Modelling the Impacts of Large-Scale Penetration of Electric Vehicle on Electricity Networks

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Abstract

Electric vehicles (EVs) offer several significant potential economic, social and environmental benefits - reductions in the transport sector's current very heavy reliance on petroleum-based fuels, improvements in urban air quality and reductions in transport sector greenhouse gas emissions. The batteries of electric vehicles, however, need to be recharged and electrification of transport systems will increase electricity loads, which could potentially place stress on some electricity distribution systems. The actual impacts of EV recharging on local distribution systems will depend on a number of factors and on the timing of the recharging events in particular. The results of the several studies have attempted to assess the potential impacts that EV recharging will have on local distribution networks suggest that coordinated managed charging of EV demand could actually have a significantly positive impact on distribution system reliability.

Predicting the potential impacts of EV recharging on electricity grids, however, is made more difficult as this transition to EVs coincides with changes in the electricity supply systems that include increased adoption of energy efficiency and increased reliance on distributed or embedded electricity generation connected to the low voltage networks. These distributed generation systems include wind and combined heat and power but the primary distribution technology being installed is solar photovoltaic (PV) systems.

Increasing penetrations of EVs in the vehicle fleet will therefore have implications for both our transport systems and for our power supply systems. In the electricity supply industry, sufficient EV recharging facilities will need to be provided to EV owners and distribution system operators will need to manage these extra loads that until now have not been considered in electricity network operation and planning. The need for this research stems from the fact that electricity supply companies have been caught out by the far greater than expected take up rates of air conditioners and PV systems and EVs have the potential to be another surprise.

Yet another change occurring in the electricity supply industry is the emergence of distributed Energy Storage Systems (ESS) that are being used to improve the reliability, efficiency, and controllability of the power distribution system and to facilitate the integration of distributed generation and to enable growth in renewable electricity generation.

The motivation of this thesis is the investigation of the potential impacts of aggregation of V2G charging on electricity distribution systems when integrated with distributed generation and distributed energy storage systems.

The forthcoming earlier chapters of this dissertation describe the considered approach towards the design and development of the power system. During the development phase the power system structure and renewable energy source namely PV system are considered. The later chapters of this thesis describe the Energy Management System (EMS) for the modelled power system.

The thesis includes the detailed modelling of the low voltage distribution grid and load flow analysis by performing in-depth mathematical analysis and computation and also proving the feasibility of the efficiency of the power systems by presenting Power Factory simulations. The advantages and disadvantages of potential impacts of increasing of the integration of EVs with distributed photovoltaic (PV) systems and ESS utilisation also are presented in this dissertation. Finally, a comparative optimal EV charging strategy for energy management is proposed with the existing electricity paradigms based on peak demand shaving, improving voltage profile and minimizing power losses and how ESS may be used as a means of mitigating the impacts of EV charging.

The thesis concludes with the summary of the whole study and also provides the reader with potential future work. The optimized energy management system for the distribution system is presented as a significant contribution to the body of knowledge of integration of distributed/renewable generation sources and ESS operating in an electric grid environment.

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Publications

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Table of Acronyms

Abbreviation	Description
ac	alternative current
AMI	Advanced Metering Infrastructure
EV	Electric Vehicle
ANL	Argon National Laboratory
BESS	Battery Energy Storage Systems
BEV	Battery Electric Vehicle
BMS	Battery Management System
CD	Charge Depleting
CER	Commission for Energy Regulation
CPP	Critical-Peak Pricing
CS	Charge Sustaining
dc	direct current
DER	Distributed Energy Resource
DG	Distributed Generation
DR	Demand Response
DSO	Distribution System Operator
DUOS	Distribution Use of Service
EMS	Energy Management System
EPRI	Electric Power Institute
ESS	Energy Storage System
ETS	Energy Transfer System
EUM	European Union Member
EVSE	Electric Vehicle Supply Equipment
FERC	Federal Energy Regulatory Commission

HV	High Voltage
ICE	Internal Combustion Engine
IEA	International Energy Agency
Li-Ion	lithium-Ion
LV	Low Voltage
MIT	Massachusetts Institute of Technology
NECs	Neutral-Earthing Compensators
Ni-MH	Nickel Metal Hydride
ORNL	Oak Ridge National Laboratory
PEV	Plug-in Hybrid Electric Vehicle
PV	Photovoltaic
RTP	Real-Time Pricing
SAE	Society of Automotive Engineers
SLD	Single Line Diagram
SOC	State of Charge
SOF	State of Function
SOH	State of Health
TOU	Time-of-Use
USABC	US Advanced Battery Consortium
V2G	Vehicle- to-Grid
WPN	Western Power Network

Chapter 1

Introduction

1.1 Research Background

Vehicle manufacturers have intermittently developed electric vehicles (EVs) on a small number of occasions over the past half-decade. This investment has been driven by the perceived economic, social and environmental benefits that EVs potentially offer. These benefits include reduced national dependency on oil and depending on how the electricity used to recharge the batteries of EVs is produced, potentially reduced greenhouse gas emissions. The reappearance of EVs on the market in recent years appears to be substantively different to previous occasions. Given the number of companies developing EVs, it is likely to be a more persistent phenomenon. While it is too early to predict the likely take-up rates, the possibility of rapid and large take up rates has given rise to concerns over the potential impacts that such a rapid shift to electrification of transportation systems could have on power supply systems. The most problematic of these power issues will be the impact of large numbers of EVs being recharged at the same time and could result in investment in new generation capacity and upgrades of transmission and distribution infrastructure being required [1]. At these times, the peak in demand could interfere with the reliable operation of the grid, specifically the distribution systems. The level of high demand impact will be influenced by a number of factors, including local grid technology and topology, the penetration rates and distribution of EVs, and the charging management schemes adopted [2], [3], [4].

The current power infrastructure is facing some critical problems. Most of them originate from the fact that load demand is increasing around 1.6% every year [5].

One of the major concerns about the existing technology in power generation, transmission and distribution, overall termed as grid, is regarding its ability to cover the future demand with the limited supply. International Energy Agency (IEA) has predicted that the existing power supply will only be able to cover the increasing load demand for the next 40 years. A further concern is attributed to the efficiency and the environmental impact of the existing grid. The existing infrastructure of power generation comprises of a centralized power plant that produces electricity which is then transmitted and distributed to the consumers. Such a centralized power grid is inefficient for the existing and future era. This inefficiency of the centralized power grid arise because of the following reasons: 1) The centralized power infrastructure does not incorporate distribution generation sources, which causes the fed load to become highly dependent on the centralized high voltage generation side, 2) Due to the long distances between the consumer load and centralized power generation source, high power losses occur which lowers the overall efficiency of the network, 3) Increase maintenance cost associated with the transmission of power from a centralized power infrastructure [6].

To manage the increase in peak demand, a considerable amount of operational, infrastructural and technological investment will be required to address energy security, reliability and affordability of supply [3]. The electricity businesses that would bear the responsibility for investing in these upgrades will need to evaluate the impacts of EVs charging and peak demand period on their grids, particularly on the distribution systems, as a first priority.

Electricity distribution systems are typically designed for specific load-carrying capability based on typical load consumption patterns of customers. If EV recharging becomes a new large load, the patterns of electric power demand would change [7], [8], [9], [10].

As almost 90 per cent of power system outages occur in the distribution system and with the average life span of a distribution transformer, the distribution systems are most likely be impacted by any such changes in demand [8], [7].

Recent studies of power systems have shown that large-scale penetrations of EVs under an uncoordinated charging management regime would impose additional loads on the distribution grid [11]. In order to mitigate such stresses on distribution systems, it will be important to understand the impacts that high EV penetration rates will have from a demand side perspective, as there is a possibility of geographic clustering of EVs in certain localities [12], [13].

In the absence of any coordinating strategy, uncontrolled charging of EVs could potentially have the following detrimental effects [8]:

- Distribution transformer losses
- Thermal loading on the distribution transformer, which reduces the transformer life
- Voltage deviations
- Peak demand necessitating additional investments on distribution side reinforcements
- Power quality issues.

1.2 Smart Grid

According to the recent studies, EV charging coordination options can be group into three approaches: (i) a time-of-use tariff schemes, (ii) centralised charging schemes, and (iii) decentralized charging [14]. The effect of time-of-use explores the effect of a higher price during peak hours on shifting EV load by providing customers with an incentive to avoid the more expensive peak load time of the day [14].

Centralised charging means a central controller coordinates charging. This centralised structure (system operator) collects all information from EVs and optimizes over the charging profiles of all EVs. The system operator sends commands to individual EVs to set charging start times/rates. Hence it relies on customer information and requires initial infrastructure investments of communication and computation requirements [15], [7], [11].

Decentralized charging means EV owners choose their own charging pattern and optimise charging behaviour instead of being instructed by a centralised infrastructure. The utility company uses signals only to guide EV owners' decision-making based on the charging negotiation procedure [16].

With the prospect of car manufacturers such as Nissan, Mitsubishi, General Motors and Chevrolet, that have recently begun to develop electric vehicles for their production lines there is likely to be an increasing fleet of electric vehicles in the short-term. However, the deployment of electric vehicles will also depend on several factors, including EV prices, petrol prices, governmental investments and security cost. This diversity and interconnectedness between factors makes it difficult to model the likely penetration of electric vehicles and makes it impossible to clearly identify any one single likely electric vehicle penetration scenario.

Hence, the most effective method to investigate the influence of EV uptake on the grid is to explore various scenarios of EVs penetration rates due to lack of electricity generation for a rapid EV adoption rate, lack of charging infrastructure and also lack of an accurate information on likely EV usage patterns. There are various projections as to the rate of EV uptake, but all predict an increase over the next ten years. Charging these EVs will produce one of the biggest loads on the low voltage network. To manage the network, not only the number of EVs taken up has to be take into account, but where on the network they are charging, and at what time. It is essential to obtain a better understanding of how EV drivers' charging behaviour and driving pattern that can be defined as the day-to-day frequency of recharging and time of day of recharging [17].

To investigate to what extent existing infrastructure can support gradual EV penetration and possibility of distribution power loss reductions, a model of a typical low-voltage (LV) distribution grid is developed in this study. In this model, interaction of EV users with distribution network is simulated, looking into different scenarios. This approach enables the assessment of the future market penetration of electric vehicles and evaluates the effects of EV adoption on a typical LV distribution grid topology in Western Australia. Western Australia has ideal potential for the best solar energy resources in country, as the solar energy radiation levels are among the highest in the world [18].

This potential gives the chance to shift the architecture of energy systems away from centralised power plants located large distances from load centers and toward any distributed generation based on renewables such as photovoltaic (PV) systems connected throughout distribution networks, often on the customer's side of the meter [11].

1.3 Distributed Energy Sources

PV systems are usually utilised to enhance the performance of the electric network by reducing the power losses and improving the voltage profile of the network. However, due to the fact that the power generated from these systems is alternate, the use of energy storage devices with PV systems is currently receiving a lot of attention. This is especially because the installation of storage devices can enhance the performance of PV systems by reducing their power fluctuations, shifting the time of their peak generation and providing reactive power support [19], [20].

Trends show that in the future, the majority of new PV installation will be grid-connected residential PVs whose capacity is normally less than 10 kW and are connected to low voltage (LV) distribution systems [21].

The owners of the aging power grids in Australia are trying to reduce the investments in new capital investments that will be required. It requires maintaining reliability and quality of supply and integrating more distributed generation resources and storage technology for sustainable power management [22].

The efficiency and reliability of distribution systems can be improved by coordinating EVs with other distributed energy resources (DERs), such as distributed generation, demand response, and energy storage systems. For example, EV charging could be controlled to follow the power generation from intermittent distributed wind and solar generation.

The design of such systems would require investments in communication infrastructure, and devising appropriate centralised or distributed control strategies.

Distributed Energy Storage (DES) aims to improve the reliability, efficiency, and controllability of the power distribution system and to facilitate the integration of distributed generations.

This thesis investigates the integration of all these technologies from a technical perspective and investigates how DES may be used as a means for mitigating the impacts of PEV charging and PV-DG interconnection.

The study analyses the impacts of increasing penetration levels of EVs in the vehicle market and comprises three main sections. The first section analyses EVs charging impacts on the distribution system. The second part of the analysis focuses on the potential impacts of increasing the integration of EVs with renewable energy resources, namely distributed photovoltaic (PV) systems.

The third part of the analysis investigates EV infrastructure integrated through solar PV-powered charging stations with energy storage.

The model developed by using daily residential loads of distribution networks to study. Selected scenarios provide the input parameters for modelling, including the density of EV penetration, charging requirements such as battery size, its state of charge and the time of day it is charged.

1.4 Scenarios for 2030

In this work, four different scenarios were defined to investigate the overloading of the LV distribution grid and energy losses after the integration of EVs incorporating with distributed generation and storage technology.

1.4.1 Scenario 1: Baseline Scenario

Initially, a typical 24-hour load profile of the selected low voltage distribution feeder is extracted from historical data and used in this analysis. A scenario without EV charging is run on the developed network to determine the baseline demand and is considered as a reference for further calculation of mass market uptake of EVs. Following this, the three scenarios were implemented.

1.4.2 Scenario 2: EVs Penetration into the Distribution Grid

This scenario investigates the impact of EVs' integration into the electricity grid with different penetration levels, distribution arrangements, and an uncontrolled charging regime from the electricity grid, with no delay.

Scenario assumptions

- EVs start charging up to full saturation of charge when they arrive home.
- EVs' batteries charging energy derived from electricity grid.

- The vehicles were randomly distributed or in a cluster arrangement and connect to the customer's side of the meter.
- EV penetration rates gradually increased to capture the uncertainty of vehicle technology, charging infrastructure and local penetration of EVs. It is assumed that 25, 50, 75 and 100 per cent of the total number of households in the considered area possess an Electric Vehicle.

1.4.3 Scenario 3: EVs Integrated with PVs and no Storage

This scenario investigates the effect of integration of EVs and PVs into the electricity grid. It is assumed that EVs are allocated to customers that also have installed PV plants. Under this scenario, different penetration of residential EVs and PVs is implemented.

Scenario assumptions:

- EVs start charging up to full saturation of charge when they arrive home.
- The vehicles were distributed in a random and cluster arrangement and connect to the customer's side of the meter.
- EVs were charged through electric grid and solar (PV-powered) charging.
- PVs penetration levels are 25, 50, 75 and 100 per cent. For instance, 5 per cent penetration of PV indicates that 5 per cent of the customers on the test feeder have PV units installed on their houses.

1.4.4 Scenario 4: EVs Integrated with PVs Utilising storage Battery

In this scenario, integration of EVs with PVs into the grid is explored but PVs are connected to storage battery. It is assumed that EVs are allocated to customers that also have installed PV plants.

EVs energy charging is derived from grid and stored energy of solar PVs. Utility scale storage battery of 600kWh is utilised for accumulating excess energy from PVs that is generated during the day. During the early evening, when the peak residential EV charging demand occurs, PV output is typically small, so storage units will supply EV charging demand.

Scenario assumptions:

- EVs start charging up to full saturation of charge when they arrive home.
- The vehicles were distributed in a random and cluster arrangement and connect to the customer side of the meter.
- EVs were charged through electric grid and solar (PV-powered) charging.
- EV penetration level is gradually increased from 25 to 100 per cent; accordingly, PV penetration level is considered 25, 50, 75 and 100 per cent.

1.5 Objective

This thesis carries out an in depth study on the potential impacts of large-scale market penetration of EVs in Western Australia, with the focus on household cars. This study includes the assessment of major challenges for electricity distribution networks that have to support extra load with incorporating of PV system and energy storage batteries. Therefore proposes a control strategy for PEV charging based on peak demand shaving, improving voltage profile and minimizing power losses.

1.6 Problem Statement

Introducing electricity and charging in the transportation system requires a number of changes in infrastructure and its extension to meet the demand or needs of a comprehensive coordination of charging regimes for EVs or utilising centralized or decentralized charging techniques.

1.7 Structure of the Thesis

Chapter 1: The thesis starts with this chapter, chapter 1, which introduces the reader an overview of the electric vehicle types, penetration rates and charging strategies. The uncoordinated charging management of EVs is presented and the potential technical issues on the grid are identified. The aim of the study is defined; to design and implement a control strategy for PEV charging based on peak demand shaving, improving voltage profile and minimizing power losses.

Chapter 2: This provides an overview of the growth of the electric vehicle sector, with focus on existing EV technologies, characteristic, usage pattern and prospects. The main aspects of EV integration into the power systems are discussed.

Chapter 3: This chapter covers a review of conventional power system. Then the transition from the conventional to the new electricity paradigms is discussed, motivated by the integration of distributed energy generation. With focus on the current standards for interconnection of distributed energy resources (DER).

Chapter 4: This chapter outlines the general strategy and design of power system simulator developed with additional components.

Chapter 5: This chapter provides a full description of the power system simulator, including the aggregate EV load models and PV system models.

Chapter 6: This chapter presents the simulation results along with a discussion of these results.

Chapter 7: This last section provides the conclusions and recommendations for future work.

Chapter 2

The Plug-in Electric vehicles

This chapter reviews some of the literature related to the Electric vehicle characteristic including types, design and usage pattern in order to determine the infrastructure power and energy requirements for recharging PEVs. The survey emphasis vehicle power and energy management, propulsion systems and influence of driving cycle that affect the overall efficiency and fuel economy. The survey also focusses driving behaviour and charging pattern analysis in order to study the effects of vehicle- to-grid (V2G) on traditional distribution system design and operation.

2.1 Introduction

The driving behaviours or driving patterns of EV owners will be determined primarily by recharging and their recharging management requirements they are likely to be very different to those of conventional internal combustion engine (ICE) vehicle owners. The fact that driving behaviours and charging patterns of EV owners are currently unknown creates challenges for both transport planning and electricity planning. In order to manage these challenges it will be essential to obtain a better understanding of how EV drivers' mobility and driving patterns will differ from the current driving patterns of drivers of conventional ICE vehicles as these changes will determine EV recharging electricity loads and, therefore, the extent to which the other potential benefits of EVs such as reduced emissions will be achieved.

To address the fundamental concerns about the potential impacts that Battery Electric Vehicles (BEVs) referred to in this study as Plug-in Electric Vehicles (PEVs) or simply as Electric Vehicles (EVs), may have on the electricity grid as well as on environmental and climate impacts, assessing EV driving patterns and recharging is essential and will allow planners to manage the electricity grid to accommodate EVs. Vehicle manufacturers and climate policy regulators also stand to benefit from a better understanding of EV driver recharging behaviour, while battery manufacturers would benefit by being able to more accurately model battery life and cost. For energy planners, the charging behaviours of EVs will be an important factor to consider in the integration of EVs to the electric grid, as this will affect the recharging demand, which could become a major component of overall load on the electricity supply system.

The recharging behaviours of EV owners will be determined by various environmental, economical and technical factors, such as the number of EVs being charged (EV penetration trend), the availability of charging infrastructure, charging voltage and current levels, charging time of day and duration, state of the battery technology, including battery specification, battery lifetime and capacity, which are all considered as technical aspects of EVs [23], [24]. The interconnection between the power supply systems, the transportation system and vehicle technology are shown in Fig. 2.1. Factors relating to each of these three domains will affect EV users' behaviours which must be considered in order to study the effects of vehicle- to-grid (V2G) on traditional distribution system design and operation.

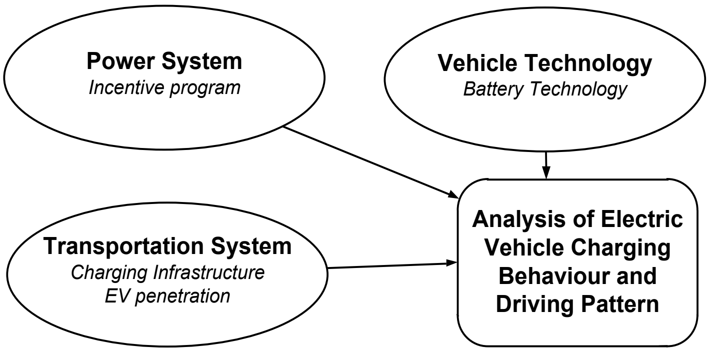

Figure 2-1: EV charging behaviour and driving pattern analysis

The study of electric vehicle integration and its impact on the electricity grid began in the 1980s. Several studies have been undertaken since then to estimate EV penetration growth rates at a regional level and their potential impacts on electricity loads [25], [26], [27], [28], [29]. A common finding of these studies has been that unmanaged charging demand would be likely to coincide in with the timing of the overall electricity system peak loads on many electricity grid [30]. These studies, however, have tended to focus primarily on the question of whether the existing and planned generation capacity would be sufficient to meet the resulting increase in load [31]. A thorough analysis of EV penetration into the regional power grid, for example, was undertaken by the Oak Ridge National Laboratory (ORNL) in the USA. That study found that all regions in the USA would need additional generation capacity to cover the increase in loads [32].

Several studies have also focused on the impacts of EV penetration on the high voltage transmission supply infrastructure [29], [33], [34]. The majority of studies, however, have concentrated on the impact that EV recharging is likely to have at the distribution network level. An evaluation of the potential impacts of BEV and PHEV charging loads on the distribution network components and its operation, however, requires a micro-level analysis that takes into account potential variations in spatial diversity of EVs throughout the network as well as temporal diversity in charging patterns and how these relate to the traditional system load [31], [35]. The concepts of smart charging and demand response management have therefore been proposed, with the aim of optimising the recharging of EVs in terms of reducing the impacts on the distribution network [36], [37], [12], [35].

A number of studies have found that the integration of distributed generation, such as small-scale renewable generators, into EV charging infrastructure, could reduce the potential negative impacts that additional EV loads could potentially have on the electricity network [38].

The focus of the more recent of these studies of EV recharging has shifted towards analysing factors resulting from the EVs' extra load on the grid. The factors include driving patterns, charging behaviour, energy cost optimisation and battery longevity [39], [17], [40], [41], [42].

2.2 Factors Influencing Charging Strategy and Driving Patterns

Charging patterns of EVs is a major criterion of EVs electric grid integration challenges as it affects the charging demand that is the major part of overall load on the power system [43].

Charging pattern can be defined as the day-to-day frequency of recharging and time of day , duration and location of recharging [17].

The charging behaviour of EVs is affected by various factors, such as battery specification, battery durability, capacity and charging voltage and current level, which are considered as technical aspects of EVs [43].

From the environmental aspect, charging point availability and number of EVs being charged are factors that have an effect on the charging behaviour trends of EV owners.

Understanding PEV battery charging parameters is necessary in order to determine the infrastructure power and energy requirements for recharging PEVs. The charge rate is one the parameters that vary and that depend on the battery pack technology and charging method. Battery packs can be charged using constant current or constant voltage or a combination of both.

These factors can be grouped into three main domains: the transport domain, the vehicle technology domain and the power system domain. The details of these three domains and the related factors are discussed in turn in the following sections.

2.3 Transport Domain

2.3.1 Projected Penetration Rates

Transportation is critical to almost every aspect of modern human activity. The current very high dependency of the transportation system on fossil fuels, and on petroleum based products in particular, holds major economic, social and environmental risks. Reducing transportation energy consumption and transportation related emissions will be challenging. Improvements in technology, by themselves, will not be sufficient and behavioural changes will also be essential. Transportation behaviour changes will involve not only choosing a fuel efficient vehicle, but also changing both the way the vehicle is used and driving patterns [31].

PEV market penetration rate estimations and statistics are important to understand the market trends and are also used to more accurately assess and predict the potential impact PEVs have on the energy sector. The results of recent studies suggest that EV uptake rates are likely to be non-linear [44], [41], [45], [46]. They are also currently at very low levels and both of these mean that at this early stage in EV market development, future EV penetration levels are difficult to predict. This is reflected in the large divergence of the projections that have been made over recent years. The EPRI and Natural Resources Defence Council (NRDC) predicted that PHEV sales would account for 37% of new vehicle purchases by 2020, 52% by 2035 and 62% by 2050 in the USA [26]. The US Department of Energy forecasted that sales of hybrids and PHEVs will reach 50–54% of total sales by 2030 [26]. The Boston Consulting Group and Deutsche Bank, however, have separately forecasted that the electric vehicles sales projection in the North American market will make up only 1–5% by 2020, based on energy prices and government regulations [47].

This lack of predictability, combined with potentially rapid and large uptake rates under certain conditions or scenarios, holds the potential for unanticipated growth in electricity demand. If the capacity of the electricity supply system is reached rapidly it could have a negative impacts on EV take up rates as a constrained electricity supply system could slow further EV take up rates. If this occurred, it would that the potential economic, social, and environmental benefits that that a rapid uptake of EVs offers would be delayed.

Several other studies have attempted to predict EV market penetration levels. These include studies undertaken by the Massachusetts Institute of Technology (MIT), the Electric Power Institute (EPRI), the National Renewable Energy Laboratory (NREL), the Argon National Laboratory (ANL), the International Energy Agency (IEA) and the Indiana University [45]. The last of these studies revealed that the market factors with largest influence on EV uptake rates are likely to be energy prices, battery characteristic (such as safety, reliability and production cost), availability of convenient, affordable recharging infrastructure and the development trend of PEVs compared to competing technologies such as improved fuel efficiencies of internal combustion engine vehicles, conventional hybrids, advanced biofuels, natural gas vehicles, and fuel cell vehicles [48].

Predicting likely EV market penetration rates is made more difficult by the fact that there are expected to be significant regional differences in EV take up rates. Regions with relatively strong PEV markets have a greater focus on market formation activities and relatively higher costs savings associated with operating an electric vehicle as compared to a conventional vehicle. To determine whether these factors are the primary determinants of PEV market shares, further research should be undertaken. A range of potential market penetration rates have been projected for different regions and a number of countries including USA, Canada, Japan, South Korea, Israel, China. Some European Union Member (EUM) countries have established EV development targets, policies and plans to deploy EVs successfully as shown in Table 2.1[49].

Table 2-1: EV global penetration target

Country	EV uptake target	Country	EV uptake target
North America	37% by 2020; 52% by 2035; 62% by 2050 [50]	UK	350,000 by 2020 [48]
Canada	500,000 by 2018 [51]	Sweden	600,000 by 2020 [48]
Australia	2020: 20% production; up to 65% mass production by 2050 [51]	Spain	One million by 2014
New Zealand	2020: 5% market share; 2040: 60% market share [51]	Netherlands	200,000 by 2040 [48]
Germany	One million by 2020 [52]	Ireland	2020: 230,000; 2030: 40% market share [48]
France	Two million by 2020	Japan	50% of new vehicles by 2020
Belgium	30% by 2030 [7]	South Korea	10% of small vehicles by 2020
Denmark	200,000 by 2020	Israel	40,000-100,000 EVs by 2012
Switzerland	145,000 by 2020 [48]	China	Five million by 2020 [48]

2.3.2 Recharging Infrastructure

EV types and locations of EV recharging infrastructure are likely to be a critical determinants of EV market development. The locations of EV recharging stations are also likely to influence EV driving patterns. Having access to fast-charging facilities for longer journeys, for example, is likely to encourage members of the public to adopt the EV technology faster.

The results of a study by the Tokyo Electric Power Company (TEPCO) over the period of 2007–2009 suggest that the availability of fast charging stations will be essential in the successful development of EVs and will have a massive effect on user behaviour [53]. It was found that EV drivers using standard recharging stations returned with, on average, 50% of remaining charge, but that when using fast chargers, EV users came back with much less charge remaining in their batteries and also that driving distances increased [53].

In addition to the types of charging infrastructure, the location for EV recharging infrastructure is also categorised by charging power levels of EVs. The EPRI defined three charging levels as shown in Table 2.2 and these were codified in the National Electric Code (NEC) in 1994, along with corresponding functionality requirements and safety systems [54].

Table 2-2: Types of charging infrastructure based on SAE standard

Charging level	**Level 1**	**Level 2 (Primary)**	**Level 3 (Fast)**
Nominal supply Voltage (Volts)	120V AC (US) single phase/ 230V AC (EU)	208–240V AC Single phase	600V DC maximum three phase
Maximum Current (Amps)	12–15	32	400
Power provided (kW)	1.44	3.3	-
Available infrastructure	Residential/Commercial	Residential/Commercial	Commercial
Connector type	General outlet	EVSE Conductive/Inductive	EVSE
Time to charge (hours)	4–11 /11–36	1–4 /2–6 /2–3	50% of charge in 15 minutes
Vehicle technology	PHEVs (5–15kWh) /EVs (16-50kWh)	PHEVs (5–15 kWh)/EVs (16–30kWh)/EVs (30–50kWh)/EVs	EVs (20–50 kWh)
Branch circuit breaker rating (Amps)	15A (min)	40A	As required

Based on the Society of Automotive Engineers (SAE) terminology, 'level' is defined for North America and term mode is defined in the International Electrotechnical Commission (IEC) standard in Europe. The IEC 61851-1 has defined four conductive charging modes. Modes 1 to 3 are referred to as charging with an on-board charger in the vehicle, while mode 4 refers to the use of an 'off-board charger' [55]. Table 2.3 lists the four charging modes defined by the IEC [55].

Table 2-3: Types of charging infrastructure based on IEC standard

Charging mode	**Nominal Supply Voltage (Volts)**	**Single phase**	**Three phase**	**Charger Type**
Mode 1	250V AC (single phase)/ 480V AC (three phase)	Max 16A 3.7kW	Max 16A 11kW	On-board
Mode 2			Max 32A 22 kW	
Mode 3			Max 63A 43.5kW	
Mode 4	-	-	400A DC	Off-board

Level 1 charging is referred to as ‘slow charging’ and is achieved through a standard 120V AC, 15 amps or 20 amps, based on the vehicle technology, battery type and capacity. This is the lowest common voltage level for residential and commercial buildings in the USA. Recharging time can take anywhere from three to 24 hours for PHEVs/PEVs. Level 1 charging is particularly suitable for overnight charging and the charging equipment is usually installed on the vehicle and the supply is brought to the vehicle via a standard plug and cord [56], [57].

Level 2 charging is usually termed the ‘primary’ and ‘standard’ method for charging the battery of an electric vehicle at both private and public facilities. Level 2 provides alternating current (AC) electricity to the vehicle. It uses a 240V AC, single-phase, 40 amps branch circuit. The vehicle’s on-board equipment converts the AC to the direct current (DC) required to charge the batteries with a higher level of safety as required by the NEC. Two types of Level 2 charging equipment have been developed‘ conductive’ and ‘inductive’ which is generally referred to as the electric vehicle supply equipment (EVSE) [57].

Level 3 charging is a high-voltage, DC ‘fast charging’ for commercial and public applications. Battery electric vehicles achieve a 50% charge in 10–15 minutes. This is referred to as ‘fast charging’. Level 3 charging and is intended to be equivalent to refuelling a conventional ICE vehicle at a petrol station [56], [57]. Level 3 charging would significantly reduce the charging time, enabling long distance travel. The maximum current specified is 400 amps. Level 3 uses an off-board charger system that is serviced by a three-phase circuit at 208 V_{ac}, 480 V_{ac}, or 600 V_{ac}. Charging equipment sizes vary from 60 to 150 kilowatts [56], [57].

2.4 Vehicle Technology Domain

2.4.1 Electric Vehicles

Electric vehicles use batteries to store the electrical energy that runs electric motor. EV batteries are charged by plugging the vehicle into the electric power grid. They consume no petroleum-based fuel when driving and, therefore, produce no tailpipe emissions.

2.4.2 Electric Vehicle Types

There are mainly three types of EVs: full EV (all-electric vehicles) or Battery Electric Vehicles (BEVs), HEVs (Hybrid Electric Vehicles) and PHEVs (Plug-in Hybrid Electric Vehicles).

BEVs: Battery electric vehicle powertrain is entirely electric and have no internal combustion engine. They run only by one or more electric motors. The electricity provided by a battery pack that is recharged by plugging into the grid. They use no petroleum-based fuel [32].

HEVs: HEVs have both powertrains of internal combustion engine (ICE) and electric motor. They rely on petroleum-based or alternative fuel for power and ICE charge the battery. The battery charge is not by plugging into the electricity. Therefore, it is essential for proper management scheme for having effective operation.

PHEVs: A plug-in hybrid electric vehicle (PHEV) is a hybrid electric vehicle, a dual- fuel car having both internal combustion engine and the electric motor which utilise rechargeable batteries. This battery energy storage capacity is large enough to drive a number of miles using only electric energy [58].

The PHEV powertrain has all capabilities of an EV and smaller size of internal combustion engine vehicle. The difference is that plug-ins has the added feature of plugging to an electric outlet to charge the battery.

PHEVs have larger battery pack compare to EVs to provide the driving range of all-electric vehicles.

The potential (main characteristic) of PHEVs is to operate in both electric and hybrid modes. PHEV uses stored electrical energy to run the vehicle and reduce petroleum consumption by the combustion engine that provides an opportunity to drive primarily in electric mode and reduce emissions in congested cities around the world [59].

Their fuel flexibility and ability to add-on the energy storage off the grid have made them a preference in development of alternative fuel vehicles [37].

A fuel cell vehicles is a type of EV that utilizes a full cell to generate electricity on-board to operate an electric motor drive. Power and speed characteristics have traditionally been the most important design factors for automotive manufacturers, but recently fuel consumption, comfort, reliability and tailpipe emissions have also been considered as priority. Because of these concerns, electric vehicles along with hybrid electric have arrived on the market [35].

There are three main EV powertrain configurations supporting the vehicle operation when designing a vehicle [60], [61].

Series: In series powertrain configuration, the vehicle runs entirely from the electrical energy until the battery needs to recharge. Series engine is considered extended range of electric vehicle. The ICE is only used to drive a generator to produce electricity.

Parallel: In parallel configuration, electric motor and engine both can be directly connected to the wheel and run the vehicle.

Power split (series-parallel) In power split configuration, the combined architecture allows running the vehicle in an optimal manner by using the electric motor only, or both the electric motor and ICE together depending on the driving conditions.

a. Battery System

Batteries play a key role in EV performance, as the energy consumption is associated with the battery system efficiency. Hence, the in-depth understanding of a battery's system and characteristic is important in the utilisation and functionality of EVs. There are two main components in a PEV's battery system: the battery pack and the battery management system (BMS). The BMS is 'the brain' of the battery pack. It constantly controls the functionality and charge of the battery's cells, monitors the state of the battery's charge and predicts the actual amount of energy that can be delivered to the load. Since the performance of the battery depends on its useable capacity and internal resistance, this is crucial in lengthening the life of the battery [62]. The battery management functions are defined as three main categories, including protection function, optimisation function, and display and diagnose functions as shown in Fig. 2.2 [63].

