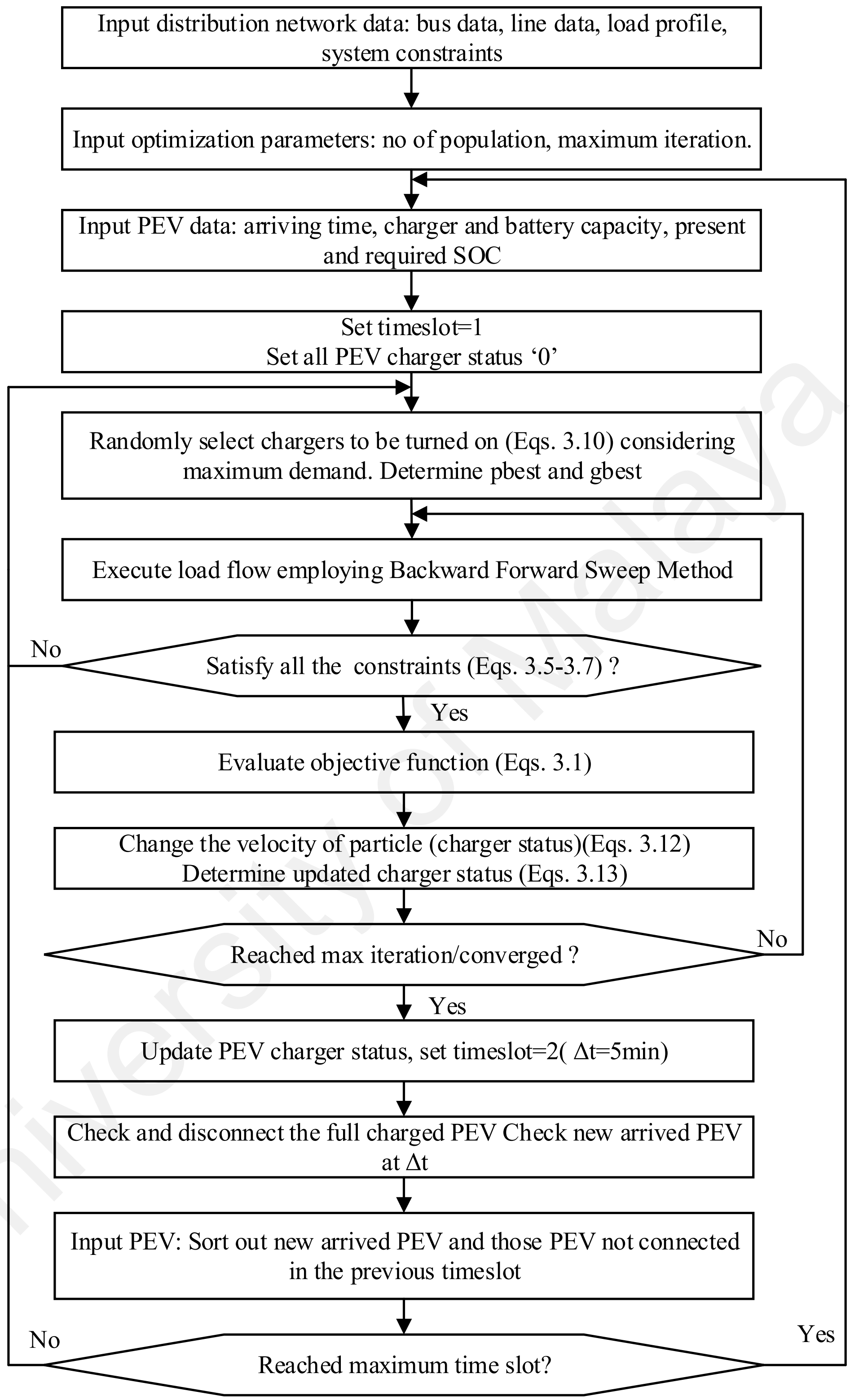


Figure 3.2: Flowchart of proposed PEV charging coordination using BPSO algorithm

3.3.2 Capacitor switching and OLTC adjustment using BPSO

Input data and parameters: In this research, the size of the capacitor and their locations are taken as input along with the network data, bus data, line data. However, a residential load data is considered over 24 hours integrating the PEV load of the previous day from the engineer experience. Furthermore, the number of tap changer position with their respective voltages are taken as input. There are some parameters are needed to be set in BPSO such as number of population, social and cognitive coefficients (C_1, C_2), initial velocity and maximum and minimum weight ($W_{\max}$, $W_{\min}$).

Initial particle: In this research, there are 5 number of capacitors located at bus no 4, 14, 16, 20 and 27. The algorithm initializes with the generation of random switching combination of capacitor. Every particle of the population represents the status of capacitor operation where digit "1" corresponds to a capacitor is turned on while digit "0" indicates the capacitor is turned off. Initial population structure is-

$$\begin{pmatrix} State_{cap\_11} & State_{cap\_12} & State_{cap\_13} & State_{cap\_14} & State_{cap\_15} \\ State_{cap\_21} & State_{cap\_22} & State_{cap\_23} & State_{cap\_24} & State_{cap\_25} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ State_{cap\_m1} & State_{cap\_m2} & State_{cap\_m3} & State_{cap\_m4} & State_{cap\_m5} \end{pmatrix} \quad (3.15)$$

Here, *m* is the number of population of capacitor switching combination. If the method is to find the optimal switching combination of capacitor, then the solution will be a set of particles.

Moreover, the tap changer position is defined as a voltage setting of the OLTC and is determined by-

$$Tap\_Position = \lfloor V_{tap1}, V_{tap2}, \ldots V_{Ntap} \rfloor \quad (3.16)$$

Evaluate Fitness: In every iteration, the fitness function is calculated based on Equations 3.1. As it is different unit for power loss and voltage deviation, the final power loss is determined from the ratio of the power loss before and after capacitor coordination of the specific hour.

Particle inertia weight: Inertia weight is an important parameter in optimization process which balance between exploration and exploitation. The inertia weight determines the contribution rate of a particle's previous velocity to its velocity at the current time step. From the Equation 3.11, the w_{max} and w_{min} is selected to be 0.9 and 0.4 respectively during the iterative process for better exploration and exploitation of global search.

Particle Velocity Update: The velocity of each particle is updated using the Equation 3.12. As the velocity has the influence over particle in changing their position, it is restricted within a range $[-V_{max}, V_{max}]$. In this case, V_{max} is set to 3 to ensure the same probability of generating '1' and '0'.

Position update and Sigmoid function: In the updating process of capacitor switching combination, the velocity of the particle is used in sigmoid function to get the new switching combination. The Equations 3.13 and 3.14 have been employed to update the particle position.

Determine the optimal particle status: The algorithm is searching the capacitor switching combination for each hour maintain all the network constraints to improve the voltage profile and reduce the power loss. The maximum switching number of capacitor is considered in this optimization as well.

Tap changer adjustment: The tap changer operation takes place simultaneously with the capacitor switching. The optimum tap changer position is determined based on the fitness function. The OLTC tap position voltage range is shown in Table 3.1. For instance, 1.0499p.u. is adjusted to 1.05p.u.

Figure 3.3 shows the flow chart of the proposed BPSO algorithm for optimal capacitor switching and OLTC adjustment.

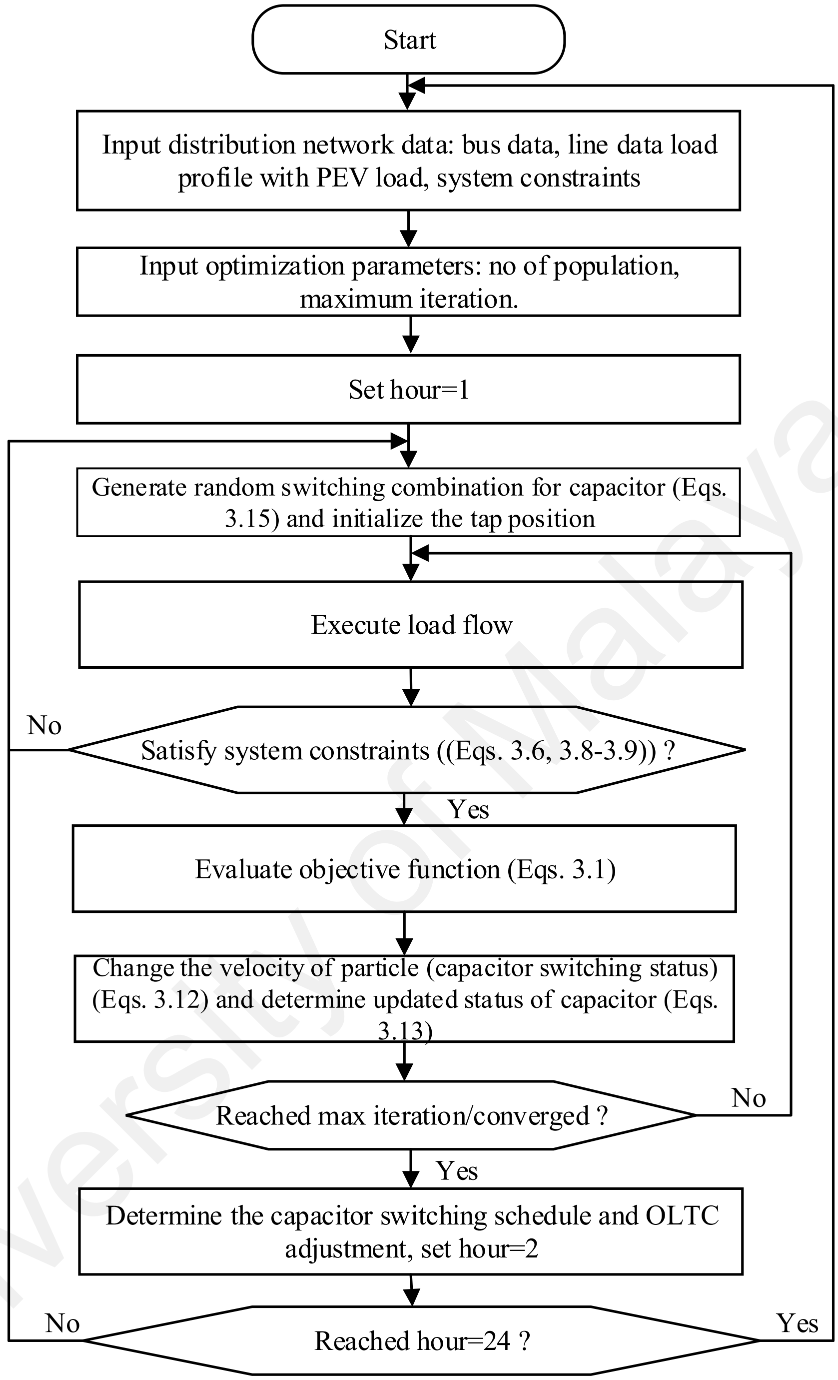


Figure 3.3: Flowchart of capacitor switching and OLTC adjustment during PEV charging activities

3.4 Proposed PEV charging coordination, capacitor switching and OLTC adjustment using Binary Grey Wolves Optimization (BGWO)

The binary grey wolf optimization (BGWO) is an evolutionary algorithm inspired from the leadership hierarchy of grey wolves in hunting and searching process of prey (Emary, Zawbaa, & Hassanien, 2016). Generally, Grey wolves prefer to live in a pack and it has severe social dominant hierarchy. The leaders are responsible for making decisions about hunting, sleeping place and is known as the alpha. The alpha is also known as the dominant wolf since all other wolves from the pack should follow its order. The second level of hierarchy of grey wolves is beta. The betas help the alpha to make the decision in various pack activities. Moreover, it plays the role of an advisor to the alpha and discipliner for rest of the pack. Finally, the lowest ranking grey wolves is omega. They are the last wolves and satisfying the entire pack as well as maintaining the dominance structure. The rest of the wolves are known as delta that dominate the omega in the pack. The group hunting is the social behavior of grey wolves and this phenomenon is utilized in the modeling of BGWO to perform optimization. However, BGWO has been chosen in this research since the required solution is in binary form. The binary value directly states the status of PEV charger and capacitor switching. It is found that, BGWO provides better convergence in real-time application (Emary et al., 2016). The details of the proposed method to implement the PEV charging coordination, capacitor and OLTC switching are based on the following steps-

3.4.1 Proposed PEV charging coordination using BGWO

Input data and parameters: All the input data are inserted in the program. This include network data, bus data, line data, residential load data and a set of PEV data. The PEV data consists of the arrival time to the charging point with charger capacity, battery size, battery initial and requested SOC by the user's. There are some parameters are needed to be set in BGWO such as number of grey wolves in the pack, number of agents and number of maximum iteration for optimization.

Generating initial wolves: The initial wolves are determined by selecting random switching of PEV charger. Each position of wolves represents the status of PEV charger. Suppose, the number of arrived PEV at the charging point is N_{PEV}. Hence, the N_{PEV} number of wolves are generated in binary form in each agent. Moreover, the leadership hierarchy for the wolves is also initialized. Here, the alpha (α) is the highest dominant wolf, the beta (β) is second dominant wolf and the delta (δ) is third dominant wolf in the pack. And rest of the wolf in the pack is omega (ω). The initial structure of the wolves to represent the PEV charger status is-

$$\text{Initial wolves} = \left[PEV_{n1} \quad PEV_{n2} \quad \cdots \quad PEV_{nd} \right] \tag{3.17}$$

Here, *n* indicates the number of population and *d* is the number of PEV in a single timeslot (Δt= 5min).

Evaluate Fitness and determine the dominant wolf: In every iteration, the fitness function is calculated based on Equations 3.1. The dominant wolves (α, β, δ and ω) in the pack is determined based on the fitness. As it is described in previous section the unit for power loss and voltage deviation are not same. In this case, the final power loss is determined using the uncoordinated power loss value of the specific time slot.

Update wolf's position: In order to update the position, each wolf follows the first three best wolves. Suppose, the first three best PEV charge switching combination influence on other switching combination to update their position. Since, the pool of solution is in binary form, a transfer function named sigmoid function as Equations 3.13

and 3.14 are employed to get the binary position of each wolf. The main updating equation can be formulated as shown in Equation 3.18.

$$X_i^{t+1} = Crossover\left(x_1, x_2, x_3\right) \tag{3.18}$$

Where,

$$x_1 = \begin{cases} 1 & x_\alpha + equation\ (3.14) \\ 0 & otherwise \end{cases} \tag{3.19}$$

$$x_2 = \begin{cases} 1 & x_\beta + equation\ (3.14) \\ 0 & otherwise \end{cases} \tag{3.20}$$

$$x_3 = \begin{cases} 1 & x_\delta + equation\ (3.14) \\ 0 & otherwise \end{cases} \tag{3.21}$$

Equation 3.14 refers the sigmoid function for transforming the encircling behavior of prey to the probability of position. Where, x_1, x_2, x_3 are binary vector representing the effect of wolf move towards the alpha, beta and delta wolves.

Evaluate the positions of each individual wolves: Once the new position of each wolf in the pack is defined, the new fitness is calculated. The leadership hierarchy (α, β, δ and ω) is determined based on the fitness function.

Check and update the number of wolf: In each timeslot, the algorithm is checking the full charged PEV that already reached to their requested SOC level. The full charged PEVs are not included as an optimization agent in the next timeslot. However, the new arrival PEV is added as agent for the next timeslot. It is observed that, in each timeslot, the number of wolf might be changed.

Figure 3.4 shows the flowchart of PEV charging coordination using BGWO

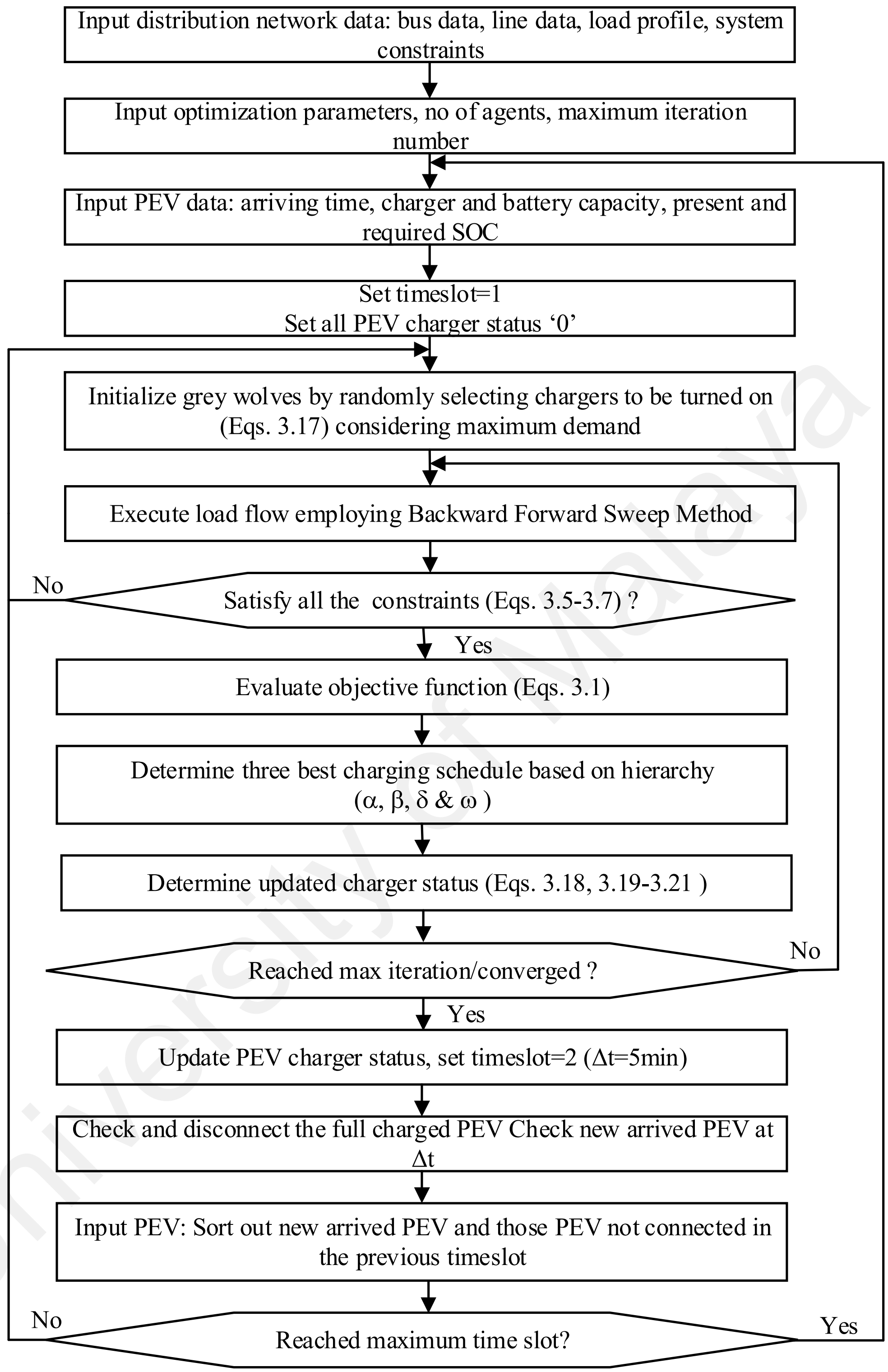


Figure 3.4: Flowchart of PEV charging coordination using BGWO

3.4.2 Capacitor switching and OLTC adjustment using BGWO

Input data and parameters: All the input data are inserted in the program. This include network data, bus data, line data, residential load profile, capacitor and OLTC data. The capacitor data consists of the number of capacitor, capacitor size and their location in the network. On the other hand, OLTC data comprises of number of tap position and their voltage level in representing tap position. There are some parameters are needed to be set in BGWO such as number of grey wolves in the pack, number of agents and number of maximum iteration for optimization.

Generating initial grey wolves: The initial wolves are determined by selecting random switching of capacitor. Each position of wolves represents the status of capacitor, whether it is 'on' or 'off'. In the studied test system, there are five number of capacitor. Hence, the initial structure of wolves is presented in Equation 3.22. The leadership hierarchy dominant wolves (α, β, δ and ω) are also initialized. The initial structure of the wolves to represent the capacitor switching status is-

$$\left\lfloor Cap_{n1} \quad Cap_{n2} \quad Cap_{n3} \quad Cap_{n4} \quad Cap_{n5} \right\rfloor \tag{3.22}$$

Where, n indicates the number of wolf in the initial timeslot (Δt= 5min).

Evaluate Fitness: In every iteration, the fitness function is calculated based on Equations 3.1. The dominant wolves (α, β, δ and ω) in the pack is determined based on the fitness. As it is described in previous section the unit for power loss and voltage deviation are not same. In this case, the final power loss is determined using the uncoordinated power loss value of the specific time slot.

Update wolf's position: In order to update the position, each wolf follows the first three best wolves (α, β and δ). Suppose, the first three best capacitor switching combination influence on other switching combination to update their position. The positions of wolves are updated using the Equations 3.18-3.21. Same as the previous section, a transfer function named sigmoid function as equation 3.14 is employed to get the binary position of each wolf.

Evaluate the positions of each individual wolves: Once the new position of each wolf in the pack is defined, the new fitness is calculated. Therefore, the best capacitor switching combination is found for one iteration. And this process is being repeated till the convergence happen or reached to maximum iteration.

Determine tap changer position: The tap changer voltage value obtained is adjusted based on the range as shown in Table 3.1.

Figure 3.5 presents the flowchart of capacitor and OLTC coordination using BGWO

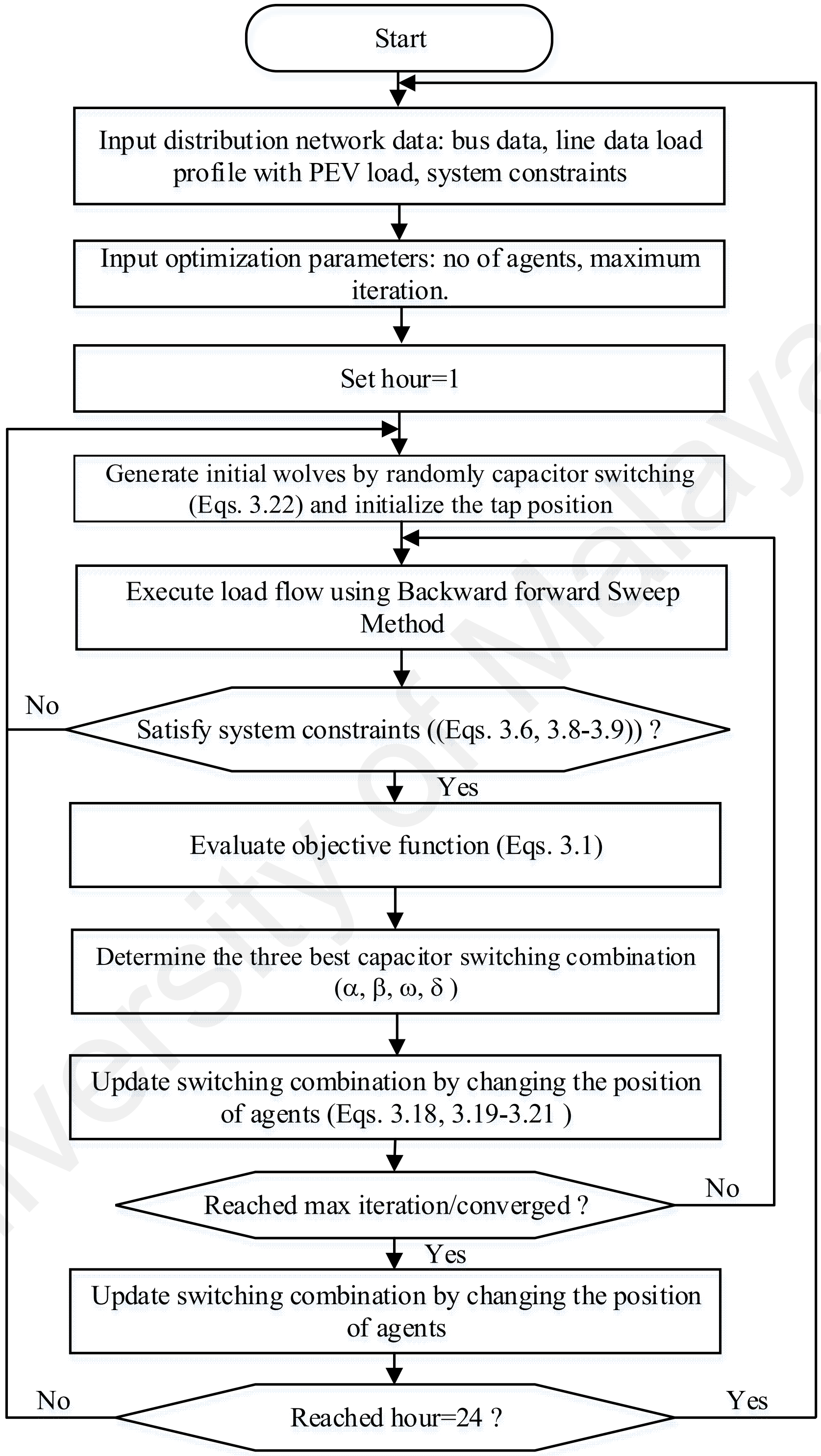


Figure 3.5: Flowchart of capacitor and OLTC coordination using BGWO algorithm

3.5 Proposed cost minimization including electrical tariff

PEV charging cost: The cost of the PEV charging refers to the cost of energy consumed by the PEV charger. The energy is stored in the battery through the charger where it acts as active load in the distribution system. The PEV charging cost depends on the different electrical tariff of the day. In this research, a method is proposed to utilize the different electrical tariff in PEV charging cost minimization while the network and PEV charger constraints are maintained. In the very first time, the proposed method calculates the required energy and time to reach required SOC of the arrived PEV in the charge points. Based on their required time to charge, the PEVs are sorted out from longer to shorter time. In every timeslot, which PEV has lower initial SOC and needs longer time to be charged, it will be sent as input in PEV charging coordination algorithm. In this case, the PEV will be started to charge maintaining system constraints, although the tariff is higher. On the other hand, PEVs with higher SOC and need lower time to charge will be sent as input in PEV charging coordination when the tariff is moderate. A que table is prepared for those PEV which need less than 12 timeslots to get full charge. However, PEVs with moderate initial SOC will be sent to the PEV que table and will be considered in medium tariff time. This table is sorted and organized based on the maximum required time and minimum charging cost. Maximum 20 PEVs can be in the que table and are divided into four groups. In each timeslot, the first group will be considered in PEV charging coordination. If more PEV come to the que table, two group will be sent at a time to the coordination. It is worthy to mention that the proposed PEV charging coordination incorporating capacitor and OLTC principle will be same as before. Figure 3.6 is the flowchart of the proposed method to include the time of use electrical tariff in minimizing the PEV charging cost.

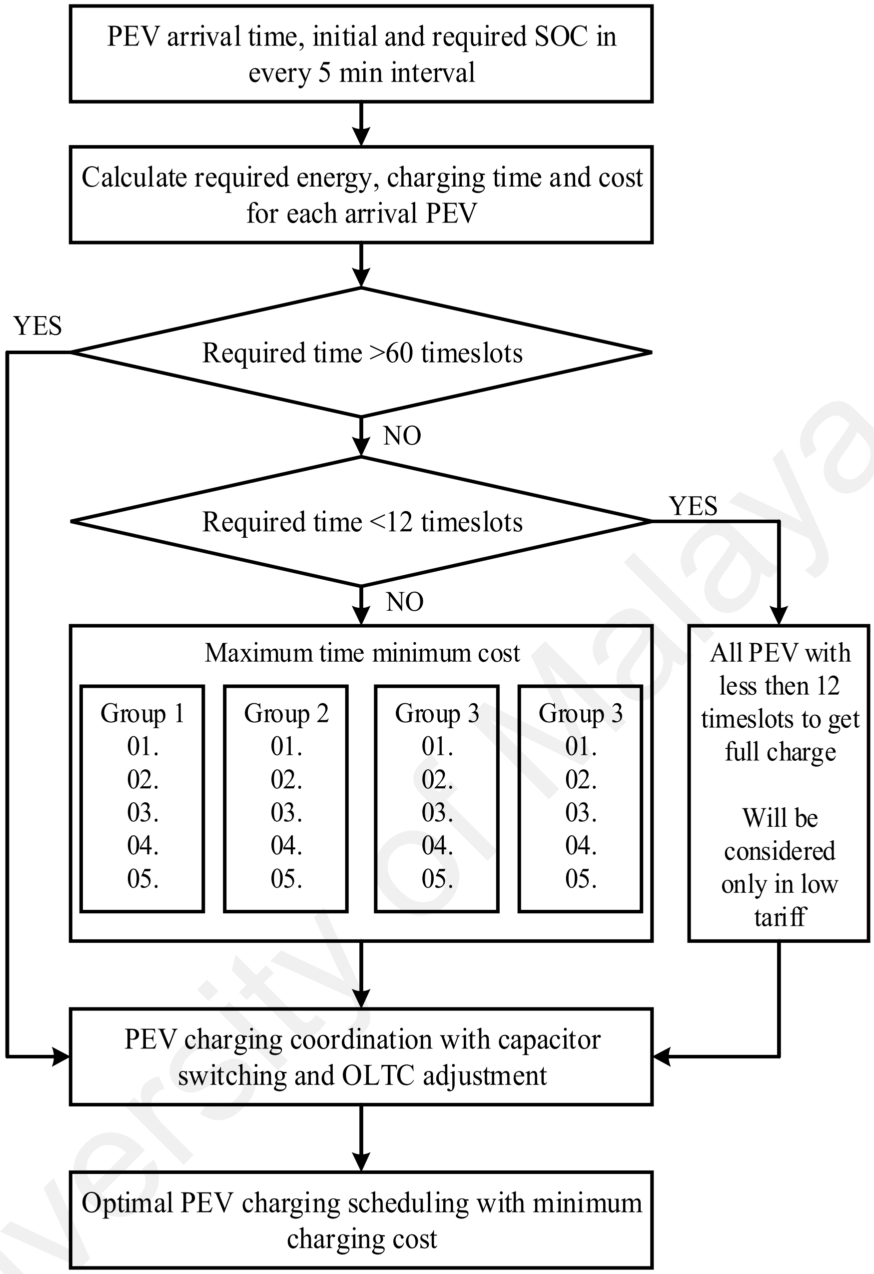


Figure 3.6: Flowchart of the proposed PEV charging cost minimization strategy

3.6 Summary

This chapter presents the detailed step by step explanation of the proposed meta-heuristic approaches BPSO and BGWO. Both algorithms are recently introduced and widely used in power system problem. The binary version the optimization techniques is to solve the objective function because of its various aspects such as nature of required solution, computing time, selection of objective function and constraints. The proposed method is expected to provide the minimum power loss and voltage deviation while the PEV charging coordination is made. Furthermore, capacitor switching and OLTC operation have been coordinated to improve further voltage profile as well the distribution system performances. The different electrical tariff in day is utilized to minimize the PEV charging cost along with the PEV charging coordination.

CHAPTER 4:

SYSTEM MODELING

4.1 Introduction

This chapter presented a practical approach to perform PEV charging coordination when the capacitor switching and OLTC adjustment are coordinated in distribution system. In this research, residential loads are considered as time varying loads in distribution networks. To investigate the robustness and effectiveness of the proposed method, comprehensive simulations are done on a modified IEEE 31 bus system. In order to perform the proposed coordination, the distribution system need to be modeled while PEV charging activities are there. This chapter started with the brief introduction of the standard IEEE 31 bus system. Then the PEV charging characteristic is studied and integrated to the network.

4.2 IEEE 31 bus system

The test system for this study is 23kV IEEE 31 bus radial distribution system as shown in Figure 4.1 (Civanlar & Grainger, 1985). The substation transformer has the maximum demand is 840kW with an on-load tap changer transformer of 17 tap positions. The system consists of six lateral branches. The one-line diagram of IEEE 31 bus system is shown in Figure 4.1 and line parameters presented in Appendix A.

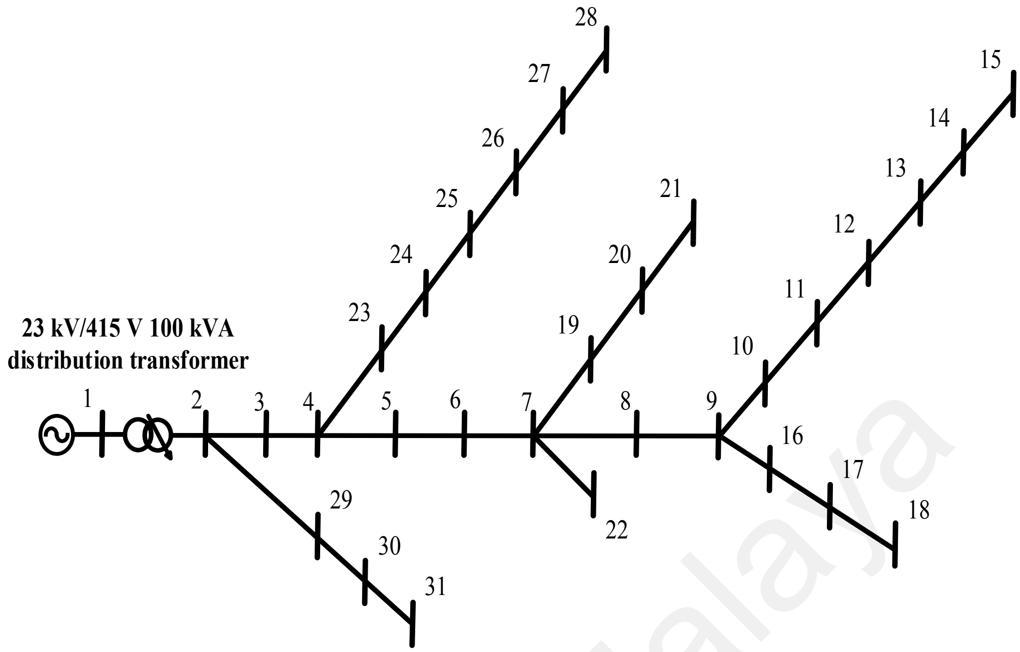


Figure 4.1: IEEE 31 node 23 kV distribution system

4.3 PEVs on Distribution network

PEVs are driven by an electric motor powered by rechargeable battery packs. These batteries are charged through the charger by plugging into any standard electric outlets. There are two main places where the batteries of PEVs can be recharged- either on a car park, corporate and public, or at home. The electrical consumption for charging PEVs depends on the capacity of the charger, size of the battery and the SOC level of the battery. Table 4.1 presents the charger capacity and battery size with the corresponding initial and required SOC for a particular feeder at 63% PEV penetration.

Table 4.1: Detailed PEV input data for a feeder at 63% PEV penetration

Description	n2	n4	n6	n7	n8	n10	n11	n13	n15	n17	n18	n19
Charger capacity (kW)	3.3	7.2	3.3	3.3	3.3	6.6	7.2	7.2	6.6	7.2	6.6	7.2
Initial SOC (%)	17	25	9	19	7	19	28	12	5	16	22	15
Requested SOC (%)	72	72	83	66	78	59	61	80	82	74	68	81

4.3.1 PEV charger capacity and battery size

In practice, PEV battery charger will have to be rated high enough to charge batteries of these sizes in reasonable time periods. Although, the battery chargers have some losses, for simplicity of the simulation, it is assumed that the charger efficiency is 100%. The charger of PEVs can be classified into three main groups, depending on the charger power as shown in Table 4.2.

Table 4.2: Classification of PEVs charger

Category	Description
Level 1	Generally, an electric outlet in resident is 115VAC, 15A or 230VAC, 6A single-phase. This connection can deliver around 1.5kW, and the charge time is varying between 7 to 30 hours based on battery size.
Level 2	A mid-sized PEV can be charged in 4-5 hours through a 230VAC, 30A two pole. This type of chargers is mostly used at home and public charging station. It delivers 7kW to feed the 6.6kW on-board PEV charger.
Level 3	The ultra-fast PEV charging utilizes 400–600VDC, up to 300A connection. The on-board charger is bypassed and feed the power directly to the battery. It produces up to 120kW to charge a Li-ion battery to 80 percent in about 30 minutes.

However, limitation of household wiring must be considered. For this research, level 2 category- 3.3kW, 6.6kW and 7.2kW chargers are selected. These types of chargers are commonly available in most single-phase residential households without having to reinforce wiring. For realistic modeling of PEV charging loads, the battery capacities are of importance to determine charging profile. PEV battery capacities typically range from a few kWh to over 50kWh (A. S. Masoum, Deilami, Moses, Masoum, & Abu-Siada, 2011). Some of the latest PEV's batteries size are shown in Table 4.3.

Table 4.3: Example of some commercial electric vehicle and battery size (Wang, Dusmez, & Khaligh, 2014)

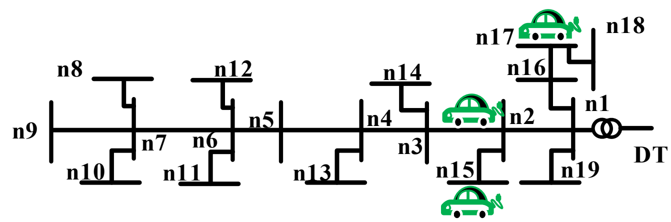
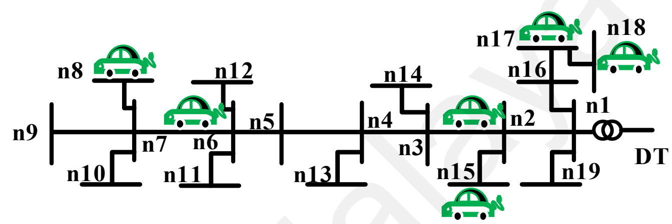
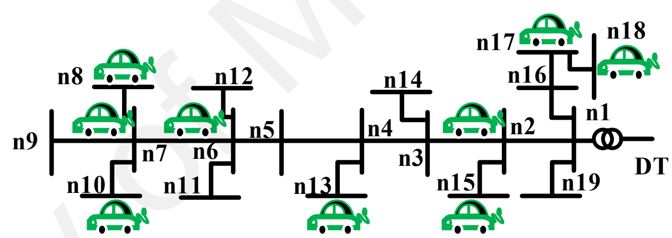
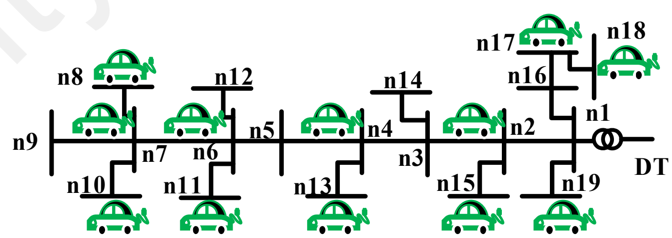
No	Model	Battery
1	Toyota Prius	6 kWh
2	Chevy Volt	16 kWh
3	Mitsubishi iMiEV	16 kWh
4	Smart Fortwo ED	16.5 kWh
5	Ford focus	19.2 kWh
6	BMW i3	22 kWh

For this research, 6kWh, 16kWh and 19.2kWh battery capacities are considered since it is expected that these battery sizes are available in the market. However, the charger capacity, battery size and corresponding initial SOC and requested SOC are presented in Appendix B.

4.3.2 PEV Penetration Levels

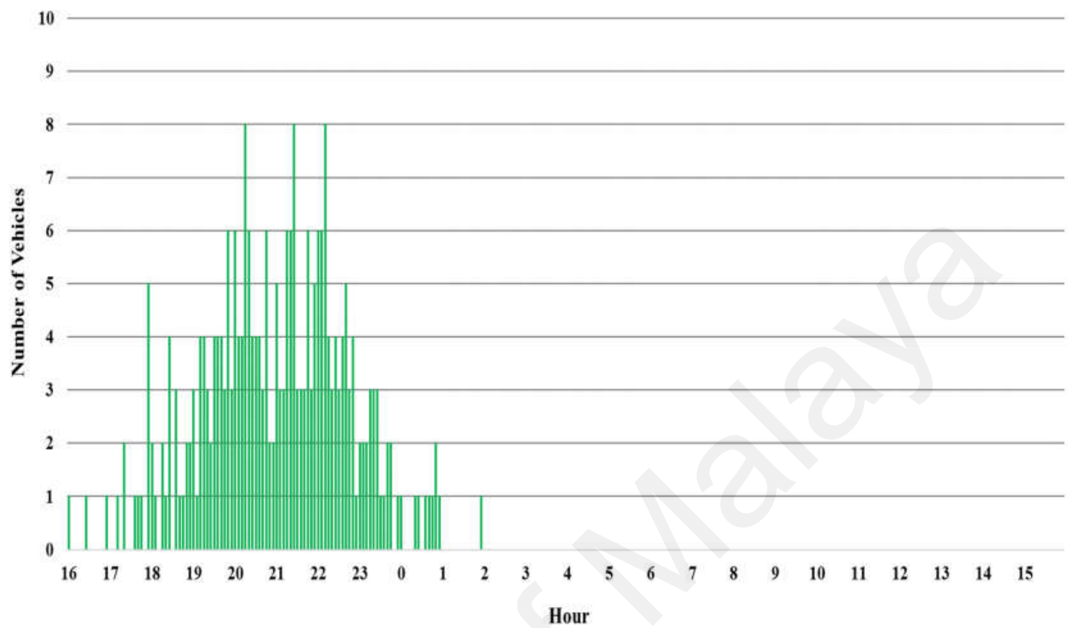
In this research, four different levels of PEV penetrations (16%, 32%, 47% and 63%) are studied to cover all reasonable PEV charging scenario in near future. The penetration levels are determined based on the ratio of number of nodes with PEV and total number of nodes. It is worthy to mention that; one household can have maximum one PEV. The selection of nodes with PEV is done based on random distribution in the low voltage feeder. Therefore, the total number of PEVs are 67, 134, 197 and 264 for the penetration level of 16%, 32%, 47% and 63% respectively. The penetration levels and the selected nodes for PEV are shown in Table 4.4.

Table 4.4: Pictorial expression of low voltage residential feeder populated with different level of PEV penetration

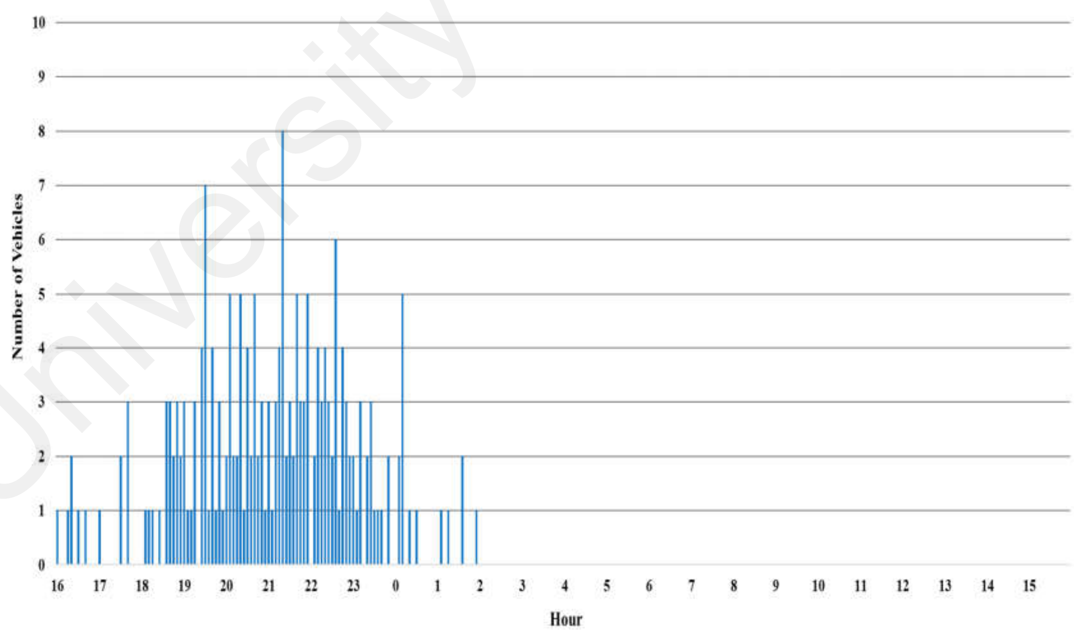
Penetration Level	Pictorial view
16%	
32%	
47%	
63%	

4.3.3 Random PEVs arrival

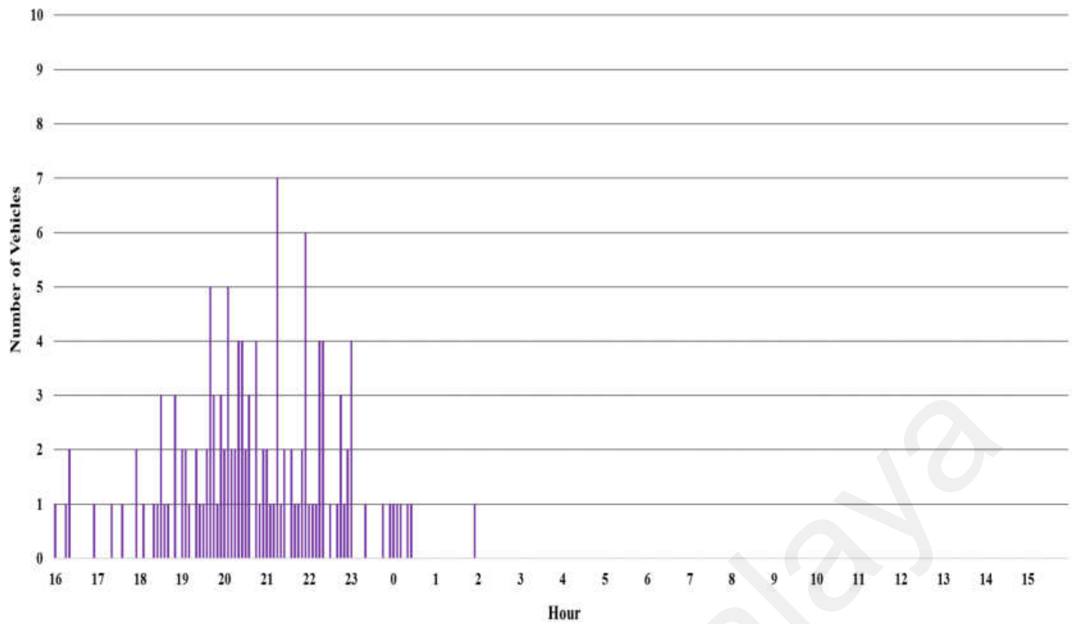
In the PEV charging coordination, PEV arrival time in charge point is one of the input parameter. This research proposes a real-time (t=5min) PEV charging coordination where the PEV arrival time is taken in real-time. In order to get PEV arrival time, a normal distribution of PEV arrivals is generated and used for each penetration as presented by the histograms in Figure 4.2 (63%. 47%, 32%, 16%). Since the studied system is a residential distribution network, random PEV arrival time is started from 16:00, when the people finish their work and return to home.



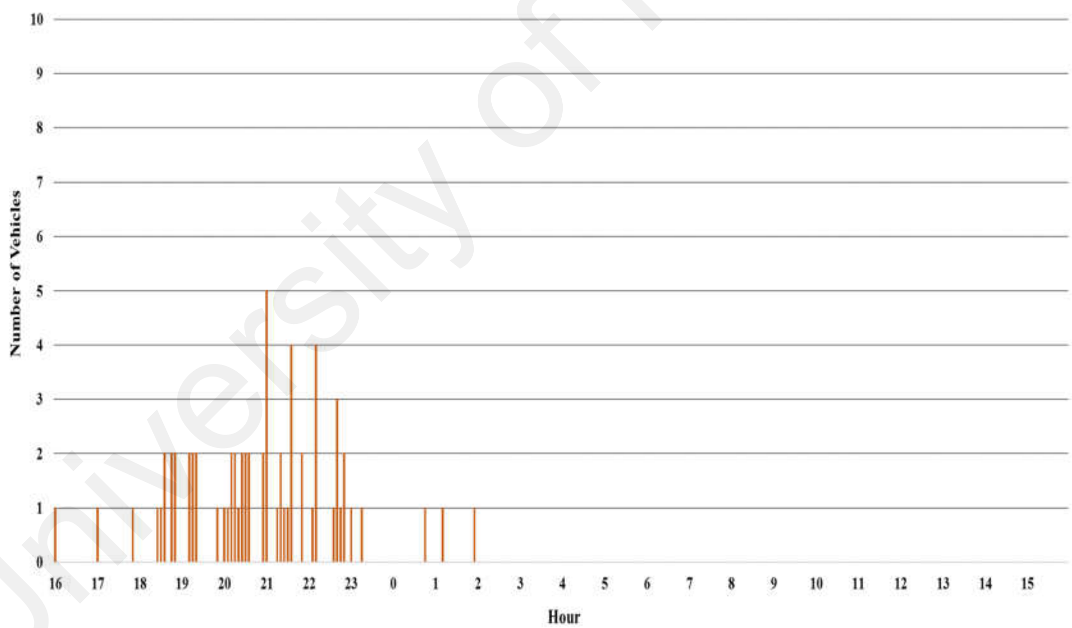
(a) PEV arrival at charge point at 63% penetration



(b) PEV arrival at charge point at 47% penetration



(c) PEV arrival at charge point at 32% penetration



(d) PEV arrival at charge point at 16% penetration

Figure 4.2: Random PEV arrival at the charge point generated using normal distribution

4.4 Capacitor size and location

The studied system is modified 23kV IEEE 31 bus system 449 nodes. In that case, one of the important task is to determine the number of capacitor and their location in the system as well each capacitor size. There are different proposed methods are found with various fitness function. The methods can be categorized into analytical methods, numerical programming methods, heuristic methods and artificial intelligent methods (Aman, Jasmon, Bakar, Mokhlis, & Karimi, 2014). In this research, the proposed method in (Aman, Jasmon, Bakar, & Mokhlis, 2012) is employed to determine the number, locations and size of the capacitor in the network. The variable load profile for 24 hours is utilized considering the random PEV charging in the network. The load profile is constructed based on the previous days experiences. The main consideration in this process is to reduce the system power loss and improve the voltage profile. The capacitors size and their locations are shown in Table 4.5.

Table 4.5: Capacitor size and location in the test system

Capacitor	C1	C2	C3	C4	C5
Bus location	4	14	16	20	27
kVAR	50	100	100	50	50

4.5 OLTC adjustment

It is difficult to specify the controlling parameters when applying automated techniques to control OLTCs at a substation level. Due to the probabilistic nature of PEV load on distribution system, it is difficult to determine the load forecasting (F-C Lu & Hsu, 1995; Viawan & Karlsson, 2008). Therefore, it is important to construct a daily load profile based on the previous days experiences with the PEV charging activities. In this test system, the OLTC has 17 tap positions, which can change the voltage from -5% to +5%. The operation of OLTC is not frequent as it reduces the lifetime and increases repairing cost. The tap changer adjustment is determined in terms of predefined voltage as presented in previous section in Table 3.1, which represents its tap position.

4.6 Residential Load Profiles

In this research, a practical domestic load curve recording from a distribution transformer is utilized (in Australia). Figure 4.3 presents a domestic load variation without PEV load for 24 hours. It is recorded that the maximum consumption of one house is around 2kW with good power factor of 0.9 (Deilami et al., 2011).

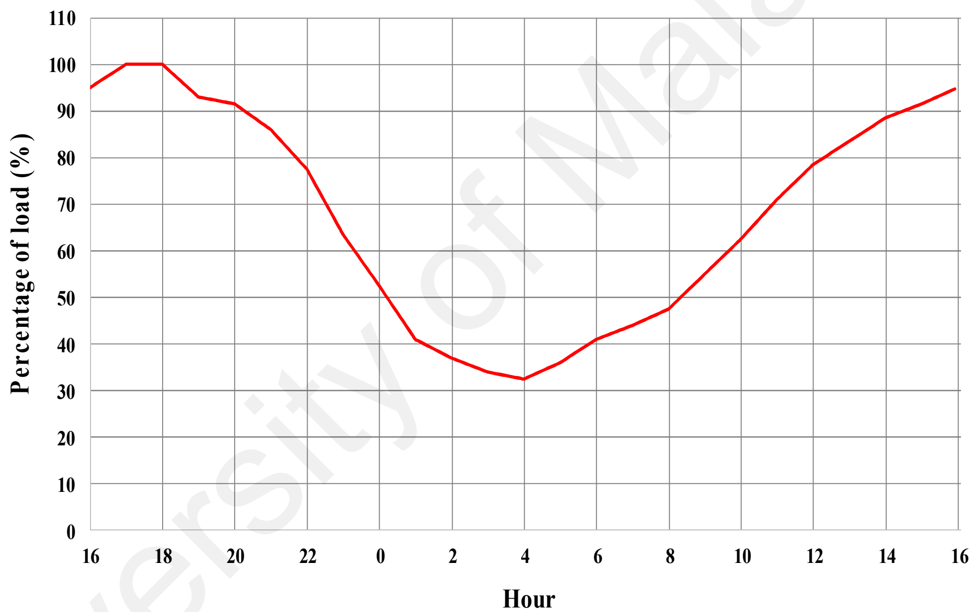


Figure 4.3: Daily residential load curve (Deilami et al., 2011)

4.7 Modeled network

A detailed smart grid test system topology is developed and studied to demonstrate the proposed methodology to adopt PEVs charging in residential distribution system. The studied test system (Figure 4.4) is a modified IEEE 31 bus 23kV distribution system which has 22 low voltage (415V) feeder. For example, two low voltage networks at feeder 15 and18 are shown with 63% PEV penetration. The rest of the low voltage feeder has the same configuration. The low voltage feeder consists of 19 nodes which represent customer household and some selected nodes are assigned for PEV. The one-line diagram and line parameters of low voltage feeder are shown in Figure 4.5 and Table 4.6 respectively. The residential load at each node is calculated 2kW and 0.97 kVAR with PEVs load in some selected nodes are presented in Table 4.6. Moreover, the system comprises with five number of capacitors at bus number 4, 14, 16, 20 and 27.