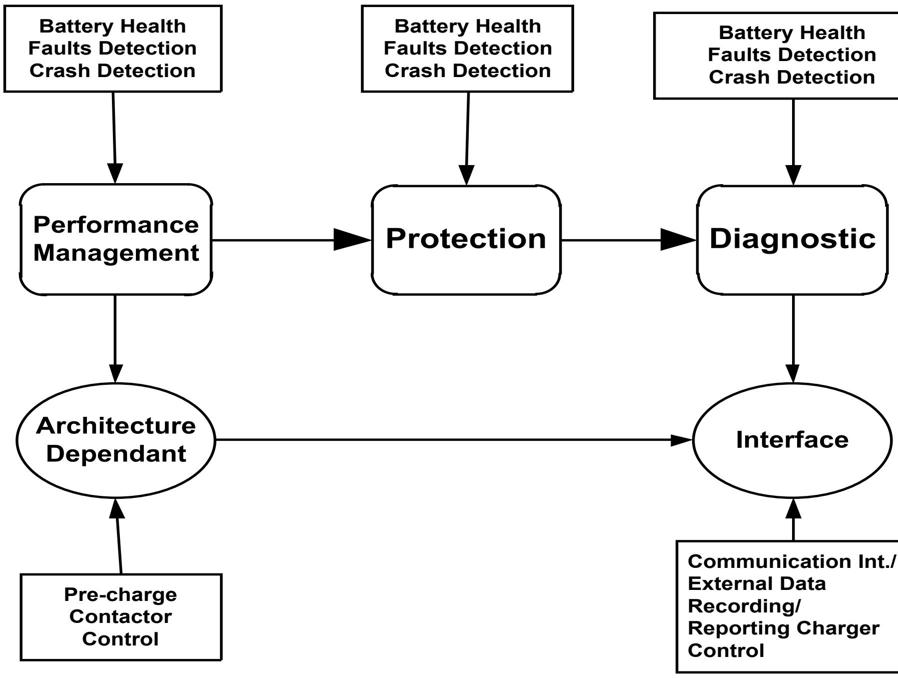

Figure 2-2: Battery management function

b. Battery Management System

The Battery Management System (BMS) is an electronic system that manages rechargeable battery cell or pack. It is a connector between the battery and the vehicle, a critical component to optimising vehicle operation in a safe and reliable condition [64].

The battery management function are defined as three main categories including security function, optimisation function, and display and diagnose functions [65].

The battery management system monitors key operational parameters, such as voltages, current, and temperatures, during charging and discharging of a vehicle's batteries. Lithium-ion batteries, in particular, are very sensitive to cover charge and deep discharge, which may damage the battery and shorten its lifetime. Therefore, this requires the utilisation of a proper battery management system to monitor battery operation range carefully to ensure energy availability, safety and life of the energy storage system. That each cell of battery is maintained within the safe and reliable function range [62].

The efficiencies of the battery and the battery management system increase the charge maintain sustainability and contribute to increased reliability of the electric vehicle [66].

The main functions of battery management system include:

- Monitoring several operating parameters of battery pack including battery voltage, current and temperature over time
- Estimate the State-of-Charge (SOC) of the battery, State-of-Health of the Battery (SOH) and State-of-Function (SOF)
- Controlling the heating and cooling
- Ensuring the isolation of high voltage from the vehicle

- Optimize the charging/discharging conditions automatically according to the temperature and charging/discharging level
- Implementing isolate communication within the vehicle

  The architecture of BMS can be determined by the physical structure of battery packed designed for the aimed application. The BMS usually consist of three layers including the elementary, the module and the pack. The overall cell string consists of number of series- connected cell segmented to the module.

c. Battery pack

In any PHEV architecture, the battery plays a critical role in storing energy from the electricity grid and from the petrol engine (through a generator), as well as transferring energy via an electric motor to maximize efficiency. Ultimately, the commercial success of the PHEV depends on the development of appropriate battery technologies [67].

A battery pack consists of several mechanical and electrical component systems. It contains battery cells that are characterised by different chemistries, sizes and shapes. The battery cells are connected in series or parallel configurations to achieve the required total voltage and current levels [54].

2.4.3 Battery Characteristics

To discuss the advantages of one battery technology over others, it is useful to identify the characteristics of an ideal battery. The most important characteristics of an ideal battery are power density, energy density, safety, cost and durability as shown in Fig.2.3 [54] .

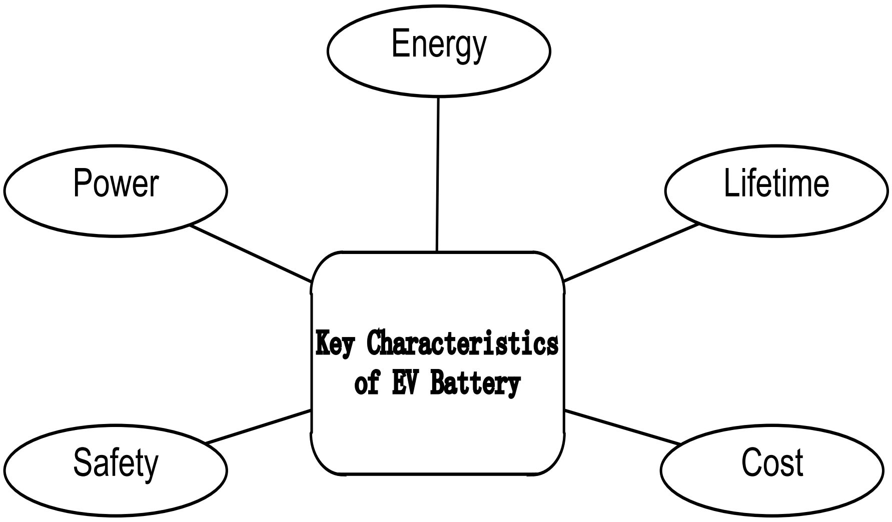

Figure 2-3: EV battery characteristics [68]

Energy density is defined as the amount of energy that can be stored in the battery per mass of the battery and is measured in watt-hours per kilogram (Why/kg) or kilojoules per kilogram (kJ/kg). The battery energy density is the most important criterion for an EV because the amount of energy that a battery can store determines the maximum range of the EV.

Power density is the amount of power that the battery can deliver per mass safely without damaging the battery and is expressed as W/m^3 which indicates the efficiency of a battery pack [54] .

Safety is defined as being protected from out-of-tolerance operating conditions and is a considerable issue for an EV battery, due to the potential risks to drivers and passengers. Undesirable use conditions (off-normal conditions) include electrical short circuit and over voltage (Electrical), thermal runaway, and crush and nail penetration (Mechanical) [69]. The key characteristics of EV batteries are defined in Table 2.4.

Table 2-4: Key characteristics of EV battery [69], [2]

Battery key Characteristic	Definition
Energy density	How much energy can be stored in the battery per mass of the battery? The energy density is measured in watt-hours per kilogram (Why/kg) or kilojoules per kilogram (kJ/kg).
Power density	The amount of power the battery can deliver per mass without causing harm to the battery [54].
Lifetime	This usually depends on the energy management of the battery and is defined with respect to Cycle life, Calendar life, Deep cycle life, and Shallow cycle life.
Safety	Condition of being protected from out-of-tolerance operating criteria such as over voltage, thermal variation and mechanical shock.

Battery lifetime is defined with respect to both Calendar life and Cycle life. Calendar life is the expected life span of the battery under storage. It can be strongly related to the temperature and State of Charge (SOC) during storage, independent of how the battery is used. Cycle life refers to deep cycle life and shallow cycle life. Deep cycle life is the number of complete charges-discharges that a battery performs in charging mode, which is normally 80%. Shallow cycle life refers to variation in SOC. These frequent shallow cycles cause less degradation than deep cycles, but still affect longevity [70].

Battery lifetime is one of the dominant factors that currently determines the vehicle's economic limitation. The battery life for the electric vehicle is defined by four criteria: calendar life, deep cycle life, shallow cycles and survival temperature range.

Calendar life is the years that a battery endures degradation, regardless of how the battery is used. The US Advanced Battery Consortium (USABC) and Massachusetts (MIT) target 15 years at temperature of 35°, and EPRI uses 10 years calendar life [10].

Deep Cycle life is the number of discharge –recharge cycles starting from eighty percent of its capacity and ending at 20 percent, recharging back to the eighty percent of SOC would complete a full cycle. After that point, the battery is still useable but the decreased range of an already limited range vehicle is not desirable and the battery is retired from the vehicle and repurposed or recycled [2].

Shallow cycle denotes the variation of SOC from CD to CS mode that happens when the battery draws electric energy from the regenerative breaking though generator and gasoline engine to inject to the electric motor when it is needed .than do deep cycles. The shallow durability cycle is set at 300,000 by the USABC, 175,000 by MIT and 200,000 by EPRI [70].

Survival temperature range sets the limits to the range of temperatures that the battery can be exposed to when operating or charging and discharging. The survival temperature is set at -46°C to +66°C by the USABC [70].

State of Charge *(SOC)* is the remaining capacity of a battery and is influenced by its operating conditions, such as load current and temperature. The SOC is the pack capacity expressed as a percentage, and can be thought of as the packs fuel gauge indicator. The battery's requirements of any PHEV design are primarily determined by peak power (kW) and energy storage (kWh) [68].

$$SOC = \frac{remaining\ capacity}{rated\ capacity} \tag{2.1}$$

State of Health *(SOH)* is the ratio of the maximum charge capacity of an aged battery to the maximum charge capacity when the battery was new. SOH is an important parameter for indicating the degree of performance degradation of a battery and for estimating the battery's remaining lifetime [68].

$$SOH = \frac{aged\ energy\ capacity}{rated\ energy\ capacity} \tag{2.2}$$

2.4.4 Battery Cost

Battery cost is the most crucial factor affecting commercial deployment of electric vehicles and has the most significant influence on vehicle price. Hence, electric vehicles and hybrid electric vehicles manufacturers need to make a trade off decision between vehicle affordability and vehicle performance [70]. The way EV drivers charge their vehicle affects degradation of the battery performance in terms of power, energy capacity, safety and potential replacement cost. Popular models of conventional cars lose 50% to 60% of their initial value (purchase price) after three years. The depreciation rate of EVs is likely to be higher and the cost of replacing the battery in an EV is therefore likely to exceed the depreciated value of the car. This could lead EV owners to operate their EVs at low SOC levels [71].

The safety, durability, and performance of batteries are highly dependent on how they are charged or discharged. Abuse of a battery can significantly reduce its life and can be dangerous. Recent studies have focused on the how driving and charging behaviour (strategy) have influenced by battery lifetime [72]. These studies have shown that the driving profile obtained from the EVs' charging behaviour can be used to predict the lifetime of a battery. The analysis of comprehensive lithium-ion battery aging tests shows that high battery SOC decreases battery lifetime, whereas the cycling of batteries at medium SOC has only a minor contribution to aging [40]. Another study of EV deployment on the distribution grid by monitoring real EVs driving behaviour in Germany has shown that charging strategies and behaviour have significant influence on the battery operation [40].

2.4.5 Battery Technology

The two most common battery chemistry technologies used in EVs are lithium-ion (Li-Ion) and nickel metal hydride (Ni-MH) because both of these two battery chemistries have relatively high energy densities. Lithium-ion technology has the potential to meet the requirements of a broader variety of EVs. Lithium batteries have increased market share due to their lightweight nature and potential for high voltage and slow loss of charge when not in use, which enables them to have higher power than Ni-MH batteries do [73].

A lithium-ion battery has the highest energy density among the entire rechargeable cell chemistries. The main concern in the development of lithium-ion battery packs for EVs is thermal management. The temperature of all cells must be precisely maintained within a few degrees Celsius across the entire pack. Thus, the charging and discharging of a lithium-ion battery should be very accurate in order to maintain an optimum internal temperature to attain maximum performance [74]. Among battery chemistries, lithium-ion has more advantages compared to more mature chemistries, such as Ni-MH. The cell voltage of a lithium-ion battery is three times higher than that of Ni-MH. Lithium-ion battery chemistry has higher energy density per unit volume, which makes it possible to have a lighter and smaller size battery system [54].

The current generation of lithium-ion batteries commonly use a carbon-based anode and a metal oxide cathode. Research on next generation lithium batteries is expected to continue to develop electrode and electrolyte materials that will increase the life and the energy density of the battery, while reducing battery size and weight. The most promising options appear to involve silicon, Sulphur and air (oxygen) [75]. The recommended charge method for Lithium-Ion batteries, which is currently the most common battery technology, is to use a combination of constant current and constant voltage profile. The main amount of the energy is charged at a constant current rate, while the voltage reaches to its upper limit which must be held constant to avoid damaging the battery. At the time of the constant voltage value, the charge current will start decreasing as the battery approaches a full state of charge [54].

Finally, charging will be finished when the current has reached a minimum threshold, for instance 3% of the rated current [54], where a cell should be at 100% state-of-charge (SOC) [56].

The recent battery research efforts worldwide are focused around cell chemistries with improved power density, thermal management, lifespan and stability at a reasonable price. Efforts are directed towards developing customised battery packs for different EVs shown in Table 2.5 [25].

Table 2-5: Comparison of Li-Ion with Ni-MH battery technology

Characteristic	Li-Ion	Ni-MH
Energy Density (Why/Kg)	94	57
Power Density (W/Kg)	540	250
Cycle life (cycles)	>3200	>3000

2.4.6 Charging Limits

Charge depleting (CD) and charge sustaining (CS). The "fully" charged PHEV is driven in CD mode which energy stored in the battery is used to power the vehicle, gradually depleting the battery's state of charge (SOC). Once the battery is depleted to a minimum level, the vehicle switches to CS mode, sustaining the battery SOC by relying primarily on the gasoline engine to drive the vehicle (like a conventional hybrid electric vehicle). CD range is the distance a fully charged PHEV can travel in CD mode before switching to CS mode (without being plugged in). In CD mode, a PHEV can be designed to use grid electricity exclusively (all-electric) or electricity and gasoline (blended). All else equal, a PHEV designed for all-electric operation requires a more powerful battery than a PHEV designed for blended operation. The CD range and operation capabilities of a PHEV will depend on the assumed drive cycle, that is, how aggressively and under what conditions the vehicle is driven.

2.4.7 Charging System

Battery charging requires recharging infrastructure, equipment and protocols which vary in different countries based on their electricity infrastructure. Recharging equipment is considered recharging interface including plug-in or inductive and conductive plate. Recharging protocol enables conversation between the vehicle and charger. Inductive chargers have the advantages of intrinsic safety and pre-existing infrastructure, while conductive ones have higher efficiency Europe prefers conductive chargers compare to US and Japan, which are using inductive connection [45].

EV battery chargers are categorised as on-board and off-board with unidirectional or bidirectional power flow. Unidirectional provide charging from the grid while bidirectional can charge the battery from the grid and battery power injection to the grid [76]. The on-board charger gives flexibility to charge the vehicle anywhere where there is an electric power outlet available. However, this type has the drawback of adding weight, volume, and cost to the vehicle. On-board chargers are divided into two categories, inductive or conductive. In conductive charging system, a direct contact is between inlet and the connector. In inductive charging is a method of transferring power magnetically rather than by direct electrical contact and the technology offers advantages of safety, power compatibility, connector robustness and durability to the users of electric vehicles but on the expense of a lower efficiency and the need of new equipment at charging sites [76] .

To understand the process of charging an EV and to assess the charging strategy of an EV's user, it is essential to have an in-depth knowledge of the safe transfer of energy between the electric utility and an electric vehicle and all components associated with the charging process. Fig. 2.4 shows an energy transfer system used for electric vehicles [68].

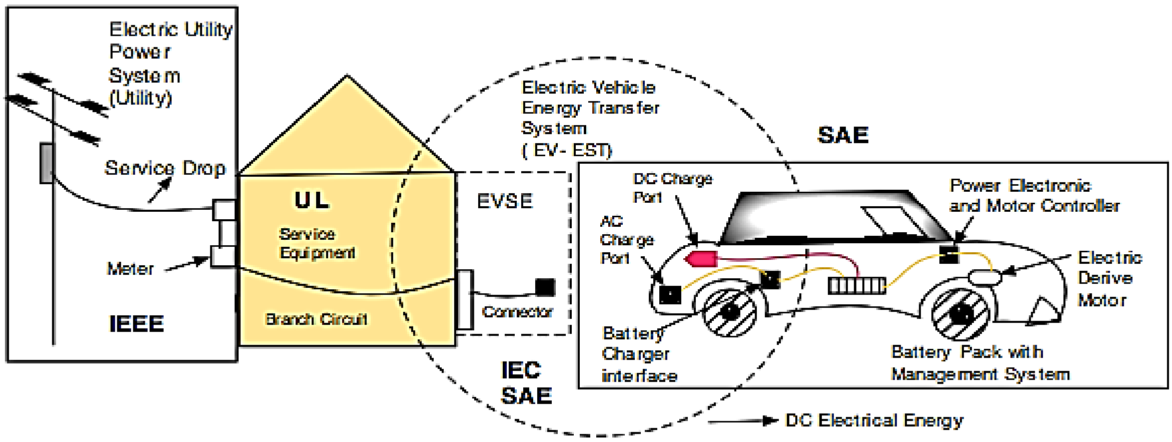

Figure 2-4: EV energy transfer system [43]

Power is delivered to the EV's on-board battery through the EV inlet to the charger. The charger converts AC to the DC that is required to charge the battery. The charger and the EV inlet are considered part of the EV. A connector is a device that, by insertion into an EV inlet, establishes an electrical connection to the electric vehicle for the purpose of charging and information exchange. The EV inlet and connector together are referred to as the coupler. The EVSE consists of the connector, cord, and interface to utility power. The interface between the EVSE and utility power will be directly 'hardwired' to a control device [77].

Energy Transfer System (ETS) refers to the transfer of electrical energy from the electricity supply network to an electric vehicle. It is responsible for three main functions: to determine when the vehicle and EVSE are ready for energy transfer; to switch and convert AC electrical power to DC; and to control the transfer of energy to the vehicle [54].

Battery charger performance depends on the type and the design of the battery as well as on the characteristics of the charger and the charging infrastructure [78]. EV battery chargers are categorised as 'on-board' and 'off-board', and can have either unidirectional or bidirectional power flow. Unidirectional power flow provides charging from the grid, while bidirectional can charge the battery from the grid and also offer battery power injection to the grid. On-board chargers are divided into two categories, inductive or conductive. Conductive charging systems use direct contact between the outlet and the connector. Inductive chargers use a magnetic field to transfer electricity for charging EVs.

Electric Vehicle Supply Equipment (EVSE) is a device or apparatus for transferring energy to the electric vehicle. The design and deployment of EVSE is an important consideration because many issues need to be addressed, such as charging time, distribution of EVs and charging process policies. EVSE is designed in two configurations: a specialised cord set, and a wall or pedestal mounted box [68]. EV charge cords, charge stands (residential or public), attachment plugs, power outlets, vehicle connectors, and protection equipment are major components of EVSE [68]. The configurations vary from location to location and country to country, depending on frequency, voltage, electricity grid connection, and transmission standards. A charging installation for Level 1 and Level 2 is shown in Fig. 2.5.

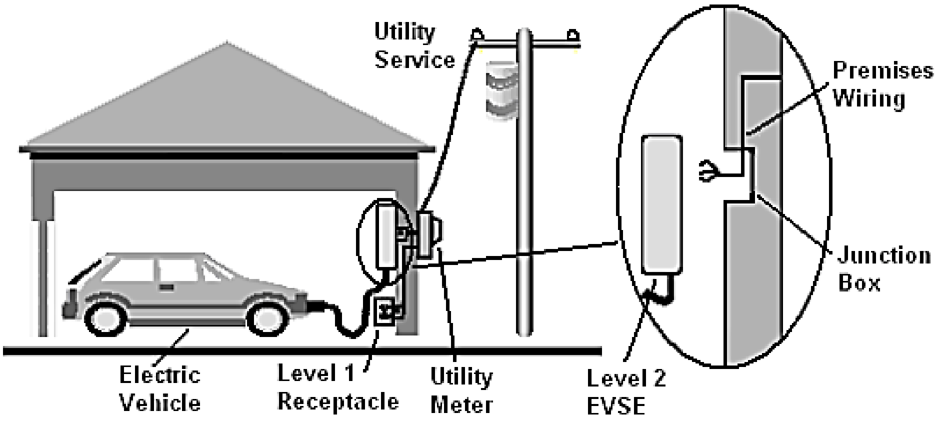

Figure 2-5: Levels 1 and 2 of residential charging installation [43]

SAE International developed the standard requirements for energy transfer systems and off-board EVSE used to transfer electrical energy to an EV from an electric utility power system. The SAE standard includes two parts:

- Part 1 SAE J2293/1 addresses the functional requirements and system architecture;
- Part 2 SAE J2293/2 addresses the communication requirements and network architecture.

There are various standards regarding the energy transfer, connection interface and communication requirements for EV charging. Table 2.6 summarises some of these standards.

Table 2-6: Standards of electric vehicle charging [30]

Standard	Description
National Electric Code Article 625	Electric vehicle charging system.
SAE J2293	Energy transfer system for electric vehicles. Off-board electric vehicle supply equipment (EVSE) used to transfer electrical energy to an EV from a utility in North America.
SAE J1772	Recommended practice for communication between plug-in electric vehicle and power inlet.
SAE J1773	Electric vehicle inductively coupled charging.
IEC 62196	Plugs, socket outlets, vehicle couplers and vehicle inlets—conductive charging of electric vehicles.
IEEE 1547.3	Interconnecting distributed resources with electric power systems.
SAE J2847	Provides requirements and specifications on the necessary communication between PHEV and power grids.
SAE J2894	Provides the charging equipment operational recommendations for power quality.
SAE J2836	Provides the practice for communications between PHEVs and power grids.

2.4.8 Communication

SAE International developed SAE J2293/2 standard for two-way communication between plug-in electric vehicle and the electric power grid for energy transfer. The SAE recommended practice SAE J2993/2 describes the network architecture and data communications requirements and specification for communication of electric vehicle and power grid.

2.5 Power System Domain; Electricity Tariffs

The major concern associated with a large-scale integration of electric vehicles into (centralized and decentralized) power supply systems is the potential impacts on peaks demand that may result from EV recharging. The first step in reducing the impact on peak demand will be to shift the charging process to time periods when there is low demand on the grid. Studies on the economic and environmental aspects of EVs have shown that EV recharging behaviour can be controlled by encouraging EV owners to charge their vehicle during off-peak charging periods by using various incentive programs [79]. This can be achieved by means of price incentives, pricing response and/or by demand-side management [80].

Demand response programs can be categorised into those that are incentive-based and time-of-use (TOU) price-based[81]. Price-based demand response (DR), including real-time pricing (RTP), critical-peak pricing (CPP), and TOU tariffs, give customers time-varying rates that reflect the value and cost of electricity in different time periods [81]. Incentive-based demand response programs such as curtailable, direct load control and emergency programs for reliability pay participants to reduce their electricity consumption (load) at times requested by the program sponsor, triggered by high electricity prices or a peak in demand prices [81], [82]. A report by staff of the Federal Energy Regulatory Commission (FERC) showed that peak demand reduction comes mostly from incentive-based DR programs [73]. Hence, it is critical to improve understanding of consumer preferences and to change consumer behaviour through the use of creative incentives by the utilities and service providers to better manage the potential impacts on the grid.

A number of interventions can be used to alter the behaviour of EV drivers, including information, incentives and institutional support. Information and education involves offering incentives of various kinds [83]. In many countries, energy regulation incentivizes network operators to prevent losses from increasing, but not to reduce them [84]. Besides this, in order to achieve the objectives of controlling the process and charging during off-peak hours, customers' needs and preferences should be taken into account.

2.6 Investigation and Analysis of the Interaction of key Factors

Of importance is how these factors discussed in the preceding sections interact to determine the complex behavioural patterns of EV drivers. A number of EV trial projects have been undertaken in different countries over recent years. The data from some of these trials are summarised in Table 2.7 [85], [41]. A consistent finding from these trials has been that the positive factors that participants focus on are economic (fuel savings), comfort and environmental, while the negative factors that they focus on are range limitations, recharging times and higher purchase costs [85]. Limited range of EVs has been found to be the main concern of the EV users [41]. Two key factors, the charging infrastructure and the battery performance, are discussed in greater detail below to indicate the way in which these interactions significantly influence EV charging patterns and driving behaviours. A more detailed discussion on the influence of these two key factors is given in the following sections.

Table 2-7: Electric vehicle trial projects

Country	Project Name	Year started
USA	The EV project17 electric vehicle (15 Mitsubishi i-MiEVs and 2 Nissan LEAFs)	2009
Australia	REV, (11 Ford)	2010
Germany	Cologn E-Mobile, (25 Ford)	2010
UK	Switch EV (44 EVs)	2010
Ireland	Active E, (20 EVs)	2011
Canada	Hydro- Quebec, (30 I-MiEVs)	2011
France	SAVE, 65 Renault –Nissan	2012

2.6.1 Battery Performance

Number of studies have shown that the energy capacity of EV batteries is sufficient to meet the daily driving needs of most people. The optimal choice of EV battery capacity depends on the distance that the vehicle will be driven between charges. The highest performance of EVs is achieved when the batteries are sized according to the charging patterns of the driver. Three potential complications arise when sizing EVs based on the number of kilometers that drivers travels: if the variance in distance travelled per day is large, then a capacity designed for the average distance may be suboptimal; it is unclear whether it is safe to assume that drivers will consistently charge their vehicles once per day. EVs in the market can finish daily commuting trips without roadside charging [86]. The results show that, for urban driving conditions and frequent charges every 15kmor less, a low-capacity EV sized battery is sufficient for less frequent charging (every 32–160km) [87]. Journey data shows that the battery range of electric vehicles (EVs) more than covers most users' needs, with most drivers finishing their daily journeys still with charge remaining. Typical users only need to recharge every 2-3 days and choose the convenience of a home charge overnight or at their place of work over 85% of the time [28]. The recent development of battery technologies has allowed greater use of the total amount of energy in the batteries. The two dominant battery technologies considered as the most promising candidates for EV applications are nickel-metal hydride (NiMH) and lithium-ion (Li-ion) batteries. NiMH batteries have performed well and have proven reliable in existing hybrids vehicles [86].

Additionally, the majority of PEVs were charged once daily during evening and night hours when the power consumption and the electricity prices are the lowest. Without charging management, EV drivers would charge between 5 pm and 9 pm-placing significant pressure on the power grid at peak hours. By matching real world driving patterns with technical specifications of electric vehicles and charging infrastructure, technical requirements for the batteries' state of charge boundaries have been identified and the actually usable battery capacity is driven. The gap between the minimal and the maximal boundary indicates the range that could be used for load levelling of the power grid or even for vehicle-to-grid applications. It has been shown that due to technical restrictions, the possibilities of utilising electric vehicles for load levelling of the power grid have to be assessed very carefully [88].

2.6.2 Charging Infrastructure

EV trial projects conducted in different countries to date have provided insights into the complex behaviour of EV drivers, and that constrained EV drivers' route choice and charging routine are two critical determinants of EV driving behaviour. Based on the observed project trials data, the analytical results show that the majority of drivers were able to complete their trips without a public charging infrastructure, but that a considerable portion of drivers remain convinced that public charging sites are essential. The potential benefits achievable from selecting optimal charging station locations were quantified and the results indicated that EV users' sense of having to plan their journeys more carefully was reduced with the increase of the experience with the vehicle, especially when the drivers desire to use their EV for longer journeys [89]. Additionally, in relation to charging behaviour, the data of the trail projects has clearly demonstrated that EV users are not motivated to recharge their vehicle's battery at a particular point of depletion; rather they are driven by convenience. It is apparent that there is an opportunity for the users to be plugged-in [88]. According to the leading providers of electric car charging infrastructure, installing charging stations in a network can provide alternative options for EV users, and that EV drivers travel further, charge their vehicles more often at public locations and are more likely to charge at night when electricity tariffs are lower [46].

Furthermore, the most popular time to charge a vehicle has been found to be overnight. But as most vehicle trip journeys are relatively short (with five average journeys per charge and each trip 15 km per day [27]), this allows scope for exactly when the car is charged each night to minimize the cost. Such evidence supports the need for automated intelligent charging technology that would allow EVs to adaptively interact with the distribution grid in an area [28]. If the timing of EV charging can be controlled, e.g. shifting to night-time hours when the demand is low, the effects of charging EVs on the electricity system can actually be beneficial, e.g. charging EVs at night would ensure "fill valleys" in the load curve, more completely using existing generation capacity. Such improvements to the utilisation factor of the generation fleet would reduce the average cost of electricity generation [28].

EV drivers with timed infrastructure can achieve a relatively higher average kilometer between charging compared with those without timed infrastructure. This suggests that timed infrastructure, which also offer slower cost off-peak electricity, is able to decrease not only the opportunistic charging during the day, but also the charging at peak times of the electricity demand [38]. The results also show that irregular charging behaviour could lead to significantly longer distances between charges than the average daily distances would suggest and, conversely, that the extensive installation of charging infrastructure in public parking places would enable charging more than once per day, enabling shorter distances between charges. But daytime across night time charging, geographic location, and effects of marginal changes in electricity demand on the mix of energy sources could all affect implications associated with electrified transportation [89].

Furthermore, the trials data shows that most corporate users had a strong pre-trial desire to have a public charging infrastructure, while private drivers reduced their desire to have a public charging infrastructure [87]. The differences are likely to have been due to the relatively routine nature of the private drivers' journeys where their home charging was sufficient for daily trip as compared to corporate drivers who did not get the opportunity to fully explore the range capabilities of the vehicles they had [46]. In addition, the fact that the distances travelled between two charging events steadily increase across all user groups shows the increasing confidence of the EV users when more journeys are undertaken between charge events. Users' concerns about limited range were reduced with the accumulation of driving experience whereby the range was judged to be sufficient. The data also showed a trend towards the drivers travelling longer journeys over time, which indicates the increased confidence and the reduced range anxiety [90]. The flowchart of proposed system is shown in Fig. 2.6.

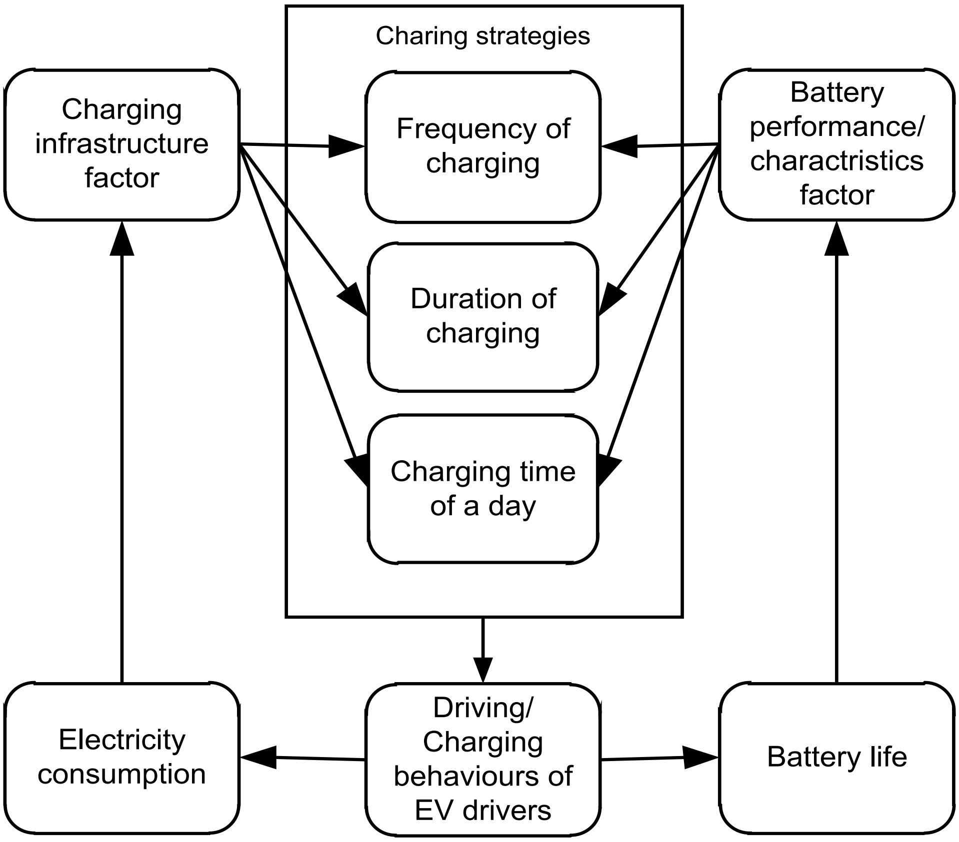

Figure 2-6: The flow chart of the purposed system

Collecting information, such as the state of charge, use of external applications (air conditioning, radio, etc.) and the frequency of use of these applications is also essential to assess the energy consumption of the EVs and their environmental performance [44].

2.7 Impacts on the Power Grid (Electric Vehicle Integration in the Power System

Electric vehicle manufacturers such as Nissan and Ford have started to develop mass-market electric vehicles. On the other hand, utilities have been faced a number of challenges in the grid operation in terms of power stability, power quality and top of that , power reliability.

To understand the impact of EV charging loads on the electricity grid and plan the opportunities of operating distribution system for higher reliability with increasing customer demand and shaving peak-load of electric vehicle, it is necessary to analyse four main aspects of EV penetration rate, EV usage pattern, household energy demand and distribution network capacity [12].

Different aspects of the electricity grid and power generation could be impacted by a large-scale penetration of EVs. Quantifying the potential impacts of EV charging on the electricity distribution networks is identified as a major challenge that needs to be addressed in order to help facilitate widespread EV adoption. Distribution networks are arranged hierarchically, from the supply point on the national grid, fanning out through distribution transformers, to the individual customers. A distribution network contains many components each needs to have a capacity sufficient to meet the expected maximum demand at that point. This information is used to determine the capacity of the lines feeding the load and the rating of system equipment such as distribution transformers. In addition, the loads must be somewhat balanced amongst the phases at a certain voltage level.

Chapter 3

The Power System

This chapter review some of the literature related to the Power system characteristic.

3.1 Conventional Power Systems

Conventional power systems are characterised by a very strict configuration. Based on centralised generation, the electric power produced by central station power plants that provide bulk power. electricity follows a very well defined path, from generation to consumption, going through transmission and distribution grids, until it reaches final consumers [91].

The structure of conventional power system is a network of the generation units' output power at the MV level. Then, the voltage is raised through step up transformers to Very High Voltage (VHV), entering the transmission level, where higher voltages are used to decrease the electrical current and thus decrease cross-sections of the overhead lines. To reach some major industrial, commercial and residential consumers and the attending to the geographical dispersion of electrical loads, the power carried by the VHV network is delivered to VHV consumers and to the distribution grid. Between transmission and distribution levels substations lower the voltage to HV as the cost of electrical insolation wins over even more reduced lines and cables cross-sections. At the HV level loads are more abundant than in VHV, still industry related. From this point onwards, as more geographical dispersion occurs and more final consumer loads are fed voltage can be decreased at intermediary substation going from HV to MV and finally achieving the last distribution level at LV [91], [92], [93].

Within conventional paradigm, the power systems are a top down vertically integrated structure, where, from the very beginning, clear rules regarding the major areas of expertise needed to run such system were created as shown in Fig.3.1. The following topics were studied, put into practice and mastered for conventional power systems: Planning, Operation, Protection and Maintenance [93].

The distribution network feeders can be in the form of overhead lines or underground cables depending on the geographical location, Cables are commonly used in urban areas and overhead lines are adopted for rural areas. Different network configurations are possible in order to meet the required supply reliability. To achieve effective and reliable operation of the distribution network protection, control and monitoring equipment are provided [93].