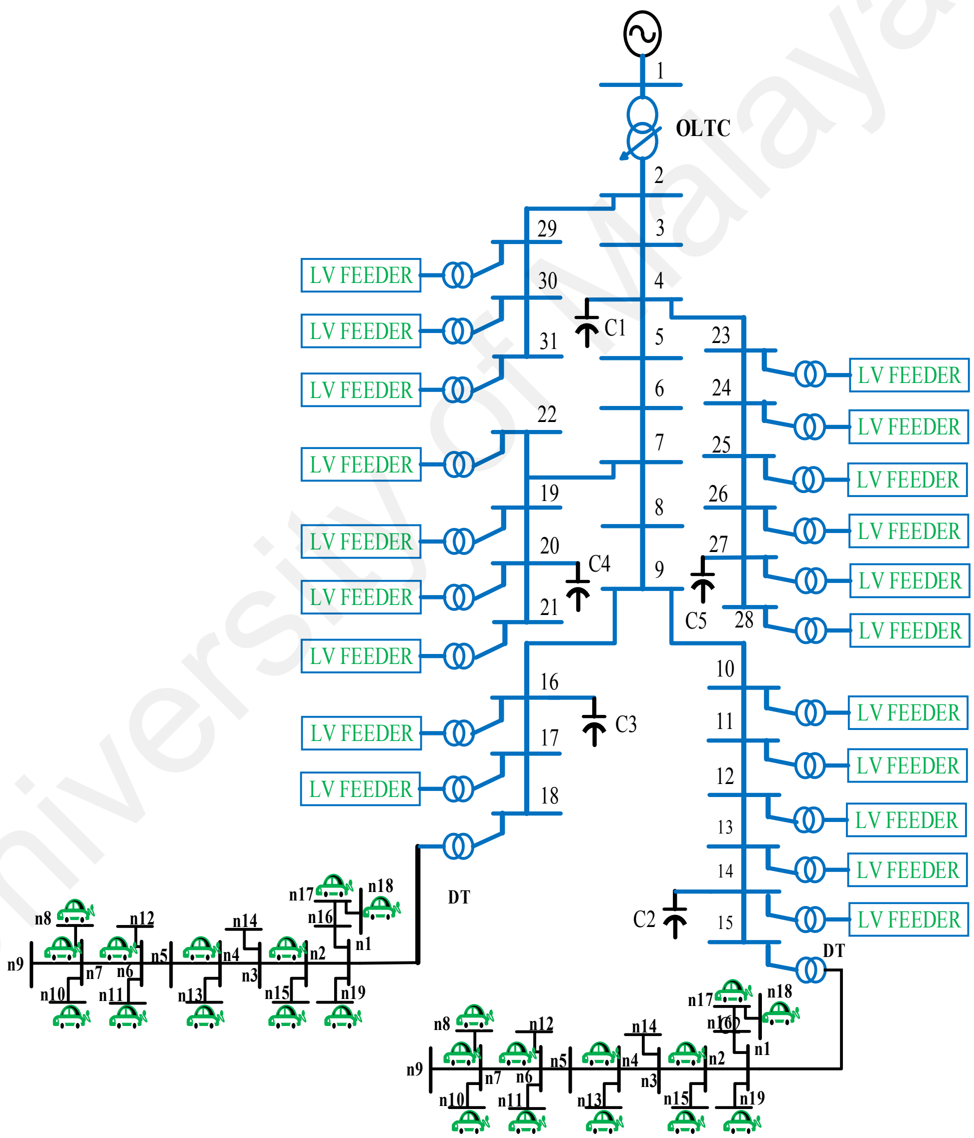


Figure 4.4: The 449-node smart grid distribution system topology populated with 63% PEVs penetration

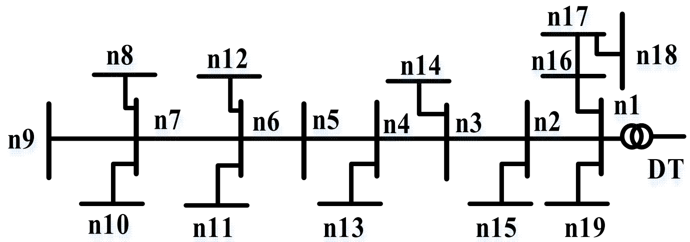


Figure 4.5: One-line diagram of 19 nodes low voltage network

Table 4.6: Line parameters (Civanlar & Grainger, 1985) of the 19 bus low voltage feeders

Line		Line resistance R (Ω)	Line reactance X (Ω)	Line		Line resistance R (Ω)	Line reactance X (Ω)
From bus	**To bus**			**From bus**	**To bus**		
n1	n2	0.0145	0.0145	n6	n12	1.3605	0.1357
n2	n3	0.0424	0.0189	n4	n13	0.1400	0.0140
n3	n4	0.0444	0.0198	n3	n14	0.7763	0.0774
n4	n5	0.0369	0.0165	n2	n15	0.5977	0.0596
n5	n6	0.0520	0.0232	n1	n16	0.1423	0.0496
n6	n7	0.0524	0.0234	n16	n17	0.0837	0.0292
n7	n8	0.0005	0.0002	n17	n18	0.3123	0.0311
n7	n9	0.2002	0.0199	n1	n19	0.0163	0.0062
n7	n10	1.7340	0.1729	Distribution transformer reactance			0.0654
n6	n11	0.2607	0.0260				

Table 4.7: Residential and PEV loads on one 19-nodes LV feeder

Residential and PEV load		Consumption	
Node	Type	kW	kVAR
1 - 19	Residential loads	2.0	0.97
Selected nodes	PEV charger	3.3, 6.6, 7.2	0

4.8 Summary

This chapter presents the detailed procedure how to model the test system to implement the proposed method. This research employs standard IEEE 31 bus system to test the performance of proposed method. The test system comes with 22 low voltage feeders and each feeder consists of 19 low voltage nodes. The PEV charging activities is added in the network in different penetration level (16%, 32%, 47% and 63%). The PEV charger and battery capacities are also described. The proposed method utilizes capacitor and OLTC operation in the network. In modeling the test system, the capacitor sizes and locations are determined. The simulation and the performance results of the test system are presented in the next chapter.

CHAPTER 5:

IMPLEMENTATION AND VALIDATION OF THE PROPOSED STRATEGY

5.1 Introduction

This chapter presents performances of the proposed PEV charging coordination along with capacitor switching and OLTC adjustment in a residential distribution system. To investigate the robustness and effectiveness of the proposed method, comprehensive simulations are done on a modified 449 node smart distribution system (Figure 4.5) with the addition of one OLTC and five capacitors.

In this proposed system, there are 30% PEV with 3.3kW and 6kWh charger and battery size respectively, 40% PEV with 6.6kW and 16kWh charger and battery size respectively and 30% PEV with 7.2kW and 19.2kWh charger and battery size respectively. In this study, backward forward sweep method has been employed to determine the power flows and voltage of each nodes. However, the charger capacities, initial SOC and requested SOC for all four level of PEV penetrations are shown in Appendix B. To demonstrate the effectiveness of the proposed method, five case studies are carried out with different consideration as presented in Table 5.1.

Table 5.1: Different cases of distribution system in PEV charging coordination

Case	Scenario
1	Uncoordinated random PEV charging
2	Coordinated PEV charging considering different objective functions
3	Optimal dispatch of capacitor during coordinated PEV charging
4	Optimal dispatch of OLTC during coordinated PEV charging
5	Optimal dispatch of capacitor and OLTC during coordinated PEV charging

5.2 Uncoordinated Random PEV Charging in Distribution Network

The uncoordinated and random PEV charging on distribution system has been observed in case 1. Figure 5.1 to 5.3 represent the impact of uncoordinated charging activities on residential distribution system. As a consequence, this charging process increases distribution system stress causing overloading, excessive power loss, unacceptable voltage deviation. From the Figure 5.1, at 63% PEV penetration the weakest node voltage is 0.81p.u. that is the worst voltage drop scenario. At 47% PEV penetration, the voltage in weakest node is below 0.82p.u. although for 32% and 16% PEV penetration the voltage is in allowable limits. Moreover, the total system power loss is presented in Figure 5.2, where it is clear that the random PEV charging process raised the power loss extremely in the peak hour of the day. In addition, the total power consumption of the distribution system is immensely high during the peak hour. As shown in Figure 5.3, for 63% and 47% PEV penetration, the distribution system is overloaded in terms of system capacity. Moreover, the distribution system is also overloaded during the lower PEV penetration (16% and 32%).

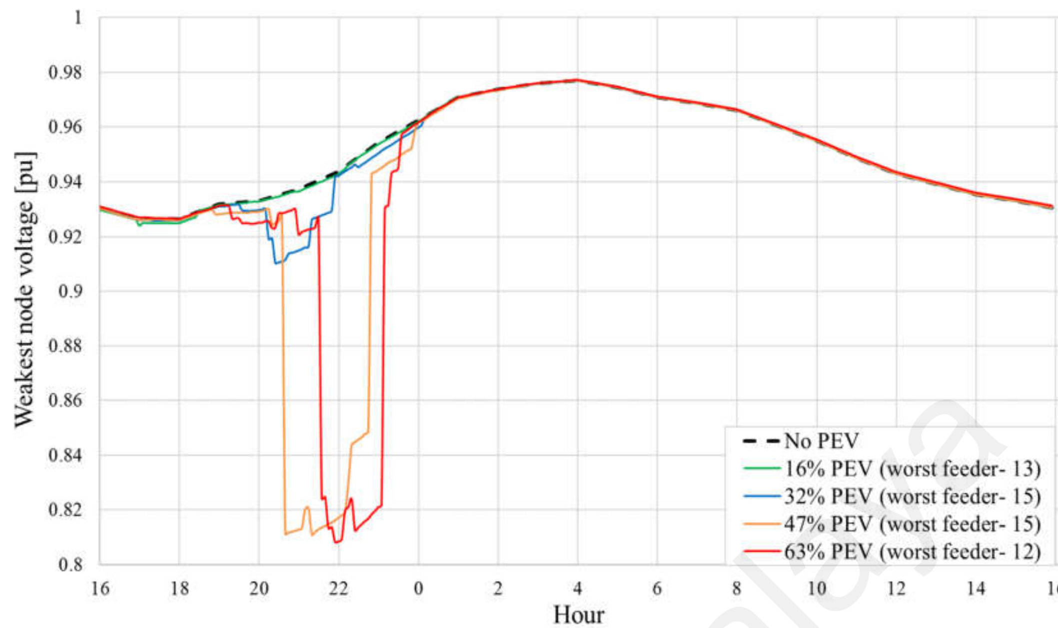


Figure 5.1: Voltage profile at the weakest node in uncoordinated PEV charging

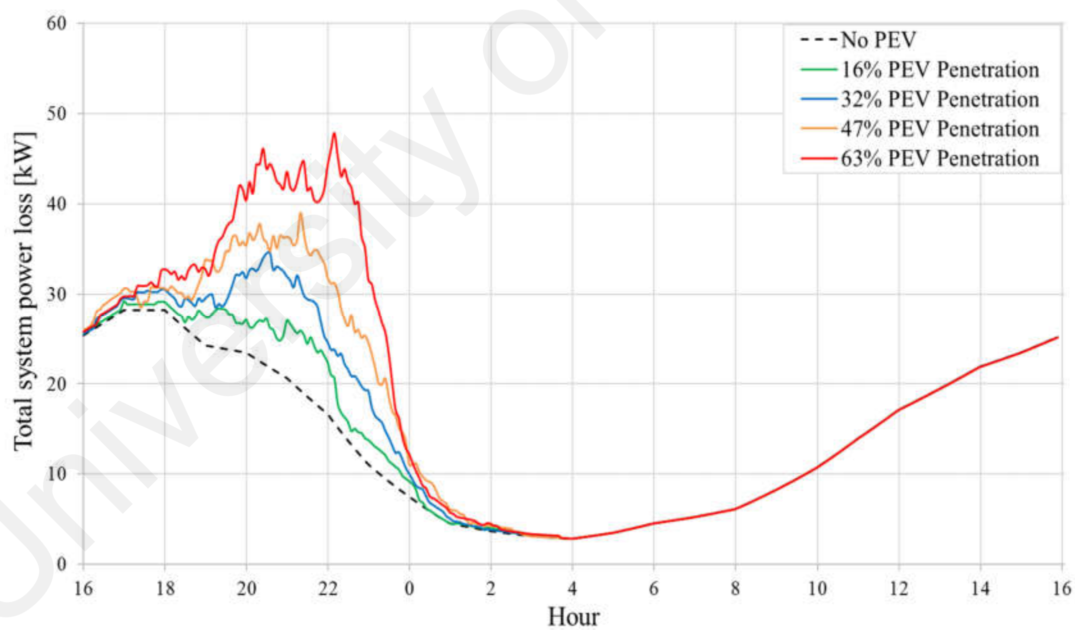


Figure 5.2: Total system power loss in uncoordinated PEV charging

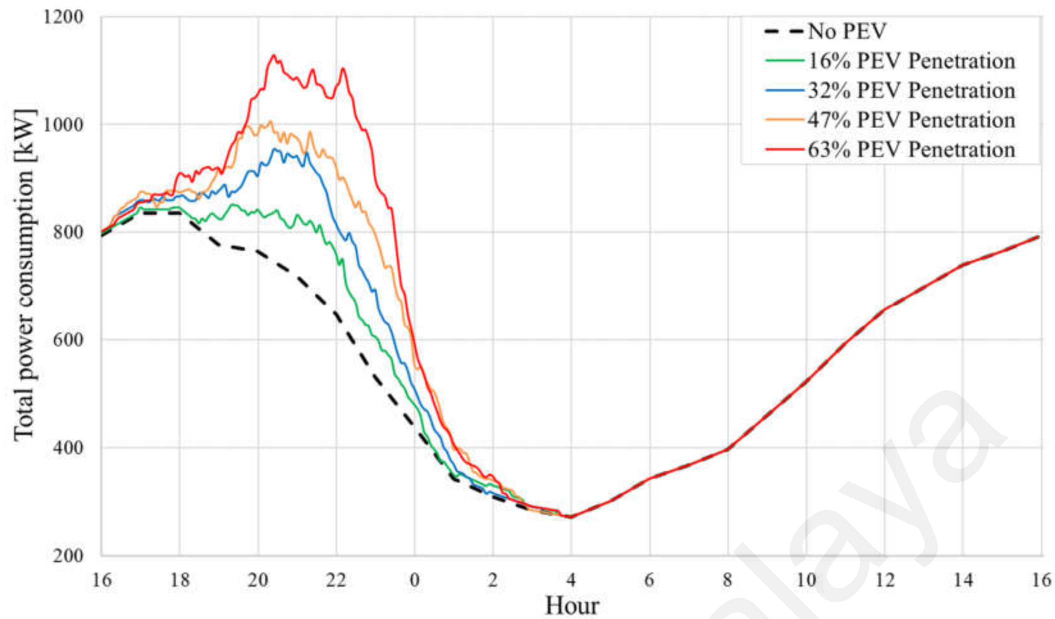


Figure 5.3: Total system power consumption in uncoordinated PEV charging

5.3 Coordinated PEV charging in Distribution Network

To overcome the devastating impacts of uncoordinated PEV charging on distribution system, a PEV charging coordination approach in real-time (5min interval) is presented in case 2. In this case, two meta-heuristic optimization BPSO and BGWO are employed. The consequences of this case are demonstrated in Figure 5.4 to 5.11 using both algorithm. The weakest node voltage is in allowable limits for all the PEV penetration levels. The power loss during the coordinated PEV charging is presented and it is not too high compare to the loss with no PEV. In case of total power consumption, it never exceeds the maximum capacity. It can be observed that there is no distribution system overloading during the PEV charging activities. From these observation, it can be seen that, the distribution system is secured from system stress. However, two different objective functions are studied in the optimization process for better performance to obtain the required solution. These objective functions are carried out using BPSO and BGWO. Objective function 1: Minimizing daily power loss and Objective function 2: Minimizing daily power loss and voltage deviation

5.3.1 Objective function 1: Minimizing daily power loss

Figures 5.4 and 5.5 are showing the weakest voltage profile of the network using BPSO and BGWO respectively. Here, the main consideration of the optimization is to minimize the daily power loss. Besides that, the voltage of each node is considered as a constraint. The allowable voltage limit is considered from 0.9p.u. to 1.1p.u. From Figure 5.4, the minimum voltage is observed 0.92p.u. and 0. 901p.u for 47% and 63% PEV penetration respectively. The minimum voltage is observed in 13th and 21th feeder for 47% and 63% PEV penetration respectively. On the other hand, from Figure 5.5 employing BGWO, the minimum voltage is observed 0.911p.u. and 0.900p.u. at feeder 13th.

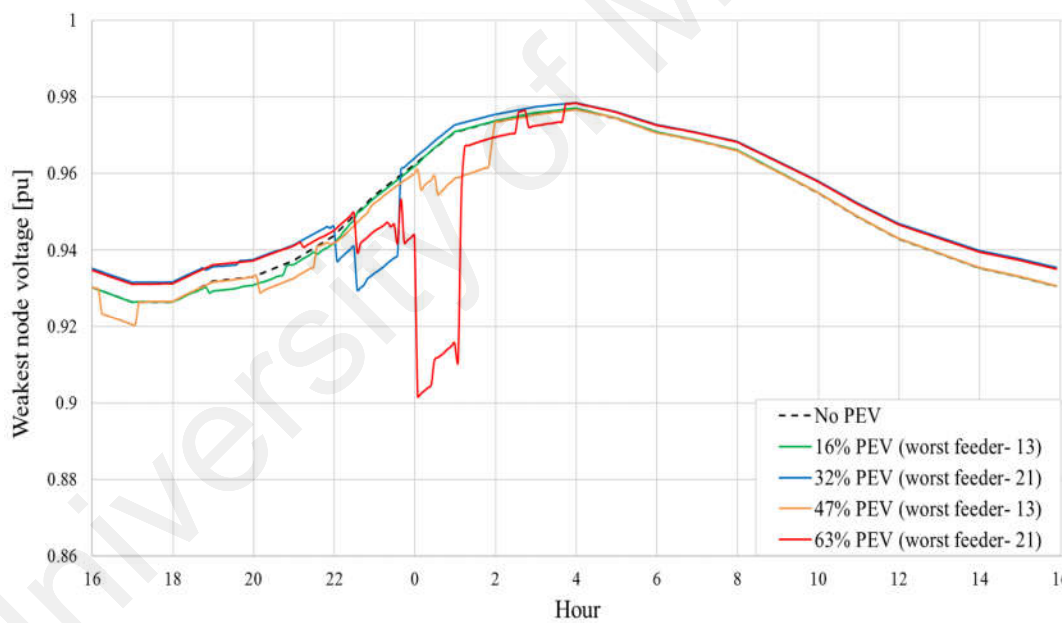


Figure 5.4: Voltage profile at weakest node in coordinated PEV charging considering power loss minimization using BPSO

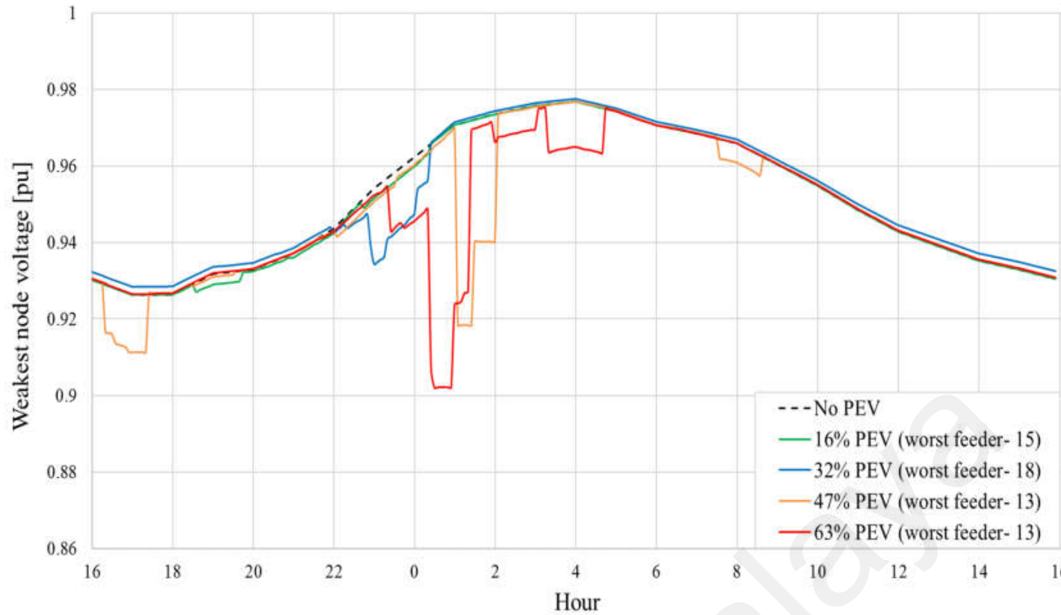


Figure 5.5: Voltage profile at the weakest node in coordinated PEV charging considering power loss minimization using BGWO

The total power loss of the system using BPSO and BGWO are presented in Figures 5.6 and 5.7. It is observed that, the power loss is reduced compare to the uncoordinated charging scenario. The maximum power loss is found 31.1kW and 33.8kW at 23:10 and 23:50 respectively for 63% PEV penetration. Compare to the power loss with no PEV (25.3kW), this power loss is considerable at the peak load.

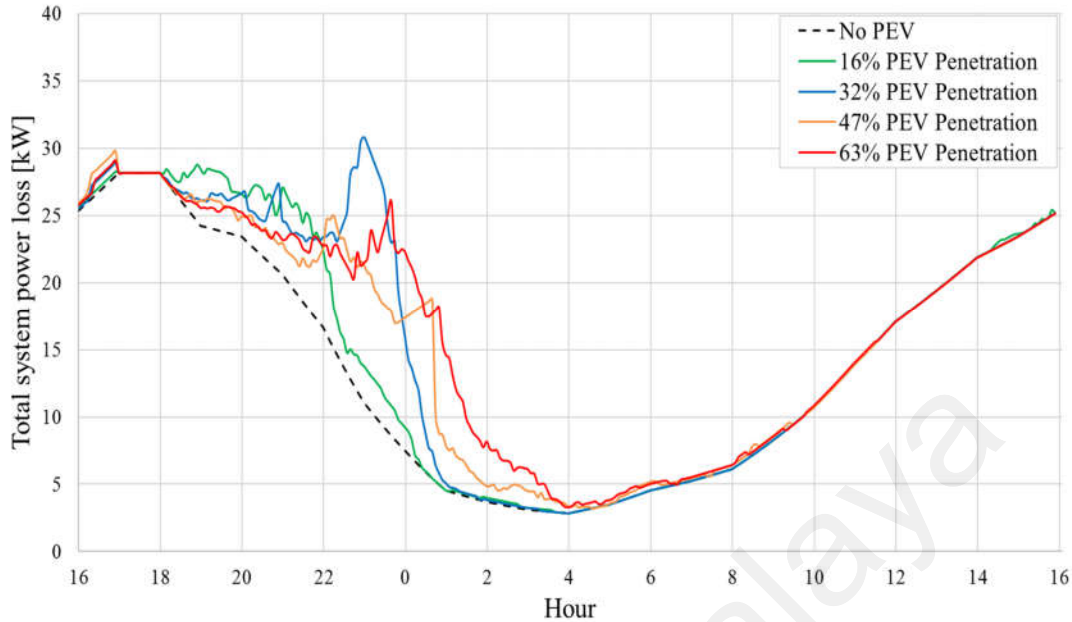


Figure 5.6: Total system power loss in coordinated PEV charging considering power loss minimization using BPSO

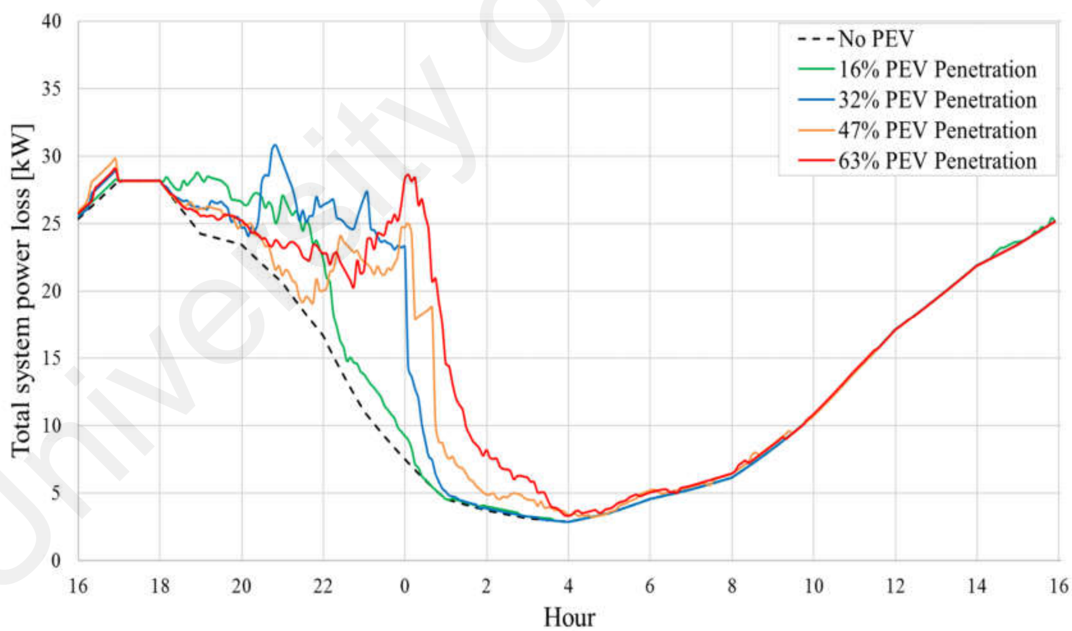


Figure 5.7: Total system power loss in coordinated PEV charging considering power loss minimization using BGWO

Figures 5.8 and 5.9 are showing the daily power consumption of the network using BPSO and BGWO respectively. It is clear that, there is no system overload during the

PEV charging activities. The power consumption level is almost equal to the maximum capacity of the system unless the PEV is decreased.

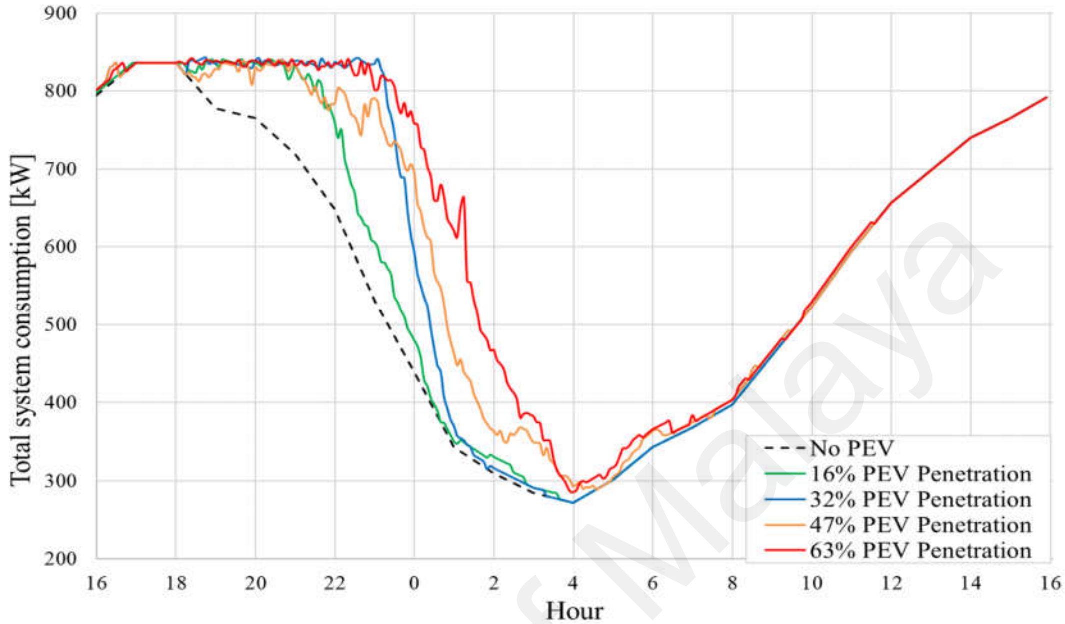


Figure 5.8: Total system power consumption in coordinated PEV charging considering power loss minimization using BPSO

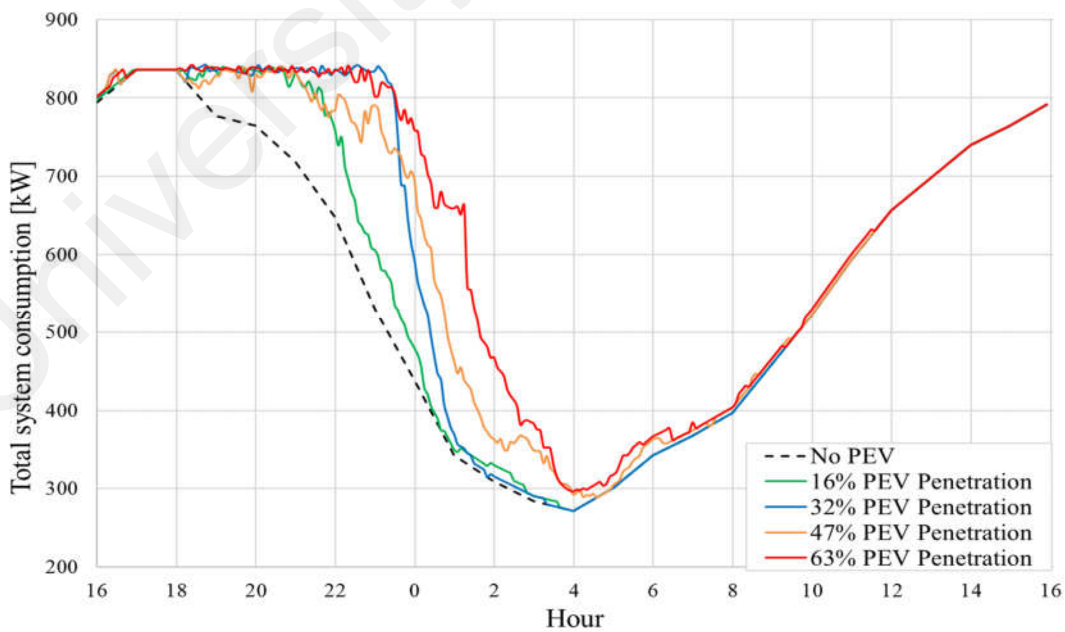


Figure 5.9: Total system power consumption in coordinated PEV charging considering power loss minimization using BGWO

5.3.2 Objective function 2: Minimizing power loss and voltage deviations

Minimization of power loss and voltage deviation are considered simultaneously in PEV charging coordination. Here, the algorithm minimizes the voltage deviation in each low voltage node for all the timeslot during the PEV charging. It is observed that, the voltage profile of the weakest node is more improved compare to the Objective 1. Although the impact of lower PEV penetration (16% and 32%) in voltage profile is less, but higher PEV penetration (47% and 63%) has a significant impact. The minimum voltage obtained employing BPSO for 47% and 63% PEV penetration are 0.914p.u. and 0.908p.u. respectively as shown in Figure 5.10. The voltage profile of low voltage node for each PEV penetrations using BGWO are shown in Figure 5.11. Here, the minimum voltage is found 0.914p.u. and 0.908p.u. for 47% and 63% penetration respectively.

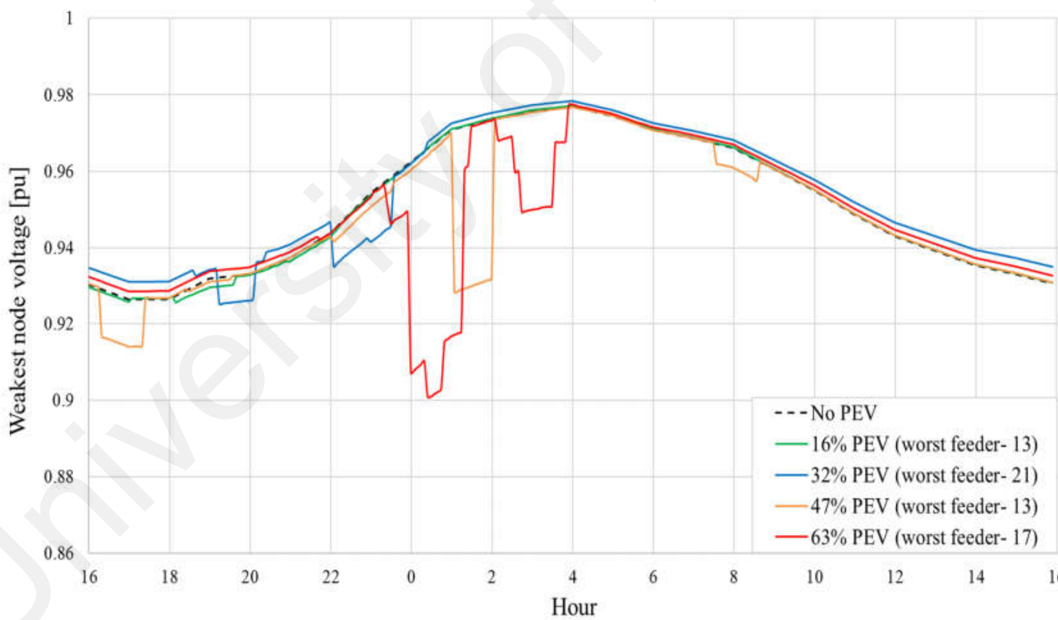


Figure 5.10: Voltage profile at the weakest node in coordinated PEV charging considering power loss and voltage deviation minimization using BPSO

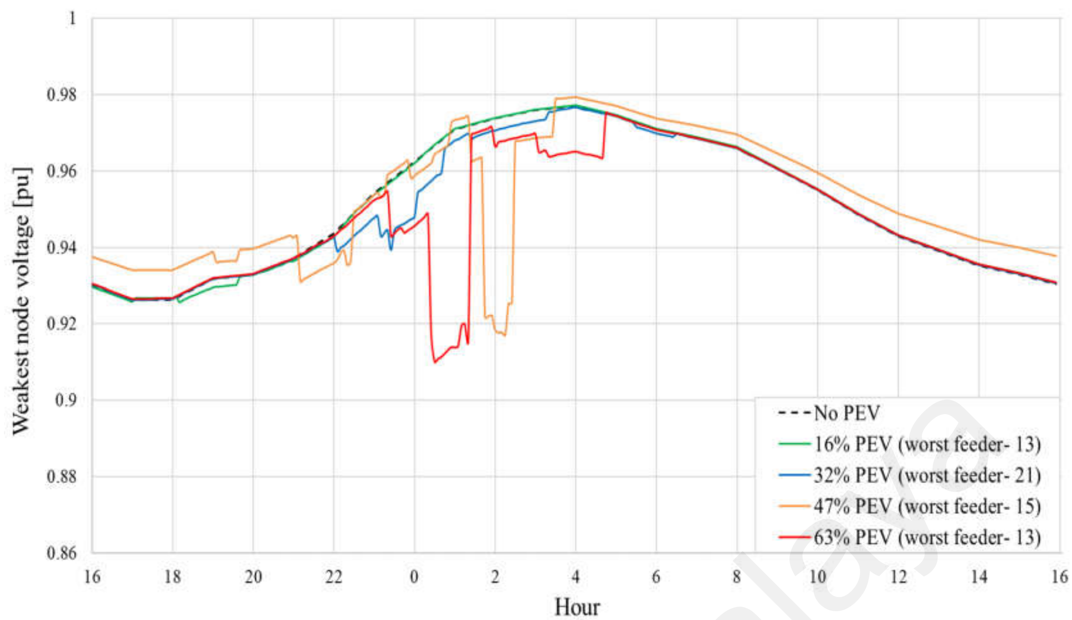


Figure 5.11: Voltage profile for weakest node coordinated PEV charging considering power loss and voltage deviation minimization using BGWO

The daily power loss considering minimization of power loss and voltage deviation is presented in Figures 5.12 and 5.13. The power loss for lower penetration is not excessive compared to the power loss when there is no PEV charging in the network. For the higher PEV penetration, the total power loss is reduced by 11% and 8% for 47% and 63% PEV penetration respectively by using BPSO. On the other hand, employing BGWO, the power loss is found as reduced by 13.2% and 9.4% for 47% and 63% PEV penetration respectively. The Figures 5.14 and 5.15 are showing the total power consumption of the distribution network while the PEV charging coordination is made considering minimization of power loss and voltage deviation. In both figures, there is no substation transformer overload and the total power consumption touches the maximum capacity of the substation transformer.

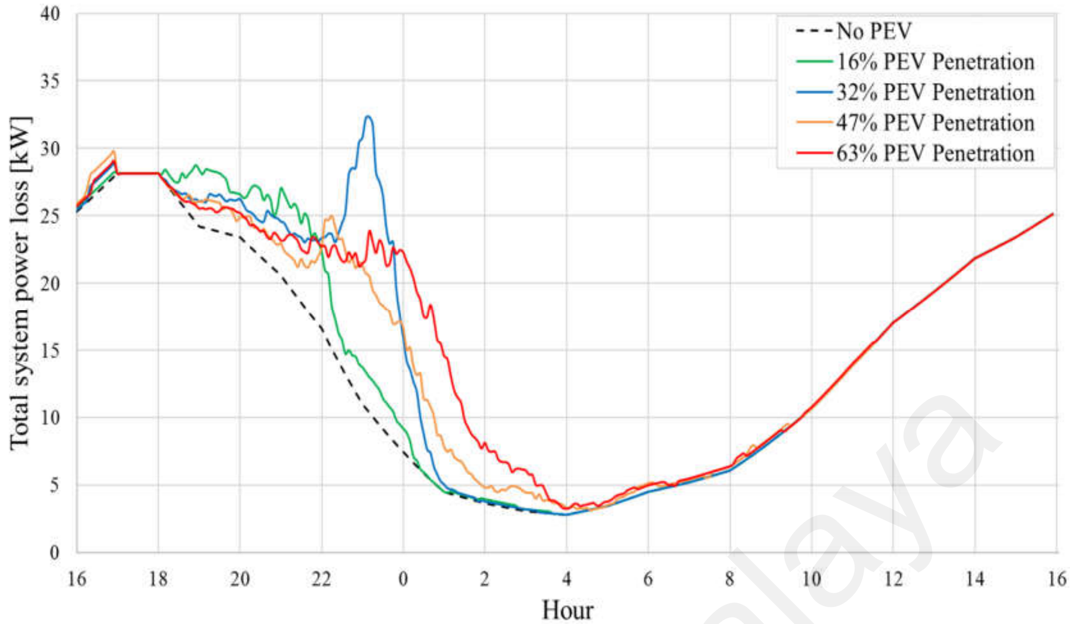


Figure 5.12: Total system power loss in coordinated PEV charging considering power loss and voltage deviation minimization using BPSO

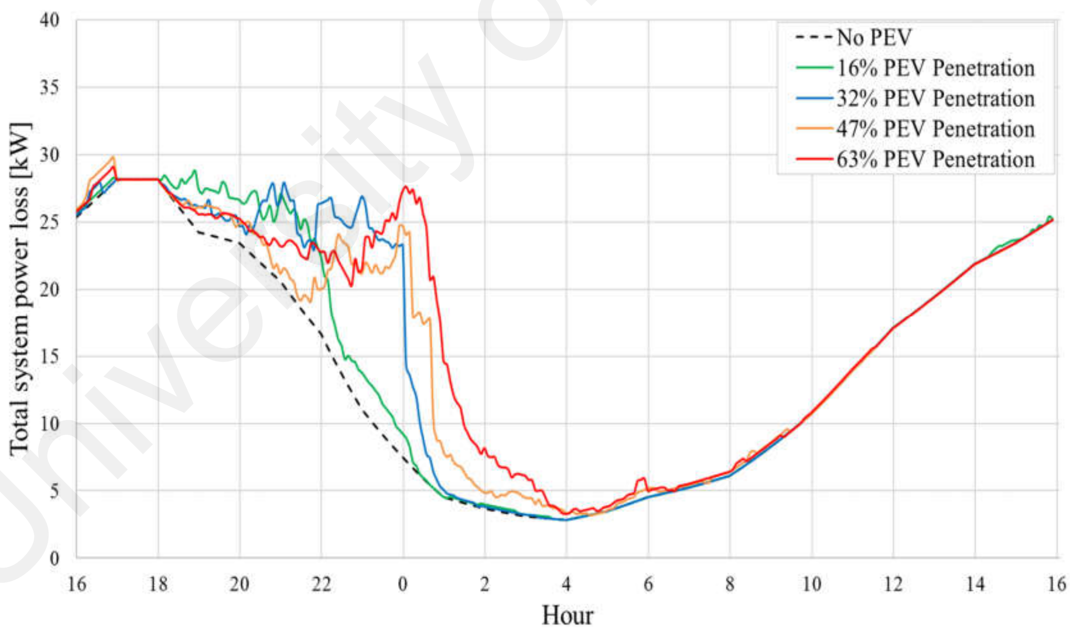


Figure 5.13: Total system power loss in coordinated PEV charging considering power loss and voltage deviation minimization using BGWO

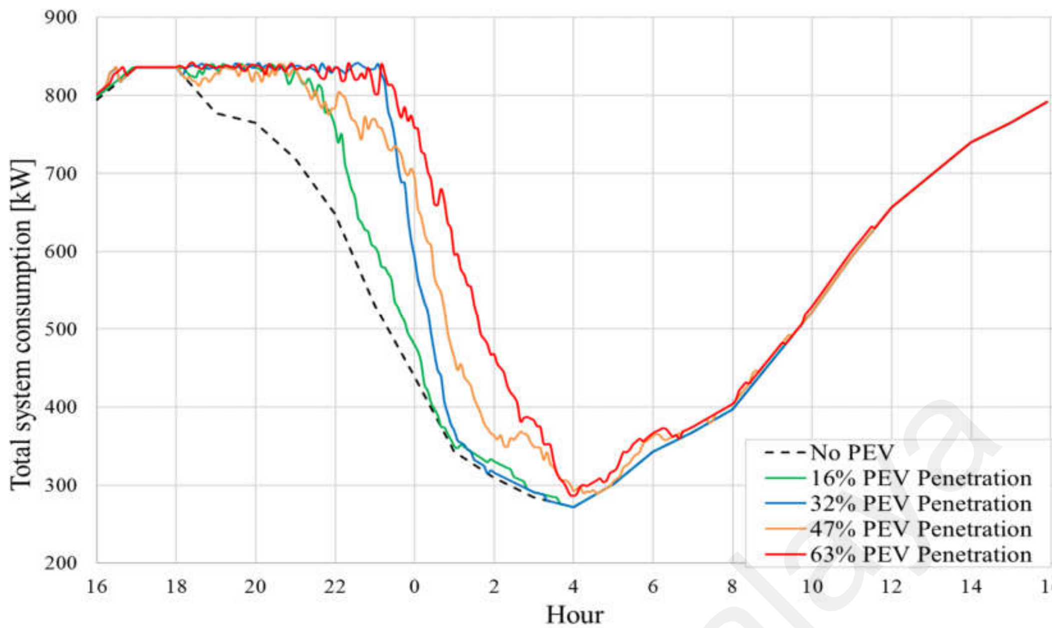


Figure 5.14: Total system power consumption in coordinated PEV charging considering power loss and voltage deviation minimization using BPSO

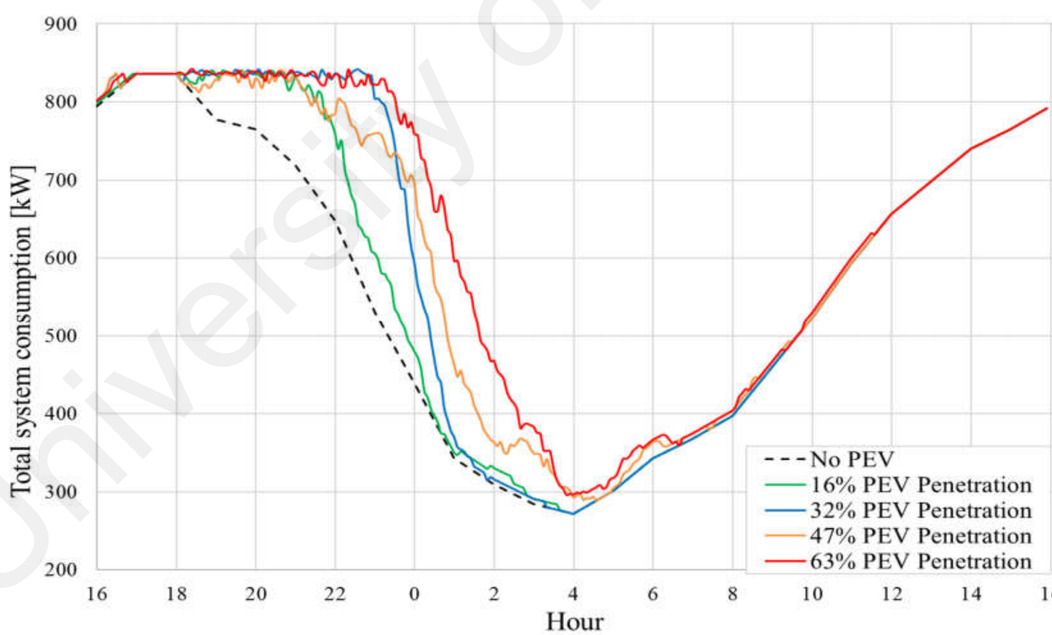


Figure 5.15: Total system power consumption in coordinated PEV charging considering power loss and voltage deviation minimization using BGWO

Figures 5.16 and 5.17 are showing the state of charge (SOC) for all vehicles in each timeslot for 63% PEV penetration at the weakest using BPSO and BGWO respectively in the network. Due to the voltage constraint at the low voltage node, it is observed from Figure 5.18, vehicles at node n4, n10, n11, n13 and n19 have not been started to charge till end of the day. As a consequence, the PEV customer at these five nodes are found not satisfied. Based on the PEV customer satisfaction, 14th feeder is the weakest feeder in this network after employing BSPO and BGWO. Similar to this, twelve more feeders are left where all the PEV customers are not satisfied. On the other hand, rest of the PEVs from other feeders are fully charged on time.

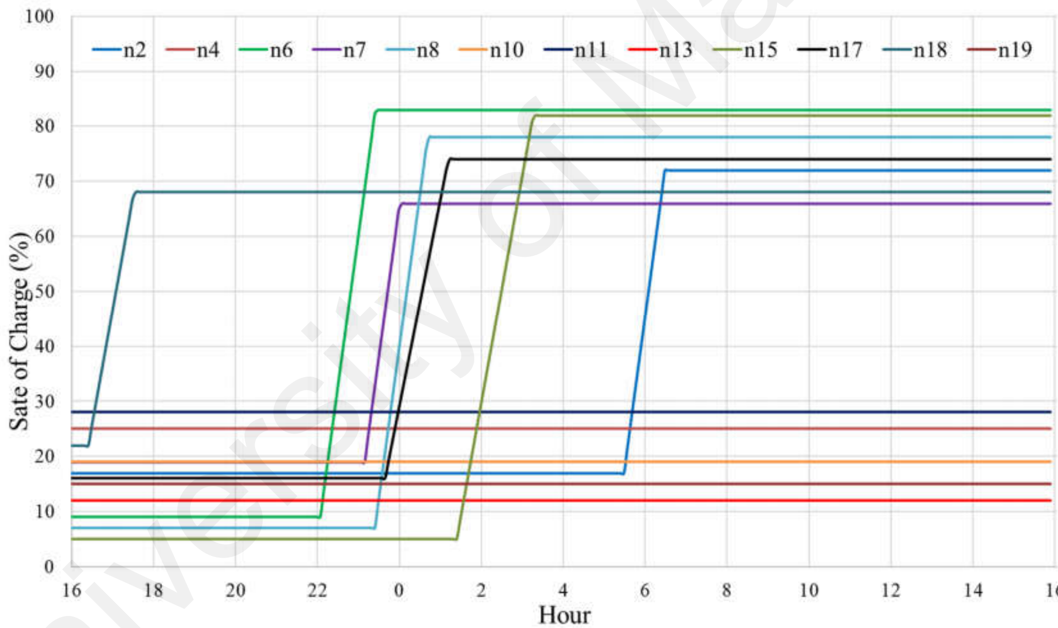


Figure 5.16: State of charge (SOC) for weakest feeder at 63% penetration in coordinated PEV charging considering power loss and voltage deviation using BPSO

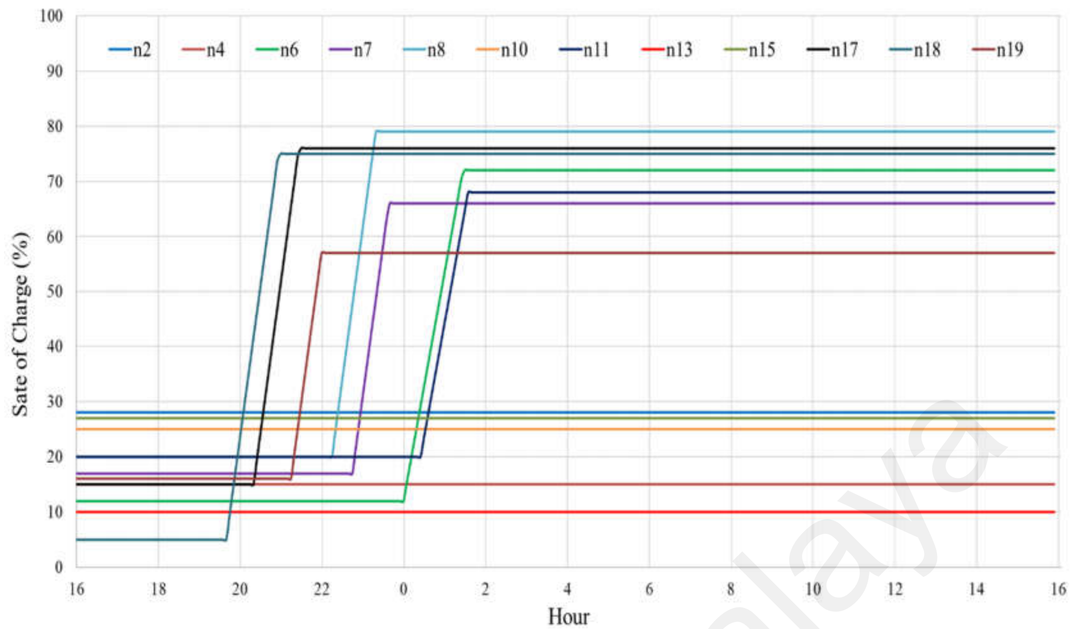


Figure 5.17: SOC for weakest feeder at 63% penetration in coordinated PEV charging considering power loss and voltage deviation using BGWO

5.3.3 Comparison of the objective functions

The optimization algorithm for PEV charging coordination is applied considering two objective functions- one is minimization of power loss and another one is minimization of power loss as well as voltage deviation together. The recorded result for the both objective functions are presented in the Table 5.2. From the Figures (5.4 to 5.9 and 5.10 to 5.15), the impact of lower PEV penetration (16% and 32%) is lesser than higher PEV penetration (47% and 63%). From the Table 5.2, it can be concluded that, objective 2 always offers better result compare to objective function 1 in terms of minimizing power loss, voltage deviation. After considering the voltage deviation with power loss minimization, the total power loss is further decreased. Therefore, in this research, minimization of power loss and voltage deviation are taken into consideration as optimization objective function. However, some vehicles are always left to be charged due to voltage constraints for the both objective functions.

Table 5.2: Comparison of two different objective functions in PEV charging coordination strategy

PEV penetration	Objective function	Optimization	V (%)	P loss (%)	PEV left to be charged
0	-	-	7.35	0	-
16%	Obj #1	BPSO	7.96	7.20	8
		BGWO	8.10	7.26	8
	Obj #2	BPSO	7.43	6.96	13
		BGWO	7.42	7.12	13
32%	Obj #1	BPSO	8.14	14.16	14
		BGWO	8.20	14.68	14
	Obj #2	BPSO	7.47	13.67	18
		BGWO	7.51	13.04	15
47%	Obj #1	BPSO	9.10	12.64	16
		BGWO	8.92	12.95	18
	Obj #2	BPSO	8.61	12.32	23
		BGWO	8.86	13.01	22
63%	Obj #1	BPSO	9.96	19.06	21
		BGWO	9.92	18.88	20
	Obj #2	BPSO	9.91	17.53	28
		BGWO	9.91	17.64	28

5.4 Incorporate power system equipment to improve voltage profile

The PEV charging coordination strategy is able to maintain the voltage level of each node and maximum power consumption inside the limit. As a consequence, the total power loss during the PEV charging is also reduced significantly. However, the vehicles in some nodes have not been started charging and PEV customer satisfaction level is decreased due to voltage limitation. To overcome this issue, power system equipment such as capacitor and on-load tap changer (OLTC) have been employed in this research.

5.4.1 Coordinated PEV charging incorporating Capacitor switching

The modeled network has five number of capacitors in selected busses. Table 5.3 represents the switching operation of each capacitor for 24 hours at 63% PEV penetration when the PEV charging coordination is made. The capacitors have been turned on and off based on estimated load profile with PEV charging activities. The main consideration in capacitor switching coordination is minimization of power loss and voltage deviation while the daily allowable number of switching is considered as constraint. In capacitor switching coordination process, BPSO and BGWO are employed as optimization algorithm and the observed results are presented in Figures 5.18 to 5.25.

Table 5.3: Capacitor switching sequence for 24 hours during PEV charging coordination

	BPSO					**BGWO**				
Hour	C1	C2	C3	C4	C5	C1	C2	C3	C4	C5
1	1	1	0	1	1	1	0	0	1	0
2	1	1	0	1	1	1	0	0	1	0
3	1	0	0	1	1	1	0	0	1	0
4	1	0	1	1	1	1	0	0	0	0
5	1	0	1	0	1	0	0	0	0	0
6	1	0	1	0	1	0	0	0	0	1
7	1	0	1	0	0	0	0	0	0	1
8	1	0	1	0	0	0	0	0	0	1
9	0	0	1	0	0	0	0	0	0	1
10	0	0	1	0	0	0	0	1	0	1
11	0	0	1	0	0	0	0	1	0	1
12	1	0	1	0	0	0	0	1	0	1
13	1	0	1	0	0	0	0	1	1	1
14	1	0	1	0	0	1	0	1	1	1
15	1	0	1	0	0	1	0	1	1	1
16	1	1	1	1	1	1	1	1	1	1
17	1	1	1	1	1	1	1	1	1	1
18	1	1	1	1	1	1	1	1	1	1
19	1	1	1	1	1	1	1	1	1	1
20	1	1	1	1	1	1	1	1	1	1
21	1	1	0	1	1	1	1	1	1	1
22	1	1	0	1	1	1	1	1	1	0
23	1	1	0	1	1	1	1	1	1	0
24	1	1	0	1	1	1	1	1	1	0

The capacitor switching operation is coordinated employing BPSO and BGWO. Figures 5.18 and 5.19 show the improvement of voltage profile of weakest node in the network for different PEV penetration level. It is observed that, the voltage profile at the weakest node for the higher PEV penetration (47% and 63%) are more improved compare to no capacitor operation. For the lower PEV penetration (16% and 32%), the voltage profile of weakest node during PEV charging is similar to the voltage profile when there is no PEV charging in the network. Moreover, the capacitor switching operation decreases the daily power loss as well as shown in Figures 5.20 and 5.21. The total power loss is reduced by 9.8% compare to no capacitor operation in the network for a day at 63% PEV penetration. In the total power consumption, there is no transformer overload in the system shown in Figures 5.22 and 5.23.