Planning of the distribution network is essential to enable the required demand can be met based on various forecast loading figures and supply security and reliability.

There are three categories of planning, namely the long-term planning, the network planning and construction planning. Long-term planning is to determine the most optimum network arrangements and the associated investment with consideration on future developments. Stage-by-stage development must be in line with the forecasted load growth so that electricity demands can be timely met. The construction planning or design is the actual design and engineering work when the required circuits and substations have been planned and adopted [94].

The distribution network is the medium and low voltage electricity network used to deliver electricity to houses, offices, shops, and streetlights. The Distribution System Operator (DSO) is responsible for building, maintaining and operating the entire distribution level network infrastructure. Distribution Use of Service (DUOS) is the charge paid for using the distribution system. These charges are ultimately passed onto customers. Commission for energy regulation (CER) directs and carries out annual reviews of these charges.

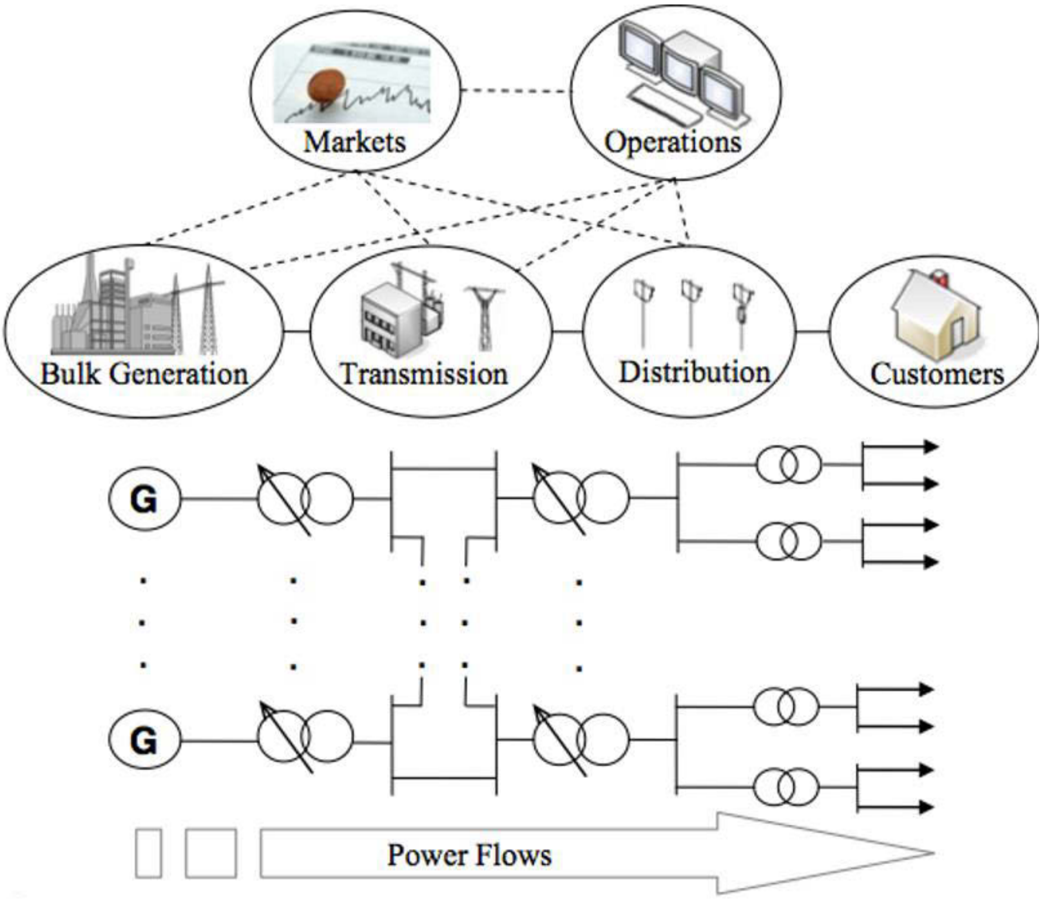

Figure 3-1: Conventional power system

3.2 Types of Distribution System Design

There are three different layout of power distribution system used by utilities including radial, loop and network system configuration [92].

The most frequently used system is the radial distribution system because it is the simplest and least expensive system to build. Operation and expansion are simple. It is not as reliable as most systems unless quality components are used. The fault or loss of a cable, primary supply, or transformer will result in an outage on all loads served by the feeder. Furthermore, electrical service is interrupted when any piece of service equipment must be de-energized to perform routine maintenance and service. Service on this type of feeder can be improved by installing automatic circuit breakers that will reclose the service at predetermined intervals.

If the fault continues after a predetermined number of closures, the breaker will lock out until the fault is cleared and service is restored by hand reset.

The loop system is more expensive to build than the radial type, but it is more reliable. It may be justified in an area where continuity of service is of considerable importance, for example, a medical center. In the loop system, circuit breakers sectionalize the loop on both sides of each distribution transformer connected to the loop. The two primary feeder breakers and the sectionalizing breakers associated with the loop feeder are ordinarily controlled by pilot wire relaying or directional overcurrent relays. Pilot wire relaying is used when there are too many secondary substations to obtain selective timing with directional overcurrent relay [92], [95].

3.2.1 The Radial Distribution System

The radial distribution system has one power source for a group of customers. If there is a power failure, the entire group loses power. In addition, a circuit failure somewhere in the system could mean a power interruption for the entire system [92].

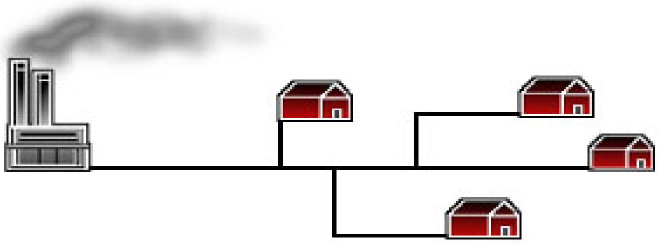

Figure 3-2: Radial configuration of distribution system

3.2.2 The Loop Distribution System

In the loop system the loops go through the service area and returns to the point of origin. The strategic placement of switches permits the electric company to supply power to customers from either direction. If one power source fails, switches are opened or closed to obtain power source.

The loop, or ring, system of distribution starts at the substation and is connected to or encircles an area serving one or more distribution transformers or load centers. The conductor of the system returns to the same substation. The loop system is more expensive to build than the radial type, but it is more reliable.

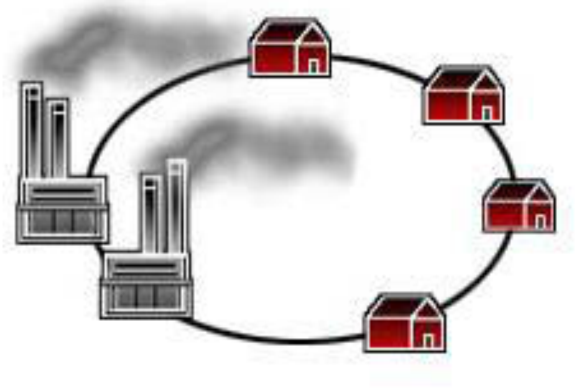

Figure 3-3: Loop configuration of distribution system

3.2.3 The Network Distribution System

The network distribution system is the most expensive, and the most reliable distribution configuration in terms of continuity of service as the customer is connected to two or more power supplies. This system consists of a number of interconnecting circuits operating at the same utilisation voltage.

The network and radial systems differ with respect to the secondary transformer. In a network system secondary transformer are in paralleled whereas in a radial system, they are not. The network is the most flexible type of primary system; it provides the best service reliability to the distribution transformers or load center, particularly when the system is supplied from two or more distribution substations. Power can flow from any substation to any distribution transformer or load center in the network system. The network system is more flexible with regard to load growth than the radial or loop system and is adaptable to any rate of load growth. Service readily can be extended to additional points of usage with relatively small amounts of new construction. The network system, however, requires large quantities of equipment and extensive relaying; therefore, it is more expensive than the radial system. From the standpoint of economy, the network system is suitable only in heavy-load-density areas where the load center units range from 1,000 to 4,000 kilovolt amperes (kVA).

The customer is connected to two or more power supplies. If one power source fails, the customer is supplied power from the other sources, without interruption.

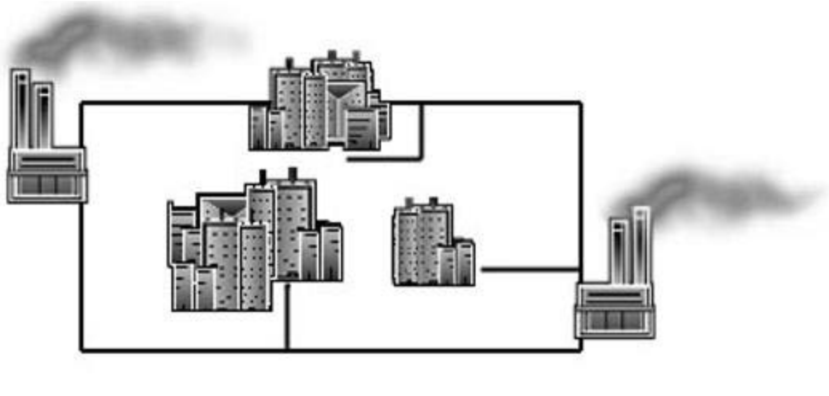

Figure 3-4: Network configuration of distribution system

3.3 The New Electricity Paradigm

In recent years, environmental, economic and social aspects have motivated a growing interest in the development of DG, instead of the traditional large central generation. DG generation plants would supply power only for nearby customers [96]. The networks were designed Direct Current (DC) based and would carry electricity over small distances to feed the demand. Alternate Current (AC) was later adopted to cover larger distances without requiring DC/AC conversion. To balance generation and consumption the system operator would resource to storage devices such as batteries and small-scale generation. Due to the variability associated to DG primary resources, storage is playing important role in energy management and its usage will be further discussed in this thesis [97], [98].

The great challenges of achieving energy sustainability in the 21st century, has been stymied by the identification of many complexities: including matching supply and demand, the scale of current and projected needs, and the difficulty of replacing the present unidirectional system with far more complex hybrid systems utilising disparate sources and supplies of energy. One of the major challenges is designing new systems that leverage existing infrastructure based on centralised generation to take advantage of alternative sources at a local level. The examination of past energy technology practices at historic sites can provide us with some lessons for new system designs that integrate centralised generation with local resources, and match distributed demand with local supply.

The great benefit of rediscovering these local energy resources is the potential to create facilities that meet all or a large part of their own energy needs without requiring long distance energy transmission. Local energy production reduces waste by lessening dependence on the infrastructure of large power plants and distribution systems which are notoriously inefficient. Pollution related to current energy production and usage can be reduced as well.

Understanding what types of energy are important and how those energy resources were used during the last 150 years can help us developing a truly sustainable approach to modern living that is far less dependent on foreign. The past approaches to solving energy challenges were limited by time and distance. In addition, this new approach represents the birth of energy industry that will provide thousands of opportunities, because the systems that will be designed, installed and maintained will be generating power from local sources. Local power supplies also mean an improved manufacturing and industrial business environment [99].

3.4 Main Distributed Energy Resources Technologies

There are various technologies that can be used for DG. These technologies are sorted into different categories including renewable based and non-renewable based [100] while others make a distinction between traditional generators (combustion engines) and non-traditional generators (all other technologies) [101].

Regardless of these classifications, the most important specifications of DG tend to be related with their controllability degree: controllable, partially controllable and non-controllable [98]. In fact, besides breaking with the conventional paradigm in terms of grid architecture centralised generation, transmission network, distribution network and final consumers the greatest difference between conventional technologies and DG lies on the capacity of the system operator to know the availability of the generation beforehand and being able to control it. This is of course valid for normal operation conditions as faulty situations or emergency operation are unexpected events that may occur in any of the cases. Table 3.1 presents a list of common DG technologies, showing the typical range of capacities and degree of controllability [98].

The following section provides overview of DG technologies and more details on the most relevant technologies for this thesis, solar PV generation, as well as energy storage solutions. These elements are particularly important in this context as the thesis aims at dealing with variability issues related with Renewable Energy Storage (RES), using storage devices to enable safe and resilient grid operation.

Table 3-1: Distribution generation technologies characteristic comparison

Technology	Typical capacity	Controllability	Status
Solar PV	A few W to a few MW	Non-controllable	Mature
Wind turbine	A few hundred to a few MW	Non-controllable/ partially controllable	Mature New designs are under development
Hydro	A few kW to hundreds MW	Non-controllable/ partially controllable	The most mature renewable power generation technology
Geothermal			Commercial exploration and drilling improvement underway
Biofuels and Waste-to-energy Production	A few tens of kW to a few tens of MW	Controllable	Mature

3.4.1 Solar Power

The core element of a solar PV system is the solar cell that is charged by sunlight, generates an open circuit terminal voltage in the range of 0.5 – 1 V and a short-circuit current of a few tens of milliamps per cm^2 [102]. These cells are connected in series and parallel and gathered in a module in order to obtain usable voltage and current levels. The modules can be further combined in series and parallel in order to obtain larger voltages and current levels that match each specific application requirements [103]. This arrangement of solar modules is usually denominated as a PV array, generator or panel. Finally, the DC electric energy produced in the photovoltaic systems is converted into AC power by means of a power electronic interface module. PV panels are usually equipped with a Maximum Power Point Tracker (MPPT) in order to operate at the maximum power point, i.e. the operating condition where the most energy is captured [104].

Typical applications for PV panels consist of:

- **Grid-connected systems** – with an inverter to serve AC loads and connect to the main electricity grid

- **Stand-alone systems** – designed to operate independently from the electric utility grid, and sized to supply certain DC and/or AC electrical loads (not in the scope of this thesis)

3.4.2 Wind Turbine

Wind energy conversion into electric energy is a mature technology used for a few decades already and thus has more cumulative experience than most other alternative energy sources. The basic operation principle is very simple to understand, the wind rotates the blades of the wind generator, which in turn rotates a shaft. This shaft provides mechanical torque to a generator that produces electricity.

There are different types of available wind generators technologies, constant-speed or variable-speed wind turbines, with induction, synchronous, DC and variable-speed AC generators, among other technologies [105].

3.4.3 Hydro

Hydro power is created by harnessing the energy of running water. The water is stored in a dam until it is needed. When the dam gates are opened the water is channelled through pipes to a turbine which cranks the metal shaft of an electric generator thereby turning mechanical energy into electricity. The generator is connected to power lines which distribute the electricity throughout the system.

The large scale hydro power which generally defined as more than 10 (MW) is receiving less attention as a means towards ultimate sustainability. Although the concept of large scale hydropower can vary depending on country, generation greater than 10 (MW) requiring a large reservoir affecting natural river flow [104]. Accounting for about 20 percent of the world's electricity generation (WCD 2000) and being traditionally viewed as a clean and renewable electricity generation source, large scale hydro projects have come under intense scrutiny due to their negative environmental and social impacts. This has led to increasing doubts regarding their overall sustainability and viability as a development model.

3.4.4 Geothermal

Geothermal energy is sourced directly from heat inside the Earth. It can be used in three different ways: 1) hot water can be piped from underground to heat buildings; 2) water can be circulated through an underground pipe system to heat or cool buildings; and 3) hot water and steam from deep beneath the Earth's surface can be piped through underground wells and used to make electricity in power plants (ground source heat pump geothermal).

The use of geothermal energy is often overlooked, but is an important part of a comprehensive distributed energy strategy. Every energy conversion results in energy losses, so matching energy types to needs is sound energy strategy. There are two types of geothermal energy, active (volcanic) and ground source. The more limited type is the volcanic type that has been utilised extensively in places like USA, Indonesia, Italy, Reykjavik, Iceland, for heating and electricity generation (shallow high temperature geothermal). The other type is ground source geothermal, which simply takes advantage of the constant temperature of around 55°F that exists underground from a depth of 0.9-1.5 meter (ground source heat pump geothermal). Ground source geothermal energy is ideal for heating and cooling applications. The geothermal constant is available virtually everywhere in the USA and offers energy savings by providing a baseline temperature that can be supplemented with a heat pump to regulate indoor temperatures with minimal cooling or heating energy.

Exploiting this temperature base for buildings to minimize heating and cooling costs is simple, cost effective and basic good facility management. Minimizing building heating and cooling costs represents a significant opportunity for energy conservation [99].

3.4.5 Biofuel and Waste- to- Energy Production

Fuel cells are built to convert chemical energy of a fuel into electricity. The fuel used is generally natural gas or hydrogen. Fuel cells are a major field of research and significant effort is put in reducing capital costs and increasing efficiency which are the two main drawback of this technology.

The US Department of Energy (US DoE) research indicates that various biological wastes such as crop residues are valuable as inputs to biofuel production. Although biofuel production from agricultural crop residues, meat and dairy processing wastes and other waste products have not been widely exploited in the US, other countries have developed significant energy generation infrastructure based on waste-to-energy technologies. For example, Brazil has become largely energy self-sufficient through the development of ethanol production from sugar cane processing waste. Japan has developed extensive recycling systems that include energy production through urban and agricultural waste incineration. In the US, the transition from landfilling waste, to energy production, is a logical and important step in developing distributed generation, preserving valuable agricultural land, and minimizing pollution.

3.5 Integrating Distributed Generation and Transportation

As the transportation industry begins to produce all-electric vehicles, there are two implications of this automotive technology that are relevant to how we should think about the design of electricity generation. The first is next generation battery technology, and the second is how the design of electric vehicles should inform our design of electrical generation systems for buildings [97], [104].

Capacity for charging electric vehicles will be integrated into residential electricity generation for overnight plugin refuelling. Parking garages can be equipped with plugin charging powered by solar arrays, and easy refuelling via battery swapping will be available for roadside assistance. Eventually, PV coatings on vehicles may allow for recharging even while underway during daylight hours. Houses and building will be operating dependently from the pipes and wires of the traditional energy delivery systems, as zero energy facilities with integrated smart building systems, to manage energy production and consumption at the site [106].

For the automotive industry, the essential challenge to building electric automobiles is the problem of battery technology. New advances in battery technology have made it possible to power automobiles using batteries that can be recharged daily for several years and will power an automobile for highway speeds. The electricity demand of a household, where there is no mobility demand, and large amounts of time in any 24 hour period during which the electrical demand is very low like when the residents are at school and work, or are asleep. By including battery-charging capacity in the building system design; backup electricity can be supplied, auto batteries can be charged. By simply regarding a car or building as an envelope with particular energy demands, the automotive technology can be implemented, including the microprocessor-driven sensor networks that manage the performance of modern cars, to a building's energy systems' design. By reframing the problem in this way, that buildings have much less complex energy and information needs than automobiles [99].

3.6 PV Grid Connected with Storage

In this configuration, a separate battery charge control device controls power collected from the PV array. This arrangement leaves the inverter to provide backup battery charge control from the utility power grid when insufficient PV power is available, but does not allow efficient extraction of excess PV power for supply to the grid when the batteries are fully charged. Figure 3.5 shows an architecture that is more common in modern grid-connected

PV power systems that allows the PV array power to be directed optimally by the inverter to batteries or the utility power grid as appropriate.

In both cases, storage provides the opportunity to supply power to critical loads during a utility outage. This feature is not available without storage.

As with the grid-connected only configuration described previously, PV generation reduces the power taken from the utility power grid, and may in fact provide a net flow of power into the utility power grid if the interconnection rules permit. Storage has been traditionally deployed for the critical load benefit also local storage can be considered as an alternate destination for energy collected during low load periods to prevent voltage rise from reverse power flow in the distribution system.

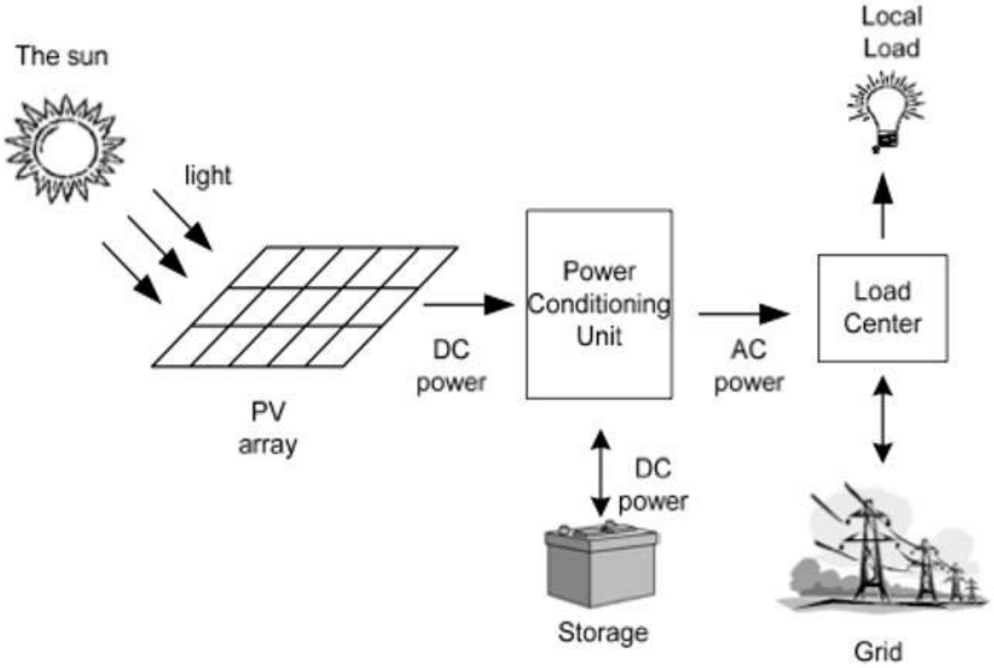

Figure 3-5: Main component of grid- connected photovoltaic system

3.7 PV Off-grid with Storage

3.7.1 Energy Storage Devices

The usage of energy storage devices is of increasing importance due to DG expansion. Using energy storage devices with DG units compensates the inability of many DG sources to perform load following and keep grid operation in compliance with network requirements [107].

There are several energy storage technologies utilised for different applications, such as: batteries, super-capacitors, flywheels, compressed-air systems, flow batteries, hydraulic and reservoirs.

The type of energy storage application is divided into two main categories [31]:

3.7.2 Small-scale Applications

The energy can be stored as kinetic energy (flywheel), chemical energy, and compressed-air or in super-capacitors for low/medium power applications in isolated areas.

3.7.3 Large-scale Applications

The energy can be stored as gravitational energy (hydraulic systems), chemical energy (accumulators, flow batteries) or compressed air (or coupled with liquid or natural gas storage) for network connection and power quality control applications.

The use of energy storage devices with PV systems is currently receiving a lot of attention, especially due to the fact that the power generated from these systems is intermittent. The installation of storage devices can enhance the performance of PV systems by bridging their power fluctuations, shifting the time of their peak generation, supplying critical loads during power outages, and providing reactive power support [108]. There are a variety of storage devices such as batteries, super-capacitors, super-inductors, flywheels, and water pumping.

These devices also vary in term of characteristics, method of operation. Therefore choosing a storage device that can perform the required function efficiently is a preliminary step. Moreover, due to the fact that the majority of storage devices are expensive, it is essential to study the economic value of using these devices.

Energy storage is a crucial element for balancing the variability of RES, being table to allow DG to operate at an approximately stable output power, to provide energy during periods when DG primary resource is not available and to enable dispatching non-dispatch able DG units due to the compensation of the primary resource intermittency. Also, storage supports the stability and reliability of the power grid and for efficiently using the energy generated by unpredictable and intermittent sources, such as solar panels and wind turbines. Electric vehicles in particular have received a lot of attention as possible power storage and power sources as they have a higher economic potential than dedicated storage systems [109], [107].

There are great benefits envisaged for both system operators and consumers to adopt DSM strategies. Due to the large deployment of RES, DSM can help shifting load to the periods when RES are available or from peak hours to valley hours, granting better prices for consumers and facilitating the grid operation for the system operator.

3.8 Challenges of the New Electricity Paradigm

These challenges are divided in three major categories [98], [110]:

3.8.1 Technical

Voltage profile, steady state and short-circuit currents, distribution network protection schemes, power quality and stability are the major challenges within the technical aspects and the key to solve them depends largely on new network operation strategies, including DSM, and planning methods for both grid expansion and retrofitting the existing infrastructure.

3.8.2 Commercial

The integrated control of generation and load requires a thorough assessment of benefits and costs that result from the implementation of such system, which afterwards need to be transposed to all the involved players following one of the three approaches: recover the cost of implementing active management directly through the price control mechanism resulting in increased charges for network use for either DG, EV owners or demand customers, establish incentives to reward companies for installing DG and for EV owners to participate in control and management schemes or establish a market mechanism that would create a commercial environment for the development of active networks.

3.8.3 Regulatory

Some regulatory barriers may slow down the large-scale deployment of DG and DSM mechanisms since there is the need for articulating appropriate policies to support them.

According to the US DoE, electric power generation plants are highly inefficient, with more than half of the energy consumed to produce electricity being lost due to energy conversions. In addition, transmission and distribution losses associated with the delivery of electricity for residential, commercial, and industrial consumption accounts for 7% of gross generation, or 246 kWh in 2011 [10]. This finding shows quantities of energy losses across energy sectors, and these numbers make a strong case for finding better efficiencies. The biggest source of energy losses, termed rejected energy, usually refers to heat produced in the generation of electricity at the plant, but not used. Many generation plants discharge excess heat from the plant as waste heat. The next largest losses are caused by transmission and distribution conversions, which is the process of moving the electricity from the generation plant to the point of consumption.

The global trend at the moment is towards the energy strategies built around the following hierarchy in energy options from the most sustainable to the least sustainable [98].

- Energy conservation: improved energy efficiency and rational use of energy
- Increasing use of renewable sources
- Exploitation of un-sustainable resources using low-carbon technologies

The shift to renewable, energy-efficient and low-carbon technologies driven by energy security and climate change concerns is making progress although at a slower pace than desired. A transition from fossil fuels to a non-carbon-based economy will more likely occur, over the longer-term.

Among new renewables, wind power was the largest addition to renewable energy capacity. Since 2000, wind power has the highest capacity of all renewables. Renewables can introduce variability, intermittency and fluctuations in the utility's distribution system. Large installations such as wind or solar farms can have these negative effects when they constitute a sizable percentage of total power produced. But even when some of the penetration levels are around 10%, some concerns have been reported. Typically, solar or photovoltaic generation is the most problematic.

The most commonly reported problem associated with high PV penetration on distribution feeders is high steady-state voltage. Severity depends on the feeder characteristics and location of the PV generation along the feeder. The impact is typically reduced as the distance of the renewable power source to the substation decreases. Several solutions are available, including more accurate and timely forecasting, which can make hardware-based systems more effective. A number of hardware solutions are available. They can broadly be divided into two groups: reactive power control and energy storage.

Utilities use reactive power control primarily for power factor correction. But this technology can also play an important role in controlling voltage levels. VAR (Volt Ampere Reactive) devices inject energy to smooth the swings in supply and keep the voltage at acceptable levels. The DC/AC inverters that connect PV to the grid, on the other hand, can serve as controllers because they can technically consume or provide reactive power quickly. Utilities need to deal with the fact, however, that regulations presently do not permit the inverters to inject reactive power into the grid when equipped with the right controls, battery energy storage systems (BESS) can be used to provide voltage smoothing. Battery charging is not sensitive to voltage intermittency and, once the batteries are charged, they provide a good source of conditioned power. BESS can be located at the substation or distributed along a feeder. An additional benefit is that they can instantaneously provide power to minimize service interruptions. Batteries can provide a firm, dispatch able and renewable resource through smart grid technology.

Another set of problems is created when a large number of small-scale PV generation sites contribute a significant portion of the power on a distribution feeder. Although some utilities can track the existence of small-scale power producers within their service area, they still do not know how much customer-side resources/storage is available at any given time. This can dramatically influence power quality characteristics on the system by introducing flicker and voltage sags.

Closely monitoring power quality in the distribution system is the first step to solving the above mentioned problems. Synchro phasor technology that monitors the distribution system by making Phasor Measurement Unit (PMU) readings at high sampling rates 30 to 120 samples per second is available today. It is also expensive. One can reasonably expect, however, that cost will decrease over time as synchro phasor technology is incorporated into other devices deployed on the grid. In a smart grid context, the ability to detect perturbations almost as quickly as they occur will allow grid operations to take immediate, and sometimes automated, corrective action using either reactive power control or storage.

3.9 Transmission System Challenges

For transmission systems, the challenges are roughly the same as the ones just discussed for distribution feeders but in larger scale, yet they are more observable due to the monitoring requirements of the grid in general and at these renewable generation sites in specific. Voltage variability, intermittency and fluctuations are all symptoms of large blocks of renewable energy impacting the system. They can be addressed by correlating renewable energy with the rest of the system load and adding flexibility to the system to correct the problems. System flexibility is the ability of a system to deploy its resources to respond to changes in net load, where net load is defined as the remaining system load not served by the renewable generation.

At the transmission level, a comprehensive approach that includes more than technology deployment is necessary for creating a truly flexible system. An emerging challenge in power system planning is to evaluate the ability of an existing system to successfully the targeted penetration levels of variable generation.

Achieving system flexibility can be accomplished through actions that can include:

- **Modifications to conventional power generation resources:** These include modifications to ramp rates, minimum up and down time and operating range, including minimum generating level and faster start-up/shut-down times.
- **Demand response:** Effective demand response programs can provide flexibility over relatively short timeframes when an unpredictable change in variable generation output occurs.

- **Variable generation power management (curtailment):** Curtailment of variable generation output may be necessary if the amount available at a specific time is more than what the grid can reliably deliver while maintaining reliability.

Other solutions to enable integration of renewable generation include:

- Seeking or demanding greater regional cooperation between balancing authorities.
- Improving compensation and allocation for ancillary services.
- Revising interconnection standards to assign renewables with costs for incremental system security and for ancillary services required to accommodate the operating profiles of their renewables.
- Building a new layer of bulk and distributed storage options, which offer greater flexibility than alternatives for meeting sub-hourly dispatch requirements.

3.10 Distribution System Challenges

The integration of DG presents new challenges for distribution system planning and operations, principally because the configuration of power lines and protective relaying in most existing distribution systems assume a unidirectional power flow and are designed and operated on that assumption. Historically, the penetration of DG was sufficiently small to be regarded as simply a reduction in load, but this will change if DG penetrations grow. While the physical wires and transformers can carry power flow in the reverse direction, DG nonetheless can have adverse impacts on system reliability, power quality, and safety.

Distributed generation imposes new challenges on distribution systems that cannot be mitigated by modifying interconnection standards. The most prominent of these impacts is the ability of DG to disrupt the operation of system protection schemes. Modern system protection schemes typically use multiple layers of coordinated protection devices, including circuit breakers and fuses, to interrupt current and short-circuit faults while affecting service to the smallest possible number of customers. These devices are set based on fault current levels and other characteristics of the local distribution network. Distributed generation units can increase current at a fault and reduce it at the protection device for the period before the DG senses the fault and disconnects, making it harder to detect a fault and complicating the coordination among protection devices [111]. In addition, fault currents at points of system protection will depend on which DG units are connected and operating at any given time. Changing fault currents with the introduction of DG could lead to unreliable operation of protective equipment and result in faults propagating beyond the first level of protection. The propagation of faults through system protection layers can reduce system reliability and safety [111].

In contrast to the passive operation approaches described here, new technologies promise to allow active management of distribution systems. For example, it has been envisioned that utilities could use real-time information about the operation of the network and the nature of connected resources to dynamically change protective relay settings. Active management distribution system operation techniques, such as actively using DG and loads for voltage control and fault current level control, can also be used to reduce the costs of mitigating [112].

3.11 Demand Side Management

The concept of Demand-Side Management (DSM) initiated by the utility industry primarily for changing the timing and level of electricity demand, i.e., the shape of electricity loads, among their customers. A widely accepted definition of electricity demand side management as the concept was first introduced in the early '70s [113].

DSM activities are those which involve actions on the demand side of the electric meter, either directly caused or indirectly, stimulated by the utility.

Demand-Side Management is the planning and implementation of those utility activities designed to influence customer use of electricity in ways that will produce desired changes in the utility's load shape such as in the time pattern and the magnitude of a utility's load [114].

The traditional DSM activities taken by the utility company to alter the load shape can be characterized into six categories based on the state of the existing utility system as shown in Fig. 3.6. These forms of load management are not mutually exclusive and often are employed as combinations [113].

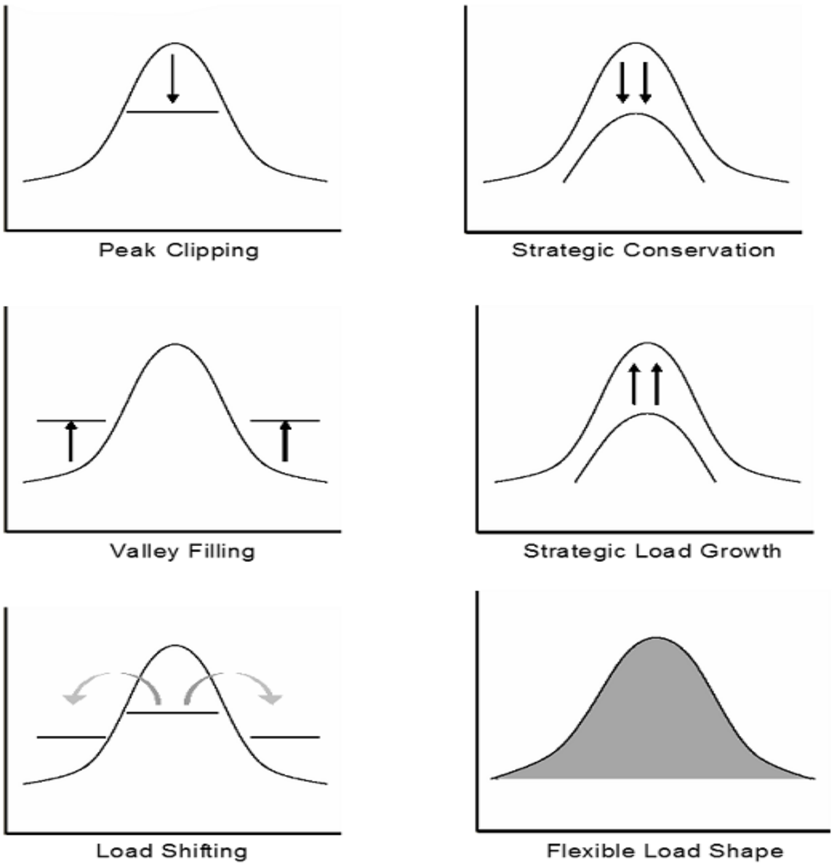
Peak Clipping
Strategic Conservation
Valley Filling
Strategic Load Growth
Load Shifting
Flexible Load Shape

Figure 3-6: Demand side management load shape change objective [113]

DSM programs consist of the planning, implementing, and monitoring activities of electric utilities which are designed to encourage consumers to modify their level and pattern of electricity usage.