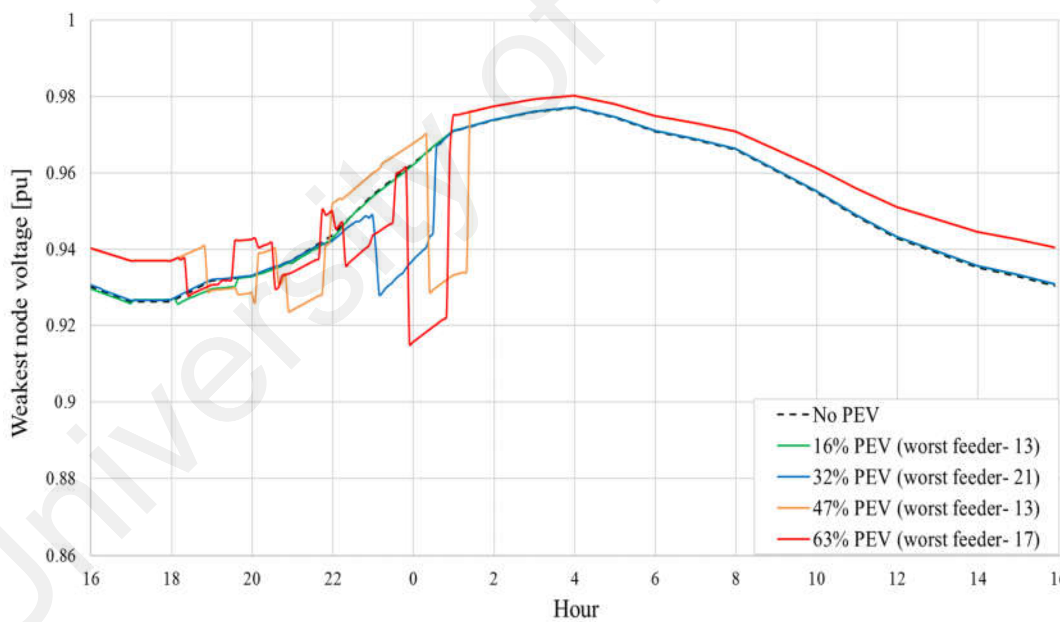


Figure 5.18: Voltage profile at the weakest node with capacitor switching during PEV charging coordination using BPSO

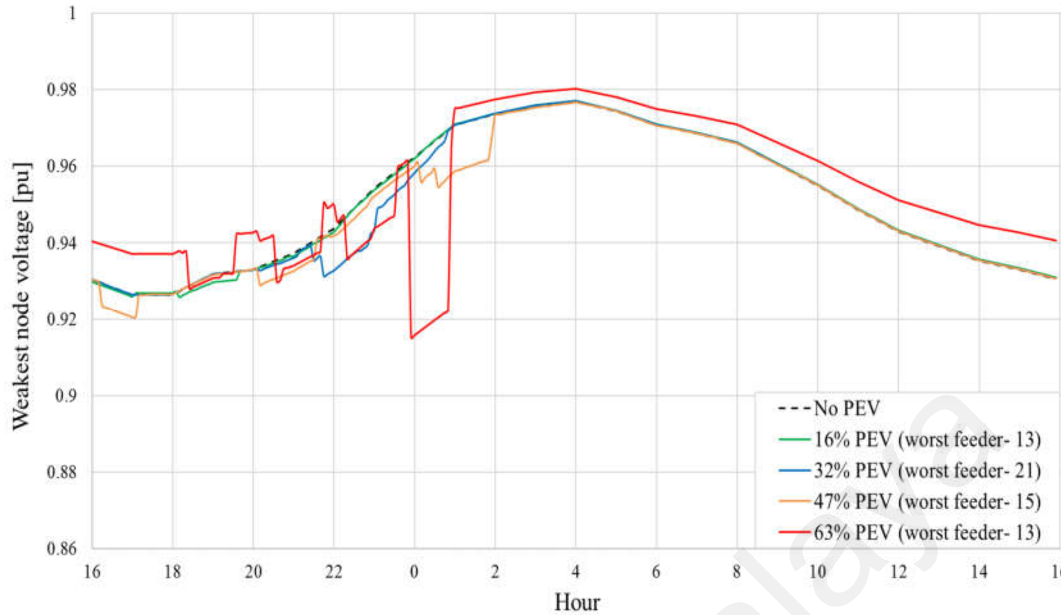


Figure 5.19: Voltage profile at the weakest node with capacitor switching during PEV charging coordination using BGWO

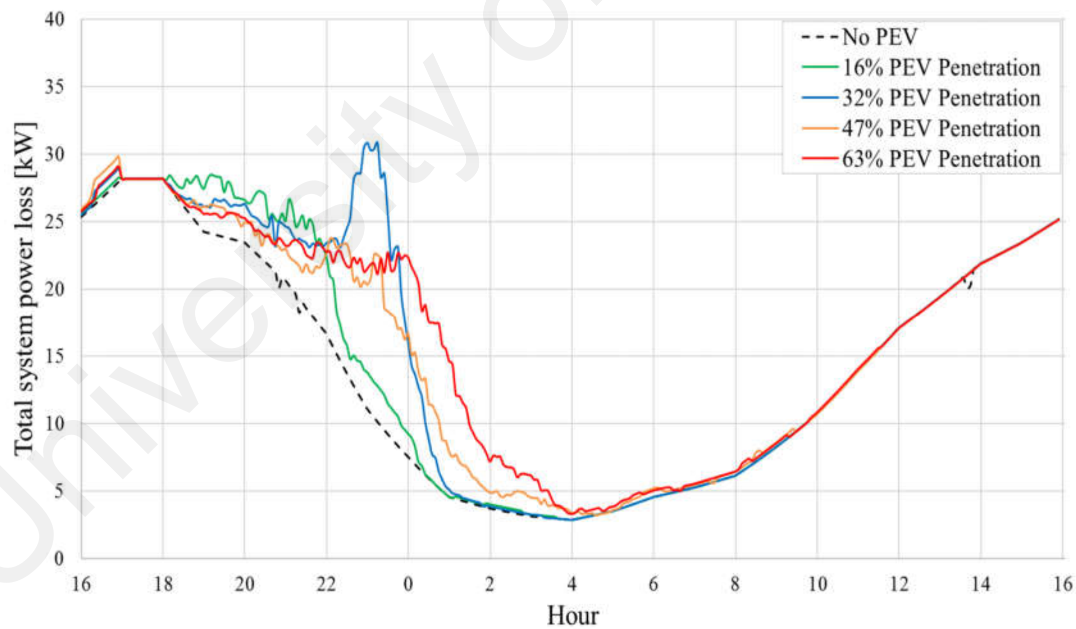


Figure 5.20: Total system power loss with capacitor switching during PEV charging coordination using BPSO

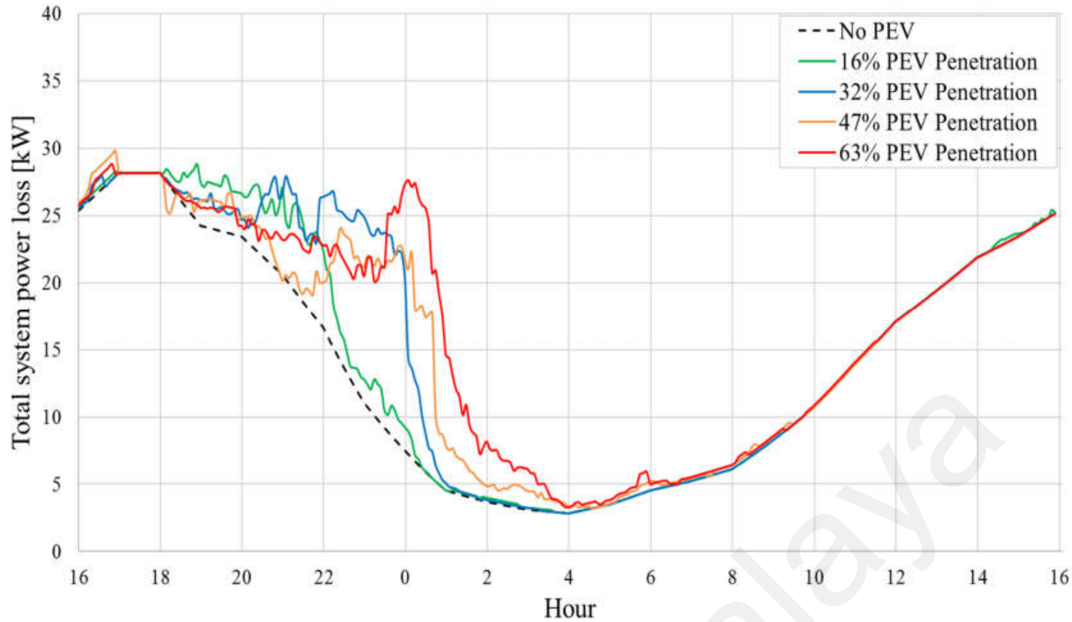


Figure 5.21: Total system power loss with capacitor switching during PEV charging coordination using BGWO

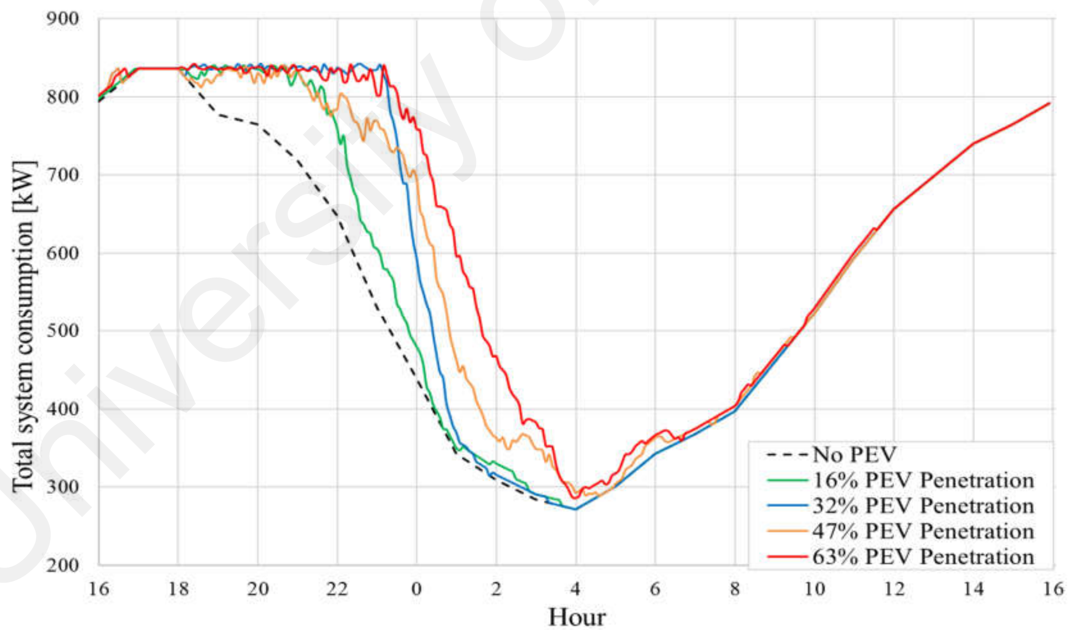


Figure 5.22: Total system power consumption with capacitor switching during PEV charging coordination using BPSO

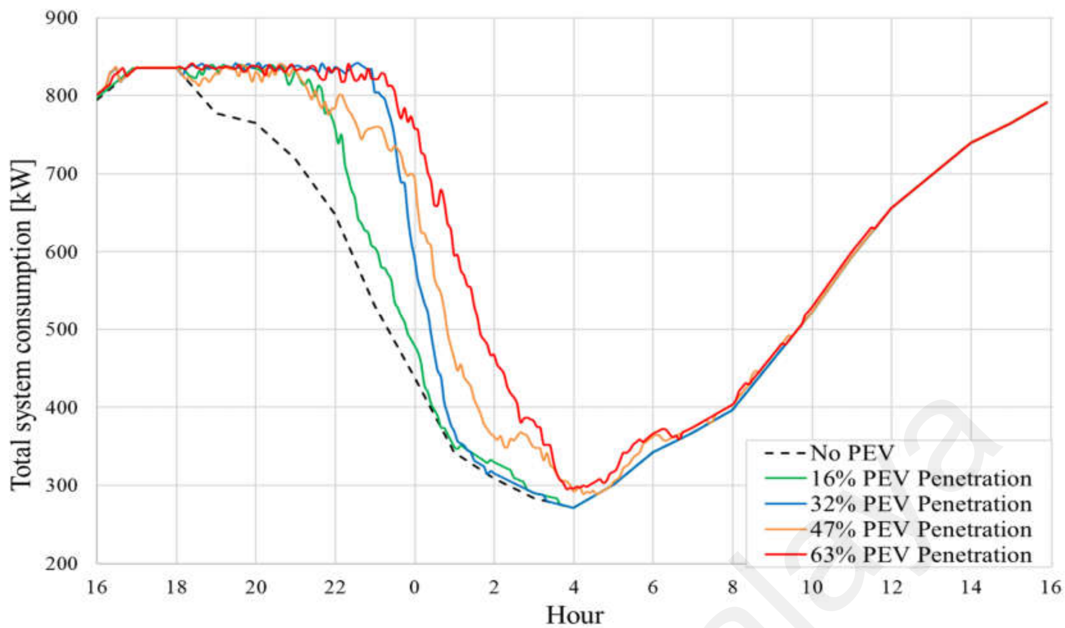


Figure 5.23: Total system power consumption with capacitor switching during PEV charging coordination using BGWO

After applying capacitor switching operation to improve the voltage profile during the PEV charging coordination, few number of PEVs are still left to be charged. Due to the higher capacity of PEV chargers (3.3kW, 6.6kW, 7.2kW) and capacitor switching constraints, the voltage level exceeds the allowable lower limit in some PEV penetration level. Figure 5.24 shows the SOC status for each vehicle at the weakest feeder where the vehicles at nodes n10, n15 and n18 are have not been started to charge at 63% PEV penetration. Similar to this feeder, some more feeders are found where some vehicles are left to be charged. Therefore, the PEV customer satisfaction is found less. On the other hand, Figure 5.25 shows the SOC status of the weakest feeder employing BGWO.

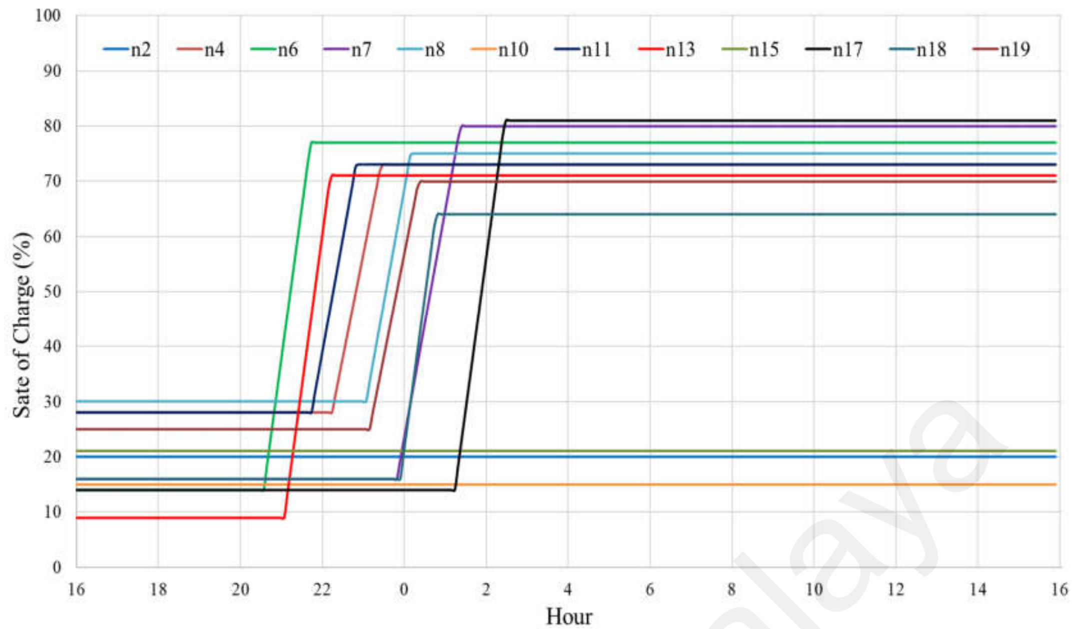


Figure 5.24: SOC for weakest feeder for 63% penetration with capacitor switching during PEV charging coordination using BPSO

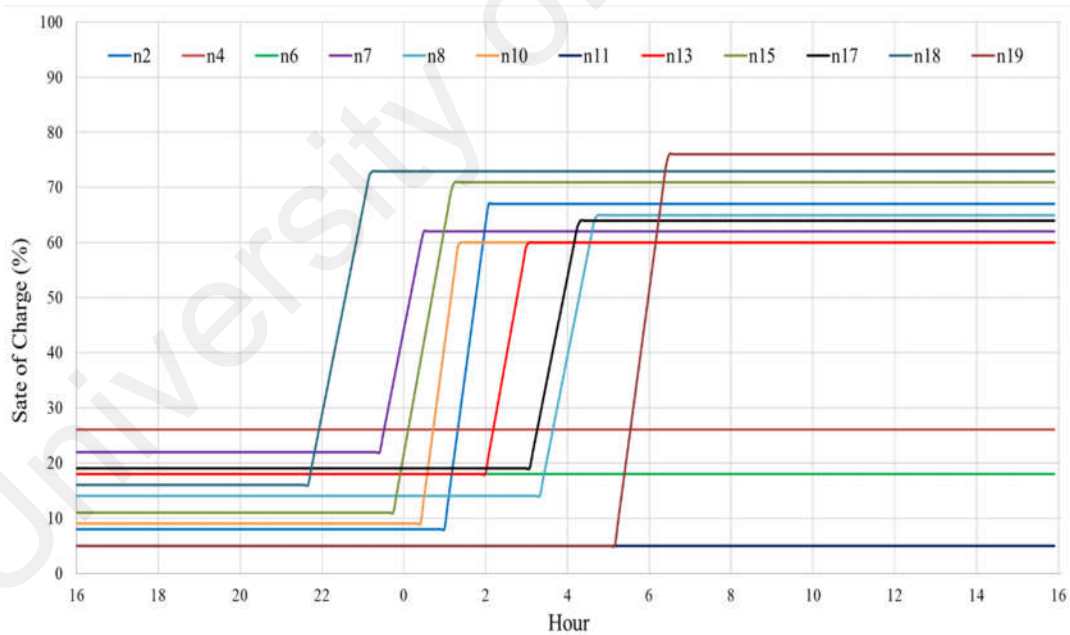


Figure 5.25: SOC for weakest feeder for 63% penetration with capacitor switching during PEV charging coordination using BGWO

5.4.2 Coordinated PEV charging incorporating OLTC operation

From the previous section results, it is seen that the capacitor switching in the distribution system is not sufficient to improve the voltage profile during PEV charging coordination. On-load tap changer transformer (OLTC) is one of the power system equipment which can improve the voltage profile. To improve the voltage profile during the PEV charging coordination OLTC is employed instead of capacitor switching. Table 5.4 shows the tap position for 24 hours at 63% PEV penetration during the PEV charging activities to improve the voltage profile of the network. Similar to the previous section, BPSO and BGWO are employed to adjust the OLTC tap position. The observations after employing OLTC adjustment in the network are presented in the Figures 5.28 to 5.35.

Table 5.4: OLTC tap position for each hour

	Tap Position			Tap Position	
Hour	BPSO	BGWO	Hour	BPSO	BGWO
1	+2	+2	13	0	0
2	+2	+2	14	0	+1
3	+1	+1	15	0	+1
4	+1	+1	16	+1	+1
5	0	0	17	+3	+2
6	0	0	18	+3	+4
7	0	0	19	+4	+4
8	0	0	20	+4	+4
9	0	0	21	+4	+5
10	0	0	22	+5	+5
11	0	0	23	+5	+4
12	0	0	24	+2	+2

Using the OLTC in the network during the PEV charging coordination, the voltage profile is improved significantly as shown in Figures 5.26 and 5.27. For both algorithm, the minimum voltage is found for higher PEV penetration (47% and 63%) 0.921p.u. at the weakest node. On the other hand, the impact of lower PEV penetration (16% and

32%) after employing OLTC operation is very less. Furthermore, the improvement of voltage profile further decreases the total power loss as shown in Figure 5.28 and 5.29. It is also observed that, the substation transformer is not overloaded during the whole of PEV charging activities as presented in Figures 5.30 and 5.31.

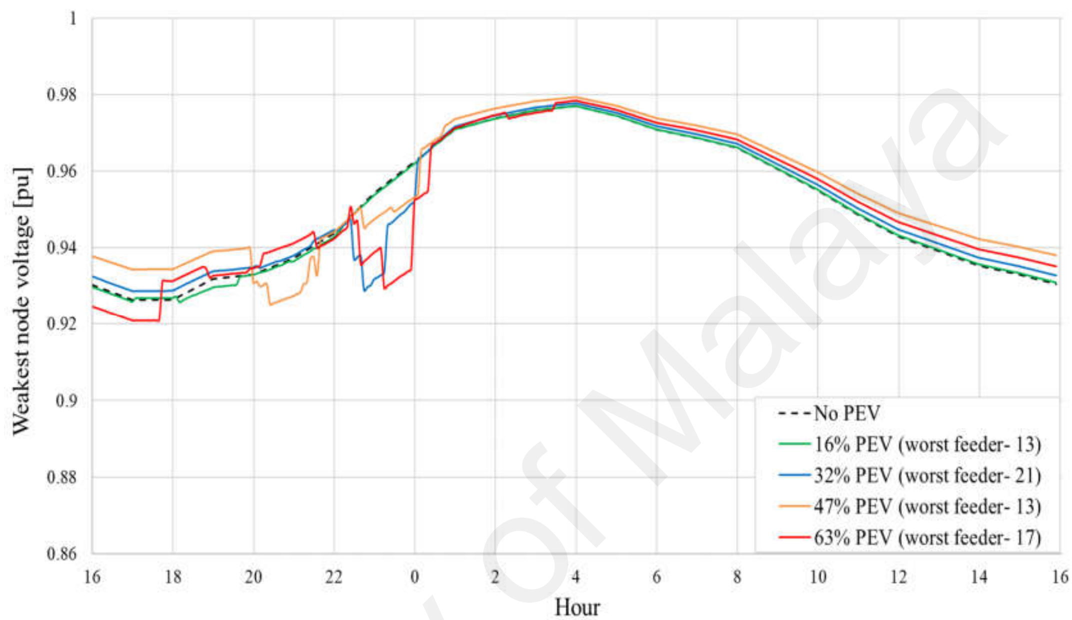


Figure 5.26: Voltage profile for weakest node with OLTC adjustment during PEV charging coordination using BPSO

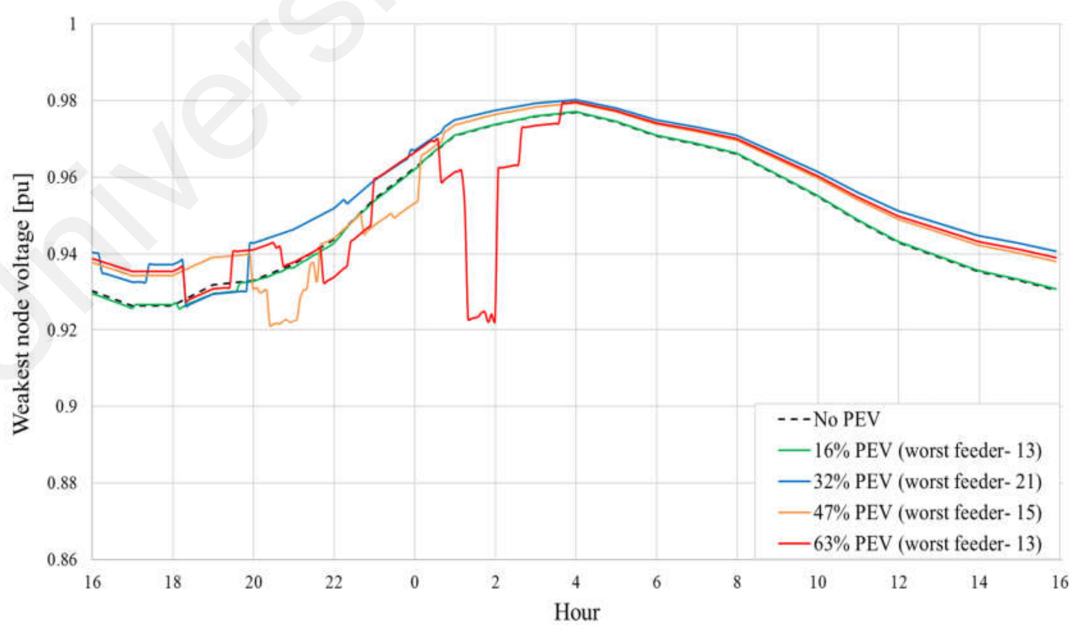


Figure 5.27: Voltage profile for weakest node with OLTC adjustment during PEV charging coordination using BGWO

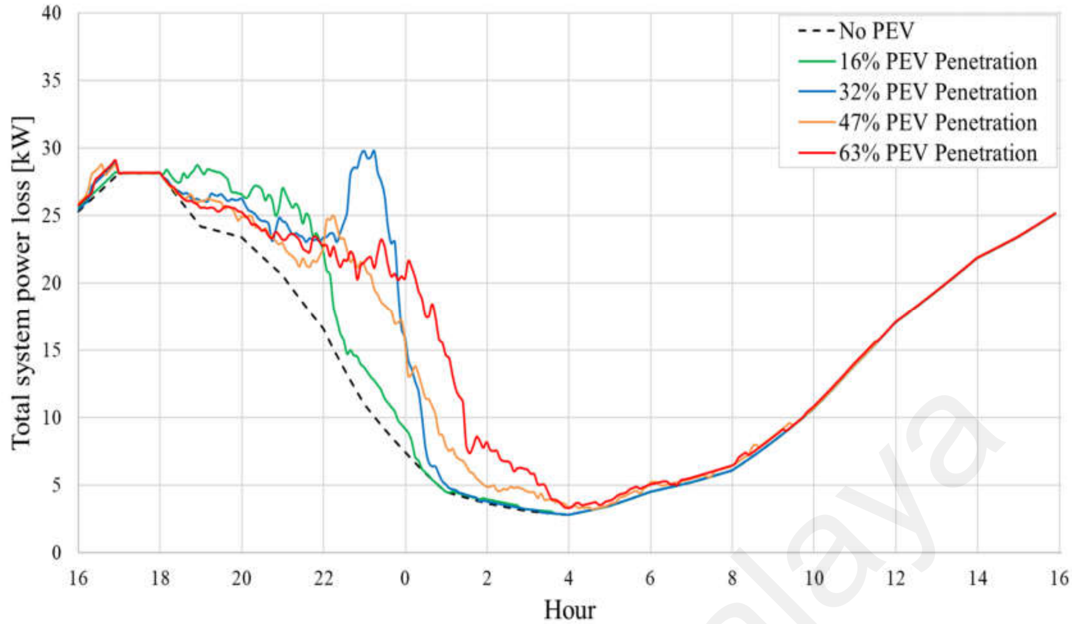


Figure 5.28: Total system power loss with OLTC adjustment during PEV charging coordination using BPSO

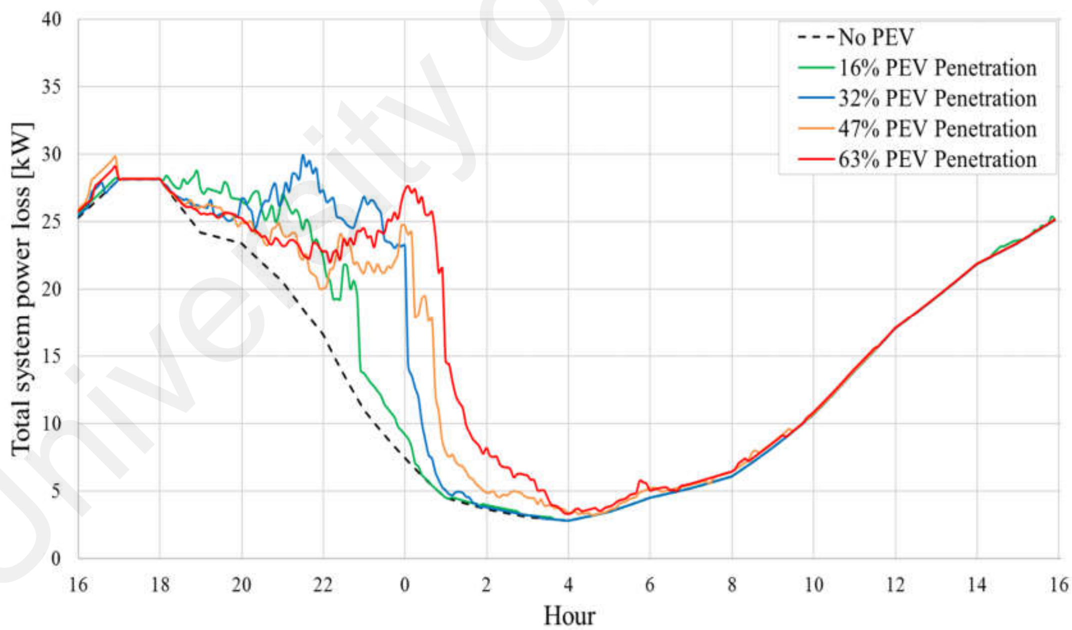


Figure 5.29: Total system power loss with OLTC adjustment during PEV charging coordination using BGWO