In the past, the primary objective of most DSM programs was to provide cost-effective energy and capacity resources to help defer the need for new sources of power, including generating facilities, power purchases, and transmission and distribution capacity additions. However, due to changes that are occurring within the industry, electric utilities are also using DSM as a way to enhance customer service. DSM refers to only energy and load-shape modifying activities that are undertaken in response to utility-administered programs. It does not refer to energy and load-shape changes arising from the normal operation of the marketplace or from government-mandated energy-efficiency standards.

3.11.1 Peak Clipping

Peak clipping is one of the classic forms of load management, which aims at reduction of system peak generally by means of direct load control. Peak clipping reduces the need to operate peaking units, and typically are used on days when maximum system peaks are likely to occur and generation might not be sufficient to meet the demand.

Tariffs use demand charges to discourage peak loads. Under this scenario, no communications would be required from the utility.

Future systems are likely to use real-time pricing schemes in which the price paid by the customer for electricity is not constant, but is determined by the market in real time. During generation shortage, supply and demand would dictate that the electricity price would increase. In a real-time pricing system, the communications system would be used to send a price signal to the customer indicating that electricity rates were rising. An EMS might then operate to shut down certain noncritical loads, especially those with built-in storage such as tank water heaters, to minimize utility bills. Systems with local energy storage might switch to these local stores, depending on the relative price of energy from storage versus energy from the utility. Either scenario would reduce the peak load for the utility.

The real-time pricing signal may be generated on time scales ranging from 1 to 60 minutes, depending on utility. Communications bandwidth requirements would depend on what level of device participates in the market. In an ideal case, every electricity load and source might participate in the real-time pricing market. However, that would require communications and intelligence capabilities in every device plugged into the wall. BPL probably could not provide enough bandwidth to realize such a system. Thus, it is more likely that EMS will integrate these functions at the facility level. The EMS would then communicate with loads, sources, and storage under its control.

3.11.2 Valley Filling

Valley filling is a form of load management that increases or builds the off-peak loads, for instance, uses of thermal storage units. This strategy may be desirable when the long-term average price is lower than the cost of load building in the off-peak hours.

3.11.3 Load Shifting

Load shifting is also one of the classic forms of load management taken by the utilities which involves shifting loads from peak to off-peak periods. Conventional devices for load shifting include space heating storage, cooling storage, domestic hot water storage, and customer load shifting.

3.11.4 Strategic Conservation

Strategic conservation is the load shape change that occurs from targeted conservation activities. This strategy is not traditionally considered by the utilities as a load management option since it involves a reduction in sales not necessarily accompanied with peak reduction. Examples of strategic conservation efforts are appliances efficiency improvement and building energy conservation. Since the energy conservation actions could result in sales reduction, evaluation of the cost effectiveness of the program is important to the utilities in stimulating those actions [40]. However, in a growing economy where electricity total consumption and peak loads continue to rise at rapid speed and the capacity installation may not be able to keep up with the demand, some forms of strategic conservation become particularly desirable to the utilities.

3.11.5 Strategic Load Growth

Strategic load growth refers to a general increase in electricity sales beyond valley filling and the spontaneous effects of economic growth. Examples of strategic load growth include electrification, substitution for primary fuels, commercial and industrial process heating and automation and other means for increase in energy intensity in industrial and commercial sectors.

3.11.6 Flexible Load Shape

Change of reliability in electricity services could be used as a demand-side option to change load shapes. Flexible reliability offers consumers with options to variations in quality of services in exchange for other benefits for lower rates. Such programs could contain interruptible loads, pooled customer energy management programs, and individual consumer load control devices with service constraints.

The first three strategies are traditional load management approaches spurred by the utilities to alter the load shapes. The utilities provide incentives to target customers for more specific load-shape changes to avoid construction of new generation units of relatively low usage at the time of high system loads. The last three strategies offer more systematic and larger-scale changes than the first three and the goal is not only to alter the peak-valley structure, but also to change the ways that electricity is used. This second type of systematic and fundamental shift in the manner that electricity is consumed is the primary focus of this study. In broader terms, this research adopts the definition of DSM described above, however, with less emphasis on traditional load management options but on the strategies that could promote efficient use of energy, stimulate energy conservation actions, increase energy intensity, sustain effective operation, and ensure quality electricity provision in a market with rapidly growing demand and potential new uses of electricity.

3.12 Coordinated Control Concepts

The generic coordination strategies for distributed energy resources (DERs), including EVs, can be divided into the following two categories:

3.12.1 Centralised Control

Where a centralised coordinator dictates when EV charging or discharging should take place and what power level to aggregate. Decisions could be made in relation to power system needs, such as ancillary services, or they could target EV user preferences, e.g. a desired time window for charging, a desired final state of charge, or a minimum charging cost [115].

3.12.2 Distributed Control

Where the individual EV owners determine their own charging or discharging patterns. Decisions on charging can be made on the basis of time of the day or electricity price. A critical aspect is that the synchronized charging activation of a large fleet of EVs, due to a common control signal, e.g. the electricity price, might lead to grid congestion issues [115].

The two coordination concepts have been described with respect to EV coordination, though the same concepts are applicable to any type of DERs [6]. The coordination of EVs can be realised with a Virtual Power Plant technology, whose possible architecture derives from the generic coordination concepts described.

Chapter 4

System Design

To determine the impact of plug-in hybrid electric vehicle charging demand on the electricity network the behaviour of several levels of the power system need to be considered along with the addition of distributed controllers. Each level of a power system has physical components along with the monitoring and controls necessary to meet the operating needs in that part of the system. Table 4.1 compares the different levels of a power system in terms of equipment, stakeholders, and monitoring and control systems that are currently used.

Table 4-1: Comparison of equipment, control system and stakeholders at different levels of the power grid

Level	Physical system	Monitoring and control	Stakeholders
Bulk transmission system	High voltage lines, central generation, transformers, protection elements	SCAD/EMS, switching, protection and compensation equipment, load shedding	Transmission owner, operators, and maintainer, generation owners, market participant, regulators
Distribution system	Primary and secondary feeders, protection elements, distributed resources	SCADA, DMS, switching, protection and compensation equipment, load shedding	Distribution system owners, operators and maintainers, end use customers, regulators
Home or business	Main , breakers, and fuses, appliances, all other end uses	Utility revenue meter, overcurrent protection switching	Building owner and /or maintainer, occupants, utility, regulators

PEV will be tied in to the power grid at the point of customer service therefore distribution system behaviour must be considered in order to study the effects of vehicle- to-grid (V2G) on traditional distribution system design and operation.

Traditionally power system modelling considers either.

1. Transmission level modelling with distribution level loading aggregated at the bus level and assuming balanced loading across phases, or

2. Distribution level modelling with the bulk system represented by an equivalent voltage source at the head of the feeder using a three phase power flow.

For a more comprehensive model it would be desirable to model the behaviour of the transmission level down to the feeder level or the point of customer service. However this involves using a full three phase power flow for the entire system. Therefore a more simplified approach will be used for the purposes of this study.

Although the vehicles are tied in at the distribution level, their behaviour as an aggregate load is better viewed from the bulk system level.

The power system model will be based on the Western Australian suburb distribution network. The developed detailed description of the power system simulator along with the implementation of the vehicle-to-grid components follows in Chapter 5.

Determining the power demand on a distribution network is a difficult task due to the stochastic behaviour of the customers connected to it and seasonal changes in both climate and light. An efficient method to predict the 24-hour total load curve at a distribution substation is to sum the load curves corresponding to the various types of customers supplied by the substation. These customer 24-hour load curves for each specific season or day show a small variation around a mean value. Thus, it is common when performing probabilistic load flow studies to assume a normal distribution of load within a time interval for each load bus and customer class on the network. The normally distributed load values are assumed to be independent of time, meaning that load values do not depend on the previous or subsequent load value.

The coincidence between peak electricity demand and vehicles returning home from daily commutes is one of the main near-term concerns for utilities when considering electric vehicles.

As PEVs numbers grow, the peak demand may increase at a higher rate than the increase in energy supplied to the network due to PEV charging. The peak demand increases more than energy growth because of a wider assumed availability of 240V chargers at residences. A further result of a higher peak demand is that the energy loss in the networks increases more than the energy growth because of the losses being a function of the square of the current. Economically this is undesirable because more energy needs to be generated to meet the incremental demand. This result is a further example of the need for vehicle charging control.

PEV demand at retail and office locations differs significantly from residential PEV demands. The urban network exhibits an increase in the demand during the daytime hours creating a morning peak on this network. Areas with high office loads, such as the urban network, may exhibit similar morning peak demands if workplaces are willing to install charging locations for their employees. A network with a high level of retail demand was not considered. It is uncertain whether the charging demand at retail locations will be significant, as vehicles will connect for only short periods of time and the demand might be spread more evenly throughout the day. Charging stations installed on streets, retail location and workplaces will mean less aggregate gasoline usage and lower vehicle emissions for PEV operators who can take advantage of these stations.

In terms of total network demand, the possible implications of large penetrations of PEVs charging in an uncontrolled fashion are higher voltage drops, lines current overloading and the possible exceedance of the network capacity. These impacts are all difficult and costly to remedy and can reduce the reliability of power supply. In any jurisdiction, networks that exhibit total demands near their capacity are at higher risk for some of these possible detrimental impacts.

Control over vehicle charging will be important in the future for shifting the vehicle charging demand into the off-peak hours. Even with charging control, it is likely that some owners will still want to charge during the peak period in order to make trips during the evening.

This control can be a program be started to keep track of the location and type of electric vehicles sold throughout a jurisdiction. This type of program will help to determine the networks that are at highest risk for some of the adverse impacts considered in this study and could help with a transition to control of vehicle charging or integration of vehicles into a smart metering infrastructure. Identifying the possible networks or areas where high penetrations of PEVs could occur will be important for predicting impacts on these areas.

4.1 PEV Energy Requirements

At 240 volts AC and connected with a 16 amp single-phase circuit in the regular Australia outlet low voltage distribution grid, the EV can be charged with 3.7 kW. If the customer uses a 400 volts AC and 32 amp three-phase circuit instead, the maximum load is 22 kW. Since most charging infrastructures on-board have a sufficient rating for 3.7 kW charging, this rate is particularly applicable in households without additional expenditures for the charging infrastructure. Long charging durations with the given rating can be compensated by a long parking duration in the household during the night.

If EV is used by commuters, charging only at home may not fulfil the energy demand of a daily trip. Additional charging infrastructures are necessary to be established at the workplace or shopping mall. Due to relatively long working time during the day, 3.7 kW may be sufficient to refill the battery. However, it is also considerable utilising 22 kW rating to extend the cruising range of commuters. For the shopping mall, the 22 kW is preferred by the customers in order to charge as much energy as possible during short shopping times. All EVs have characteristic of Ford Focus electric car with total capacity of 23 kWh consuming 242 Why/Km including charging losses. It take approximately 10 hours to charge the car from empty to full.

The charging concept is shown in Table 4.2 with charging rating and corresponding parking place, which are investigated in this work. The same recharging rating is assumed with the charging rating of corresponding standing place. Table 4.3 shows type, energy requirement and penetration level.

Table 4-2: PEV charging concept and requirements

Charging place	Voltage	Current
Home	240 V AC	16 Amp single phase

Table 4-3: EV type and level of penetration

Type of EV	Penetration percentage	PEV (kWh)	PEV (kW)
Ford Focus	25%, 50%, 75%, 100%	23 kW-hrs./100 mi	3.7

4.2 Grid Topology

The radial Western Australian network used in this analysis shown in Fig. 4.1. It includes a 66kV/6.6kV substation that supplies 15 feeders. Each feeder serves approximately 300-500 customers, not evenly distributed among three transformers. One feeder is modelled in detail and the rest as lumped loads.

The line impedances are adapted to achieve tolerable voltage deviations and power losses. Each node is a connection with a residential load and some, randomly chosen, nodes will have PEVs charging.

The Fig.4.1 shows the load area of the Networks substation bounded in blue. The orange lines represent HV distribution lines (6.6kV nominal). The orange lines with dashes are underground whilst the solid orange lines are overhead. Nedlands substation is shown in the centre marked as a red square. Nedlands geographical substation feeders are shown in Fig.4.2 and Nedlands substation single line diagram in Fig.4.3.

Other equipment in the substation has been excluded, such as surge arrestors, capacitor banks and Neutral-Earthing Compensators (NECs). Surge arrestors don't have any effect in a steady-state load-flow. Inclusion of the NECs is only significant for short-circuit analysis, which is not in the scope of the study. The capacitor banks are not included because of the way in which the loads are created – their contribution is generally included in the loads.

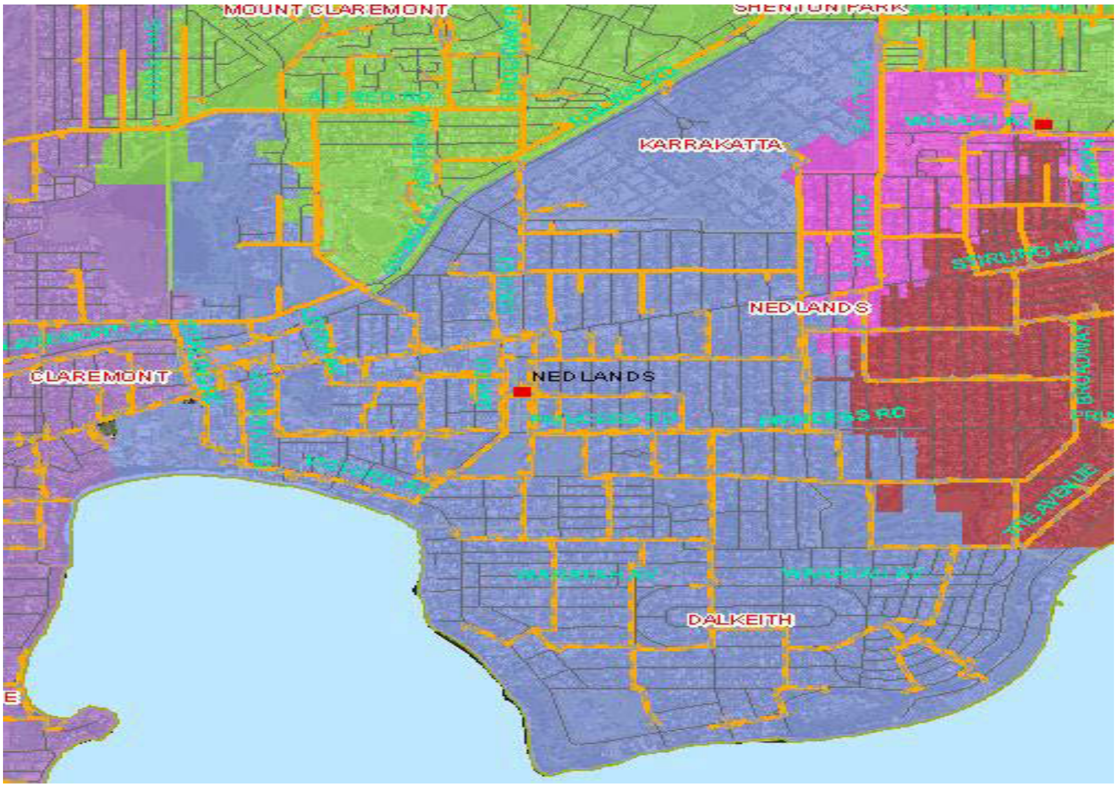

Figure 4-1: Load area of Nedlands substation (Source: Western Power)

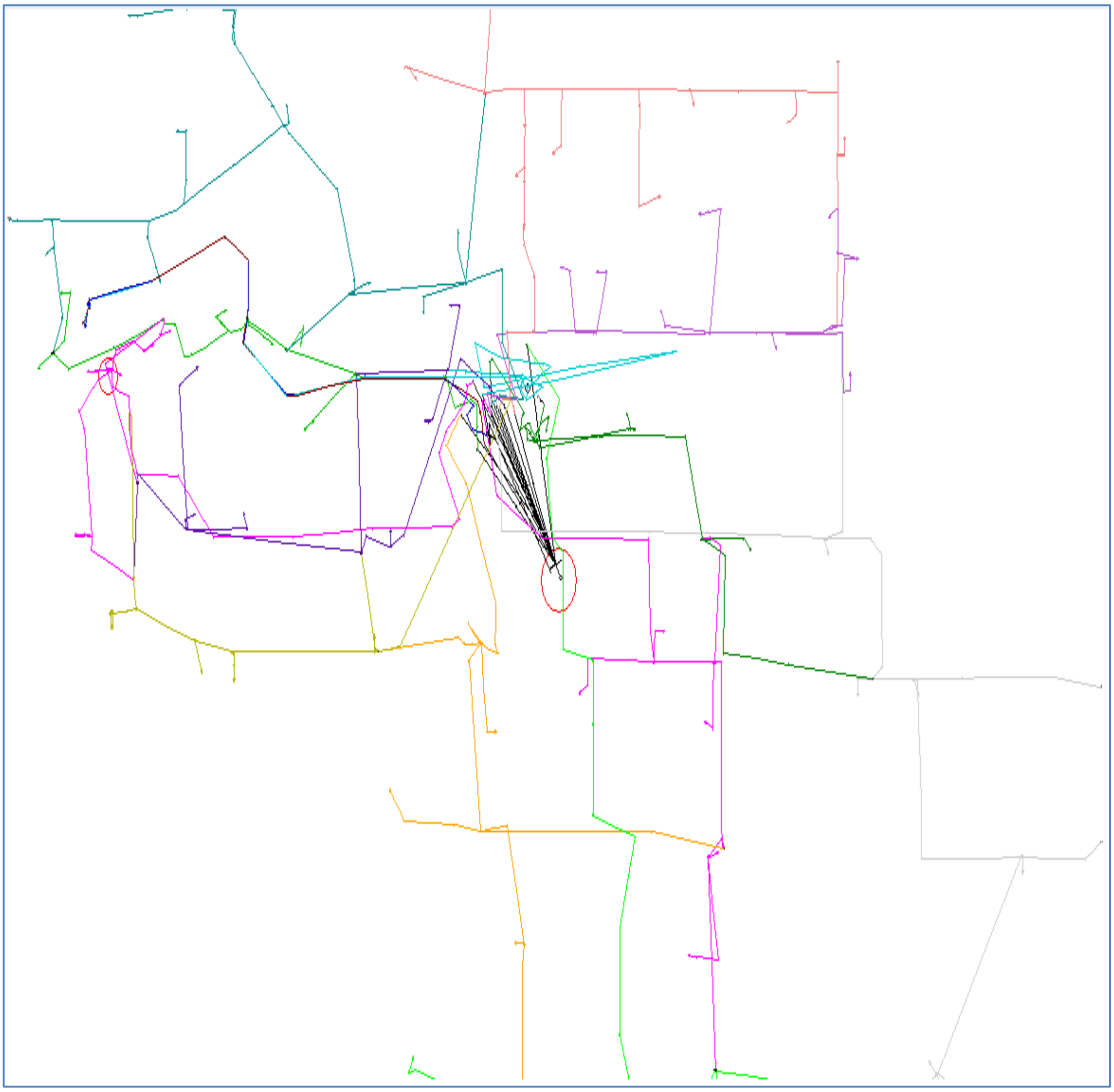

Figure 4-2: Nedlands substation feeders (Source: Western Power)

4.3 Substation Information

To assess potential upstream network limitations for EV charging, uncoordinated charging regime is implemented based on the 66k/6.6k residential distribution substation feeding houses per phase.

Load information for the substation is shown in Table 4.4. However, additional information is available from the included excel files which shows the SLD for the Nedlands substation and capacity information for the transformers (Appendix -4).

Table 4-4: Load information for Nedlands substation (Source: Western Power)

Substation Transformers (66kV/6.6kV)							
		AMP	kV	MW	MVAr	MVA	Tap
Transformer 1	N225	922.18	6.15	-9.18	-3.64	9.88	4
Transformer 2	N206	1022.41	6.36	-11.01	-2.19	11.23	6
Transformer 3	N209	753.21	6.45	-7.58	-3.25	8.25	7

6.6kV Feeders								
		Winter MVA	AMP	kV	MW	MVAr	MVA	%Gth
Edith Cowan University L/S	N201	1.85	184.43	6.36	NM	NM	2.03	9.73
27 Rockton Rd Zone 2	N202F	0.78	77.10	6.36	NM	NM	0.85	8.97
41 Alexander RD	N202R	2.90	275.33	6.36	NM	NM	3.03	4.48
Loftus St	N204	2.96	278.87	6.36	NM	NM	3.07	3.72
13 Taylor Rd	N205	2.33	214.42	6.36	NM	NM	2.36	1.29
70 Melvista Ave	N207	2.04	189.33	6.45	NM	NM	2.12	3.92
8 Gugeri St 3	N208	0.49	72.53	6.45	NM	NM	0.81	65.31
23 Melvista Ave	N210F	1.63	145.33	6.45	NM	NM	1.62	-0.61
8 Gugeri St 1	N210R	0.76	130.39	6.45	NM	NM	1.46	92.11
7 Goldsworthy Rd	N211	2.62	226.17	6.45	NM	NM	2.53	-3.44
125 Dalkeith Rd	N221	2.89	275.57	6.15	2.80	0.94	2.94	1.73
33A Agett Rd	N222	1.99	191.86	6.15	1.85	0.83	2.04	2.51
1 Bay Rd	N224	2.31	222.94	6.15	2.17	0.99	2.37	2.60
27Rockton Rd Zone 1	N226F	0.46	67.90	6.15	NM	NM	0.72	56.52
339 Striling Hwy Suite 2	N226R	1.67	162.52	6.15	NM	NM	1.73	3.59
		Total: 2714.69						

66kV Line						
Western Terminal / North Fremantle	NWT/NF71	AMP	kV	MW	MVAr	MVA
		66.43	67.80	-7.60	-2.45	7.99
University 71	NU71	87.80	67.91	10.12	1.72	10.27
West Terminal 71	NWT71	282.15	67.96	-32.19	-10.73	33.93

6.6 kV Capacitors						
		AMP	kV	MW	MVAr	MVAr (clac)
Capacitor 21	N223	0.00	6.15	NM	0.00	
Capacitor 22	N212	237.50	6.45	NM	NM	2.65
	Total:	237.50				

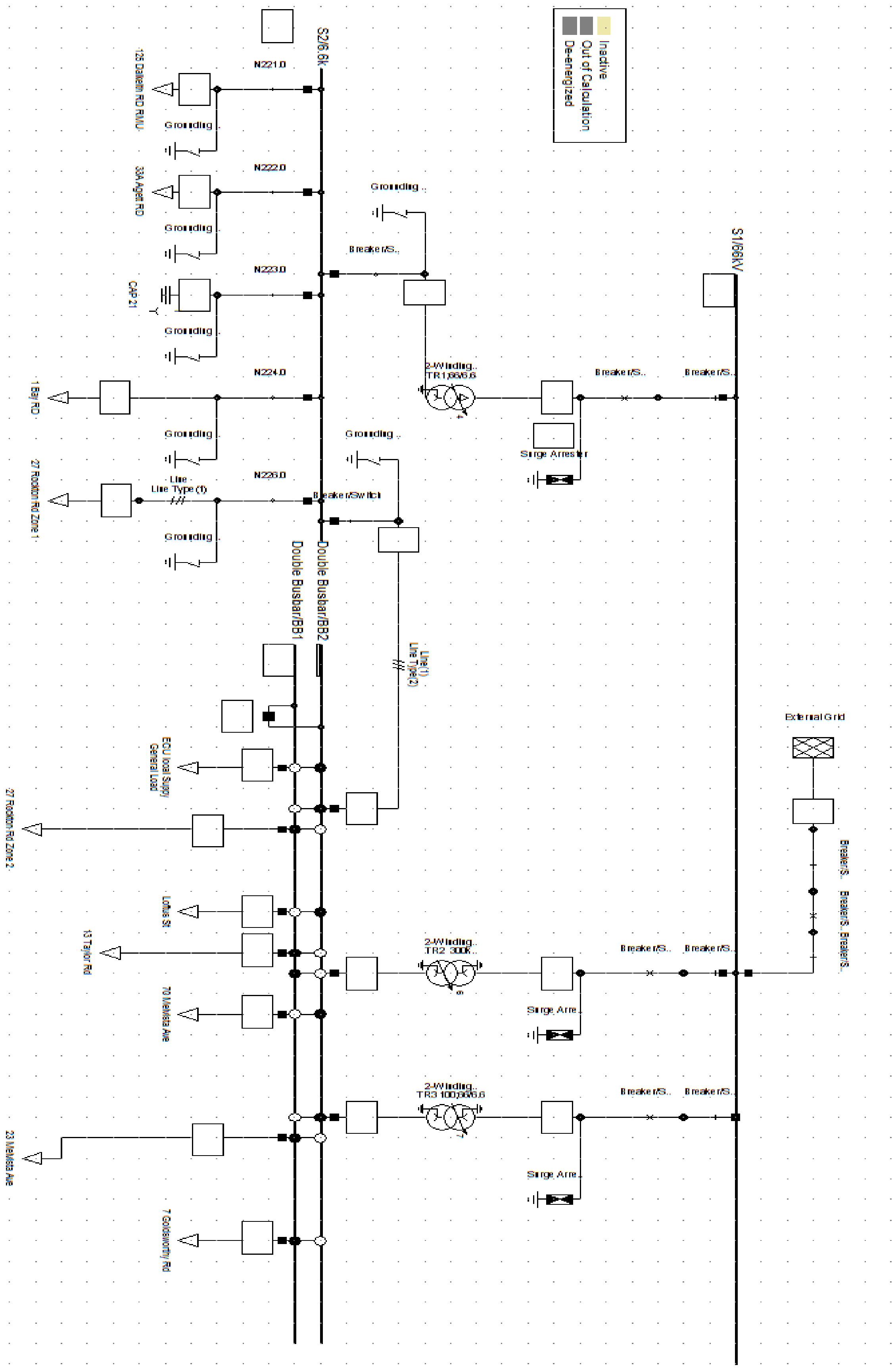

Figure 4-3: Nedlands substation single line diagram

4.4 Residential Load Profile Data

The peak day load profile for the Nedlands substation is shown in Fig.4.4, broken down by transformer loading. Additional load information of Nedlands feeder is provided in Appendix 4.

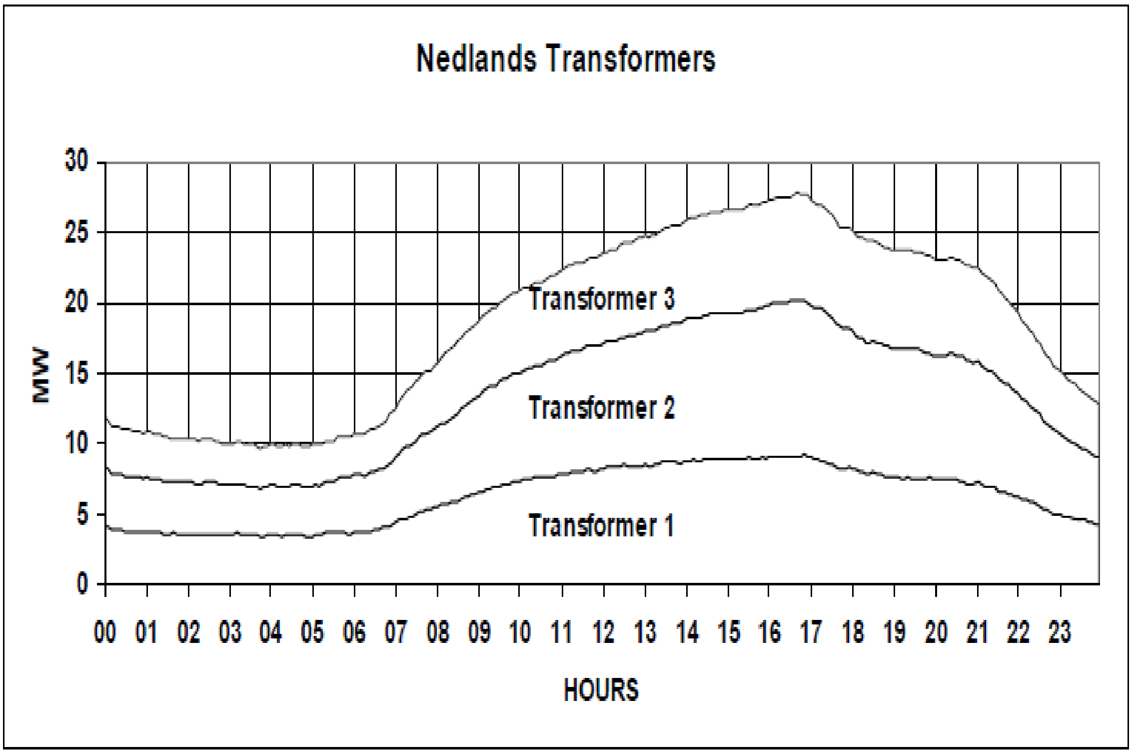

Figure 4-4: Peak day load profile for the Nedlands substation

4.5 Feeder Breakdown

The following figures show geographical view of Low voltage (LV) and High Voltage (HV) supply to houses of N224 feeder to the houses of the Nedlands suburb which is used for the purpose modelling this study.

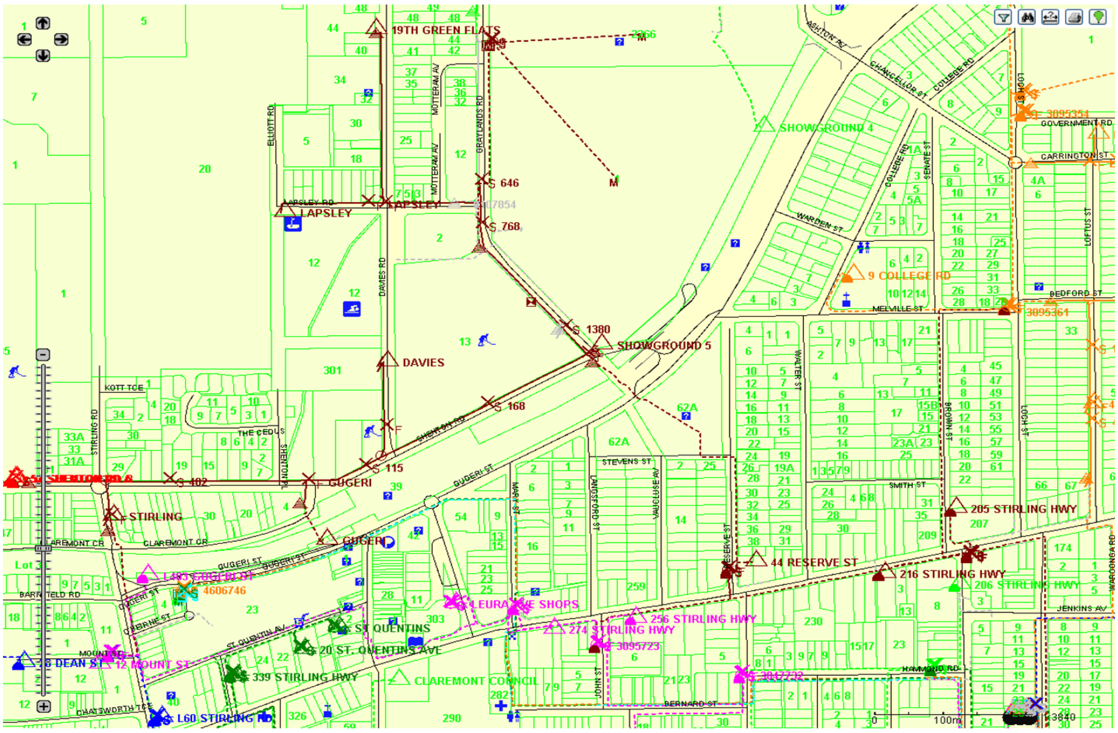

Figure 4-5: Geographical view of N224 Feeder

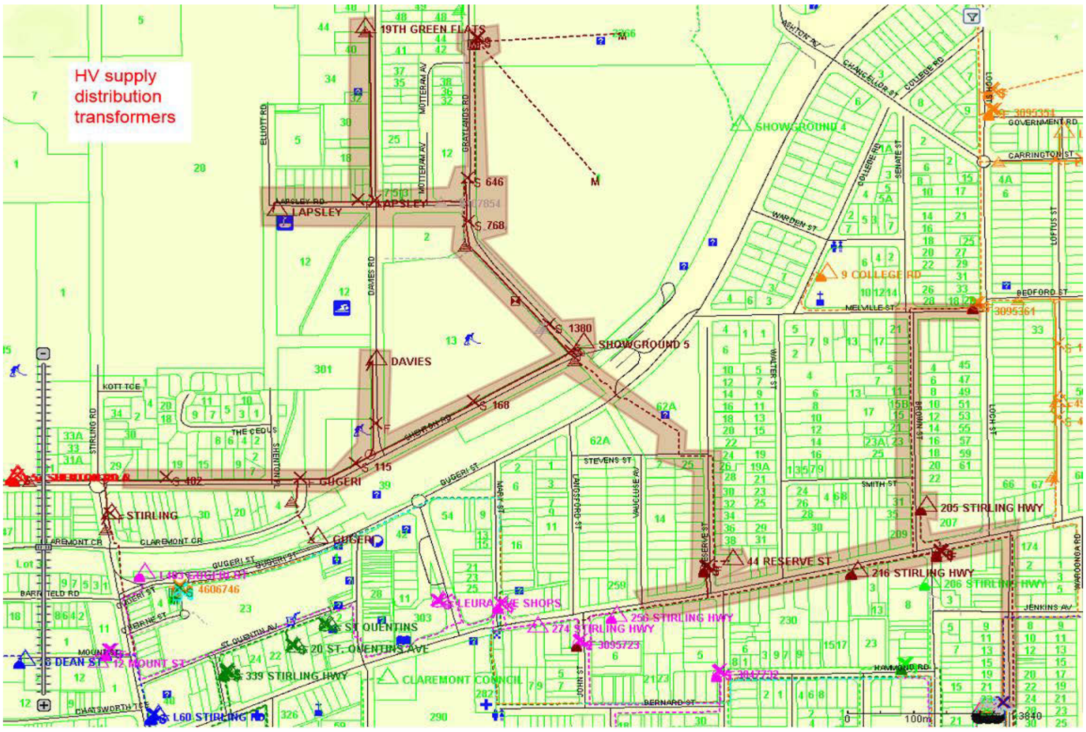
HV supply distribution transformers

Figure 4-6: Geographical view of HV supply distribution of N224 feeder

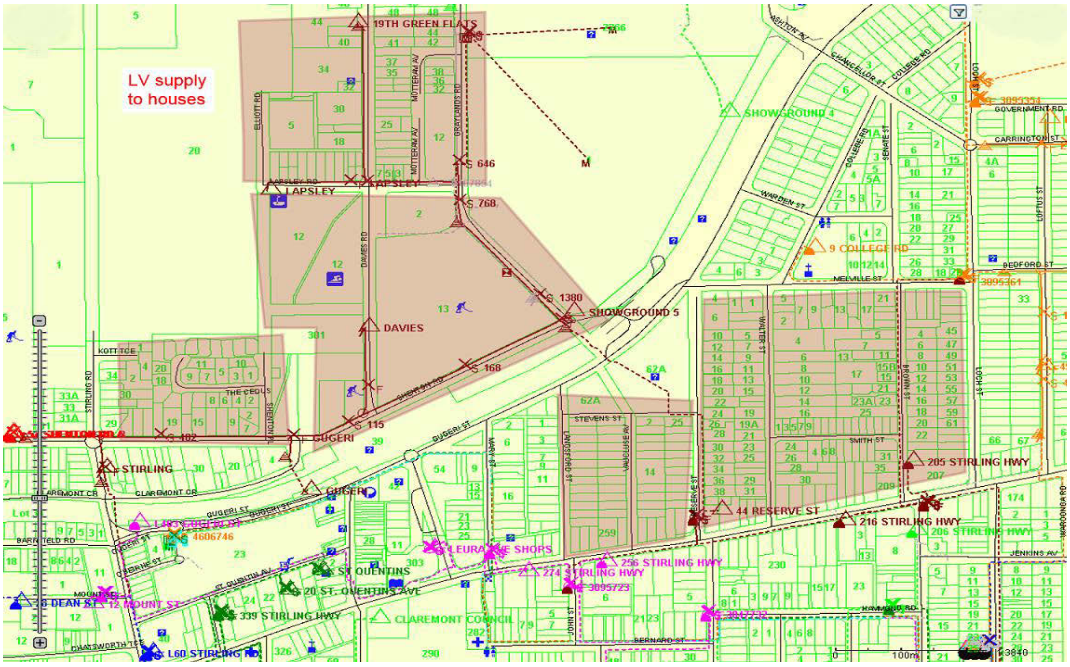

Figure 4-7: Geographical view of LV supply to houses of N224 feeder

Table 4-5: Number of Households and Average Power Consumption for each feeder

Feeders (Bus)	Number of Households	Average Power Consumption (kw/h)
N 201.0 Edith Cowan University L/S	532	1596
N 202.0 27 Rockton Rd Zone 2	943	2829
N 204.0 Loftus St	979	2937
N 205.0 13 Taylor Rd	516	1548
N 207.0 70 Melvista Ave	525	1575
N 210.0 23 Melvista Ave/ 8 Gugeri St	374	1122
N 211.0 7 Goldsworthy Rd	459	1377
N 221.0 125 Dalkeith Rd	663	1989
N 222.0 33A Agett Rd	513	1539
N 224.0 1 Bay Rd	481	1443
N 226.0 27 Rockton Rd Zone 1	115	345
Nedlands	5204	15612

4.6 Assumption

Two different grid metrics can be monitored, the Grid Frequency Control (GFC) and voltage measurement to evaluate “grid stress” and adjust charging power [116].