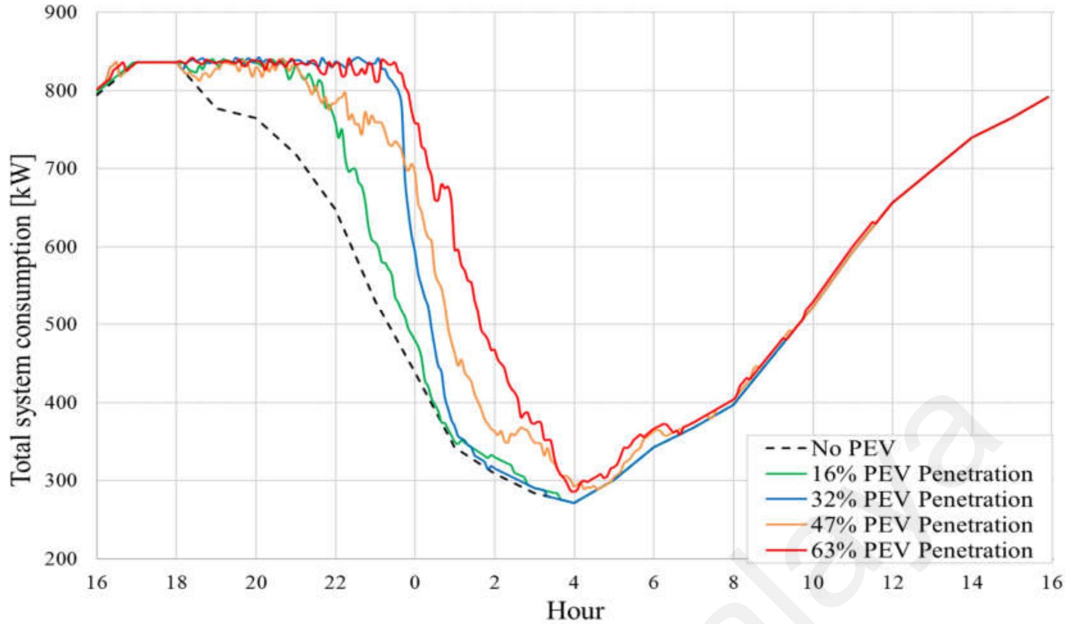


Figure 5.30: Total system power consumption with OLTC adjustment during PEV charging coordination using BPSO

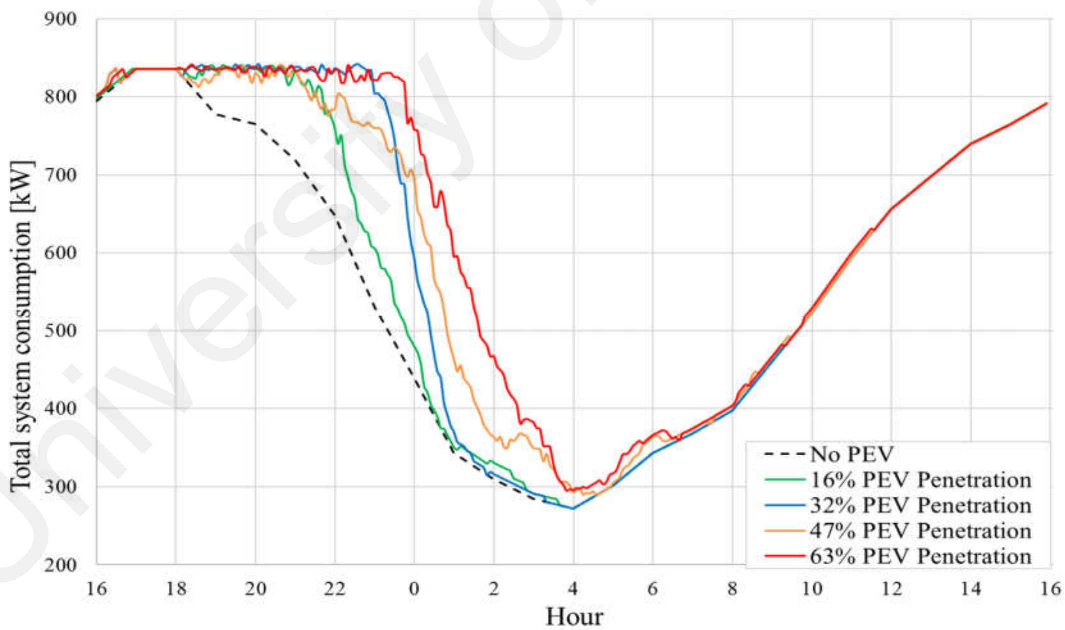


Figure 5.31: Total system power consumption with OLTC adjustment during PEV charging coordination using BGWO

After employing the OLTC operation with the PEV charging coordination, some PEVs are still left to reach their required state of charge (SOC). Although, the number of not charged PEV compared to capacitor integration is less. Some PEVs are left to be charged till their required SOC due to lower voltage limit at the node. The SOC status of each PEV for 63% penetration in the weakest feeder is shown in Figure 5.32 using BPSO. The PEVs at node n10 has not been started to charge. Figure 5.33 shows the SOC status for 63% PEV penetration of the weakest feeder in the network using BGWO. Similar to this, 10 number of feeders are found where some vehicles are left to be charged.

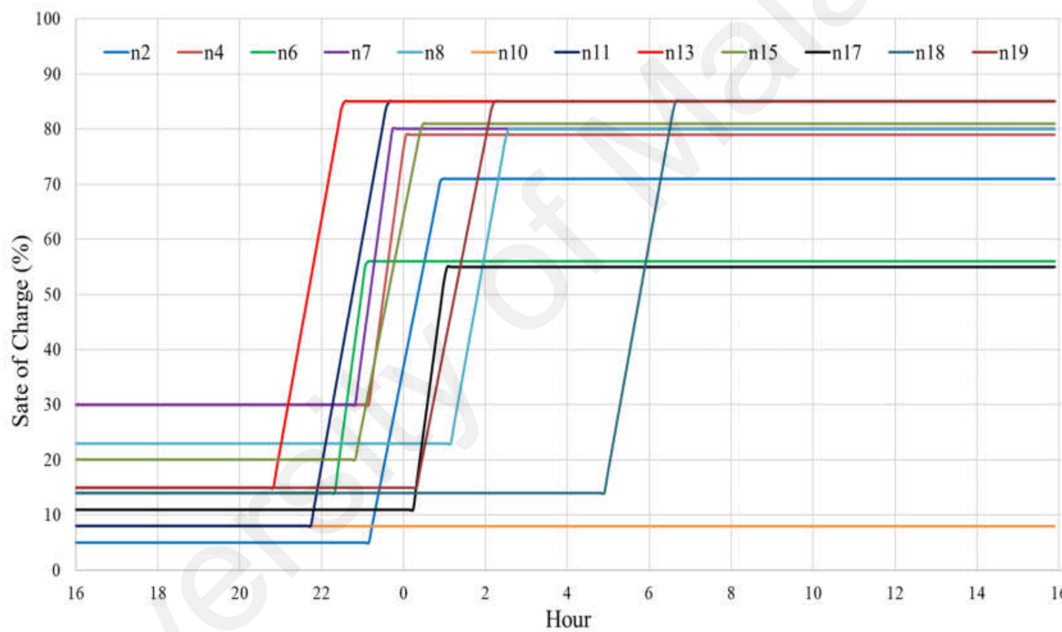


Figure 5.32: SOC for weakest feeder for 63% penetration with OLTC adjustment using BPSO

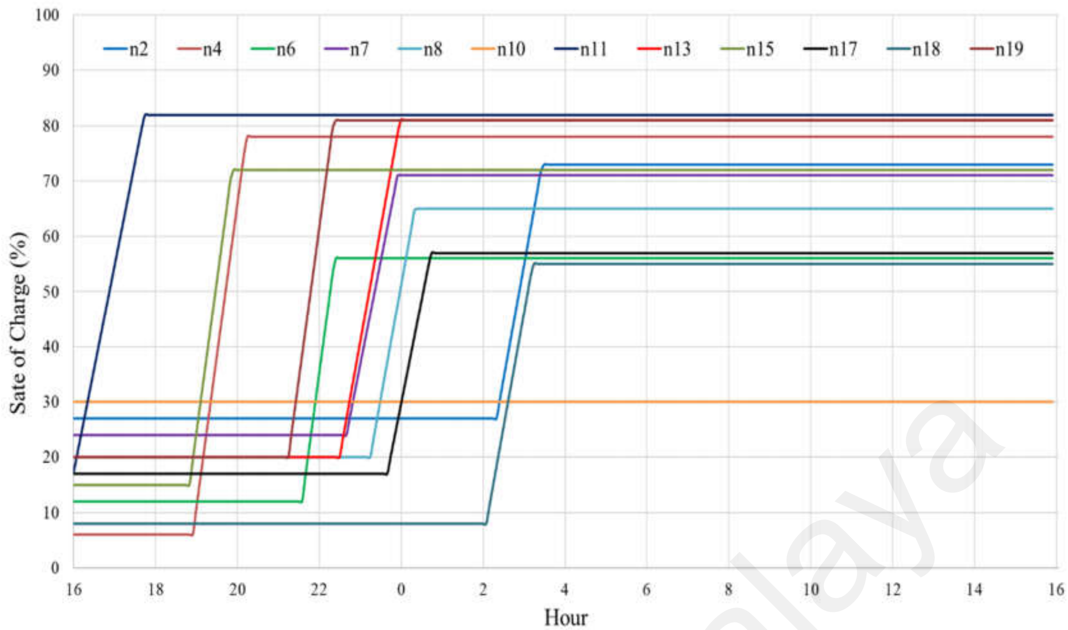


Figure 5.33: SOC for weakest feeder for 63% penetration with OLTC adjustment using BGWO

5.4.3 Coordinated PEV charging incorporating Capacitor and OLTC

In the previous sections, the integration of capacitor and OLTC operation have been observed separately and the result is recorded. However, in both cases, the voltage profile is more improved and the power loss is reduced significantly during the PEV charging coordination. Nevertheless, some of the PEVs are left to reach their required SOC in some of the specific nodes in both cases. From this observation, it can be concluded that, only the capacitor switching or OLTC adjustment is not able to improve the coordination performance. To overcome this issue, this research proposed capacitor switching and OLTC operation simultaneously. The main contribution of capacitor and OLTC operation in the system to ensure the allowable voltage limit in each node during the PEV charging activities. Because of voltage improvement, the overall power loss will be reduced significantly. The switching operation of five capacitors in the network and the OLTC tap position for every hour are presented in Table 5.5 at 63% PEV penetration using BPSO and BGWO.

Table 5.5: Capacitor and OLTC switching sequence in a day

	BPSO						**BGWO**					
Hour	Tap	C1	C2	C3	C4	C5	Tap	C1	C2	C3	C4	C5
1	+1	0	1	1	0	1	+1	0	1	1	0	1
2	+1	0	1	1	0	1	+1	0	1	1	0	1
3	+1	0	1	1	0	0	+1	0	1	1	0	1
4	+1	0	1	1	0	0	0	0	1	1	0	1
5	0	0	1	1	0	0	0	0	0	1	0	1
6	0	0	1	1	0	0	0	0	0	1	1	1
7	0	0	1	1	0	0	0	0	0	1	1	1
8	0	0	1	0	0	0	0	0	0	1	1	0
9	0	0	1	0	0	0	0	0	0	1	1	0
10	0	0	1	0	0	0	0	0	0	1	1	0
11	0	0	1	0	0	0	0	0	0	1	1	0
12	0	0	1	0	0	0	0	0	0	1	1	0
13	0	0	1	0	0	0	+1	1	0	1	1	0
14	0	0	1	0	1	0	+1	1	0	1	1	0
15	+1	0	1	0	1	0	+2	1	0	1	1	0
16	+3	1	1	0	1	0	+2	1	0	1	1	0
17	+3	1	1	0	1	1	+4	1	1	1	1	0
18	+4	1	1	0	1	1	+4	1	1	1	1	1
19	+4	1	1	0	1	1	+4	1	1	1	1	1
20	+4	1	1	0	1	1	+4	1	1	1	0	1
21	+2	1	1	0	0	1	+4	1	1	1	0	1
22	+2	1	1	0	0	1	+2	1	1	1	0	1
23	+2	1	1	0	0	1	+2	1	1	1	0	1
24	+2	0	1	1	0	1	+1	1	1	1	0	1

The weakest node voltage profile is improved after using the capacitor switching and OLTC operation as shown in Figures 5.34 and 5.35 employing BPSO and BGWO respectively. In Figure 5.34, the minimum voltage is found 0.920 and 0.918 for 47% and 63% PEV penetration respectively. The voltage profile of weakest node with the lower PEV penetration (16% and 32%) is more improved due to simultaneous activities of capacitor and OLTC.

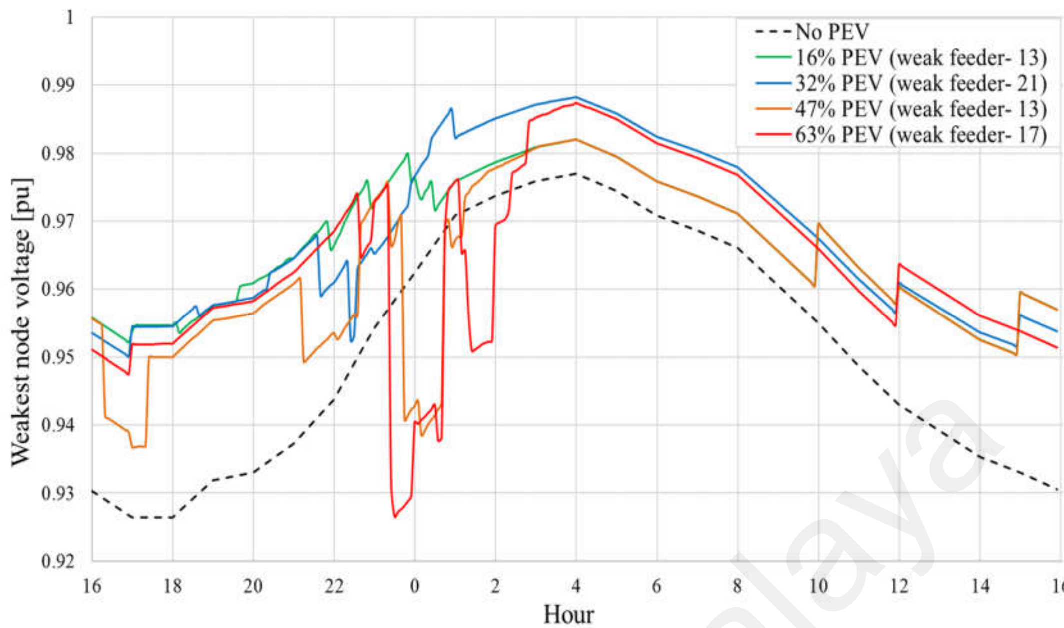


Figure 5.34: Voltage profile for weakest node with capacitor switching and OLTC adjustment during PEV charging coordination using BPSO

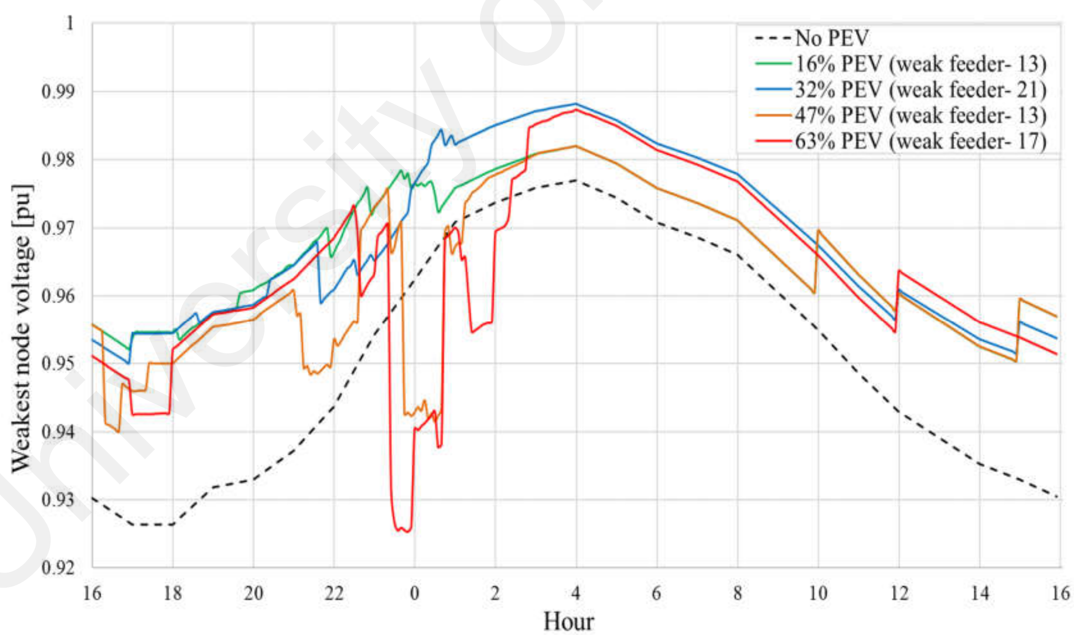


Figure 5.35: Voltage profile for weakest node with capacitor switching and OLTC adjustment during PEV charging coordination using BGWO

This proposed method reduces the network stress in terms of total system power loss reduction during the PEV charging activities. From the Figures 5.36 and 5.37, it is observed that, the total power loss in every timeslot is not excessive like uncoordinated PEV charging activities when no vehicles are left to be charged. The maximum power loss is found for 63% PEV penetration is 35.12kW at time 23:10 which is acceptable since all the PEV got charge. For 16%, 32% and 47% PEV penetration, the maximum power loss is recorded 28.16kW which is equal to the power loss with no PEV in the network. Therefore, the impact of PEV charging activities in the distribution network can be optimized by using capacitor and OLTC operation during the PEV charging coordination. Moreover, using the proposed method, there is no substation transformer overload during the PEV charging in the peak hour also shown in Figures 5.38 and 5.39.

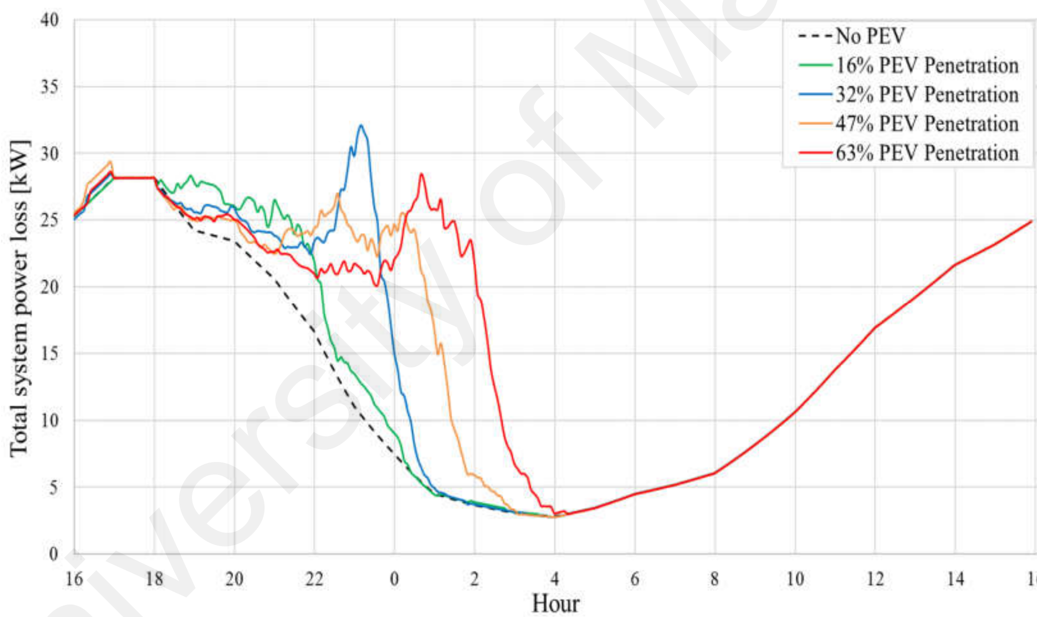


Figure 5.36: Total system power loss with capacitor switching and OLTC adjustment during PEV charging coordination using BPSO

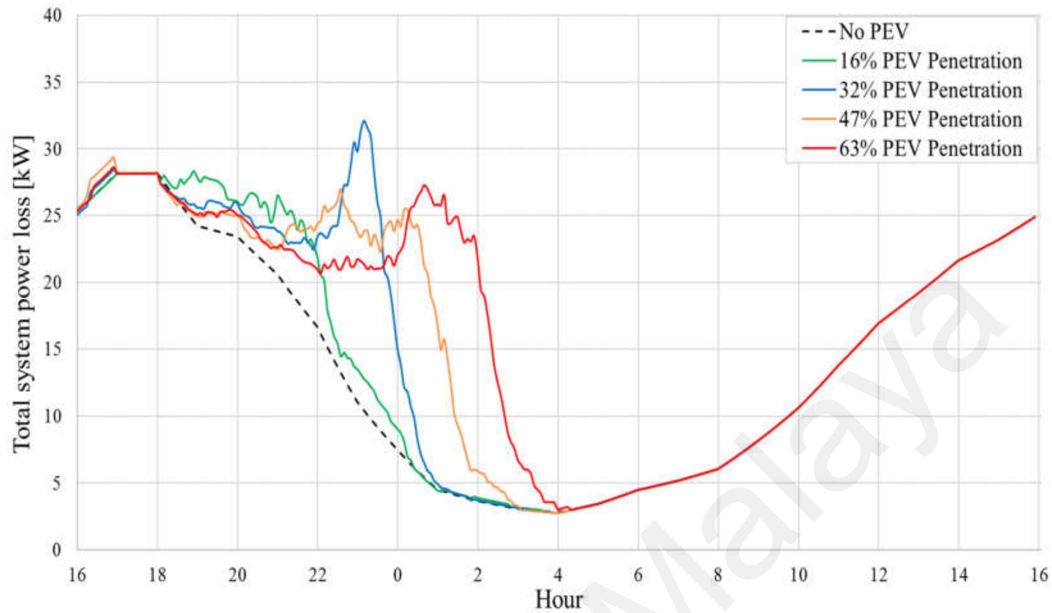


Figure 5.37: Total system power loss with capacitor switching and OLTC adjustment during PEV charging coordination using BGWO

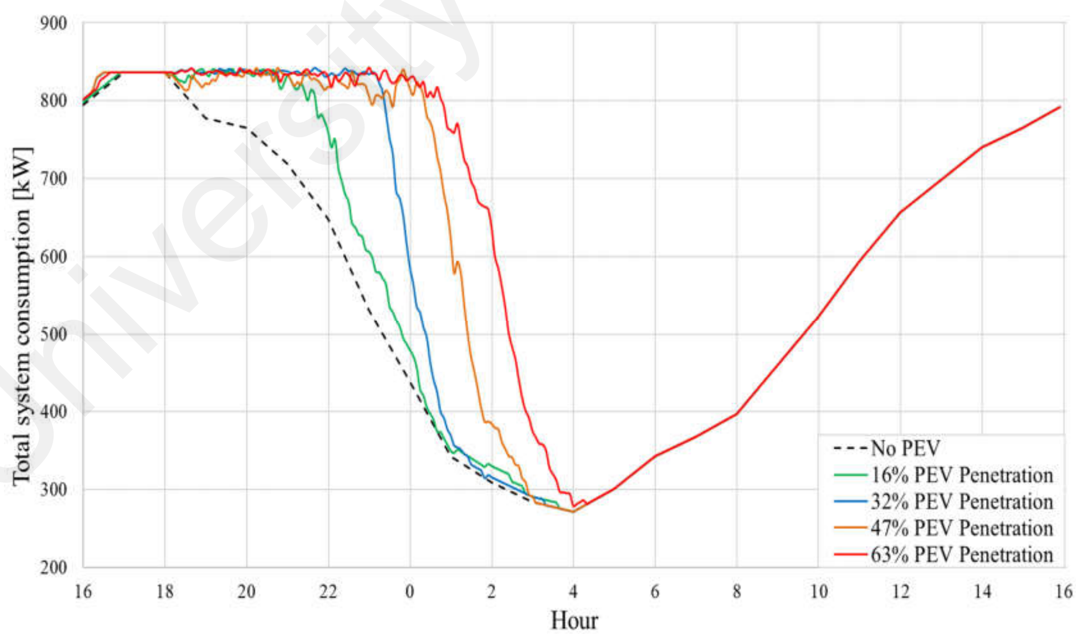


Figure 5.38: Total system power consumption with capacitor switching and OLTC adjustment during PEV charging coordination using BPSO

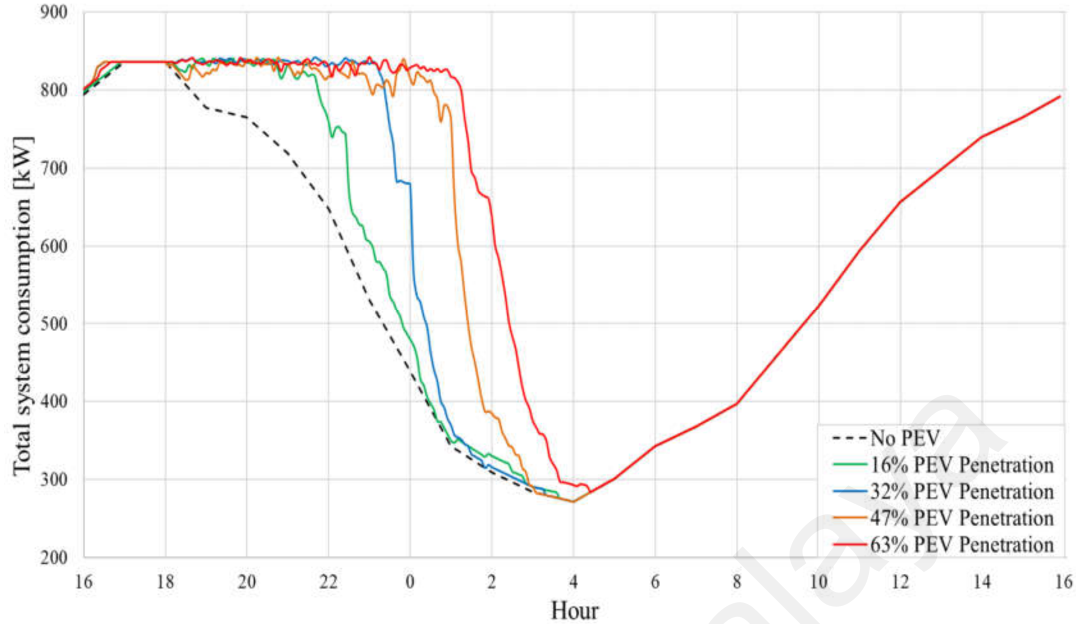


Figure 5.39: Total system power consumption with capacitor switching and OLTC adjustment during PEV charging coordination using BGWO

The main contribution of this proposed method in this research is the 100% PEV customer satisfaction. After applying the capacitor and OLTC operation during the PEV charging coordination, all the PEVs are found full charged. Figures 5.40 and 5.41 represent the SOC at 63% PEV penetration for the weakest feeder using BPSO and BGWO respectively. All the PEVs are charged to their respective required SOC by time 3:50 at the weakest feeder. On the other hand, the PEVs in the best feeder are charged in faster time compare to previous case studies.