The second grid metric is local voltage measurements at the charging residence. Similar to frequency, a decrease in local grid voltage can be an indicator of increased loading and stress on the system. Under this condition, the GFC would reduce PEV charging to help stabilize the system If the voltage rises significantly, it can be an indication of excess localized generation such as a cloud transient clearing on a PV array, or a sudden drop in load [116].

The two different “grid stress” metrics also represent two different levels of impact.

The frequency metric is typically associated with the power system as a whole and represents an indication of global stability (and bulk-power stability) on the power system. Voltage, on the other hand, is a much more local phenomenon. Voltage variations can be indicative of the full power system, but are often a direct result of local loading and system operation conditions. In a real deployment, both of these would be monitored simultaneously [116].

Voltage drop is an aspect to consider for reliable operation of a distribution network. Excessively low voltages can cause electrical equipment to malfunction and damage to electric motors [116]. Increasing the impedance on a line causes more power loss, resulting in an increased voltage drop. Thus, as the distance from the source (substation transformer) increases on a network, so does total impedance causing the lowest system voltages to occur at the extreme buses of a network.

The voltage results for the network for all scenario are analysed for the lowest occurring line--to--neutral voltage on the network and the bus location. This minimum voltage bus is then used to analyse the impact of PEV charging on network voltage drop by creating histograms to compare the voltage magnitude with and without PEV charging on the network.

4.7 Grid Technical Constraints

A. Voltage limits

LV networks in Western Australia have a nominal line to neutral voltage of 230V. The actual voltage has to be within ±6% from this value.

$$V^{min} \leq V_k \leq V^{max}, for\ k = 1, \dots, n \tag{4.1}$$

B. Total system demand

$$Demand^h = \sum P_{k,load}^h \leq D_{max,} for\ h = 1, \dots, 24 \tag{4.2}$$

$$min \sum Demand^{\ h} = min \sum_{h=start}^{h_{end}} \sum_{k=1}^{n} p_{k,load}^h \tag{4.3}$$

Where h_{start} and h_{end} correspond to the starting and ending of charging hours within the selected charging time zone. $P_K^h\ load$ is the load demand of node k at hour h.

C. Power loss

The loss minimization objective is defined as the minimization of incremental system losses within the 24 h.

$$minW_{loss} = \sum_{h=1}^{24} P_{loss}^h \tag{4.4}$$

$$P_T = P_L + P_{PEV} \tag{4.5}$$

P_T represents the total power demand in the residential load and P_L and P_{PEV} represents the power demand of residential load and the correspond PEV of that load.

4.8 Model Description

4.8.1 Load Profiles

The model developed by using daily residential load profile of distribution networks to study. Initially, a typical 24-hour load profile of the selected low voltage distribution feeder is extracted from historical data and used in this analysis when electricity demand was particularly high. A scenario without EV charging is run on the developed network to determine the baseline demand and is considered as a reference for further calculation of mass market uptake of EVs. Following this, the three scenarios were implemented.

4.8.2 Baseline Charging Scenario

Using knowledge from previous Western Power on power demand, baseline scenario was created and applied to electricity load demand from one Western Australian region. The baseline scenario is presented with peak load day identified.

Electricity generation begins to ramp up starting at 4 am up until 6 pm where it peaks. Electricity load decreases at a faster rate than its initial ramp- up and between the hours of 7 pm and 9 pm, load levels are sustained for a brief period. Peak hours roughly occur between 4 pm and 6 pm. The scenario above represents vehicle owners that all recharge at the same time in the evening (6pm) resulting in a sudden spike in demand. The small penetration of PEV 25% demand over 0.75 MW of additional power. In the extreme case, a100% market penetration of plug-in hybrid requires over 1.5 MW power. In all penetration scenarios, the additional demand required by PEV is sustained for almost five hours, in order to fully recharge the vehicle.

4.9 Variations to Baseline Scenarios

Once the baseline PHEV scenarios were analysed with the electricity load data and impacts on scenarios. The baseline scenario incorporated different market penetrations of PEV Ford Focus recharging in the evening, using a level 2 AC circuit [117]. While these parameters formed the basic analysis, it is also important to estimate how modifications to these scenarios could change the result.

Scenario assumptions:

- EVs start charging up to full saturation of charge when they arrive home.
- EVs' batteries charging energy derived from electricity grid.
- The vehicles were randomly distributed or in a cluster arrangement and connect to the customer's side of the meter.
- EV penetration rates gradually increased to capture the uncertainty of vehicle technology, charging infrastructure and local penetration of EVs. It is assumed that 25, 50, 75, 100 per cent of the total number of households in the considered area possess an Electric Vehicle. EV penetration level with associated power consumption information for Nedlands is presented in Table 4.6.

Table 4-6: EV penetration level with associated power consumption information

EV Penetration (%)	Number of House holds	Average Power Consumption (Kw/h)
5%	260	780
10%	520	1560
15%	781	2343
20%	1041	3123
25%	1301	3903
50%	2602	7806
75%	3903	11709
100%	5204	15612
200%	10408	31224

4.10 PV Plants Specifications

To model the production of the PV panels, the same approach as the base load profile has been used. The 5 kW with average solar power irradiance in summer at Western Australia is used for PV panels in the distribution network. The PV system specifications are listed in Table.4.7.

Table 4-7: PV system specification

DC system size	5 kW
Module type	Standard
Array type	Fixed (rooftop)
System losses	80
Tilt (degree)	22
Azimuth (degree)	0
Month	January
Solar radiation (kWh/m^2)	8.22
AC energy (kWh)	208

4.11 Storage Battery Specification

To mitigate the problem of unwanted intermittency of PV panel caused by voltage instabilities and to store excess power during day time, utility scale storage battery of 500kWh is used.

4.12 Uncoordinated Charging

There is no smart metering available for charging PEVs, so the vehicles will be charged without coordination. Uncoordinated charging indicates that the batteries of the vehicles are either start charging immediately when plugged in, or after a user-adjustable fixed start delay. The vehicle owners currently do not have the incentive nor the essential information to schedule the charging of the batteries to optimise the grid utilisation. The fixed start delay is introduced to give the vehicle owner the possibility to start charging using off-peak electricity tariffs. The uncontrolled charging cases add considerable load coincident with period of high demand, and add to peak capacity requirements. New generation capacity is required for this additional PEV load to reduce the power loss and enhance the power quality of the distribution network. In order to reduce the negative effect of PEV load, all charging should occur in the overnight hours. This is the main point of off-peak charging scenario, aiming at matching the PEV charging load to periods of minimum demand. This allows the use of most optimal charging electricity and improving overall system performance.

The basic principles of the load-flow are to calculate voltage magnitude and phase angle at each bus in a power system. As a by-product of this calculation, real and reactive power flows in equipment such as transmission lines and transformers, as well as equipment losses can be computed. There required input data consists of bus data, distribution line data, and transformer data. Depending on the type of bus, some variables are known while others are to be calculated by the program. Each bus falls under one of the categories:

- Swing Bus – Otherwise known as the reference bus, the voltage is set normally at $1\angle 0^0$ per unit. Active and reactive power is to be calculated.
- Load (PQ) bus – Active and reactive power is input data and voltage magnitude and angle is to be calculated.
- Voltage controlled (PV) bus Power and voltage magnitude is input data. Calculates reactive power and phase angle.

In terms of the Nedlands substation, the 66kV bus is the swing bus as it is connected to the External Grid. Each of the 6.6kV buses is a PQ bus but their voltage is controlled by the transformer taps, to some degree.

4.13 Substation Topology

The Nedlands substation model includes only the necessary network elements to perform a load flow. These elements and their required inputs are listed in Table 4.8.

Table 4-8: Substation elements and required inputs for the modelling

Network Element	Required Inputs
Busbar	Nominal voltage
Transformers	Impedance, voltage regulation
Loads	Active and reactive power

The double busbar system is connected as shown in the SCADA snapshot (Nedlands Substation Information (Fig. 4.8).

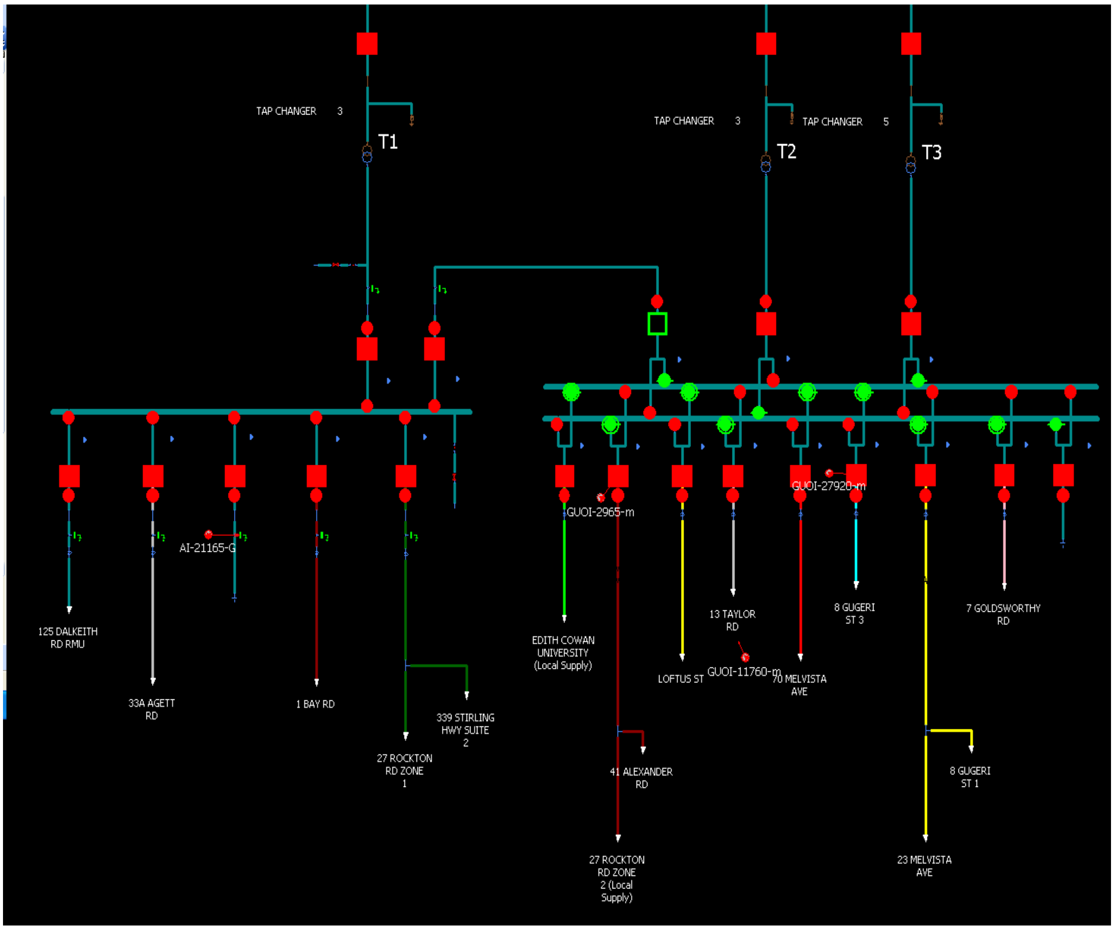

Figure 4-8: Nedlands substation single line diagram

4.14 Creating Load Profiles

This project requires 24-hour profiles of the loads, which is unusual in terms of transmission planning, where scenarios of {minimum, shoulder and peak loads} is sufficient. An hourly load profile is necessary because time is an important variable when studying the connection of electric vehicles.

The technique for combining a steady-state simulation (load flow) with a time-dependent load is derived from Western Power's method of storing the forecasted peak load in the Power Factory database. The yearly forecast is replaced with a 24-hour time scale. When a load-flow is performed, the program uses the "study time" to index a 24-element array and assign the correct value of the load. Each load now needs to be assigned appropriate P and Q values for each hour of the day, represented by a 24-element vector. If a simulation is performed in between the hour, at 4:30pm for example, then linear interpolation is used to estimate the load.

The vectors are created in Excel by scaling the peak load to the percentage load at a given time. This process can be examined by looking at the spread sheet formulas in a 24-hour "load Scale" is derived from the transformer recordings, representing the percentage load at each hour. This is multiplied by the "feeder peak MW" to obtain the "feeder MW at each hour". The contribution from electric vehicles is added based on the number of households serviced by the feeder, and adds active power only. This means that EVs have the indirect effect in improving the power factor.

For the loads at Nedlands substation, the "load Scale" was obtained by observing the peak graph of 2012. The N224 distribution loads use a more precise method by deriving from 2012 transformer recordings that was since made available as shown in Fig.4.9.

This is a more precise method because it is closer to source data and does not suffer the truncation effects of picking numbers off a graph.

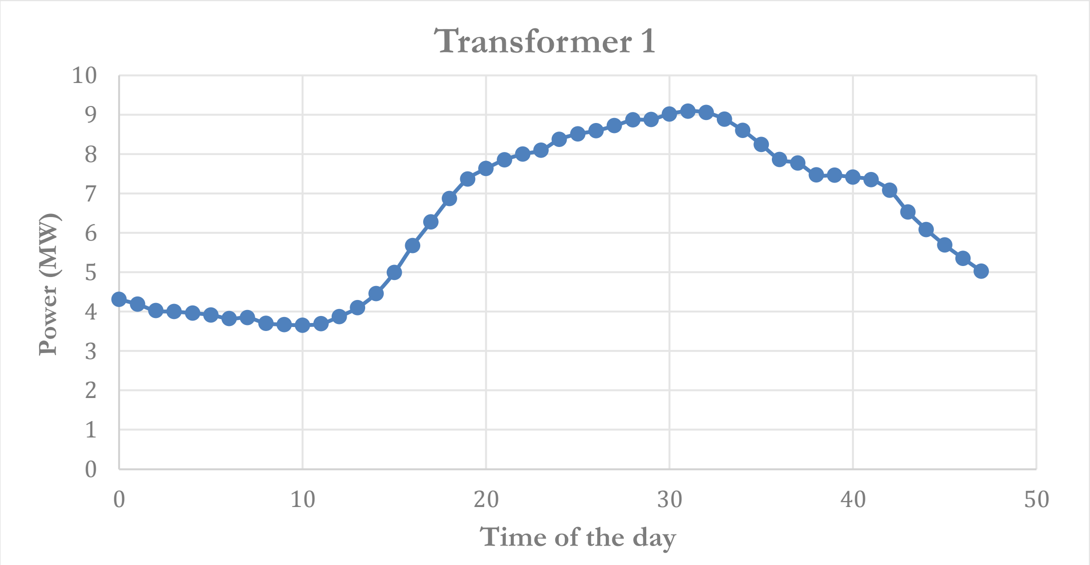

Figure 4-9: Transformer 30 min profile

4.15 Impact of PV Generation on Peak Demand

PV system penetration on the Western Power Network (WPN) has grown substantially over recent years. PV system have noticeable impact on the network through changes to energy consumption. The impact of PV installation on substation peak loads varies widely depending on the time of the substation peak. In summer, substations with a primarily residential customer base are expected.

The majority of individual PV installations involve residential customer. Therefore particular attention is given to the effect of PV on a residential feeder.

The average PV generation profile with the highest PV output is assumed to be co-incident with the summer peak demand day in summer. In summer the peak demand is still occurring around 6 to 9 pm is residential areas and not during the day time. The values in the WPN occur on bright clear summer which provide high PV outputs.

4.16 Electric System Concerns

Distributed PV generation on the electric system can cause a wide range of concerns for the host utility system. IEEE Standard 1547, "Standard for Interconnecting Distributed Resources with Electric Power Systems," addresses these concerns. While this standard does not specifically address distributed PV systems, it does provide the requirements for interconnecting DG facilities with the electric system. It also provides details for issues such as allowable voltage drop, short-circuit currents, and voltage flicker. Host utility owners have many other concerns such as asset impacts (e.g. loss of asset life due to increased regulator and capacitor bank switching) and feeder control (voltage and reverse power flows), which interconnection studies need to address.

Recent PV integration studies revealed circuit performance depends on several critical factors, including feeder characteristics and voltage class, PV site distance from the substation, feeder load characteristics, penetration level, and system control settings.

Feeder characteristics play an important role in how circuits perform when distributed PV is added. Circuits with higher nominal voltage will generally perform better than lower voltage circuits. PV output curves tend to match up better with commercial circuit load profiles than with residential circuits, which reduces back-feed concerns.

4.17 Demand Response & Smart Control Strategies

To reduce the impacts of electric vehicle charging on the local distribution transformer, the simple alternative could be upgrading of the transformer and the other network assets associated with it, which needs significant investment. Other methods include the controlled charging as examined in the previous sections and demand response (load control) possible in households.

The demand response strategy is a subset of demand side management, which aims to reduce the peak to average demand in the premises of the customer through automation and intelligent devices. They are time dependent strategies which either shifts or reduce the electricity use of individual households. The daily operation of the household loads like the electric cars, heaters, dryers, coolers etc. could be prioritised based on the consumer comfort and preferences. The non- critical loads could be shed, during the electric vehicle charging period. The household loads including the electric vehicles and the electricity consumption have to be monitored continuously.

If the peak load set for a household is reached, the loads could be shed in order of their lowest priority. The transformer demand needs to be monitored continuously to send control signals to a 110 household controller to perform such demand response and load control strategy. To monitor and control the household loads and electric vehicle unit with remote control switches, an Advance Metering Infrastructure (AMI) is required [131]. The basic components of AMI are the smart meters and two-way communication interfaces. The infrastructure could monitor, measure and analyse the electricity used by sending data over the bidirectional communication network connecting the utility control systems and smart meters [132]. [133], [134].

Chapter 5

System Modelling

In the context of the bulk power system the basic objective is to make sure that there is enough power being generated to supply the power drawn by the system load; providing customers with a secure and reliable electrical energy supply. There are several types of measures to determine how well the system is operating including: power balance, voltage performance, and financial returns. Each consumer and stakeholder will have a unique set of expectations and desired outcomes with respect to power system performance.

To simulate the use of plug-in electric vehicles (PEV) as a source of power consumer a model including power system behaviour, PEV loads, and additional controllers is necessary.

A radial Western Australian network modelled in this analysis shown in Fig.4.3. It includes a 66kV/6.6kV substation suppling 15 main feeders. Each feeder serves approximately 500 customers, not evenly distributed among three transformers. For the purpose of in-depth analysis one feeder is modelled in detail and the rest as lumped loads.

The line impedances are adapted to achieve tolerable voltage deviations and power losses. Each node is a connection with a residential load and some, randomly chosen, nodes will have PEVs charging.

5.1 Power System Simulator

The Medium Voltage (MV) distribution network Nedlands of Western Australia is considered here as the test case. The Nedlands 66kV radial power distribution network modelled in the DIgSILENT PowerFactory software with the distribution transformers, generators, shunts and aggregated loads in the 6.6kV system. The distribution system is a 66kVnetwork connected to the 66kV substation which is considered as the external grid. There is one substation at the 66kV voltage level including 3 power transformers (66/6.6kV) with a total capacity of 27.77 MW. Fig.5.1 shows a case of the 66kV radial network considered here for the substation. The aggregated system loads and EV loads are distributed across the 6.6kV voltage levels. Table. 5.1 depicts the Power Factory model information used in this analysis.

Table 5-1: System model parameter

Main Power factory Model	**Value**			
Number of buses	28			
Penetration Percentage	**25%**	**50%**	**75%**	**100%**
Number of PEV charging	120	240	361	481
PEV Load (MW)	0.36	0.72	1.083	1.443
Peak System Load (MW)	2.49	2.85	3.21	3.57
PV Generation (MW)	0.6	1.2	1.805	2.405

5.2 Scenarios and Projections

Four different scenarios were defined in order to investigate the power loading of the LV distribution grid and the energy losses after the introduction of electric vehicles. In these scenarios, it was assumed that 25%, 50%, 75% and 100% of the total number of households in the investigated area possess an electric vehicle.

The four scenarios utilised in the model are presented below:

- The baseline scenario (Scenario 1) represents the case prior to the introduction of electric vehicles and will be utilised as reference in order to calculate the energy saving potentials after the mass market introduction of electric vehicles.

- The uncontrolled charging scenario (Scenario 2), assumes that EV users plug-in the chargers to their vehicles' batteries when they return at home. The charging process starts with no delay and no control is applied.
- The Optimized charging towards incorporating PV system in Power system (Scenario 3). This scenario represents the effect of integration of EVs and PVs into the electricity grid. It is assumed that EVs are allocated to customers that also have installed PV plants. Under this scenario, different penetration of residential EVs and PVs is implemented.
- The optimised charging represents utilising energy storage case where the energy content that fulfils the energy needs of both household loads and EVs is drawn from grid and stored energy of PV system at the same power level during the day (load levelling). The power load is assumed ideally levelled, regardless the availability of plugged-in electric vehicles as a function of time in the investigated area.

Owner of plug-in hybrid electric vehicles (PEVs) will have the freedom to choose charging their own charging programs, completely unrestricted, similar to any other appliance with a regular retail electricity price, Aggregators will manage to store excess energy of PV system and provide power demand of PEV charging, so that it does not cause peak power on system load hours, or so that it does not overload distribution transformers.

5.3 System Load Model

The plug-in EV loads are added to the system demand in steps of 25% based on the EV distribution scenario. The impacts of these additional loads on the key operational parameters of the distribution grids are analysed using load flow studies simulated for each hour of the typical hot day considered. The effect on the system, voltage profile per feeder, daily system losses, peak demand period are investigated for an increased penetration of electric vehicle loads. A DPL (DIgSILENT Programming Language) script is developed in the Power Factory software for using the charging profile of electric vehicles in the model and also to perform the hourly load flow analysis.

Non-PEV bus loads were based on real-time 30-minute load data from the eleven nodes in the Western Australia. Using weather data January 25th, 2012 was chosen as a basis for the bus loads; the day had highs and lows in the 43.3 (°C) and 26.6 (°C) in zero precipitation (Appendix 4). This implies that the system did experience high loading in the afternoon which might be experienced with higher temperatures. Fig. 5.1 depicts the typical load demand curve in Perth, Western Australia used in this analysis.

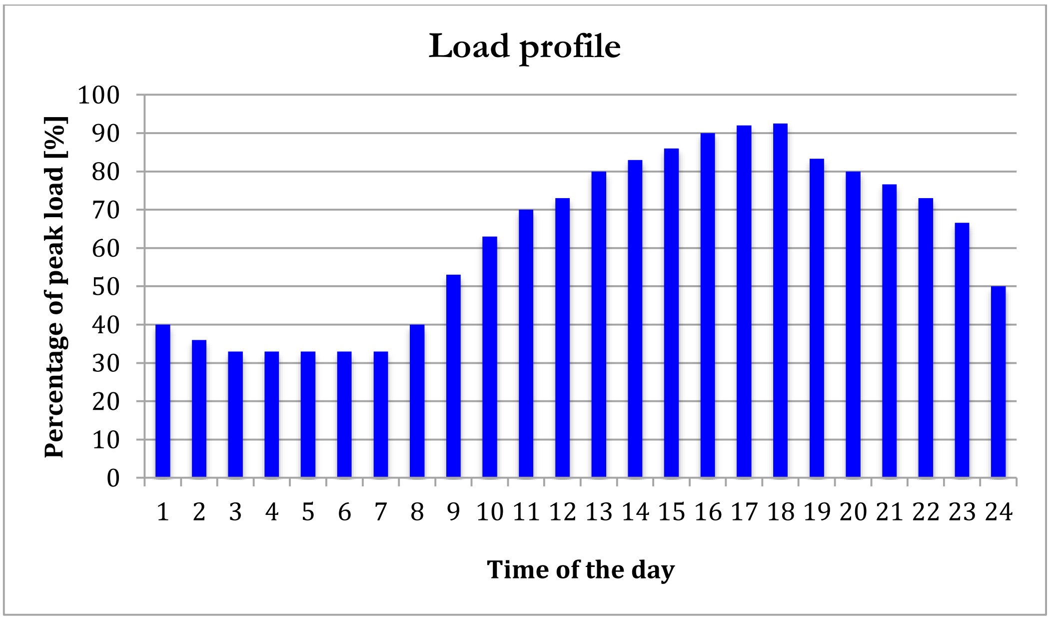

Figure 5-1: 30 min on-line load data for system

The development of the load models used for the PEV participating in vehicle-to-grid is discussed in Section 5.2. A continuous 24-hour load curve for each bus was also developed, which fit a fourth order polynomial trend line to the 30-minute load bus data.

5.4 Network Model

The power flow that also includes the network model consisting of the distribution lines, is implemented within the Digsilent model. The distribution system model including 28 bus is shown in Fig.5.2.

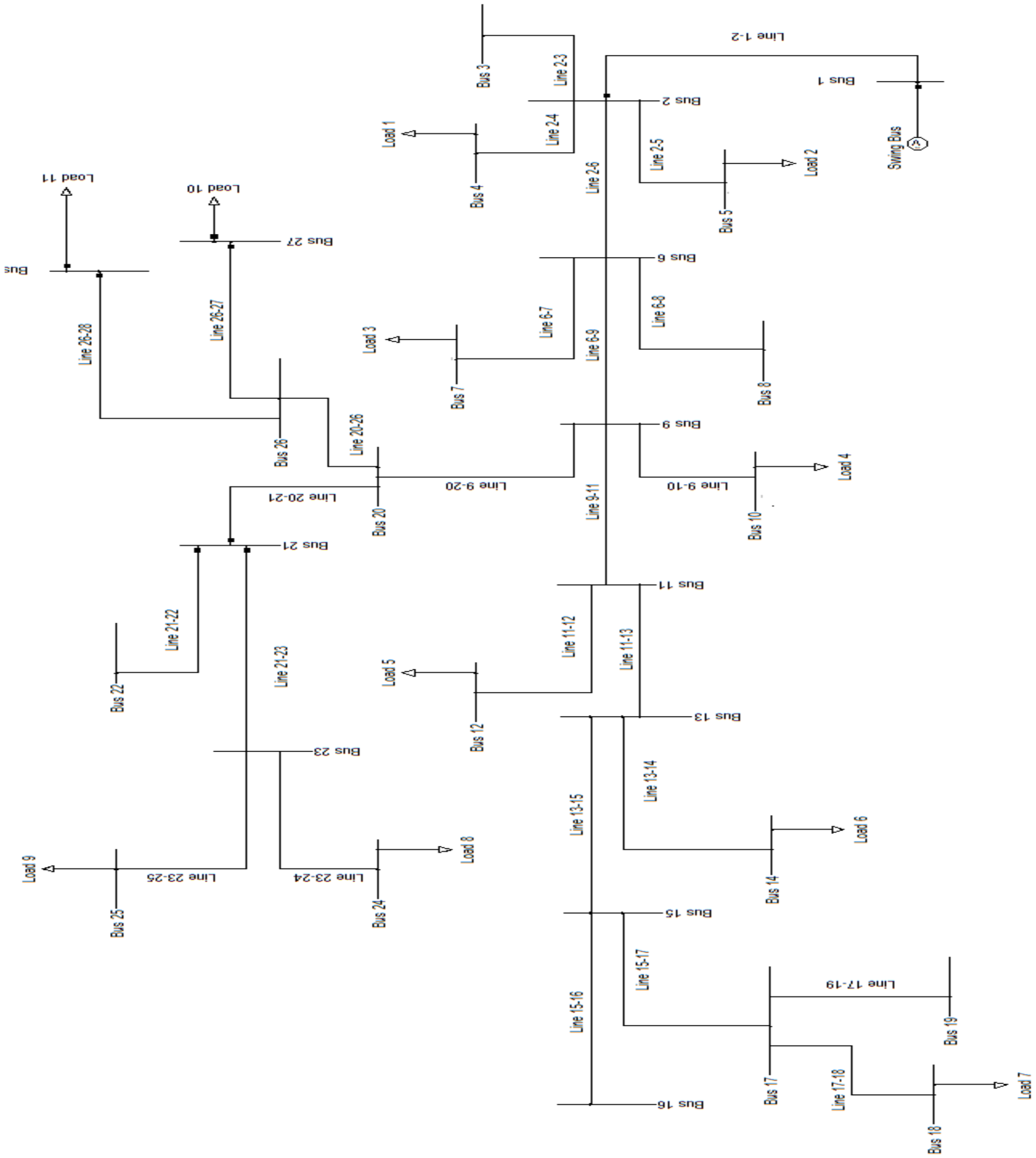

Figure 5-2: The Distribution system including 28 node

Table 5.2 describes the lines resistance information used within the network model along with the modifications to the buses after events occur in the system.

Table 5-2: Bus resistance characteristic

Name	R1 (Ohm)	X1 (Ohm)	From Bus	To Bus
Line 1-2	0.044266	0.045632	Bus 1	Bus 2
Line 11-12	0.147612	0.059475	Bus 11	Bus 12
Line 11-13	0.066096	0.042936	Bus 11	Bus 13
Line 13-14	0.111201	0.024621	Bus 13	Bus 14
Line 13-15	0.161935	0.105193	Bus 13	Bus 15
Line 15-16	0.061137	0.040892	Bus 15	Bus 16
Line 15-17	0.012579	0.018438	Bus 15	Bus 17
Line 17-18	0.001304	0.001007	Bus 17	Bus 18
Line 17-19	0.029567	0.030879	Bus 17	Bus 19
Line 2-3	0.055897	0.057862	Bus 2	Bus 3
Line 2-4	0.133394	0.017667	Bus 2	Bus 4
Line 2-5	0.164474	0.021586	Bus 2	Bus 5
Line 2-6	0.041991	0.043263	Bus 2	Bus 6
Line 20-21	0.055226	0.027104	Bus 20	Bus 21
Line 20-26	0.037711	0.038712	Bus 20	Bus 26
Line 21-22	0.031671	0.012726	Bus 21	Bus 22
Line 21-23	0.132273	0.053151	Bus 21	Bus 23
Line 23-24	0.153201	0.061721	Bus 23	Bus 24
Line 23-25	0.27311	0.107706	Bus 23	Bus 25
Line 26-27	0.000435	0.000336	Bus 26	Bus 27
Line 26-28	0.000435	0.000336	Bus 26	Bus 28
Line 6-7	0.054825	0.007196	Bus 6	Bus 7
Line 6-8	0.030183	0.031082	Bus 6	Bus 8
Line 6-9	0.097807	0.112089	Bus 6	Bus 9
Line 9-10	0.020265	0.010572	Bus 9	Bus 10
Line 9-11	0.190026	0.123441	Bus 9	Bus 11
Line 9-20	0.127786	0.08301	Bus 9	Bus 20

The 28 Bus System is used as a testbed for this study. The system is developed based on the real distribution system.

The 28 bus system includes 3 transformers and 11 buses with load attached. To capture the behavior of PEV while plugged-in to the grid, an aggregate load profile will be included at each of the load buses in the system. Fig. 5.3 shows the one line for the 11 bus system with the aggregate PEV load

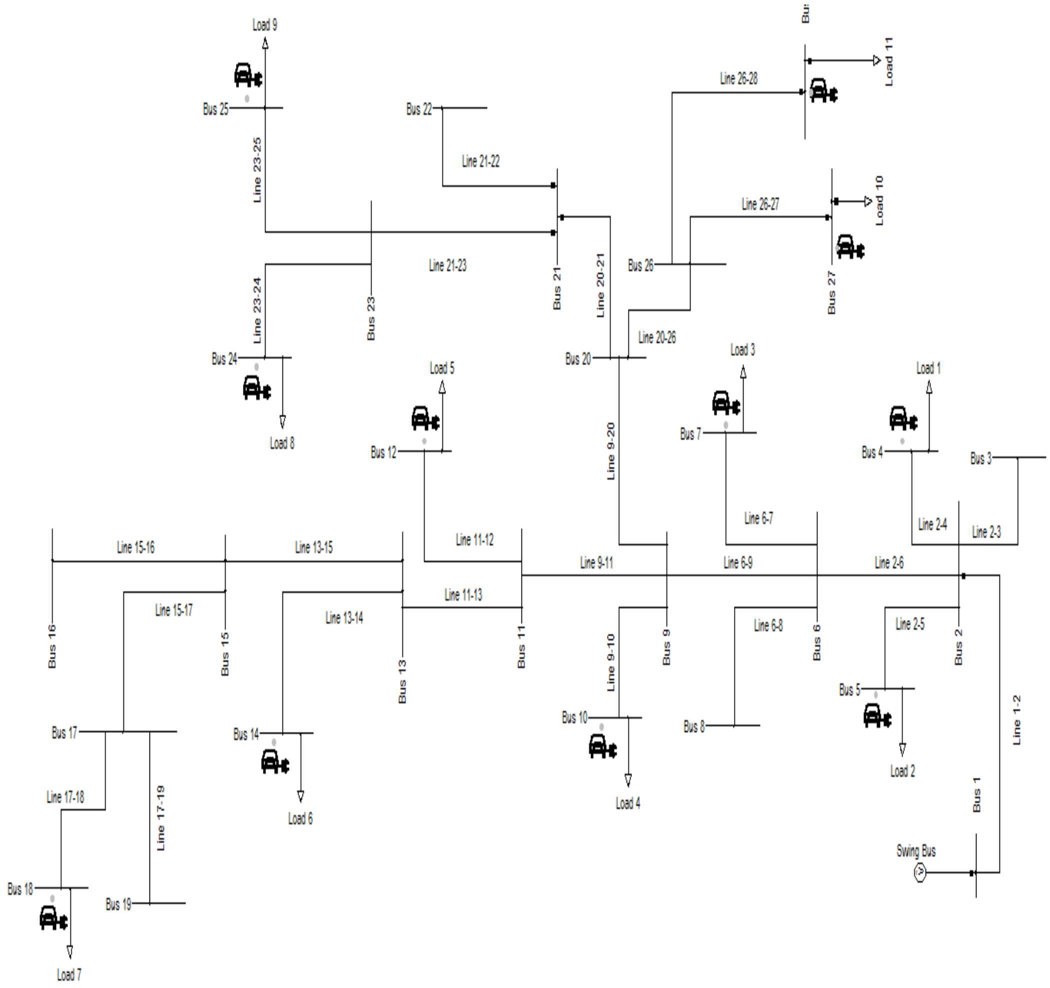

Figure 5-3: The 28 bus system with aggregate PEV loads

The active power, reactive power, apparent power along with the terminal for the non-PEV loads for the total system can be seen in Table 5.3. The feeders load characteristic is described in Table 5.4.

Table 5-3: Bus load characteristic

Name	Grid	Terminal	Active Power	Reactive Power	Apparent Power
		Busbar	MW	Mvar	MVA
Load 1	N224	Bus 4	0.2268	0.1701	0.2835
Load 10	N224	Bus 27	0.18	0.04072	0.04072
Load 11	N224	Bus 28	0.18	0.04072	0.04072
Load 2	N224	Bus 5	0.36	0.27	0.45
Load 3	N224	Bus 7	0.18	0.135	0.225
Load 4	N224	Bus 10	0.18	0.135	0.225
Load 5	N224	Bus 12	0.1134	0.08505	0.14175
Load 6	N224	Bus 14	0.18	0.135	0.225
Load 7	N224	Bus 18	0.1134	0.08505	0.14175
Load 8	N224	Bus 24	0.056	0.042	0.07
Load 9	N224	Bus 25	0.108	0.081	0.135

Table 5-4: Feeder load characteristic

Name	In Folder	Total load, Active Power	Total Load, Reactive Power	Total Load, Apparent Power
N201	Feeder	1.912	1.434	2.390
N2012R41 Alexander RD	Feeder	1.802	1.352	2.253
N202 27 Rockton RD Zone 2	Feeder	2.771	2.078	3.463
N204	Feeder	2.591	1.943	3.328
N205	Feeder	2.117	1.588	2.647
N207	Feeder	1.830	1.372	2.287
N208	Feeder	1.035	0.000	1.035
N210 F 23 Melvista Ave	Feeder	1.487	1.115	1.859
N210 R8 Gugeri St	Feeder	1.611	0.000	1.611
N211	Feeder	2.171	1.628	2.714
N221	Feeder	2.830	2.123	3.538
N222	Feeder	1.802	1.352	2.253
N224	Feeder	2.170	1.627	2.712
N226 27 Rockton Road Zone 1	Feeder	0.945	0.000	0.945
N226 339 Stirling	Feeder	1.968	1.476	2.460

Chapter 6

Simulation Result and Discussion

This chapter discusses the three simulations that were performed using the simulator as described in Chapter 5.

6.1 Uncontrolled (Uncoordinated) Charging

From the simulation results, plots were created for the distribution feeder daily active power loading for the baseline scenario and the scenario of uncontrolled charging, assuming that each household possesses an EV. The two scenarios of incorporating PV system and battery energy storage integrated are then analysed. What can be seen from this analysis is that the peak demand for charging power coincides with the peak power demand from household loads. Most of the power for charging purposes is provided before the conclusion of the day, and this is mainly due to the high demand for energy, as well as due to the fact that most users initiate the charging process when they return at home.

The load Unbalance occurs mainly during the second half of the day because most of the drivers return at home after 18:00 hours and this is the time period that most of the demand for charging power occurs.

Moving one step further, it is also interesting to investigate if the feeders are able to transfer the additional power for charging purposes. For the case of one of the system's most loaded feeders (connected to a number of 481 households), the maximum allowable power that can be drawn is approximately 2.14 MW, limited by the feeder's safety fuses. The daily active power load for the investigated feeder has been plotted for all four scenarios considering uncontrolled charging, assuming 25%, 50%, 75% and 100% of the total households possess an EV. For a relative small portion 25% of the total households possessing an EV, the load of the feeder exceeds the maximum allowable rate of 2.14 MW, and that this occurs a few minutes after 18:00 hours. In a real system, this situation would probably cause the electrical fuse to blow and would lead to a subsequent outage, affecting at least all of the customers connected to this phase [118]. Although there is a significant amount of available capacity for transferring electrical energy through this feeder, it is the combined and coincided demand for power from end-users during peak demand hours that create this problem. If no charging control is applied, the feeder would have to be reinforced in order to cope with the extra load during peak demand hours.

6.2 Scenario 1: Base Case

The first case presents the feeder power demand considering a 24 hours profile. The daily load curve for N224 feeder without PEV is shown in Fig.6.1.

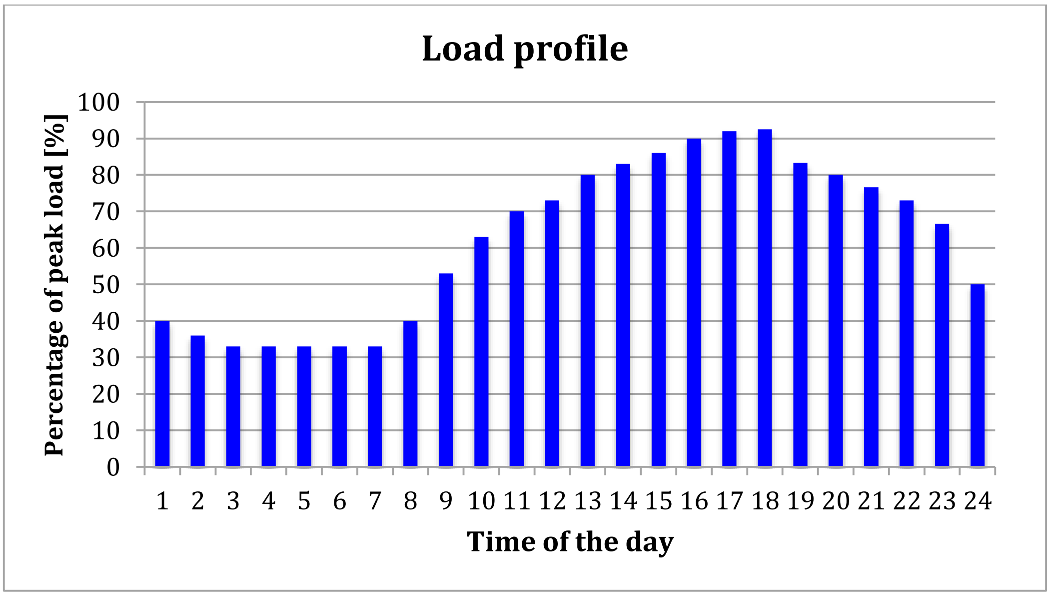

Figure 6-1: Typical daily load curve (without PEVs) for WA residential network

6.3 Scenario 2: Impact of EV Loads on the Distribution System

The baseline scenario and the scenario of uncontrolled charging assuming household stepped increases in EV penetration levels is analysed on the distribution feeder as explained in Chapter 5. The key operational parameters of the electrical distribution system, including voltage profile, feeder loading peak demand and system losses, are examined for an increased penetration of 25%, 50%, 75% and 100% electric vehicle loads. The impacts on the distribution network were considered.

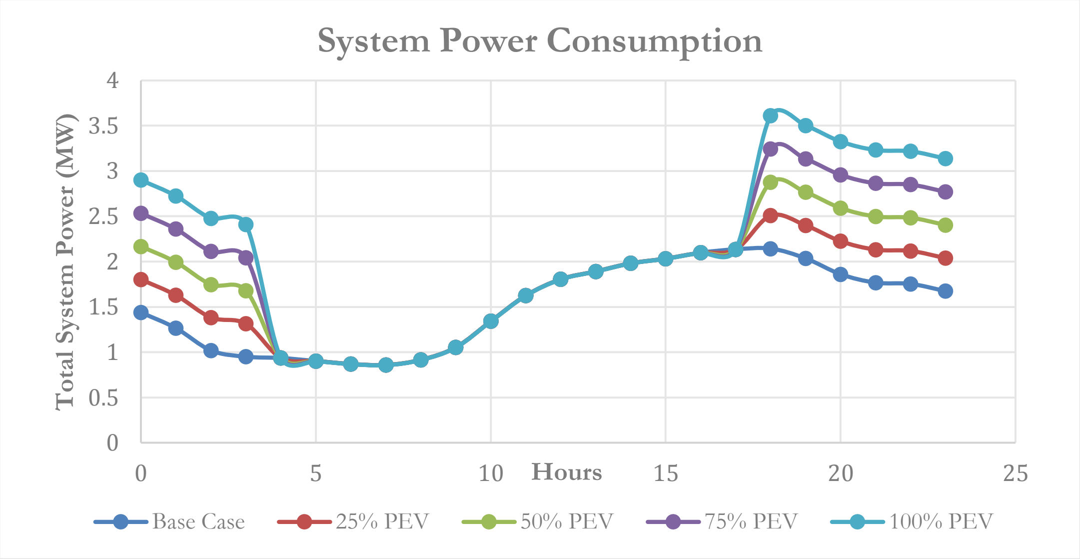

Figure 6-2: System load curve for uncoordinated charging considering PEV owner priorities with different PEV penetration level

The distribution system peak demand for uncontrolled charging scenario is illustrated in Fig. 6.2. The resultant load demand curves obtained from incorporating additional electric vehicles loads ranging from 0% to 100% for the entire day. The result is that EV charging adds to the pre-existing peak load and gives an even charger peak. It is noted that an increase of about 14.4 % in maximum demand results for 25%, 17.4% for 50%, 38.4% for 75% and 48.6% for 100% increase in houses with EVs respectively.

It is evident that peak demand for charging power coincides with the peak power demand from households' loads. The load unbalance occurs mainly during the second half of the day because most of the drivers return at home after 18:00 hours when the most of the demand for charging power happens.

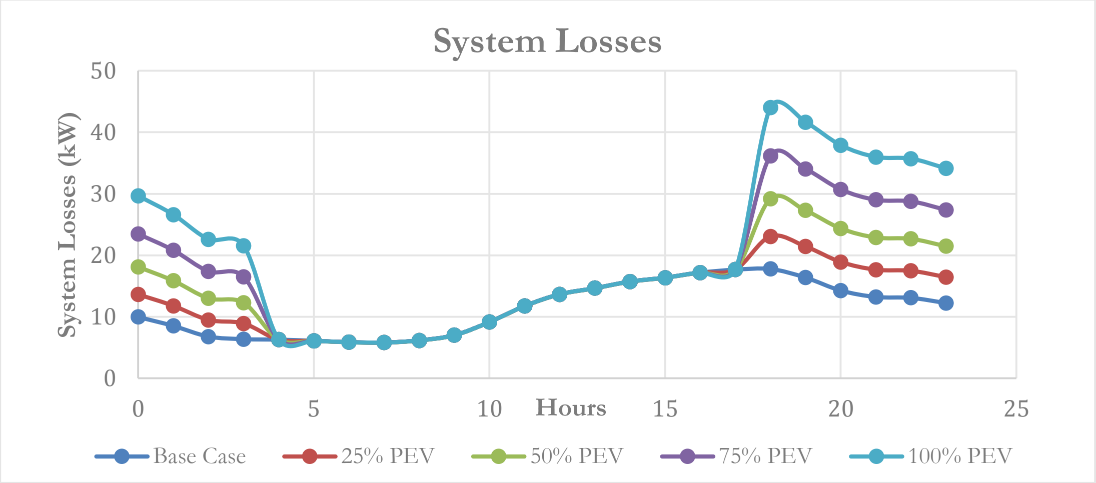

Figure 6-3: System loss curve for coordinated charging considering PEV owner priorities with different PEV penetration level

Fig. 6.3 illustrates the power loss for the scenario of uncontrolled charging due to the gradual increase in power losses with increasing numbers of EVs. Power losses in the investigated grid are as a percentage of the total energy input for each scenario.

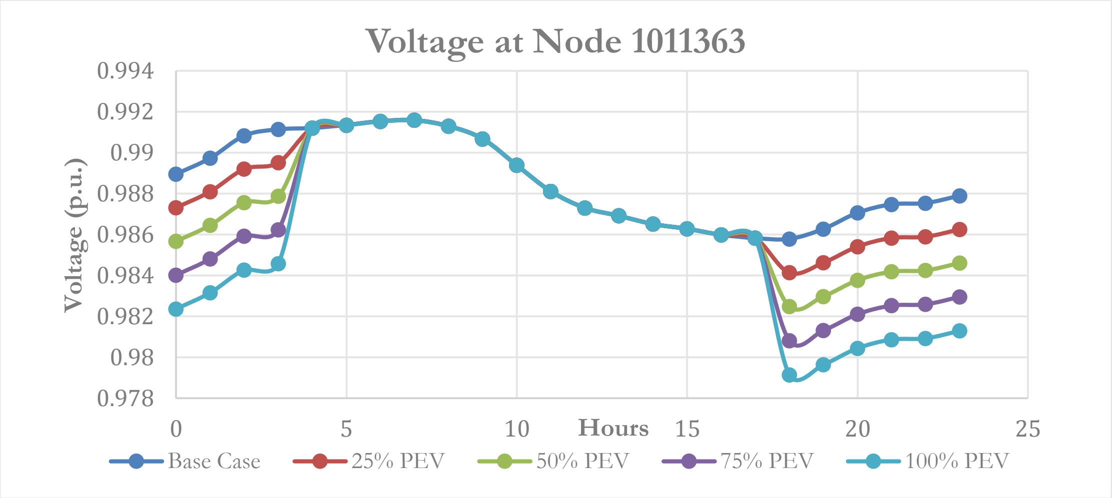

Figure 6-4: Voltage profile for uncoordinated charging considering PEV owner priorities with different PEV penetration level

The average voltage drop of the critical feeders in the network for the uncontrolled charging mode of the electric vehicles is shown in Fig. 6.4.

The result shown in Fig 6.4 indicates that for an increasing number of electric vehicles, the voltage of these feeders doesn't drop below the reference voltage ±6% for LV feeders (Western Power regulation) to a level beyond the normal acceptable limit of 0.94 p.u.

6.4 Scenario 3: EVs Integrated with PVs

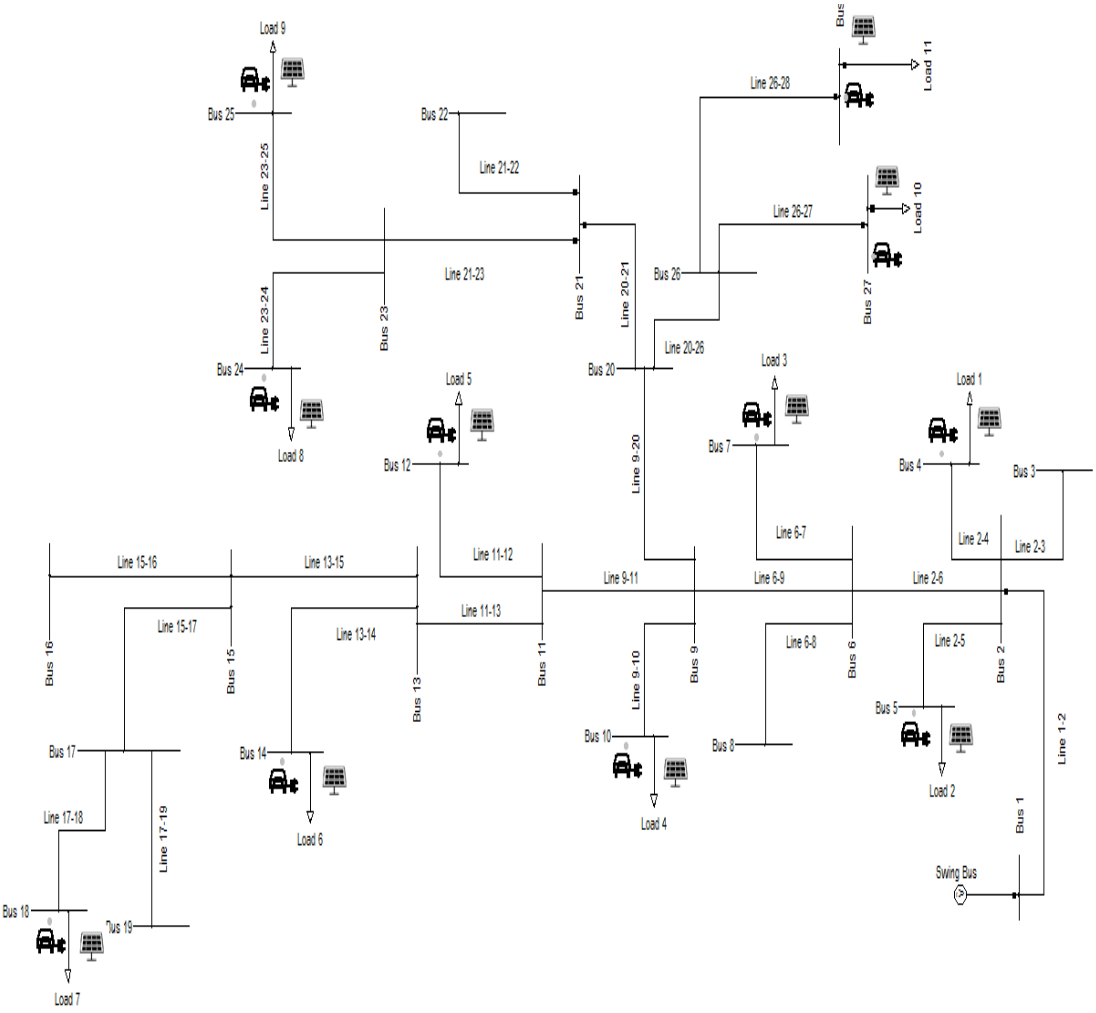

Figure 6-5: Distribution feeder with aggregate PEV loads and PV system

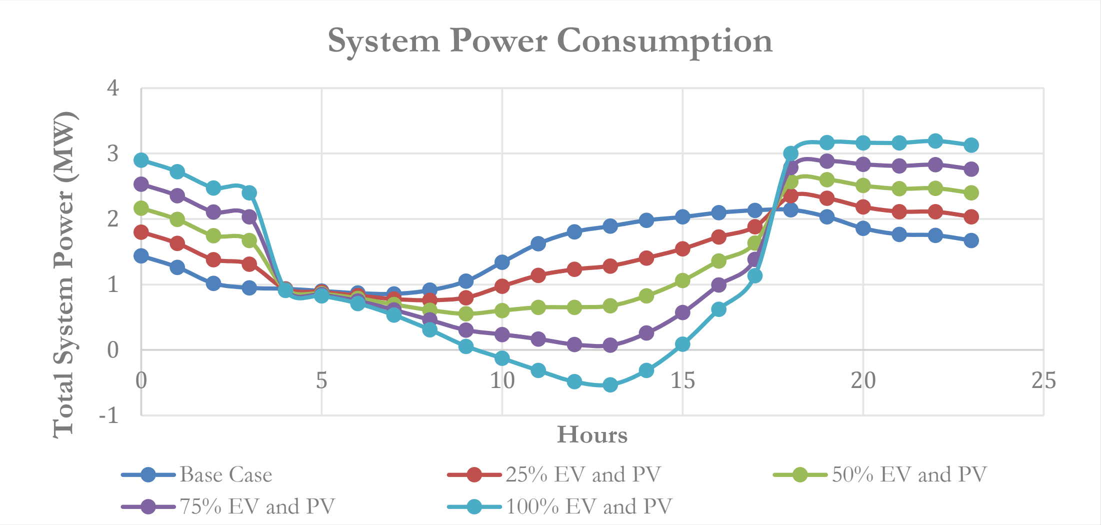

Figure 6-6: Total system power consumption for uncoordinated PEV charging and incorporated PV system at different penetration level

The simulation results of the solar integration scenario are illustrated in Fig. 6.6. As observed, solar PV shows strong effect of distribution investment. It firstly satisfies local demands and secondly mitigates network congestion and consequently supports the grid. Under this scenario, system power demand decreases during the day time due to the output of the PV systems. The graph indicates that less power is drawn from external grid during operating hours and that the PV systems are able to export power under 100% PV penetration.

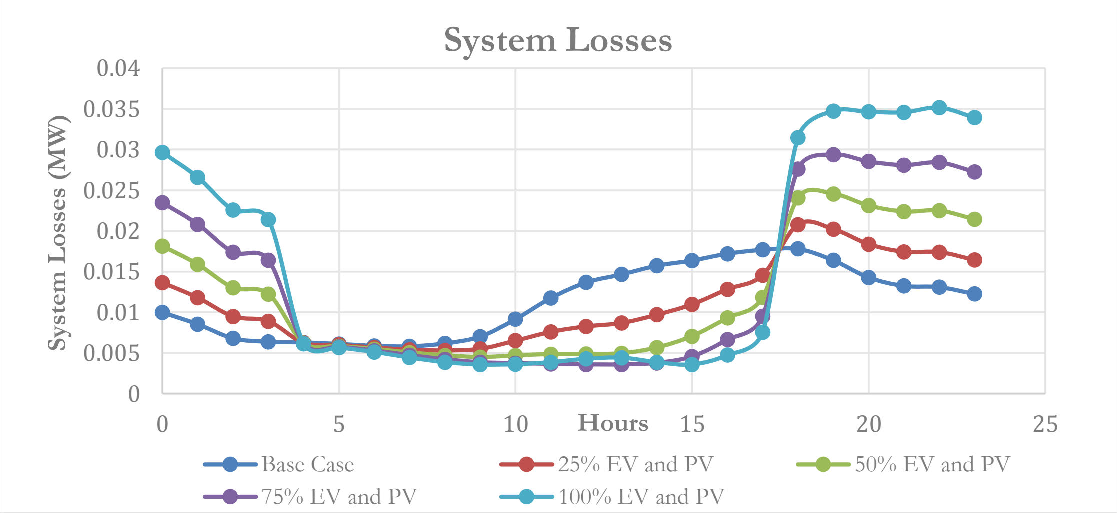

Figure 6-7: System power loss for PEV charging incorporated PV system at different penetration level

Fig 6.7 shows system power losses, with losses increasing when the penetration level reaches 100%.

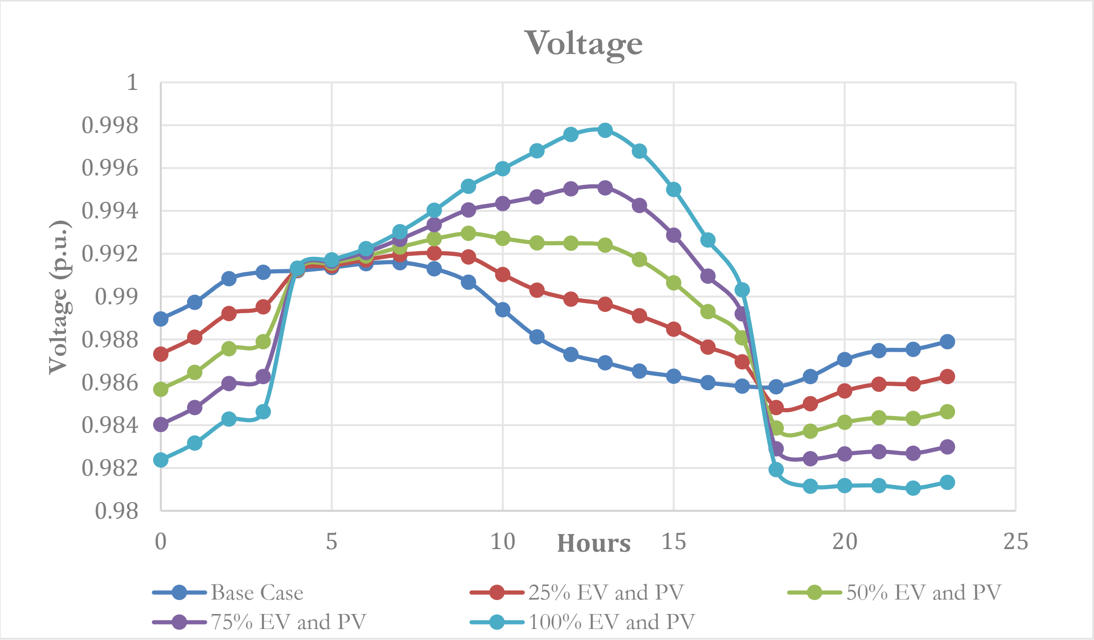

Figure 6-8: Voltage profile for PEV charging incorporated PV system at different penetration level

Fig 6.8 illustrates the voltage profile for EV charging incorporated PV system at different penetration level. The voltage is pushed up and the voltage variation is not problematic, indicating that voltage regulation is not required. Voltage was not found to violate limit conditions for the considered feeder N224.

6.5 Scenario 4: EVs Integrated with PVs Utilising storage Battery (Grid Connected with Storage)

Fig.6.9 shows energy charge and discharge comparison for the battery storage. It is shown the power being charge and discharge in the utility energy storage for the different percentage of PV penetration rate.

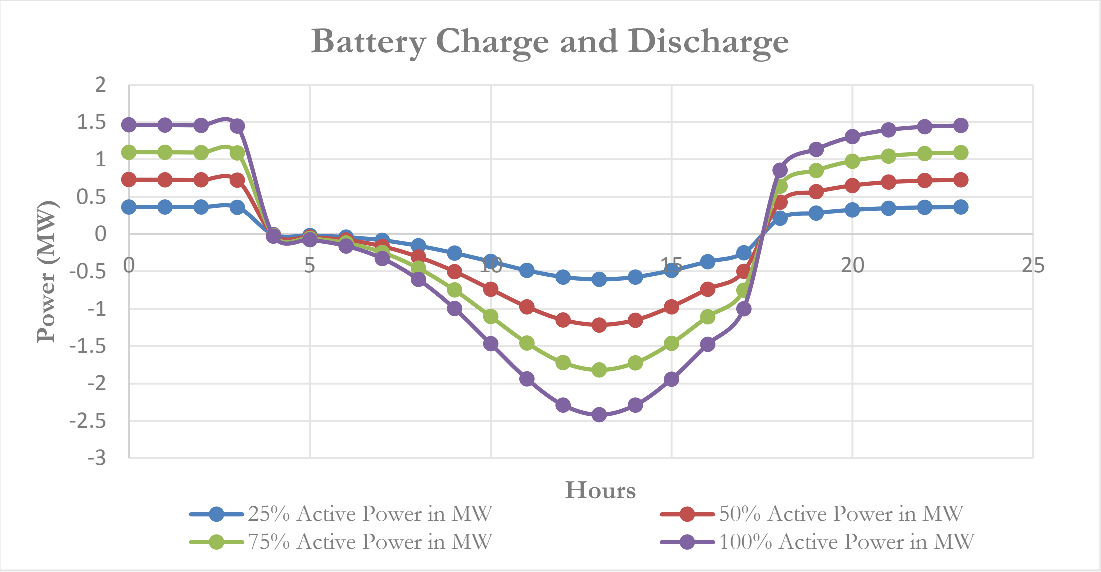

Figure 6-9: Energy charge and discharge comparison

6.5.1 Comparison of Result for 25% Penetration

Fig. 6.10, 6.11 and 6.12 shows simulation results of the grid-connected PV with storage for each 25% percentage of PV and EV penetration level. The obtained graphs present the effect of the utilisation of energy storage which resulted in 0.15 MW decrease for 25% increase in EV and PV penetration. This arrangement provides opportunities to supply backup for utility when power is insufficient and critical loads during utility outage. With grid connected configuration, PV generation reduces the power taken from the utility.

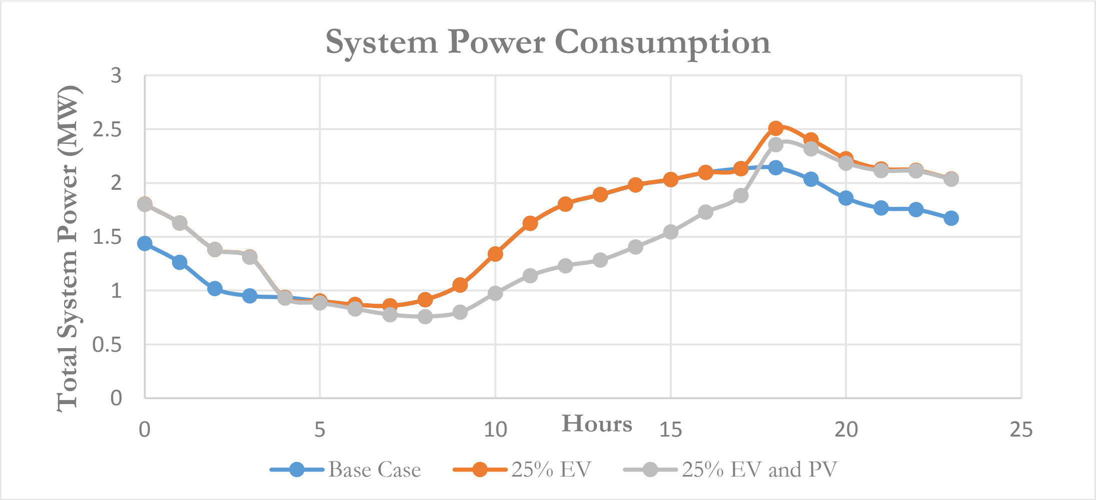

Figure 6-10: Total system power under 25% penetration (EV-PV) and storage

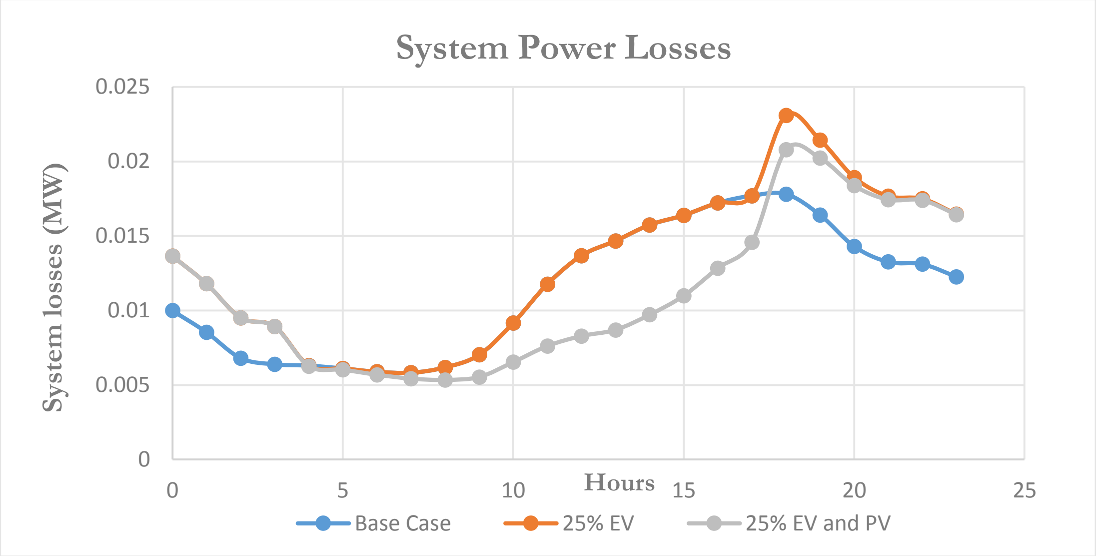

Figure 6-11: System power losses under 25% penetration (EV-PV) and storage

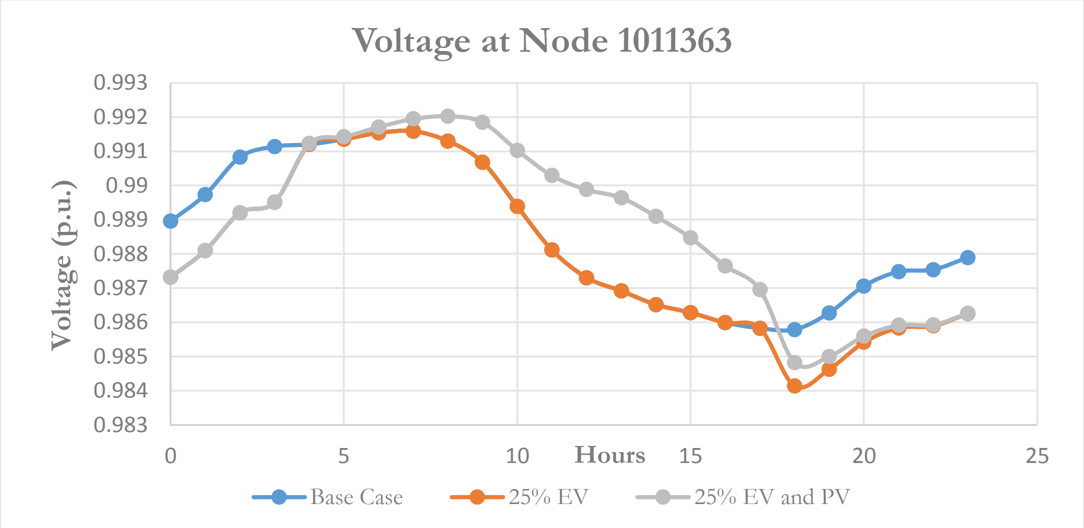

Figure 6-12: Voltage profile under 25% penetration (EV-PV) and storage

6.5.2 Comparison of Result for 50% Penetration

Fig 6.13, 6.14 and 6.15 show the total system power, system losses and voltage profile at the distribution feeder N224 under 50% EV and PV penetration level. In 50% penetration case the total power demand decreased 0.37 MW for 50% which is 10.7%, and no voltage violation occurred. The total power loss is acceptable. The following figures clearly show that the grid could sustain 50% of household having EV without any problem.