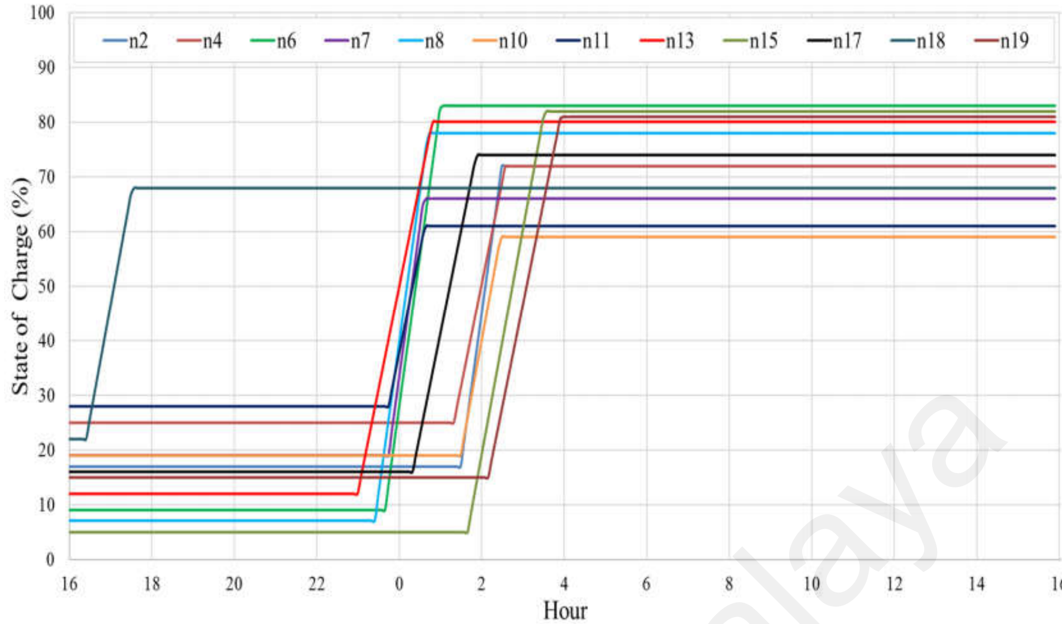


Figure 5.40: SOC for weakest feeder for 63% penetration with capacitor switching and OLTC adjustment using BPSO

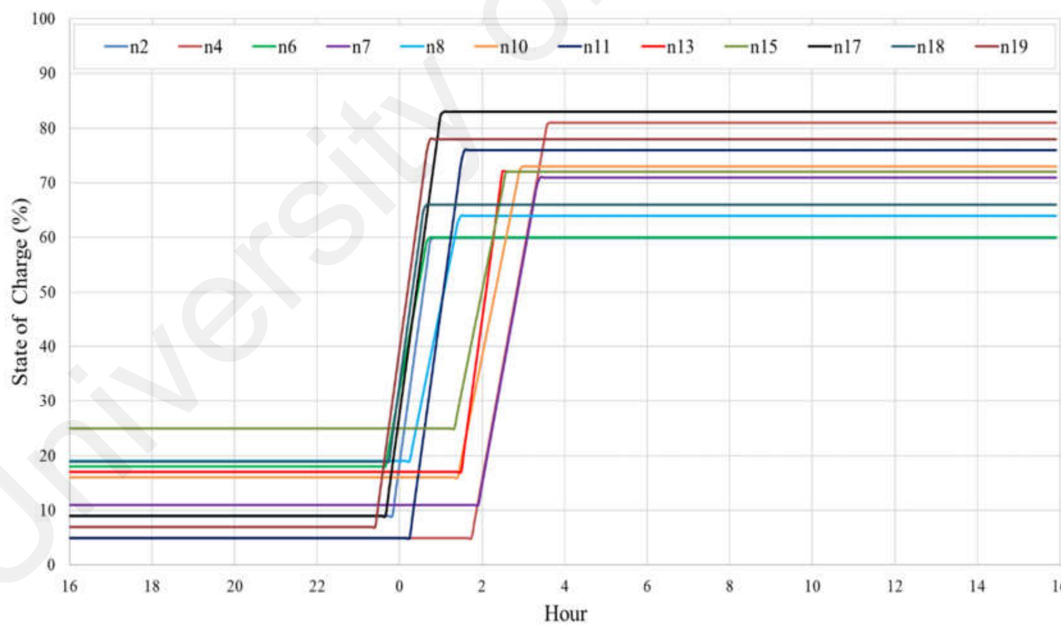


Figure 5.41: SOC for weakest feeder for 63% penetration with capacitor switching and OLTC adjustment using BGWO

5.4.4 Performance comparison

The simulation results considering capacitor and OLTC operation during the PEV charging coordination using BPSO and BGWO are summarized in Table 5.6. It is observed that, the PEV customer satisfaction is full (100%) for all the PEV penetration levels when capacitor and OLTC operation are integrated simultaneously (case 5) during PEV charging coordination. For the other cases, the PEV customer satisfactions are found lesser. It is also observed that, the overall voltage profile of the network is improved significantly in case 5. Moreover, in terms of power loss, the network is performed better it satisfies all the PEV customer. However, it cannot be concluded that BPSO and BGWO performs better because of many factors are related to the overall performance. The proposed method with the combination of capacitor and OLTC with the PEV charging coordination offers minimum power loss and voltage deviation while satisfying all the PEV customer.

Table 5.6: Impact of PEV charging on distribution system in different cases

Scenario	PEV (%)	ΔV (%)		Increase in loss* (%)		Satisfaction ratio**	
No PEV	0	7.35		0		-	
Case 1	16	7.61		6.97		-	
	32	8.95		14.59		-	
	47	17.27		23.08		-	
	63	19.16		33.85		-	
Algorithm		BPSO	BGWO	BPSO	BGWO	BPSO	BGWO
Case 2	16	7.43	7.42	6.96	7.12	18/4	18/4
	32	7.47	7.51	13.67	13.04	15/7	14/8
	47	8.61	8.86	12.32	13.01	8/14	7/15
	63	9.91	9.91	17.53	17.64	3/19	3/19
Case 3	16	7.42	7.42	7.10	7.18	21/1	21/1
	32	7.33	7.36	13.89	13.33	20/2	19/3
	47	7.61	7.95	12.82	13.89	10/12	9/13
	63	8.49	8.49	18.01	18.12	7/15	7/15
Case 4	16	7.42	7.42	7.65	7.26	21/1	21/1
	32	7.13	7.37	13.72	13.41	20/2	19/3
	47	7.48	7.88	13.01	13.95	10/12	9/13
	63	7.89	7.79	17.89	18.10	7/15	7/15
Case 5	16	4.96	4.96	5.53	5.53	22/0	22/0
	32	4.99	4.99	11.86	11.91	22/0	22/0
	47	6.32	6.51	17.28	17.32	22/0	22/0
	63	7.34	7.89	23.03	23.23	22/0	22/0

*Increase in loss compare to no PEV case
**Number of satisfied feeder/number of unsatisfied feeder

Moreover, the bar chart in Figure 5.42 shows the effectiveness of this proposed method in terms of satisfaction level. The three important concerns related to PEV charging on distribution system are illustrated in bar chart. Although the PEV customers are satisfied in uncoordinated charging scenario, the utilities are in risk. However, coordinated PEV charging can secure the distribution system while it failed to fulfill the customer satisfaction. Then, this research has studied separately the effectiveness of capacitor and OLTC operation during the coordinated PEV charge activities, but it failed to satisfy all the customers. After employing the proposed method, it has fulfilled the satisfaction level from the customer and utility side together.

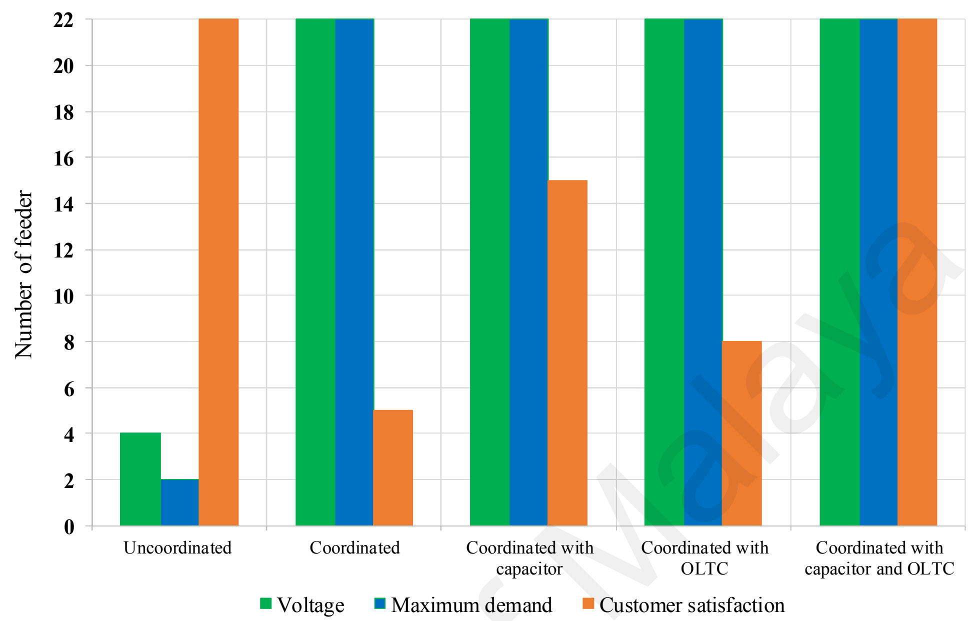


Figure 5.42: Comparison of customer and utility side satisfaction for different cases at 63% PEV penetration level

There are several studies on PEV coordination with various objective function, constraints and strategies in the distribution system as shown in Table 5.7. All the proposed conventional methods only coordinate the PEV charging. However, there are no researches have been conducted to integrate any power system tools such as capacitor, OLTC- to improve the system performances during the PEV charging. In addition, only few papers have considered maximization of PEV customer satisfaction (Hajforoosh et al., 2016). The main advantage of this proposed method is that it has a capability to schedule the PEVs' so that they charged in short span of time to enhance the customer satisfaction. Moreover, it also improves the voltage profile of the system during the PEV charging while considering the capacitor and OLTC switching in the distribution network.

Table 5.7: Comparison of the proposed method over similar conventional method

Applied algorithm/strategy	Objective function	Customer satisfaction	Different charge and battery size	Different SOC	Voltage improvement using Capacitor and OLTC switching	Charging termination time
Quadratic program (Clement-Nyns et al., 2010)	Power loss and Voltage deviation	No	No	No	No	NA
MSS (Deilami et al., 2011)	Minimize energy cost	No	No	No	No	6:10am
Valley filling (Jian et al., 2014)	Mitigate surplus power	No	No	No	No	NA
CAPSO (Hajforoosh et al., 2016)	Maximize customer satisfaction	Yes	Yes	Yes	No	5:50am
GA (Alonso et al., 2014)	Minimize substation load deviation	No	No	No	No	NA
Proposed method	Power loss and Voltage deviation	Yes	Yes	Yes	Yes	3:50am

5.5 Cost minimization

The main consideration of this proposed method in this research is to secure the residential distribution network in terms of avoiding transformer overload, reducing power loss and voltage deviation. Furthermore, the proposed method also ensures the fairness of the PEV charging coordination activities so that there is no PEV left to be charged. However, the minimization of energy generation cost and PEV charging cost are important study in PEV charging coordination strategy. In the centralized PEV charging coordination strategy, the utilities are responsible to charge the PEV in their designated time period. Therefore, the minimum PEV charging cost will encourage the PEV users to use the charging coordination service. There are two types of cost associated with the PEV charging coordination- the energy generation cost and PEV charging cost. However, the simulation results are carried out using BPSO algorithm.

5.5.1 Energy generation cost

The energy generation cost is the total cost of purchasing or producing the energy for charging PEVs plus the associated grid energy losses. In this research, the minimization of energy cost is done by reducing the energy losses. Table 5.8 shows the energy generation cost for one day when the PEV take charge in the network. Since, there is no PEV left to be charged after employing proposed method, the results are compared with the uncoordinated PEV charging when all the PEV get required charge. As the increase of PEV penetration in the network, the energy consumption is increasing. Therefore, in this research, the cost of energy loss is reduced in terms of minimize the daily power loss. The Table 5.8 clearly stated that, the proposed method curtails the daily energy generation cost significantly. However, the cost of energy generation is considered AUD50/MWh (A. S. Masoum, Deilami, Moses, Masoum, & Abu-Siada, 2011).

Table 5.8: Cost of energy generation in different scenario

Charging scenario	PEV penetration (%)	Increase in Power loss (kW)	Generation cost/day ($)	Total cost/day ($)	Increase in cost (%)
No PEV	0	0	802.5	818.1	-
Uncoordinated charging	16	6.97	872.5	896.0	9.5
	32	14.59	927.5.	952.4	16.41
	47	23.08	967.5	1008.0	23.21
	63	33.85	1008.5	1089.2	33.13
Proposed method	16	5.53	852.5	871.0	6.46
	32	11.86	909.5	922.1	12.71
	47	17.28	942.5	956.1	16.86
	63	23.03	982.6	997.1	21.87

5.5.2 PEV charging cost

Figures 5.44 to 5.46 present the impact of PEV charging activities on the distribution network to minimize the PEV charging cost utilizing electrical tariff. Figure 5.44 shows the weakest node voltage profile for all PEV penetration level. It is observed that, the voltage is in allowable range and the lowest voltages are recorded at midnight when the residential load is lower. Figure 5.45 and 5.46 are showing the daily power loss and total power consumption. It can be seen that, the PEV charging load is distributed in different timeslot based on the electrical tariff.

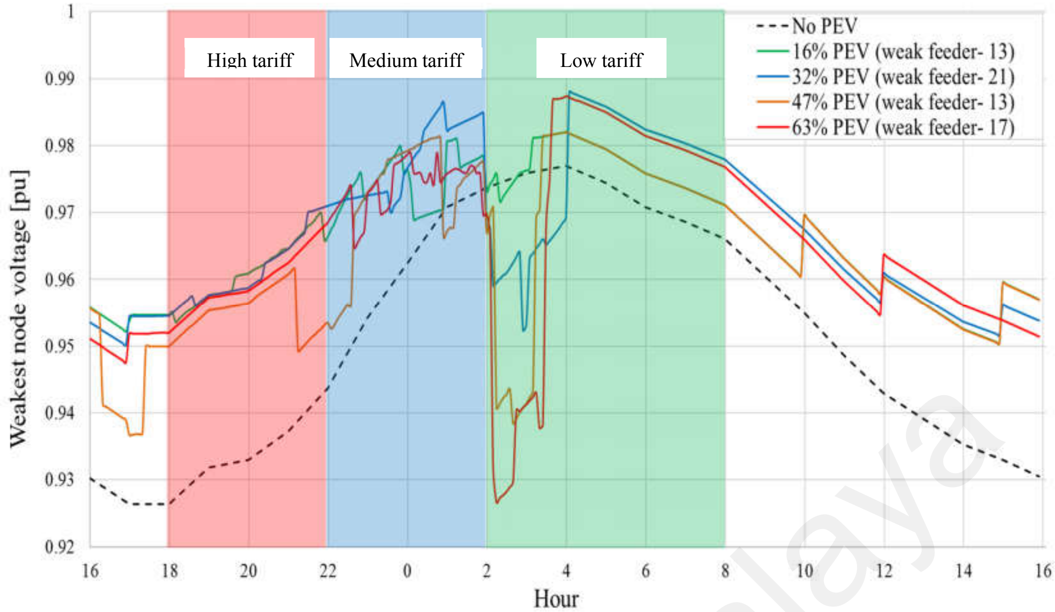


Figure 5.43: Voltage profile at the weakest node employing cost minimization

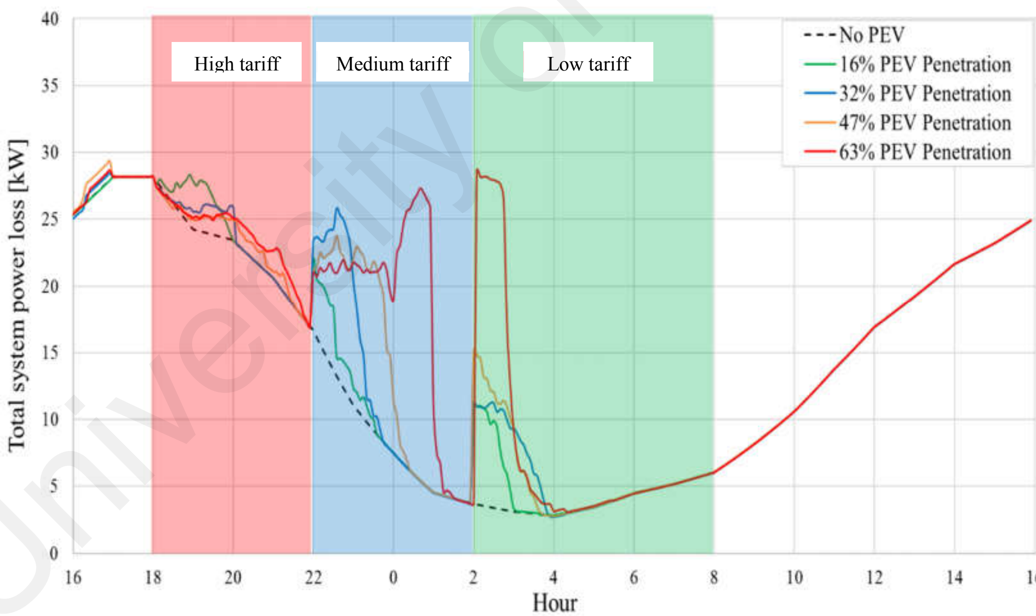


Figure 5.44: Total system power loss employing cost minimization

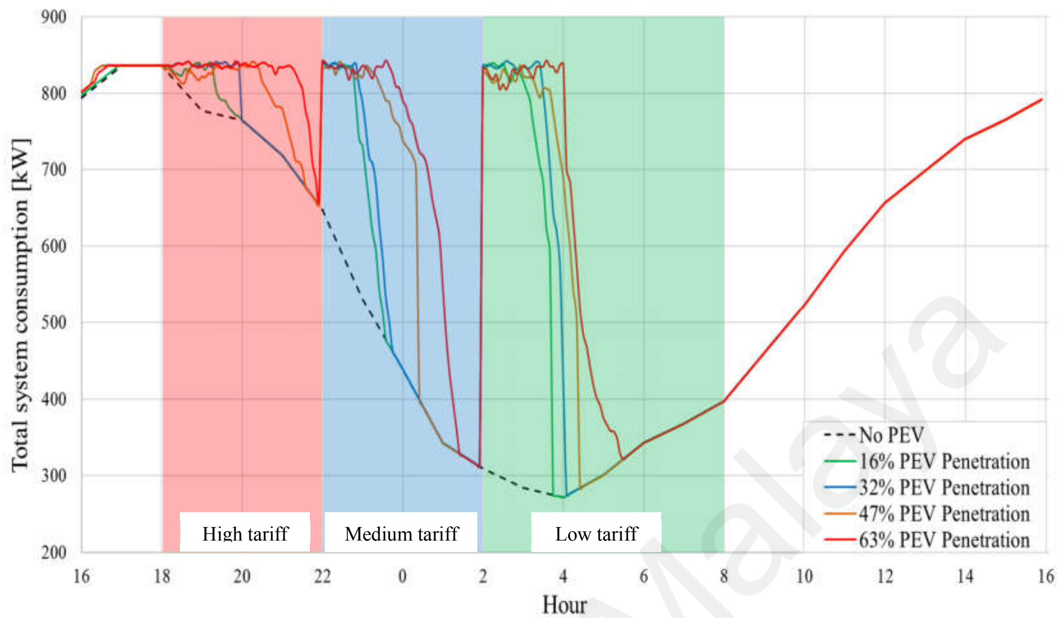


Figure 5.45: Total power consumption during the PEV charging coordination employing cost minimization

The changes of charging cost considering different scenarios for different PEV penetration level are summarized in Table 5.8. Three different scenarios are studied here since all the PEV customer satisfaction are found full. However, after including charging cost minimization utilizing tariff, the PEV charging cost is intensely reduced. The total PEV charging cost of 12 PEVs at 63% penetration for a specific feeder is considered in this table.

Table 5.9: Summary of PEV charging cost in different cases

Charging Scenario	PEV penetration (%)	Decrease in PEV charging cost (%)
No PEV	0	-
Uncoordinated PEV charging	16	-
	32	-
	47	-
	63	-
Coordinated PEV charging without considering tariff	16	2.01
	32	3.56
	47	7.14
	63	11.45
Proposed method including electrical tariff	16	2.52
	32	5.45
	47	9.42
	63	15.89

5.6 Summary

The proposed method (case 5) always gives minimum power loss and voltage deviation during the PEV charging activities on the distribution network. The capacitor switching and OLTC adjustment during the PEV charging have been studied in case 5. However, the individual operation of capacitor switching and OLTC adjustment are also studied in case 3 and case 4 respectively. It is found that power loss and voltage deviation can be reduced in both cases, but some of the PEVs are left to be charged. Other case studies, case 1 and case 2 give more power loss and voltage deviation. In case 1, the voltage at the low voltage nodes exceed the allowable limit and power loss is unacceptably high. On the other hand, case 2 is able to maintain all the system constraints, although a large number of PEV are left to be charged. To be summarized, the capacitor switching and OLTC adjustment during the PEV charging activities reduce the distribution system stresses and enhance the performances of PEV charging coordination.

However, from case 2 to case5, all the cases are carried out using BPSO and BGWO. It cannot be concluded that BPSO or BGWO performs better since the number of PEV might be changed in every timeslot and the solution is not same in every run.

In addition, electrical tariff is included to minimize the PEV charging cost by shifting the PEV load in lower tariff. It is observed that the charging cost is reduced significantly after including tariff, while all the system constrains are maintained.

CHAPTER 6:

CONCLUSION AND FUTURE WORKS

6.1 Conclusion

In distribution system, uncoordinated and random PEV charging activities impose substantial incremental loading to distribution transformer, severe voltage deviation and extensively increase system power losses. As a consequence, the overall operational cost will increase significantly. In this research, PEV charging coordination of randomly arrived PEVs, has been proposed to minimize the power loss and voltage deviation. In the meantime, this proposed method coordinate capacitor switching and OLTC adjustment to further improve the voltage profile and overall performance of the network. The main purpose of this research is to develop the optimal charging decision for all PEV in the distribution system. Therefore, meta-heuristic optimization algorithm has been employed, since the conventional optimization approaches are computationally intensive for real-time application. On the other hand, PEV charging cost is an economic concern for PEV customer, and it is required to be minimized to encourage the user. Hence, time of use tariff in 24 hours is considered to the proposed method in reducing PEV charging cost.

The proposed PEV charging coordination with the simultaneous operation of capacitor switching and OLTC adjustment gives the minimum power loss and voltage deviation while considering all the system constraints. It is found that the performances of the distribution system are improved significantly in all PEV penetration levels. Particularly, in higher PEV penetration at 63%, the power loss and voltage deviation are reduced by 10.83% and 11.82% respectively compared to uncoordinated charging using BPSO. In the same time, it is observed that there is no transformer overload in system. As a result, the power peaks are reduced and it released the burden of local distribution system.

Furthermore, the inclusion of time of use electrical tariff in proposed charging coordination along with the capacitor switching and OLTC adjustment reduced the charging cost significantly. The simulation results showed that in higher PEV penetration at 63%, the PEV charging cost is reduced by 4.44%.

The proposed approach used meta-heuristic techniques (BPSO, BGWO) to determine the PEV charge coordination and capacitor switching and OLTC adjustment to minimize power loss and voltage deviation. Both optimization methods are able to provide PEV charging coordination with minimum power loss and voltage deviation. However, it cannot be concluded that BPSO or BGWO performs better since some other arbitrary factors are related to this optimization such as PEV customer satisfaction, random arrival of PEV. Moreover, the number of PEV is changing in every timeslot due to its different initial and required SOC level.

6.2 Future works

In addition, some suggestions for future research are presented as follows:

1) In this research, capacitor and OLTC operations are incorporated to PEV charging coordination. In the forthcoming research, the impact of capacitor and OLTC during PEV charging activities on P-V and Q-V curves for voltage stability can be investigated.
2) The proposed method can be further improved by considering other power system devices such as distributed generation (DG), voltage regulator. The optimal size and placement for DG with the PEV charging activities will improve the voltage profile and overall performance of the system.
3) The proposed method can be applied in the larger distribution system such as IEEE 69 and IEEE 118 bus system. Different load profile from different region can be studied to proof the effectiveness of the proposed method

REFERENCES

Adnan, N., Nordin, S. M., & Rahman, I. (2017). Adoption of PHEV/EV in Malaysia: A critical review on predicting consumer behaviour. *Renewable and Sustainable Energy Reviews, 72*, 849-862.

Alonso, M., Amaris, H., Germain, J. G., & Galan, J. M. (2014). Optimal charging scheduling of electric vehicles in smart grids by heuristic algorithms. *Energies, 7*(4), 2449-2475.

Aman, M., Jasmon, G., Bakar, A., & Mokhlis, H. (2012). Optimum capacitor placement and sizing for distribution system based on an improved voltage stability index. *International Review of Electrical Engineering-Iree, 7*(3), 4622-4630.

Aman, M., Jasmon, G., Bakar, A., Mokhlis, H., & Karimi, M. (2014). Optimum shunt capacitor placement in distribution system—A review and comparative study. *Renewable and Sustainable Energy Reviews, 30*, 429-439.

Arias, N. B., Franco, J. F., Lavorato, M., & Romero, R. (2017). Metaheuristic optimization algorithms for the optimal coordination of plug-in electric vehicle charging in distribution systems with distributed generation. *Electric Power Systems Research, 142*, 351-361.

Azimi, R., & Esmaeili, S. (2013). Multiobjective daily Volt/VAr control in distribution systems with distributed generation using binary ant colony optimization. *Turkish Journal of Electrical Engineering & Computer Sciences, 21*(3), 613-629.

Bansal, R. C. (2005). Electric vehicles. *ELECTRICAL AND COMPUTER ENGINEERING, 125*, 55.

Bessa, R. J., & Matos, M. A. (2012). Economic and technical management of an aggregation agent for electric vehicles: a literature survey. *International Transactions on Electrical Energy Systems, 22*(3), 334-350.

Chang, R., & Lu, C. (2002). *Feeder reconfiguration for load factor improvement.* Paper presented at the Power Engineering Society Winter Meeting, 2002. IEEE.

Civanlar, S., & Grainger, J. (1985). Volt/var control on distribution systems with lateral branches using shunt capacitors and voltage regulators part III: The numerical results. *IEEE Transactions on Power Apparatus and Systems*(11), 3291-3297.

Clement-Nyns, K., Haesen, E., & Driesen, J. (2009). Analysis of the impact of plug-in hybrid electric vehicles on the residential distribution grids by using quadratic and dynamic programming. *World Electric Vehicle Journal, 3*.

Clement-Nyns, K., Haesen, E., & Driesen, J. (2010). The impact of charging plug-in hybrid electric vehicles on a residential distribution grid. *IEEE Transactions on Power Systems, 25*(1), 371-380.

Clement-Nyns, K., Van Reusel, K., & Driesen, J. (2007). *The consumption of electrical energy of plug-in hybrid electric vehicles in Belgium.* Paper presented at the Proceedings of EET-European Ele-Drive Transportation conference.

Dallinger, D., & Wietschel, M. (2012). Grid integration of intermittent renewable energy sources using price-responsive plug-in electric vehicles. *Renewable and Sustainable Energy Reviews, 16*(5), 3370-3382.

Deilami, S., Masoum, A. S., Moses, P. S., & Masoum, M. A. (2011). Real-time coordination of plug-in electric vehicle charging in smart grids to minimize power losses and improve voltage profile. *IEEE Transactions on Smart Grid, 2*(3), 456-467.