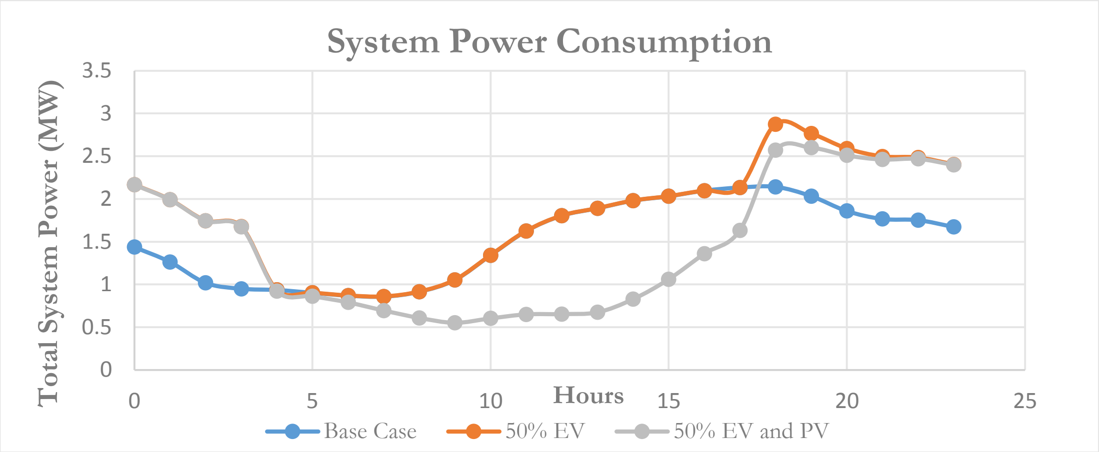

Figure 6-13: Comparison of total system power consumption under 50% penetration (EV-PV) and storage

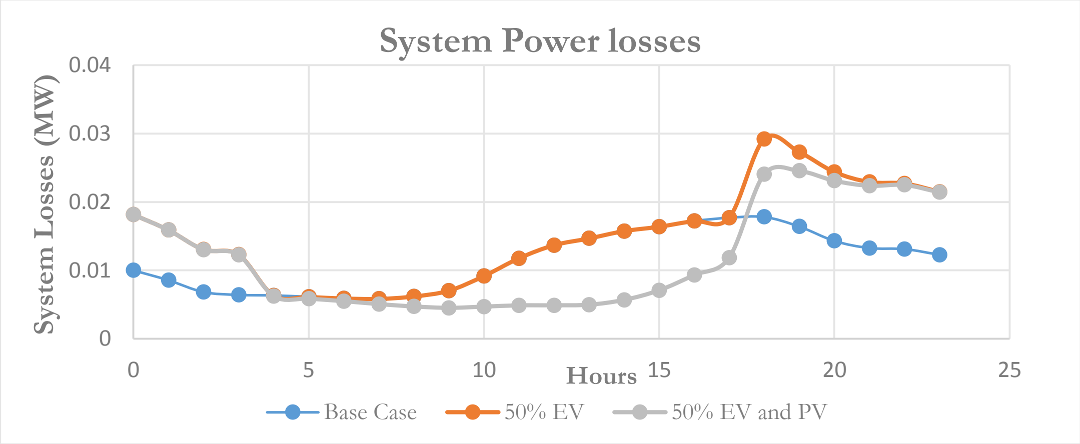

Figure 6-14: Comparison of system losses under 50% penetration (EV-PV) and storage

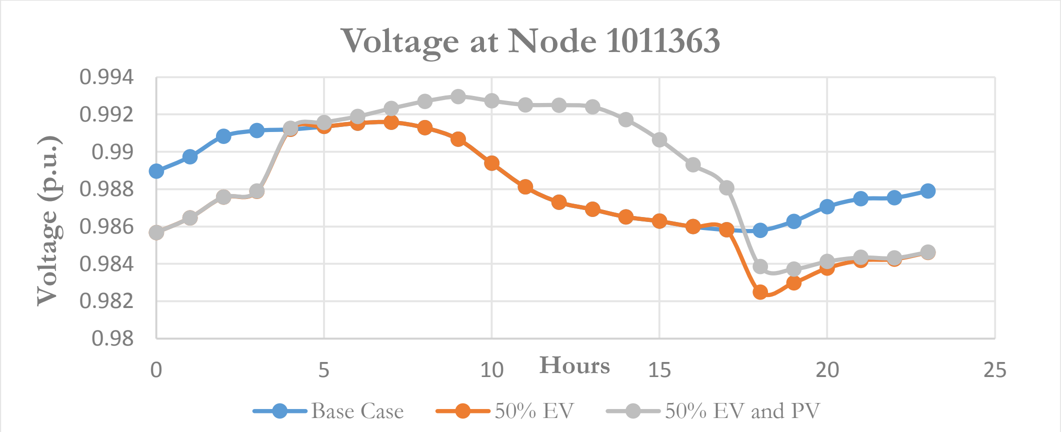

Figure 6-15: Comparison of voltage profile under 50% penetration (EV-PV) and storage

6.5.3 Comparison of Result for 75% Penetration

Fig 6.16, 6.17 and 6.18 show the total system power, system losses and voltage profile at the distribution feeder N224 in the 75% EV and PV penetration level. In the 75% penetration scenario, the total power demand decreased by 0.46 MW (15.6%) and no voltage violation occurred. The total power loss is acceptable. The following figures clearly show that the grid could sustain 75% of household having EV without any problem.

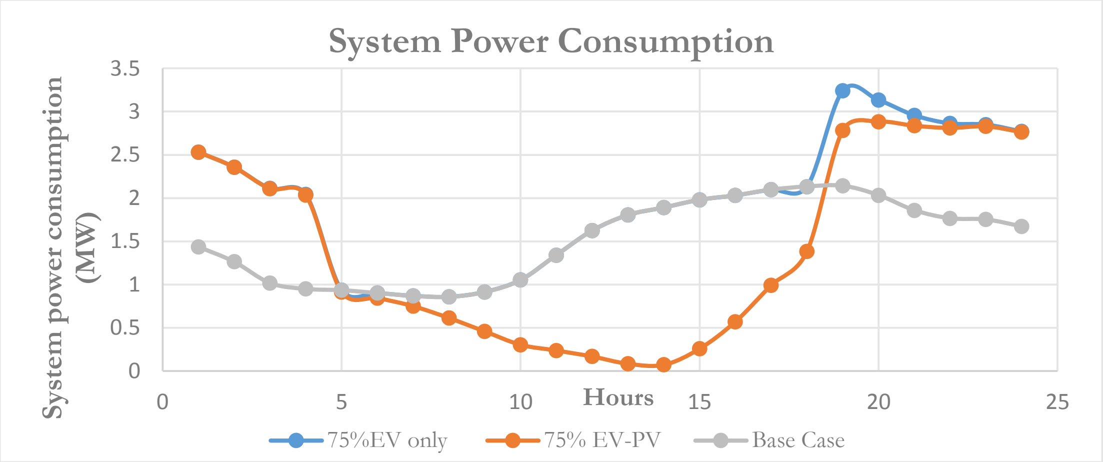

Figure 6-16: Comparison of total system power under 75% penetration (EV-PV) and storage

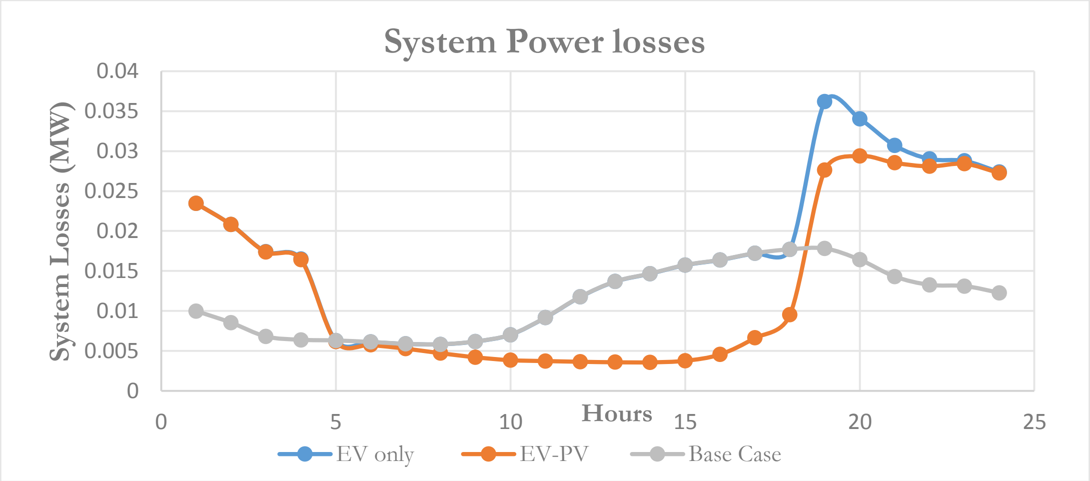

Figure 6-17: Comparison of system losses under 75% penetration (EV-PV) and storage

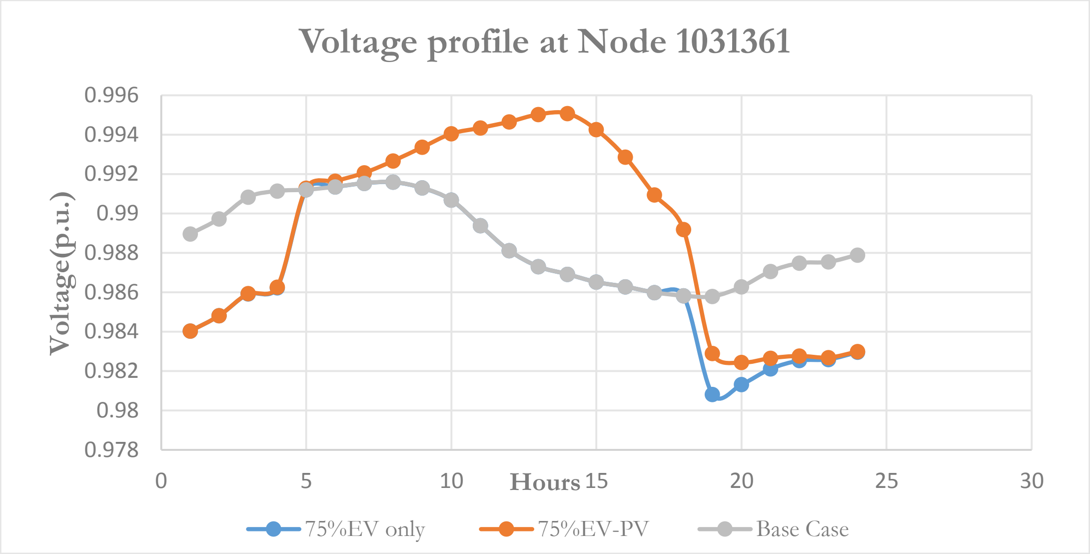

Figure 6-18: Comparison of voltage profile under 75% penetration (EV-PV) and storage

6.5.4 Comparison of Result for 100% Penetration

Fig 6.19, 6.20 and 6.21 show the total system power, system losses and voltage profile at the distribution feeder N224 under 100% EV and PV penetration level. In 100% penetration case the total power demand decreased by 0.71 MW (19.6%) and no voltage violation occurred. The total power loss is acceptable.

The simulation results of the solar integration scenario are illustrated. The following figures clearly show that when PV penetration increases to 100%, the PV systems are able to satisfy 100% EV power demand and to also export 0.52 MW power into the grid and the total power demand decreased by 0.86 MW (23.7%).

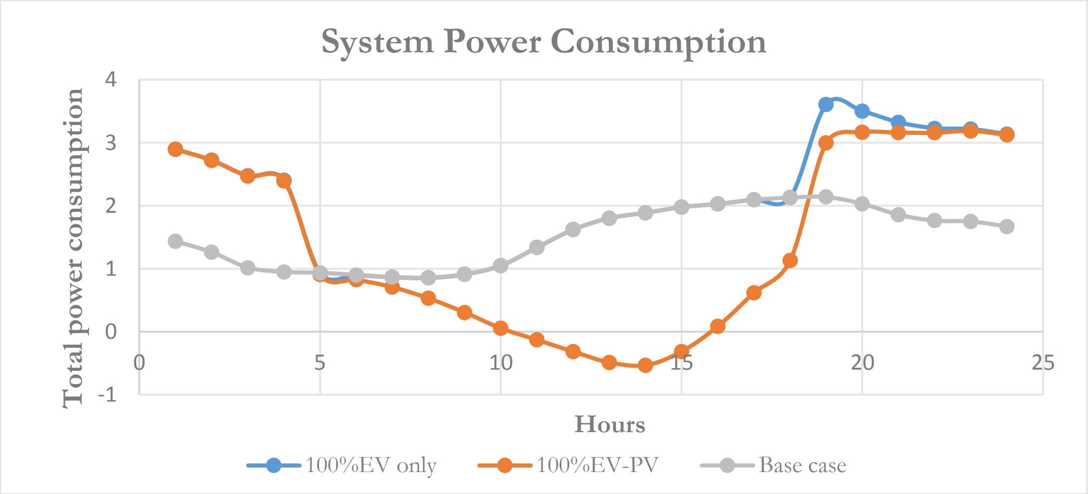

Figure 6-19: Comparison of power consumption under 100% penetration (EV- PV) and storage battery

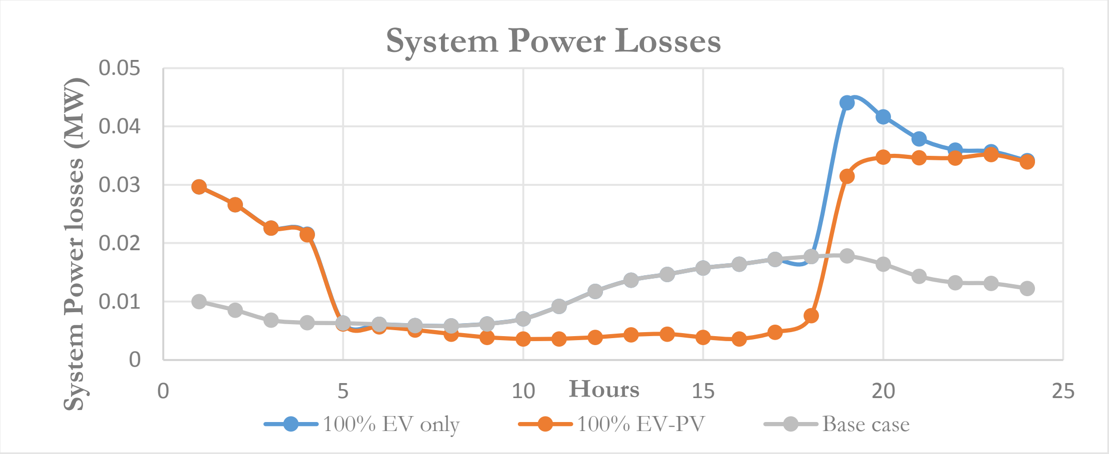

Figure 6-20: Comparison of system losses under 100% penetration (EV-PV) and storage

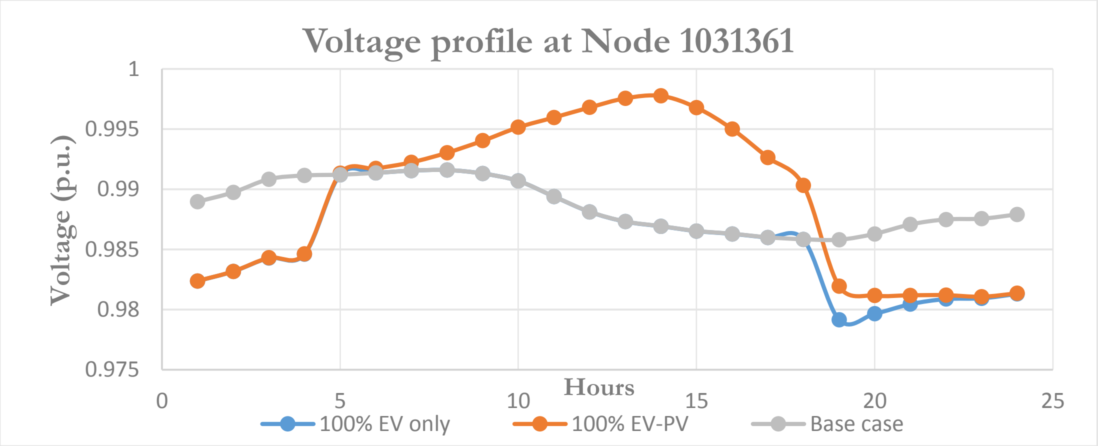

Figure 6-21: Comparison of voltage profile under 100% penetration (EV-PV) and storage

6.6 Discussion (Load Optimisation)

The inclusion of high penetrations of electric vehicles and solar photovoltaic generation had mixed impacts on the test distribution feeder. Increasing the number of vehicles increased the overall load of the system, which typically results in greater burden on the distribution system components, which in turn can cause a greater longer transformer overload periods. Increasing the PV arrays typically increased the burden on the voltage regulation. The combination of the two technologies yielded both positive and negative results, depending on the scale of the penetration of each of the technologies.

Without applying any charging strategies (unmanaged charging), the combined impacts of PEV and PV are often synergistic to a certain degree. The improvement in reduced distribution feeder overloading was about 15.6% when 50% of the homes were equipped with PV arrays at a 50% PEV penetration scenario. Additional PV penetration achieved diminishing returns on overloading improvements. For voltage control problems, the study indicated significant sensitivity to high penetrations of PV rooftop technology. The simulation showed no impacts on voltage control even up to about 100% of penetration... The additional load of PEVs is then reducing the voltage in the feeders and thus improving the overall voltage control. However, because of the non-coincidence between PEV charging and PV electricity output, the mitigation effectiveness is relatively weak.

6.7 Simulations performed for four scenarios

The resultant load demand curves obtained from incorporating additional electric vehicle loads ranging from 0-100% for the entire day. The loading profiles of the congested distribution line are illustrated in Fig. 6.11 to Fig. 6.22 for the uncontrolled and PV incorporated with energy storage charging modes respectively. The results showed that without incorporating electrical energy storage systems, the grid encountered power loss and voltage quality issues in high EV and PV penetration conditions. To mitigate the problems of unwanted shutdowns of PV systems, battery storage capacity was incorporated. Charging the battery during the daytime when solar is available and discharging the battery during the night when no energy is produced by PV panels. The charge interval is set to 08:00-16:00, while the remaining time the battery is discharged. If the discharge rate of the batteries higher than the consumption rate of the houses, excess is injected into the grid, which happens at more than 50% PV penetration.

The loading exceeds the 100% limit for the considered distribution feeder in the uncontrolled mode of charging. The congestion level of the most critical branch is exceeded when the electric vehicle load penetration is more than 100% for the uncontrolled mode. If the electric vehicles are following the controlled charging mode, the line loadings for all the lines are within the permissible loading range.

The distribution system losses on the peak demand distribution for both the uncontrolled and installed PVs with energy storage mode are illustrated. The losses are increased by 59% and 49% for the uncontrolled and controlled Scenarios mode respectively from 0% (reference scenario) to 100% of electric vehicle integration.

It can be inferred that the voltage drop in the feeder is more critical than the substation loading for the same levels of electric vehicle integration as evident from the results. Thus, the network parameters analysed so far act as limiting factors to higher levels of electric vehicle integration in a distribution network. The network utility has to utilise the energy storage in the grid capacity in order to handle the larger peaks, higher losses and congestions resulting from the electric vehicle integration. The electric vehicle loads are more distributed across the low system demand periods for charging mode. This results in a better method of integrating electric vehicles in a distribution network.

All the DIgSIELENT simulation result of the voltage and power plots resulting from employing the proposed method under mentioned scenarios are depicted in the Appendix 1, Appendix 2 and Appendix 3.

Chapter 7

Conclusion and Future Work

This dissertation presents the detailed modelling and development of a proposed Energy Management method for a LV network. Due to the current global transition towards alternative energy sources, the author selected to represent the DER integration into the main power network. In order to investigate to what extent existing electricity network infrastructures can support various penetrations of electric vehicles and the possibilities for distribution energy loss reduction, a complete model of a low voltage grid was developed. PEV, solar photovoltaic and battery energy storage characteristic behaviours and projections were presented to identify modelling needs to be addressed for the most successful integration of these technologies.

This study examined the impacts of random uncoordinated charging scenarios of residential PEV charging activity on a distribution system. The integration of these technologies from a technical perspective and how DES can be used as a means for satisfying local demands and mitigating impacts due voltage drop due to PEV charging and voltage increase as a result of PV system was investigated. A large capacity battery energy storage system of 500 kWh was utilised for an optimal distribution system operation and to facilitate the integration of distributed solar PV generation. Simulations were conducted for four case studies on an actual distribution feeder, and results have been presented and discussed. The results are promising in that they show that DES holds has the potential for mitigating the impacts of PEV charging and PV-DG interconnection.

By simulating the interaction of electric vehicles' users with electricity distribution networks and looking into different scenarios, insights were obtained into the energy saving potentials and also the possible barriers that might arise in the short term at the residential level.

The results of the simulation modelling show that if the charging process of the vehicles' batteries is left uncontrolled and unmonitored, then the gradual introduction of electric vehicles will have a negative impact on electricity distribution systems in terms of overloaded circuits and increased energy losses, but that the combined penetration of EVs and PV systems in the network, both the voltage drop and the voltage rise issue can be solved. The simulation indicated that without incorporating an energy storage system, the grid encountered voltage quality issues under high EV and PV system penetration conditions.

This finding indicates the need for developing charging control mechanisms and business models prior to the introduction of electric vehicles. Distribution networks are relatively extended and electric vehicle technology can play an important role in releasing the system's capacity and improving system reliability. An effective control mechanism would result in a higher utilisation ratio of assets, while preventing feeders and transformers from being overloaded.

Model results show that as vehicles return home and begin charging, they can cause a large increase in the peak demand on a network. In the suburban and urban networks, the peak simulated network demand is not high enough to cause overloading above the suggested network capacity. Thus, increased peak demand from PEV charging does not appear to be a significant concern for the reliable supply of power, even for high PEV penetrations of up to 100%. For the rural network, the measured peak demand is near the suggested network capacity. As a result, PEV penetrations in excess of 15% on this network cause overloads and excessive voltage drops during high demand days.

The results of this study has aid in developing an understanding of how EV consumers may utilize and recharge their vehicles and this improves the ability to make a general prediction of the state of charging networks for future developments. The same penetration rates for both technologies (PV, PEV) were considered.

Under four above mentioned scenarios, there is almost no increase in average household electricity usage by 2030 relative to current household electricity usage. However, if the residential consumer is unable to achieve a high rate of electricity efficiency improvement (as in Scenarios 1 and 2), the best option for the household is to install a solar PV system as this will result in a modest reduction in costs relative to retail supply only. By 2030, the projections indicate that it would be financially preferable for all residential consumers to have some type of on-site generation rather than to rely solely on the grid to supply all of the electricity.

The resulting power system may be expanded to help inform a discussion on how markets for near-real time energy management services may be structured. The unique contributions resulting from this work include:

- Studied PEV energy systems and limitations on battery charging/discharging
- Reviewed standards for interconnection of distributed resources and electric vehicle charging
- Explored strategies for distributed of PEV charging incorporated with PV system
- Developed a real distribution network simulator to accommodate PEV charging, and
- Developed a simulator combining a power system model and PEV components. There are several ways that the simulator may be extended to include more variables, and model more sophisticated behaviour including:

7.1 Future Work

- There are several ways that the simulator may be extended to include more variables, and model more sophisticated behaviour including:
- Plugging in at public charging stations,
- Interruption of charging,
- Effects of varying charge duration and supply amount,
- Unique battery characteristics and V2G controllers for each PHEV, and hybrid transmission-distribution system modelling.

The model developed and used in this study could be extended to include other forms of stationary distributed storage in place of the PEV. This could be a battery pack placed in the garage, a flywheel providing neighbourhood level storage, or any number of small scale energy storage systems. In addition, power systems PEV accommodating, ancillary services contributing to the accommodation of higher shares of renewable generation in the electric power system may be considered. The methodology can be extended to evaluate and optimize the design of multiple PEV chargers (such as in a public PEV charging application) that utilize multiple renewable distributed generation sources and storage units.

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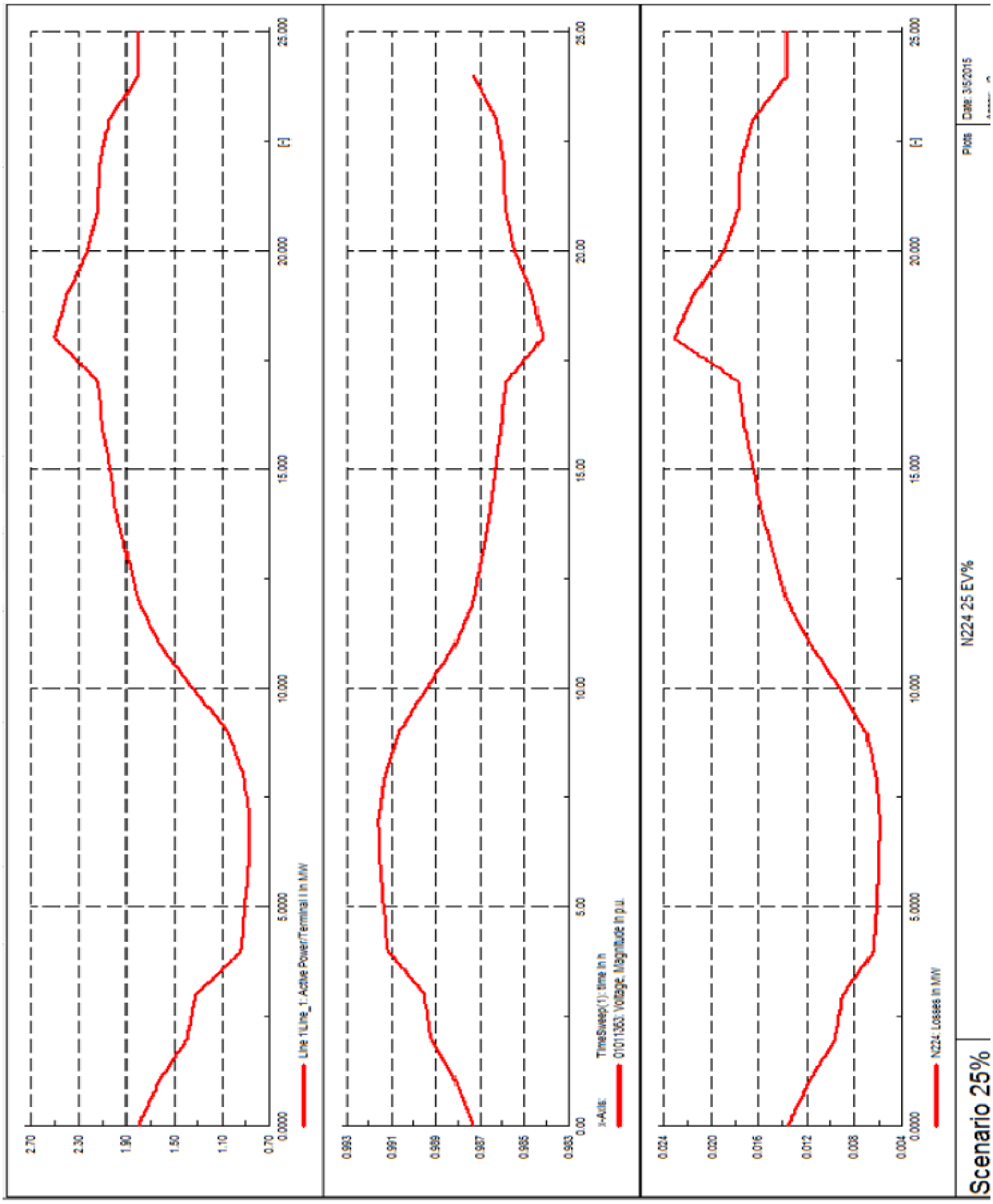
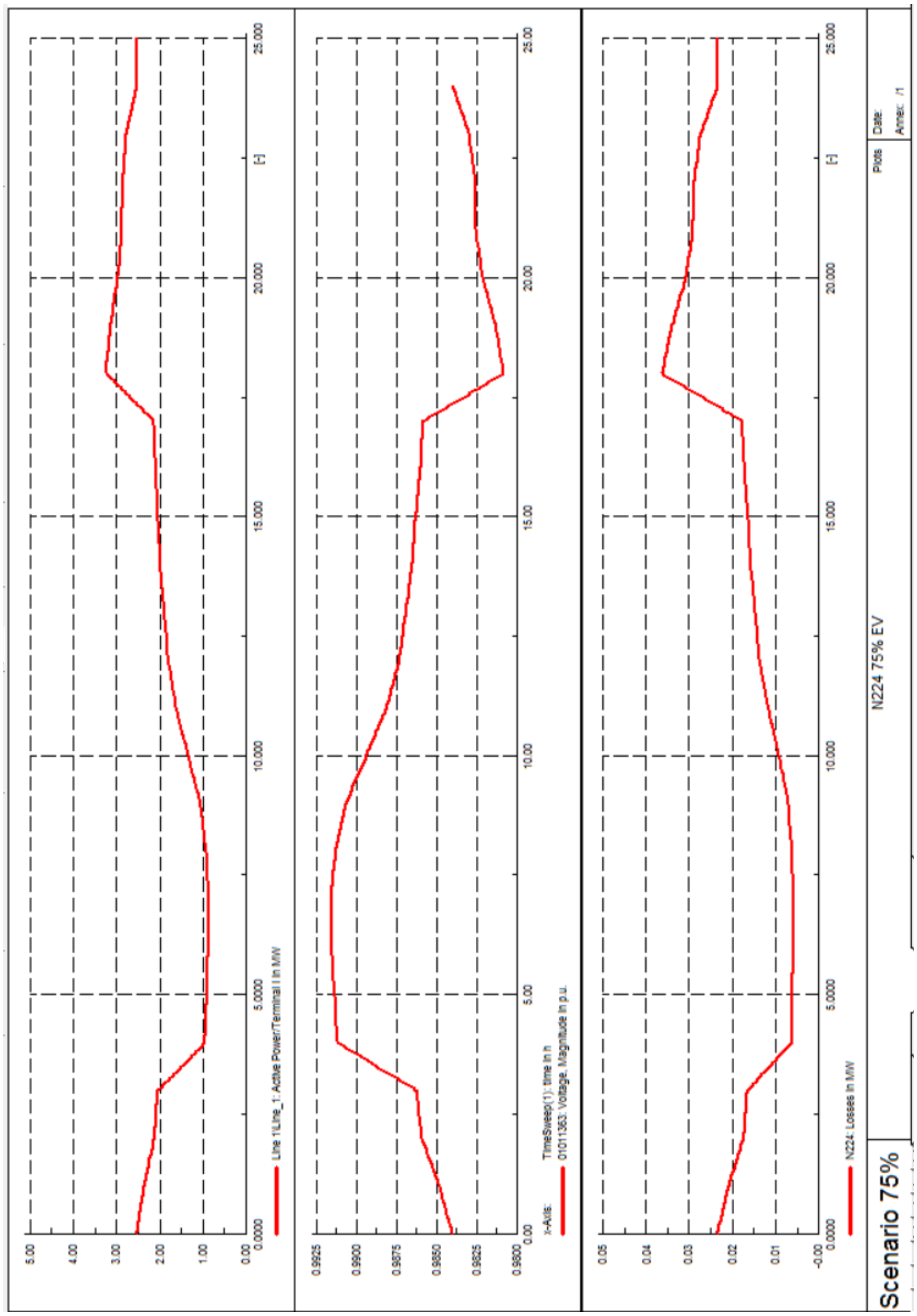
Appendix-1