Del Valle, Y., Venayagamoorthy, G. K., Mohagheghi, S., Hernandez, J.-C., & Harley, R. G. (2008). Particle swarm optimization: basic concepts, variants and applications in power systems. *IEEE transactions on evolutionary computation, 12*(2), 171-195.

Duvall, M., Knipping, E., Alexander, M., Tonachel, L., & Clark, C. (2007). Environmental assessment of plug-in hybrid electric vehicles. *EPRI, July*.

Emadi, A., Lee, Y. J., & Rajashekara, K. (2008). Power electronics and motor drives in electric, hybrid electric, and plug-in hybrid electric vehicles. *IEEE Transactions on industrial electronics, 55*(6), 2237-2245.

Emary, E., Zawbaa, H. M., & Hassanien, A. E. (2016). Binary grey wolf optimization approaches for feature selection. *Neurocomputing, 172*, 371-381.

Fan, Z. (2012). A distributed demand response algorithm and its application to PHEV charging in smart grids. *IEEE Transactions on Smart Grid, 3*(3), 1280-1290.

Fang, X., Misra, S., Xue, G., & Yang, D. (2012). Smart grid—The new and improved power grid: A survey. *IEEE communications surveys & tutorials, 14*(4), 944-980.

Galus, M. D., Vayá, M. G., Krause, T., & Andersson, G. (2013). The role of electric vehicles in smart grids. *Wiley Interdisciplinary Reviews: Energy and Environment, 2*(4), 384-400.

Gan, L., Topcu, U., & Low, S. H. (2013). Optimal decentralized protocol for electric vehicle charging. *IEEE Transactions on Power Systems, 28*(2), 940-951.

García-Villalobos, J., Zamora, I., San Martín, J., Asensio, F., & Aperribay, V. (2014). Plug-in electric vehicles in electric distribution networks: A review of smart charging approaches. *Renewable and Sustainable Energy Reviews, 38*, 717-731.

Gharavi, H., & Ghafurian, R. (2011). Smart grid: The electric energy system of the future.

Gungor, V. C., Sahin, D., Kocak, T., Ergut, S., Buccella, C., Cecati, C., & Hancke, G. P. (2011). Smart grid technologies: Communication technologies and standards. *IEEE transactions on Industrial informatics, 7*(4), 529-539.

Hajforoosh, S., Masoum, M. A., & Islam, S. M. (2015). Real-time charging coordination of plug-in electric vehicles based on hybrid fuzzy discrete particle swarm optimization. *Electric Power Systems Research, 128*, 19-29.

Hajforoosh, S., Masoum, M. A., & Islam, S. M. (2016). Online optimal variable charge-rate coordination of plug-in electric vehicles to maximize customer satisfaction and improve grid performance. *Electric Power Systems Research, 141*, 407-420.

Hawkins, T. R., Singh, B., Majeau-Bettez, G., & Strømman, A. H. (2013). Comparative environmental life cycle assessment of conventional and electric vehicles. *Journal of Industrial Ecology, 17*(1), 53-64.

Hsu, Y.-Y., & Kuo, H.-C. (1993). *Dispatch of capacitors on distribution system using dynamic programming.* Paper presented at the IEE Proceedings C (Generation, Transmission and Distribution).

Hsu, Y.-Y., & Lu, F.-C. (1998). A combined artificial neural network-fuzzy dynamic programming approach to reactive power/voltage control in a distribution substation. *IEEE Transactions on Power Systems, 13*(4), 1265-1271.

Hu, Z., Wang, X., Chen, H., & Taylor, G. (2003). Volt/VAr control in distribution systems using a time-interval based approach. *IEE Proceedings-Generation, Transmission and Distribution, 150*(5), 548-554.

Iversen, E. B., Morales, J. M., & Madsen, H. (2014). Optimal charging of an electric vehicle using a Markov decision process. *Applied Energy, 123*, 1-12.

Jian, L., Zhu, X., Shao, Z., Niu, S., & Chan, C. (2014). A scenario of vehicle-to-grid implementation and its double-layer optimal charging strategy for minimizing load variance within regional smart grids. *Energy Conversion and Management, 78*, 508-517.

Kang, J., Duncan, S. J., & Mavris, D. N. (2013). Real-time scheduling techniques for electric vehicle charging in support of frequency regulation. *Procedia Computer Science, 16*, 767-775.

Karfopoulos, E. L., & Hatziargyriou, N. D. (2013). A multi-agent system for controlled charging of a large population of electric vehicles. *IEEE Transactions on Power Systems, 28*(2), 1196-1204.

Kennedy, J., & Eberhart, R. (1995). *Particle swarm optimization.* Paper presented at the Neural Networks, 1995. Proceedings., IEEE International Conference on.

Kennedy, J., Eberhart, R., & Shi, Y. (2001). Swarm Intelligence, Morgan Kaufmann Publishers. *Inc., San Francisco, CA*.

Kennedy, J., & Eberhart, R. C. (1997). *A discrete binary version of the particle swarm algorithm.* Paper presented at the Systems, Man, and Cybernetics, 1997. Computational Cybernetics and Simulation., 1997 IEEE International Conference on.

Liang, R.-H., Chen, Y.-K., & Chen, Y.-T. (2011). Volt/Var control in a distribution system by a fuzzy optimization approach. *International journal of electrical power & energy systems, 33*(2), 278-287.

Liang, R.-H., & Cheng, C.-K. (2001). Dispatch of main transformer ULTC and capacitors in a distribution system. *IEEE Transactions on Power Delivery, 16*(4), 625-630.

Lopes, J. A. P., Soares, F. J., & Almeida, P. M. R. (2011). Integration of electric vehicles in the electric power system. *Proceedings of the IEEE, 99*(1), 168-183.

Lu, F.-C., & Hsu, Y.-Y. (1995). Reactive power/voltage control in a distribution substation using dynamic programming. *IEE Proceedings-Generation, Transmission and Distribution, 142*(6), 639-645.

Lu, F.-C., & Hsu, Y.-Y. (1997). Fuzzy dynamic programming approach to reactive power/voltage control in a distribution substation. *IEEE Transactions on Power Systems, 12*(2), 681-688.

Luo, X., Xia, S., & Chan, K. W. (2014). A decentralized charging control strategy for plug-in electric vehicles to mitigate wind farm intermittency and enhance frequency regulation. *Journal of Power Sources, 248*, 604-614.

Ma, Z., Zou, S., Ran, L., Shi, X., & Hiskens, I. A. (2016). Efficient decentralized coordination of large-scale plug-in electric vehicle charging. *Automatica, 69*, 35-47.

Masoum, A. S., Deilami, S., Moses, P., Masoum, M., & Abu-Siada, A. (2011). Smart load management of plug-in electric vehicles in distribution and residential networks with charging stations for peak shaving and loss minimisation considering voltage regulation. *IET Generation, Transmission & Distribution, 5*(8), 877-888.

Masoum, M., Ladjevardi, M., Fuchs, E., & Grady, W. (2004). Application of local variations and maximum sensitivities selection for optimal placement of shunt capacitor banks under nonsinusoidal operating conditions. *International Journal of Electrical Power & Energy Systems, 26*(10), 761-769.

McArthur, S. D., Davidson, E. M., Catterson, V. M., Dimeas, A. L., Hatziargyriou, N. D., Ponci, F., & Funabashi, T. (2007). Multi-agent systems for power engineering applications—Part I: Concepts, approaches, and technical challenges. *IEEE Transactions on Power Systems, 22*(4), 1743-1752.

Nguyen, H. K., & Song, J. B. (2012). Optimal charging and discharging for multiple PHEVs with demand side management in vehicle-to-building. *Journal of Communications and networks, 14*(6), 662-671.

Oliveira, D., de Souza, A. Z., & Delboni, L. (2013). Optimal plug-in hybrid electric vehicles recharge in distribution power systems. *Electric Power Systems Research, 98*, 77-85.

Park, J.-B., Lee, K.-S., Shin, J.-R., & Lee, K. Y. (2005). A particle swarm optimization for economic dispatch with nonsmooth cost functions. *IEEE Transactions on Power Systems, 20*(1), 34-42.

Ramadan, H., Bendary, A., & Nagy, S. (2017). Particle swarm optimization algorithm for capacitor allocation problem in distribution systems with wind turbine generators. *International Journal of Electrical Power & Energy Systems, 84*, 143-152.

Raskin, A., & Shah, S. (2006). The emerge of hybrid electric vehicles. *Alliance Bernstein*.

Ruiz-Romero, S., Colmenar-Santos, A., Mur-Pérez, F., & López-Rey, Á. (2014). Integration of distributed generation in the power distribution network: The need for smart grid control systems, communication and equipment for a smart city—Use cases. *Renewable and Sustainable Energy Reviews, 38*, 223-234.

Sallam, A. A., Desouky, M., & Desouky, H. (1994). Shunt capacitor effect on electrical distribution system reliability. *IEEE transactions on reliability, 43*(1), 170-176.

Segawa, N., Natsuda, K., & Thoburn, J. (2014). Affirmative action and economic liberalisation: the dilemmas of the Malaysian automotive industry. *Asian Studies Review, 38*(3), 422-441.

Shaaban, M. F., Ismail, M., El-Saadany, E. F., & Zhuang, W. (2014). Real-time PEV charging/discharging coordination in smart distribution systems. *IEEE Transactions on Smart Grid, 5*(4), 1797-1807.

Sheikhi, A., Bahrami, S., Ranjbar, A., & Oraee, H. (2013). Strategic charging method for plugged in hybrid electric vehicles in smart grids; a game theoretic approach. *International journal of electrical power & energy systems, 53*, 499-506.

Shi, Y., & Eberhart, R. (1998). *A modified particle swarm optimizer.* Paper presented at the Evolutionary Computation Proceedings, 1998. IEEE World Congress on Computational Intelligence., The 1998 IEEE International Conference on.

Short, T. A. (2014). *Electric power distribution handbook*: CRC press.

Singh, M., Kumar, P., & Kar, I. (2012). Implementation of vehicle to grid infrastructure using fuzzy logic controller. *IEEE Transactions on Smart Grid, 3*(1), 565-577.

Soares, F., Almeida, P. R., & Lopes, J. P. (2014). Quasi-real-time management of Electric Vehicles charging. *Electric Power Systems Research, 108*, 293-303.

Sortomme, E., & El-Sharkawi, M. A. (2011). Optimal charging strategies for unidirectional vehicle-to-grid. *IEEE Transactions on Smart Grid, 2*(1), 131-138.

Sortomme, E., Hindi, M. M., MacPherson, S. J., & Venkata, S. (2011). Coordinated charging of plug-in hybrid electric vehicles to minimize distribution system losses. *IEEE Transactions on Smart Grid, 2*(1), 198-205.

Subramanian, A., Garcia, M., Dominguez-Garcia, A., Callaway, D., Poolla, K., & Varaiya, P. (2012). *Real-time scheduling of deferrable electric loads.* Paper presented at the American Control Conference (ACC), 2012.

Sundhararajan, S., & Pahwa, A. (1994). Optimal selection of capacitors for radial distribution systems using a genetic algorithm. *IEEE Transactions on Power Systems, 9*(3), 1499-1507.

Tushar, M. H. K., Assi, C., Maier, M., & Uddin, M. F. (2014). Smart microgrids: Optimal joint scheduling for electric vehicles and home appliances. *IEEE Transactions on Smart Grid, 5*(1), 239-250.

Unda, I. G., Papadopoulos, P., Skarvelis-Kazakos, S., Cipcigan, L. M., Jenkins, N., & Zabala, E. (2014). Management of electric vehicle battery charging in distribution networks with multi-agent systems. *Electric Power Systems Research, 110*, 172-179.

Valentine, K., Temple, W. G., & Zhang, K. M. (2011). Intelligent electric vehicle charging: Rethinking the valley-fill. *Journal of Power Sources, 196*(24), 10717-10726.

Van Mierlo, J., Maggetto, G., & Lataire, P. (2006). Which energy source for road transport in the future? A comparison of battery, hybrid and fuel cell vehicles. *Energy Conversion and Management, 47*(17), 2748-2760.

Vayá, M. G., & Andersson, G. (2012). *Centralized and decentralized approaches to smart charging of plug-in vehicles.* Paper presented at the Power and Energy Society General Meeting, 2012 IEEE.

Viawan, F. A., & Karlsson, D. (2008). Voltage and reactive power control in systems with synchronous machine-based distributed generation. *IEEE Transactions on Power Delivery, 23*(2), 1079-1087.

Wang, H., Dusmez, S., & Khaligh, A. (2014). Design and Analysis of a Full-Bridge LLC-Based PEV Charger Optimized for Wide Battery Voltage Range. *IEEE Transactions on Vehicular Technology, 63*(4), 1603-1613. doi:10.1109/TVT.2013.2288772

Zakariazadeh, A., Jadid, S., & Siano, P. (2014). Multi-objective scheduling of electric vehicles in smart distribution system. *Energy Conversion and Management, 79*, 43-53.

Zhang, K., Xu, L., Ouyang, M., Wang, H., Lu, L., Li, J., & Li, Z. (2014). Optimal decentralized valley-filling charging strategy for electric vehicles. *Energy Conversion and Management, 78*, 537-550.

Zhang, W., Liu, Y., & Clerc, M. (2003). An adaptive PSO algorithm for reactive power optimization.

Zhou, K., & Cai, L. (2014). Randomized PHEV charging under distribution grid constraints. *IEEE Transactions on Smart Grid, 5*(2), 879-887.

Zielinska, B., Sagebiel, J., McDonald, J. D., Whitney, K., & Lawson, D. R. (2004). Emission rates and comparative chemical composition from selected in-use diesel and gasoline-fueled vehicles. *Journal of the Air & Waste Management Association, 54*(9), 1138-1150.

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Paper

Optimal Fixed Charge–Rate Coordination of Plug-In Electric Vehicle Incorporating Capacitor and OLTC Switching to Minimize Power Loss and Voltage Deviation

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Integration of plug-in electric vehicles (PEVs) in a smart grid largely deteriorates the performances of the system. This paper proposes a two-stage optimization approach to optimize customer satisfaction as well as grid performances when fixed charge–rate PEV coordination, switching capacitor and on-load tap charger (OLTC) are coordinated simultaneously. To coordinate PEV charging, capacitor and OLTC, an efficient binary particle swarm optimization (BPSO) has been applied. The main consideration in this optimal coordination is to minimize the daily power loss and voltage deviation while maximizing customer satisfaction. Simulation results are compared with the variable charge–rate coordination that is proposed previously. © 2018 Institute of Electrical Engineers of Japan. Published by John Wiley & Sons, Inc.

Keywords: PEV coordination; fixed charge–rate; OLTC; capacitor; customer satisfaction

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1. Introduction

Plug-in electric vehicles (PEVs) are environment-friendly green transportation because of their pollution-free operation. PEVs are becoming the more prominent choice in recent years as a consequence of greenhouse gas (GHG) emission in the environment. Moreover, the lower daily running cost of PEVs over the conventional combustion engine has drawn the attention of the vehicle users [1].

Basically, PEVs utilize large battery capacities that require frequent charging to run high power-rated motors [2]. These vehicles are charged by plugging into electric outlets in corporate or residential car parking. A PEV's load is considered extra large and undesirable peak electrical consumption on residential distribution systems. The charging of PEVs has a significant impact on power distribution systems. Hence, uncoordinated and random PEV charging activities can overload the system, and in many cases, it can cause power quality issues such as voltage sag as well as increase the system's power loss [3,4]. In order to counter the massive increase in PEV loads, particularly during peak hours, many countries are introducing smart metering and smart appliances [5]. Large integration of PEVs has influenced researchers to work on developing a coordination strategy for PEV charging in distribution systems. In general, the coordination strategies for PEVs can be categorized into two types: centralized approach and decentralized approach. In decentralized coordination of PEV charging, the charging time is decided by the PEV customer based on the system capacity and constraints. Different types of decentralized methods are proposed for PEV charging, which are based on tariffs, voltage profile [6] and energy cost sharing models [7]. However, the decentralized approach cannot guarantee an optimal solution as the customer can decide on their charging patterns independently. In contrast, centralized coordination is more effective as it has a central control system with high-speed, bidirectional, smart grid communication for each PEV. The charging decision is taken by the central control system considering several system constraints as well as customer's satisfaction. Much research on centralized PEV charging coordination has been proposed to minimize distribution system power losses [8], generation cost [9] considering time-varying market energy prices and customer priority [3]. A two-stage optimization procedure is proposed in [10] to charge the PEV optimally considering customer satisfaction as well as charging cost minimization. Moreover, an optimal variable charge–rate scheduling of PEVs is introduced [11] to ensure priority fairness for all PEVs in distribution.

Nevertheless, due to the undergoing development of smart technologies between central control and PEV charger, sometimes, the charging rate cannot be controlled precisely as required [3,12]. In addition, fixed charging of the PEV battery is considered a fast process over the variable charge–rate coordination strategy [13]. Since, the buses which are located at the end line of the distribution network have lower voltage, no PEV in that area can charge earlier even though the system has available capacity. Furthermore, end buses PEV cannot be considered a priority due to its voltage violation in the earlier stage of coordination.

According to recent literature review, numerous aspects of the PEV coordination problem in residential distribution systems have been studied. However, only a few studies [8,14] have considered power loss and voltage deviation as an objective function together. Furthermore, as far as the authors' knowledge, no research has been conducted to improve the end buses voltage of the distribution during PEV charging by considering switching capacitors on feeder and on-load tap charger (OLTC). Therefore, an intelligent PEV

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APPENDIX A

Table A.1: IEEE 31 bus Radial Distribution System Data (Civanlar & Grainger, 1985)

Branch	Form	To	R (Ω)	X (Ω)	R (pu)	X (pu)
1	1	2	0.0021	0.0365	0.0004	0.0069
2	2	3	0.2788	0.0148	0.0527	0.0028
3	3	4	0.4438	0.4391	0.0839	0.0830
4	4	5	0.8639	0.7512	0.1633	0.1420
5	5	6	0.8639	0.7512	0.1633	0.1420
6	6	7	1.3738	0.7739	0.2597	0.1463
7	7	8	1.3738	0.7739	0.2597	0.1463
8	8	9	1.3738	0.7739	0.2597	0.1463
9	9	10	1.3738	0.7739	0.2597	0.1463
10	10	11	1.3738	0.7739	0.2597	0.1463
11	11	12	1.3738	0.7739	0.2597	0.1463
12	12	13	1.3738	0.7739	0.2597	0.1463
13	13	14	1.3738	0.7739	0.2597	0.1463
14	14	15	1.3738	0.7739	0.2597	0.1463
15	9	16	0.8639	0.7512	0.1633	0.1420
16	16	17	1.3738	0.7739	0.2597	0.1463
17	17	18	1.3738	0.7739	0.2597	0.1463
18	7	19	0.8639	0.7512	0.1633	0.1420
19	19	20	0.8639	0.7512	0.1633	0.1420
20	20	21	1.3738	0.7739	0.2597	0.1463
21	7	22	0.8639	0.7512	0.1633	0.1420
22	4	23	0.4438	0.4391	0.0839	0.0830
23	23	24	0.4438	0.4391	0.0839	0.0830
24	24	25	0.8639	0.7512	0.1633	0.1420
25	25	26	0.8639	0.7512	0.1633	0.1420
26	26	27	0.8639	0.7512	0.1633	0.1420
27	27	28	1.3738	0.7739	0.2597	0.1463
28	2	29	0.2788	0.0148	0.0527	0.0028
29	29	30	0.2788	0.0148	0.0527	0.0028
30	30	31	1.3738	0.7739	0.2597	0.1463

APPENDIX B

Table B.1: Selected PEV input parameters for the different case studies at 63% PEV penetration

Node #	Charger (kW)	Battery (kWh)	SOC int	SOC req	Node	Charger (kW)	Battery (kWh)	SOC int	SOC req
12	7.2	19.2	26	73	232	6.6	16	21	77
14	6.6	16	7	79	234	6.6	16	23	82
16	6.6	16	8	75	236	6.6	16	22	59
17	7.2	19.2	19	63	237	6.6	16	12	56
18	7.2	19.2	14	64	238	7.2	19.2	6	60
20	6.6	16	6	55	240	3.3	6	28	85
21	7.2	19.2	5	78	241	3.3	6	14	64
23	7.2	19.2	16	80	243	7.2	19.2	28	61
25	6.6	16	19	81	245	6.6	16	5	74
27	6.6	16	15	85	247	3.3	6	18	60
28	7.2	19.2	24	57	248	6.6	16	29	85
29	3.3	6	17	81	249	7.2	19.2	7	61
32	7.2	19.2	29	74	252	3.3	6	23	71
34	3.3	6	23	67	254	6.6	16	9	77
36	3.3	6	9	60	256	7.2	19.2	14	72
37	3.3	6	23	79	257	6.6	16	20	68
38	6.6	16	22	56	258	7.2	19.2	29	69
40	7.2	19.2	15	55	260	7.2	19.2	6	74
41	3.3	6	25	65	261	7.2	19.2	28	61
43	7.2	19.2	18	64	263	3.3	6	26	60
45	6.6	16	20	67	265	3.3	6	11	56
47	6.6	16	23	75	267	6.6	16	28	77
48	3.3	6	21	84	268	6.6	16	24	69
49	3.3	6	25	78	269	7.2	19.2	17	60
52	7.2	19.2	20	83	272	6.6	16	14	62
54	7.2	19.2	28	73	274	6.6	16	5	79
56	3.3	6	14	77	276	7.2	19.2	9	62
57	6.6	16	16	80	277	7.2	19.2	15	65
58	6.6	16	30	75	278	6.6	16	17	66
60	7.2	19.2	15	72	280	7.2	19.2	22	56
61	6.6	16	28	73	281	6.6	16	21	69
63	3.3	6	9	71	283	6.6	16	12	78
65	6.6	16	21	62	285	3.3	6	15	79
67	3.3	6	14	81	287	3.3	6	21	78
68	3.3	6	16	64	288	3.3	6	24	85
69	7.2	19.2	25	70	289	3.3	6	29	84
72	3.3	6	8	67	292	3.3	6	27	57
74	7.2	19.2	26	84	294	3.3	6	19	84
76	7.2	19.2	18	73	296	3.3	6	22	70

77	7.2	19.2	22	62	297	7.2	19.2	18	68
78	7.2	19.2	14	65	298	3.3	6	10	73
80	3.3	6	9	60	300	6.6	16	17	66
81	6.6	16	5	81	301	6.6	16	6	70
83	6.6	16	18	60	303	3.3	6	28	80
85	6.6	16	11	71	305	6.6	16	21	77
87	7.2	19.2	19	64	307	6.6	16	5	73
88	7.2	19.2	16	73	308	7.2	19.2	5	72
89	3.3	6	5	76	309	6.6	16	27	80
92	3.3	6	17	72	312	3.3	6	7	80
94	7.2	19.2	25	72	314	3.3	6	14	85
96	3.3	6	9	83	316	3.3	6	12	56
97	3.3	6	19	66	317	7.2	19.2	25	65
98	3.3	6	7	78	318	3.3	6	7	80
100	6.6	16	19	59	320	6.6	16	12	77
101	7.2	19.2	28	61	321	6.6	16	5	73
103	7.2	19.2	12	80	323	3.3	6	29	81
105	6.6	16	5	82	325	6.6	16	24	75
107	7.2	19.2	16	74	327	6.6	16	10	63
108	6.6	16	22	68	328	7.2	19.2	15	81
109	7.2	19.2	15	81	329	6.6	16	25	70
112	7.2	19.2	15	76	332	6.6	16	13	64
114	7.2	19.2	10	56	334	7.2	19.2	19	65
116	6.6	16	30	67	336	6.6	16	18	70
117	3.3	6	21	64	337	6.6	16	20	72
118	6.6	16	16	83	338	7.2	19.2	17	65
120	7.2	19.2	6	85	340	7.2	19.2	14	69
121	7.2	19.2	24	72	341	3.3	6	25	82
123	6.6	16	12	56	343	3.3	6	7	75
125	7.2	19.2	15	58	345	3.3	6	8	80
127	3.3	6	16	74	347	7.2	19.2	14	55
128	6.6	16	8	73	348	3.3	6	15	76
129	7.2	19.2	21	66	349	3.3	6	30	70
132	3.3	6	9	64	352	6.6	16	22	65
134	6.6	16	14	62	354	6.6	16	28	85
136	6.6	16	7	55	356	6.6	16	5	73
137	7.2	19.2	12	63	357	3.3	6	13	67
138	3.3	6	8	55	358	6.6	16	15	72
140	7.2	19.2	8	57	360	6.6	16	21	83
141	7.2	19.2	17	60	361	7.2	19.2	21	73
143	6.6	16	8	59	363	6.6	16	24	70
145	7.2	19.2	17	80	365	6.6	16	8	58
147	6.6	16	15	82	367	6.6	16	10	74
148	6.6	16	30	71	368	6.6	16	25	85
149	3.3	6	25	62	369	7.2	19.2	23	62
152	3.3	6	22	69	372	6.6	16	17	69
154	7.2	19.2	6	59	374	6.6	16	23	63
156	7.2	19.2	11	61	376	3.3	6	7	59
157	3.3	6	11	80	377	7.2	19.2	24	73

158	6.6	16	24	55	378	7.2	19.2	28	62
160	3.3	6	7	77	380	3.3	6	29	69
161	7.2	19.2	26	66	381	7.2	19.2	27	82
163	7.2	19.2	14	66	383	3.3	6	24	56
165	3.3	6	11	81	385	3.3	6	16	80
167	6.6	16	24	62	387	6.6	16	27	72
168	7.2	19.2	14	58	388	6.6	16	15	85
169	6.6	16	13	78	389	6.6	16	16	64
172	7.2	19.2	28	63	392	3.3	6	17	58
174	7.2	19.2	15	64	394	7.2	19.2	18	72
176	6.6	16	12	72	396	3.3	6	18	80
177	3.3	6	17	66	397	7.2	19.2	15	82
178	3.3	6	20	79	398	7.2	19.2	22	81
180	7.2	19.2	25	69	400	3.3	6	30	74
181	6.6	16	20	68	401	3.3	6	30	84
183	6.6	16	10	72	403	6.6	16	11	57
185	7.2	19.2	27	76	405	6.6	16	9	74
187	3.3	6	15	76	407	3.3	6	20	76
188	3.3	6	5	75	408	3.3	6	10	83
189	3.3	6	16	57	409	3.3	6	26	73
192	7.2	19.2	5	71	412	6.6	16	28	73
194	3.3	6	30	79	414	6.6	16	10	72
196	3.3	6	14	56	416	7.2	19.2	13	58
197	3.3	6	30	80	417	3.3	6	28	84
198	6.6	16	23	80	418	3.3	6	24	73
200	7.2	19.2	8	59	420	6.6	16	5	80
201	6.6	16	8	85	421	3.3	6	14	85
203	6.6	16	15	85	423	3.3	6	26	70
205	7.2	19.2	20	81	425	6.6	16	21	78
207	3.3	6	11	55	427	7.2	19.2	18	81
208	6.6	16	14	85	428	6.6	16	22	58
209	7.2	19.2	15	85	429	6.6	16	22	74
212	6.6	16	27	73	432	7.2	19.2	15	57
214	3.3	6	6	78	434	6.6	16	10	85
216	3.3	6	12	56	436	7.2	19.2	26	66
217	7.2	19.2	24	71	437	7.2	19.2	29	74
218	6.6	16	20	65	438	7.2	19.2	15	56
220	6.6	16	30	71	440	3.3	6	30	84
221	7.2	19.2	17	82	441	7.2	19.2	26	69
223	6.6	16	20	81	443	3.3	6	25	56
225	3.3	6	15	72	445	3.3	6	22	77
227	7.2	19.2	17	57	447	7.2	19.2	30	78
228	6.6	16	8	55	448	3.3	6	23	69
229	3.3	6	20	81	449	6.6	16	21	70