Scenario 2: EV- 25% penetration

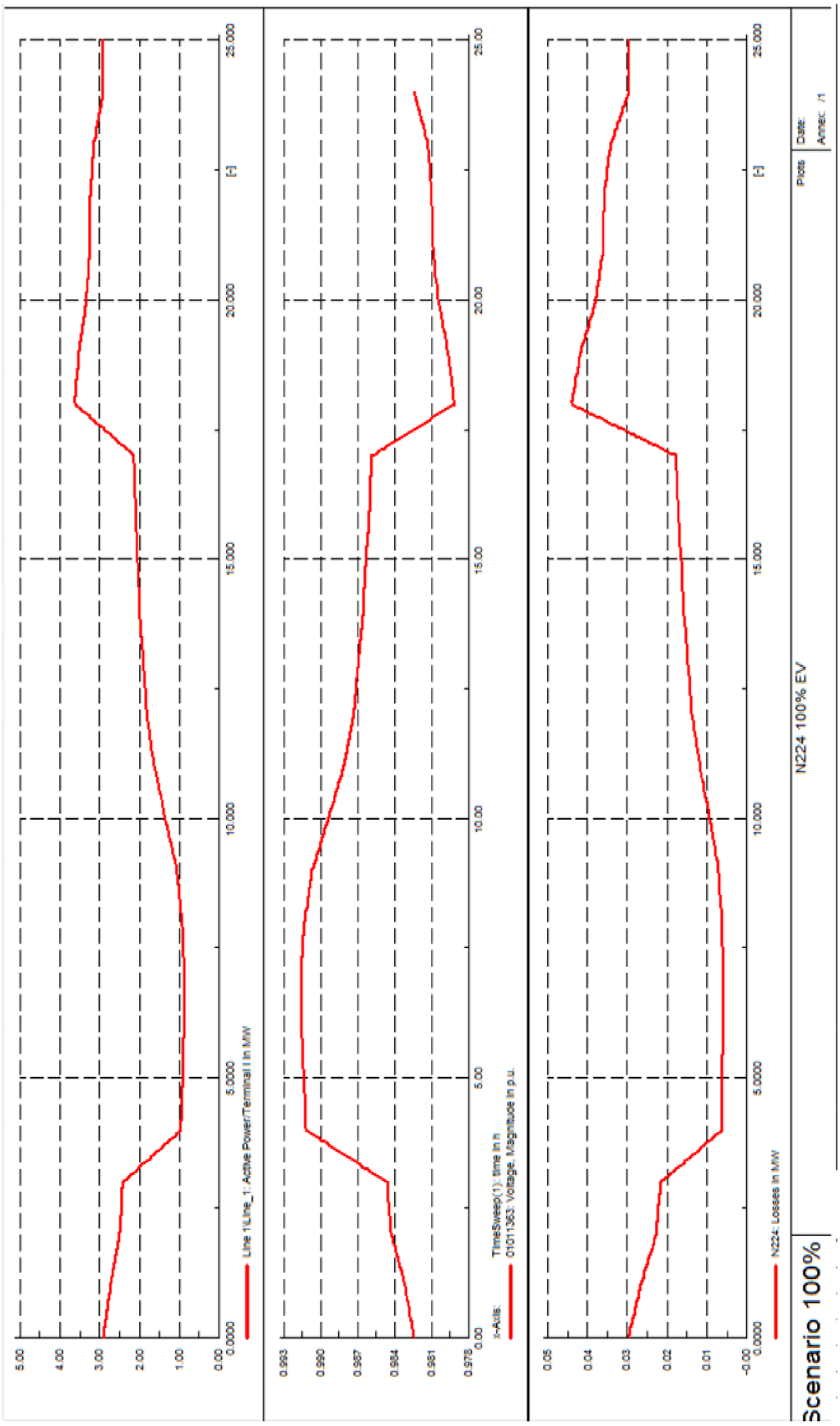


Scenario 2: EV-50% penetration

Scenario 2: EV- 75% penetration

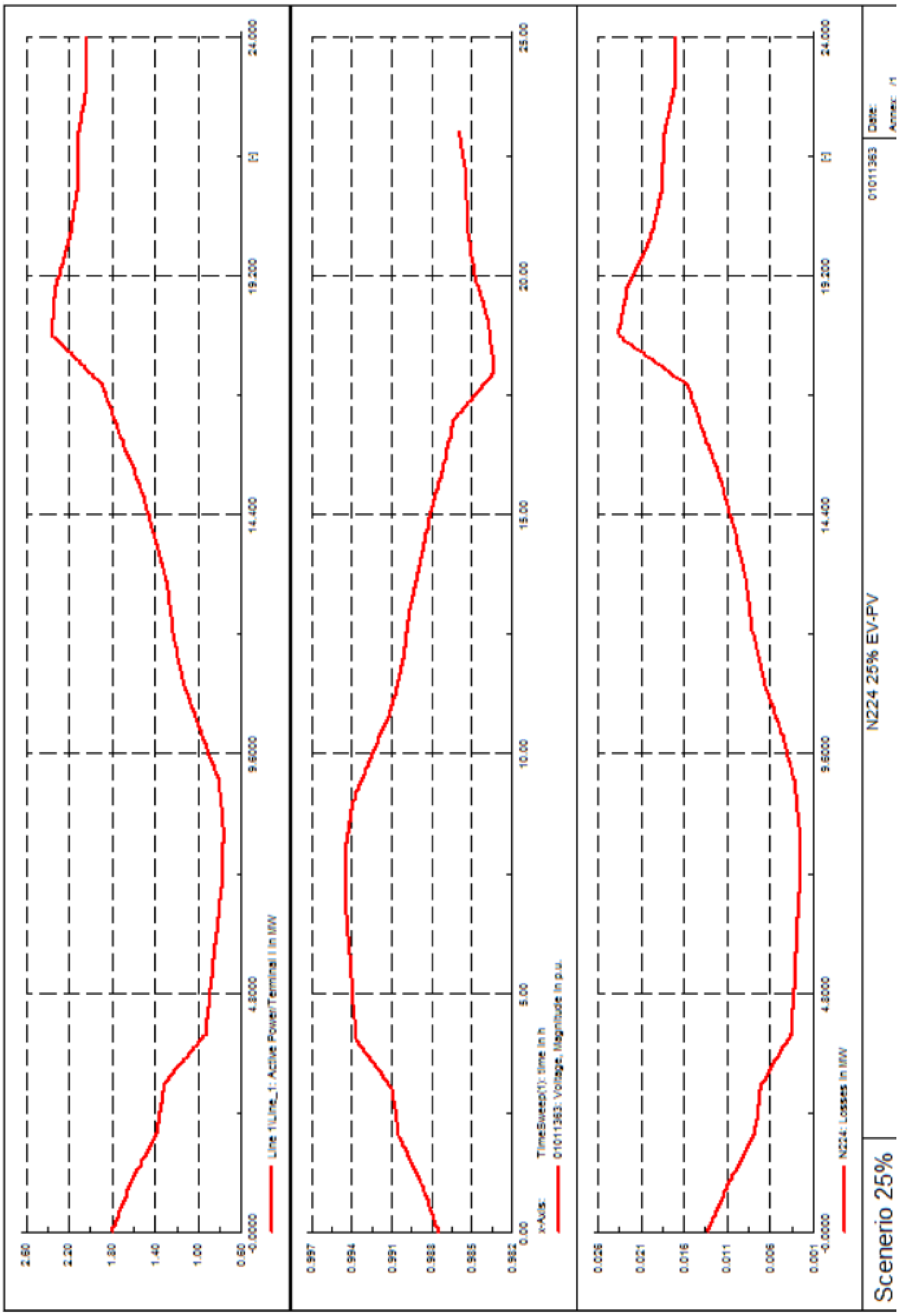


Scenario 2: EV- 100% penetration

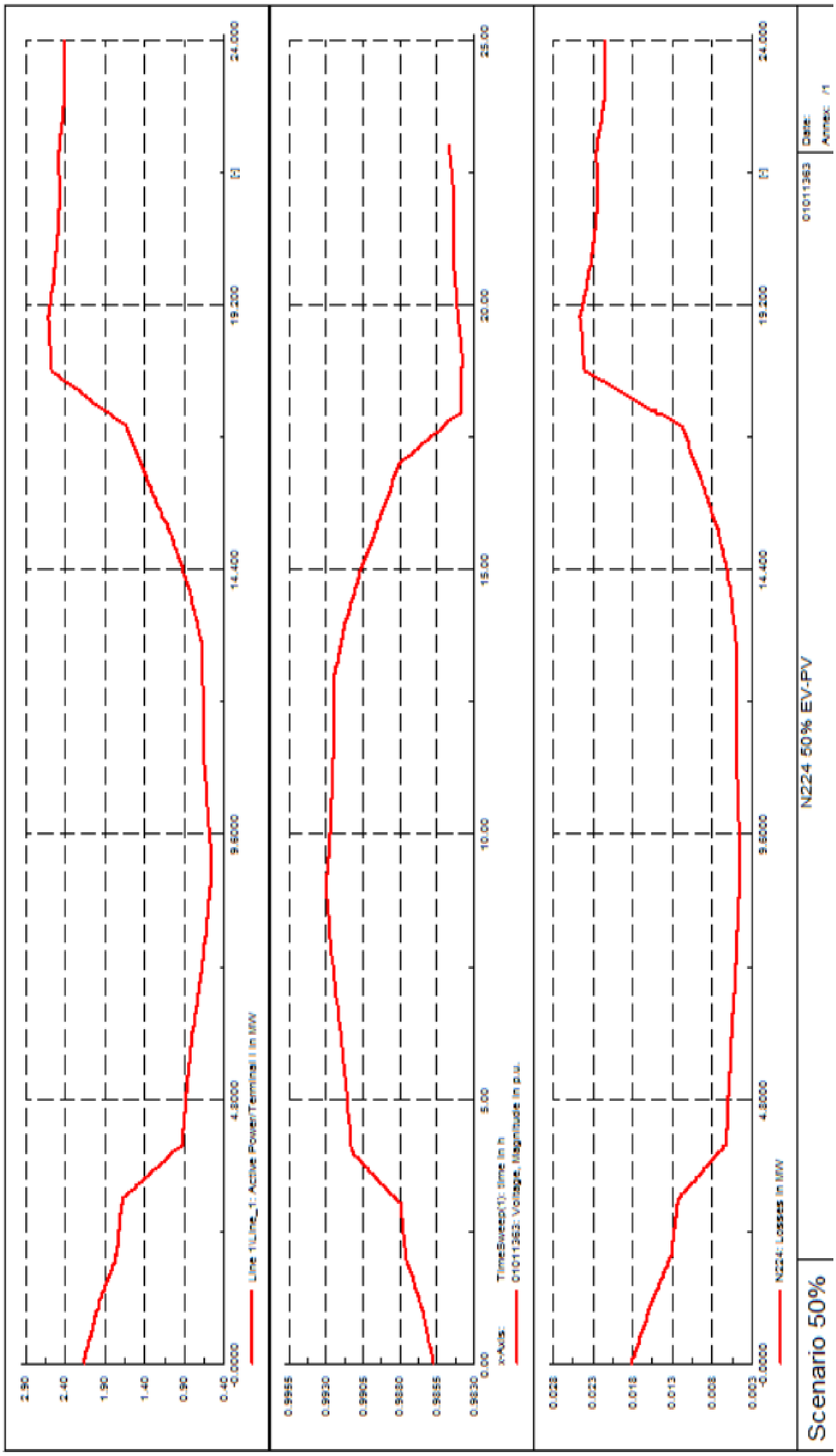


Appendix -2

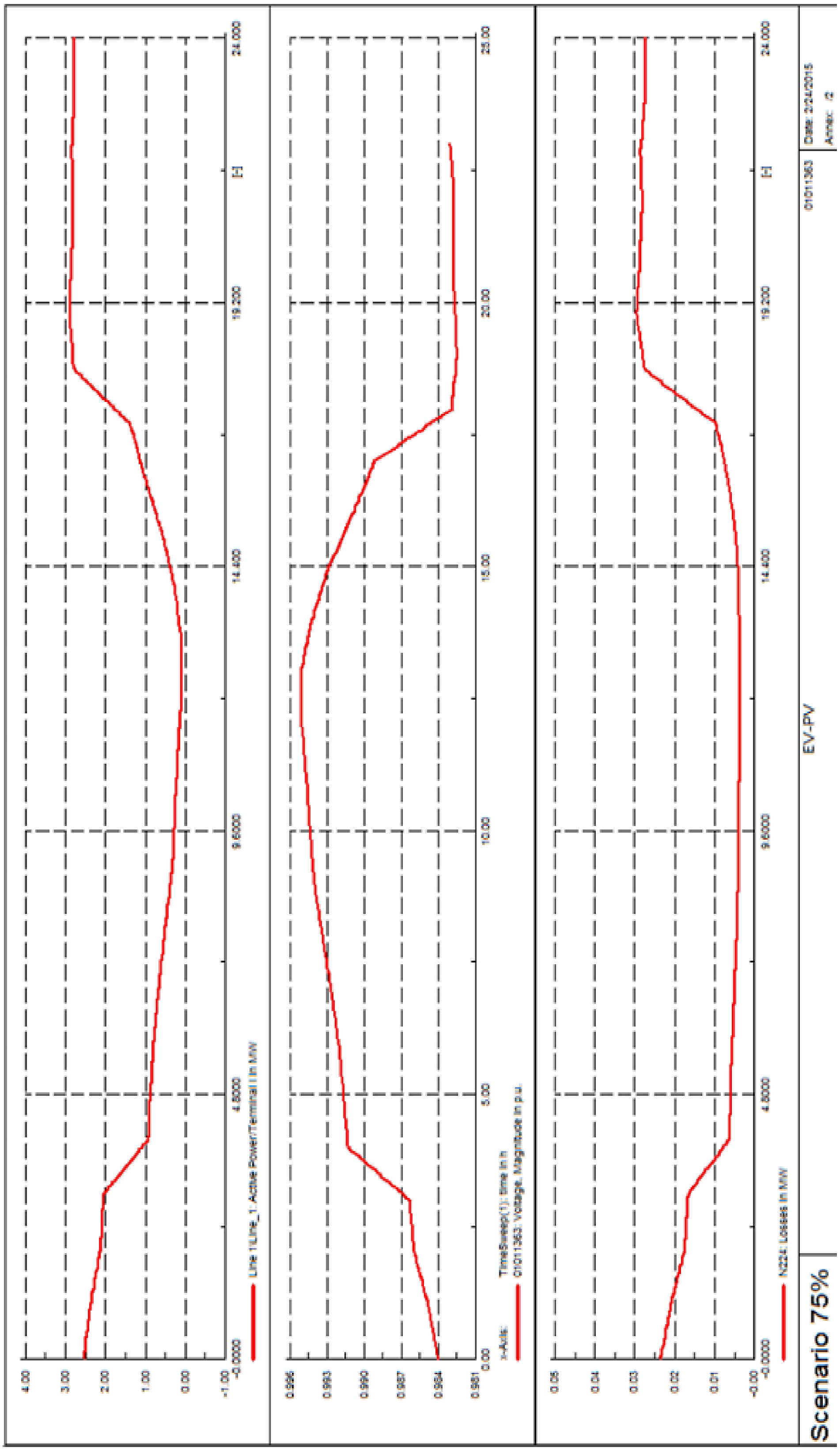
Scenario 3: EV-PV- 25% penetration



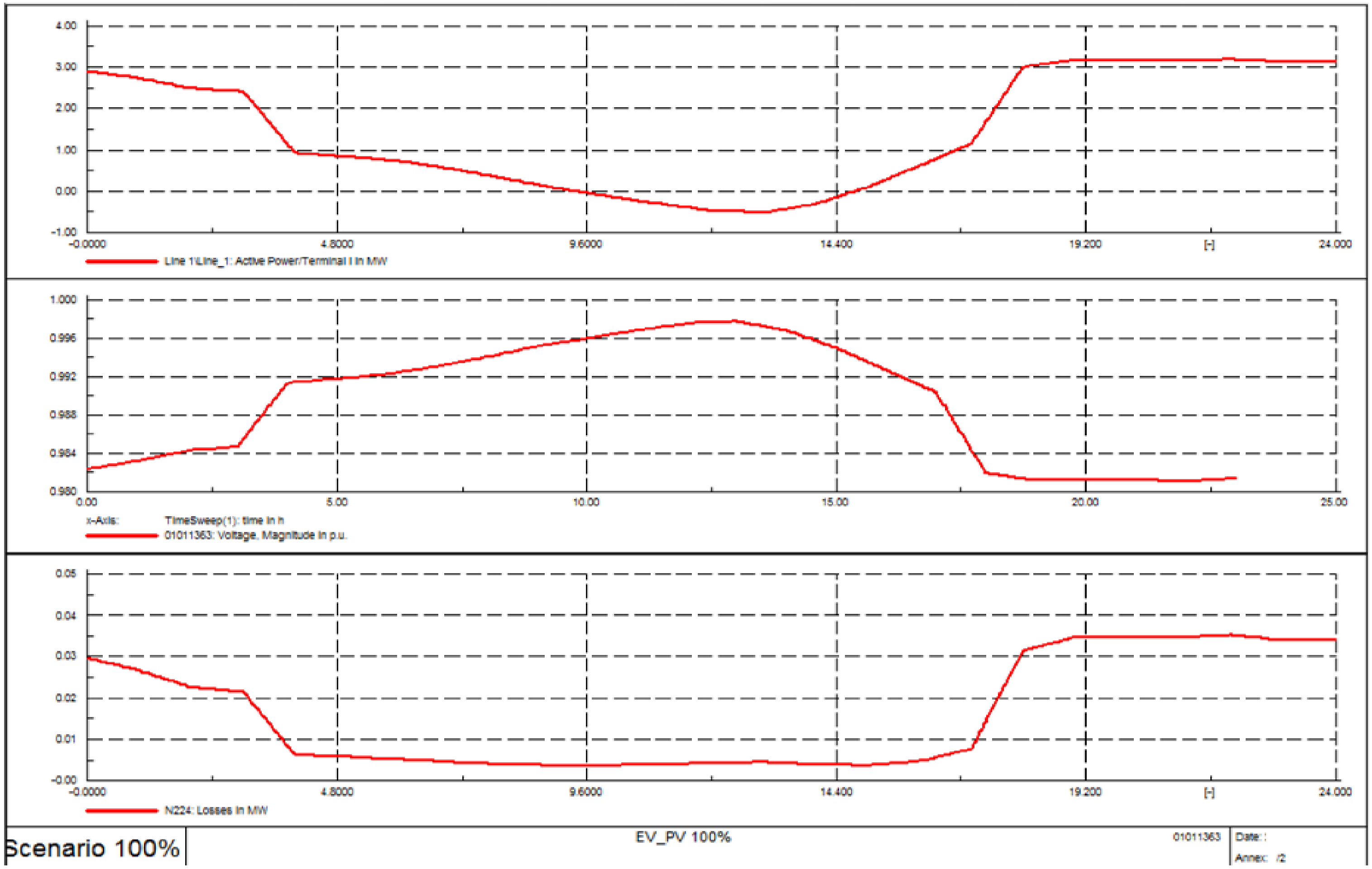
Scenario 3: EV-PV 50% penetration



Scenario 3: EV-PV 75% penetration

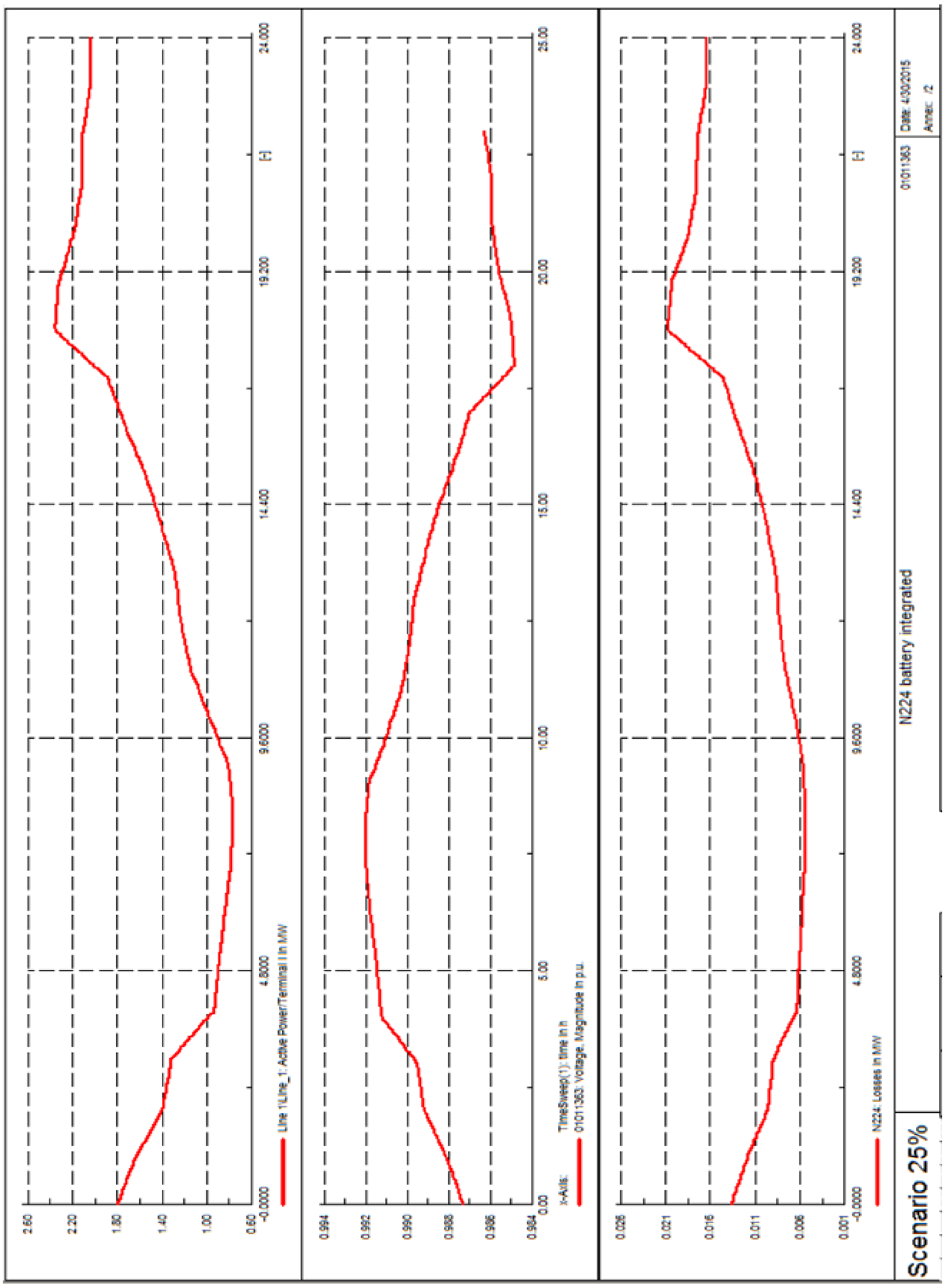


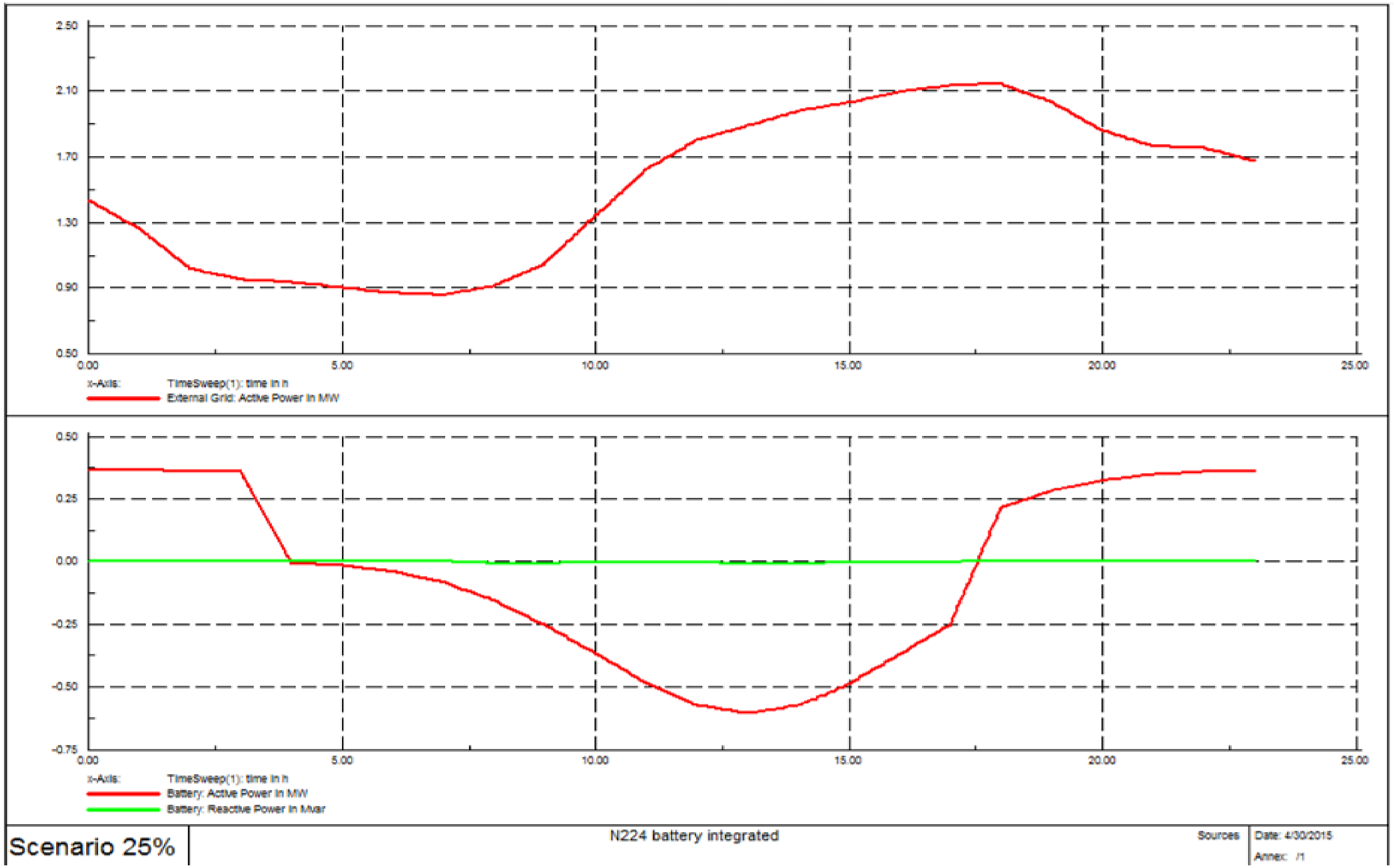
Scenario 3: EV-PV 100% penetration



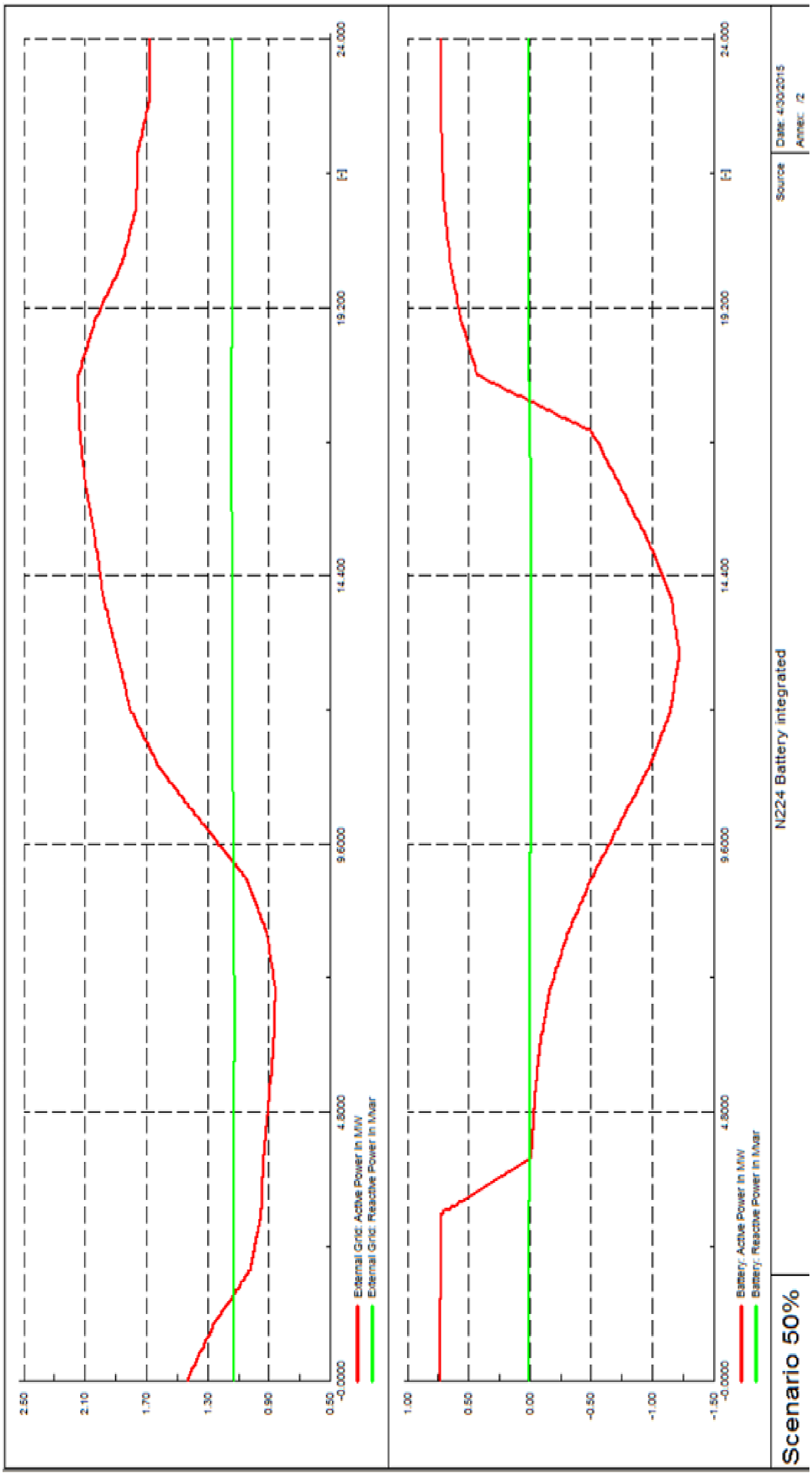
Appendix -3

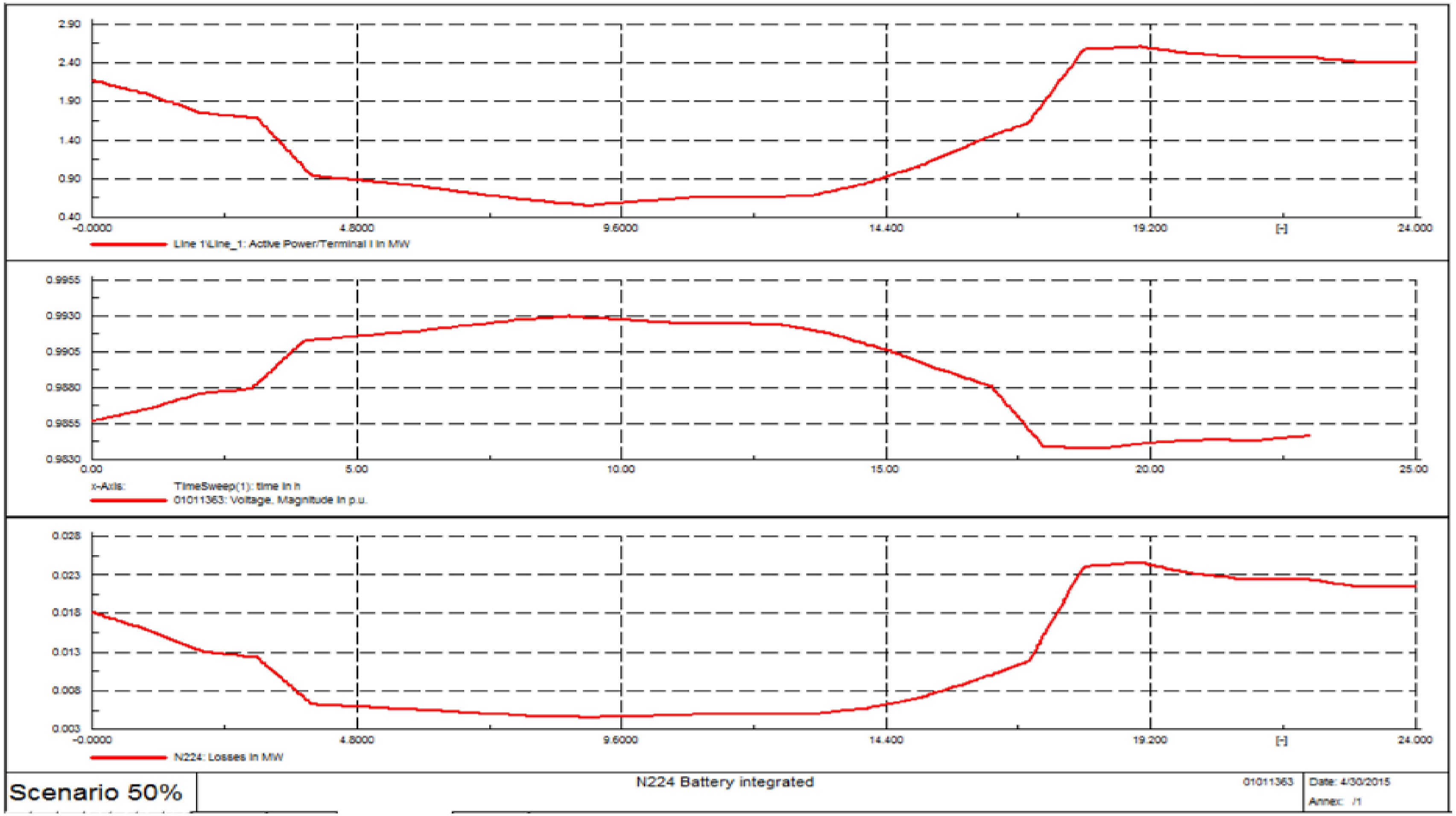
Scenario 4: Battery integrated- 25% penetration



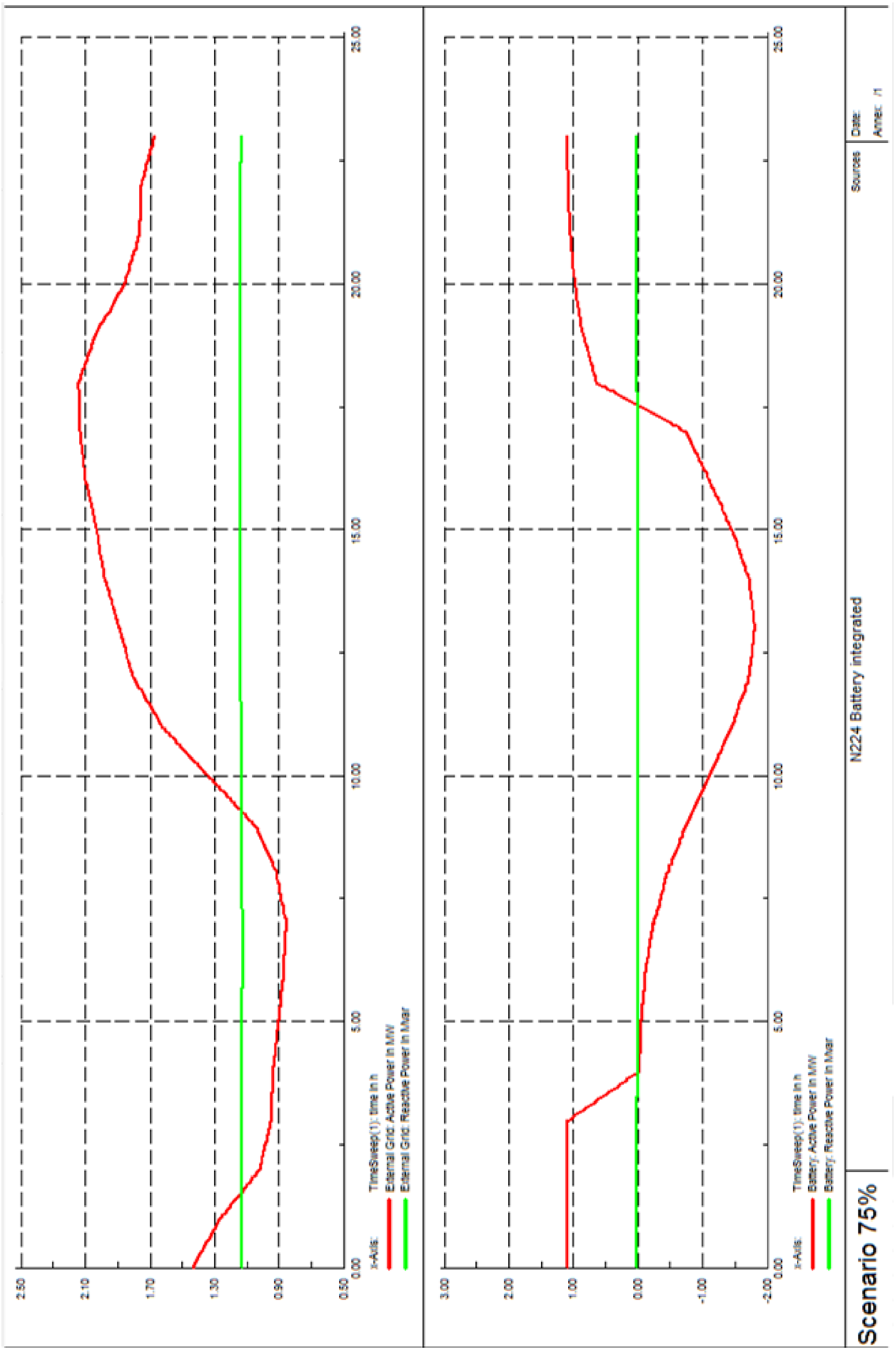

2.50
2.10
1.70
1.30
0.90
0.50
0.00
5.00
10.00
15.00
20.00
25.00
x-Axis:
TimeSweep(1): time in h
External Grid: Active Power in MW
0.50
0.25
0.00
-0.25
-0.50
-0.75
0.00
5.00
10.00
15.00
20.00
25.00
x-Axis:
TimeSweep(1): time in h
Battery: Active Power in MW
Battery: Reactive Power in Mvar
Scenario 25%
N224 battery integrated
Sources
Date: 4/30/2015
Annex: /1

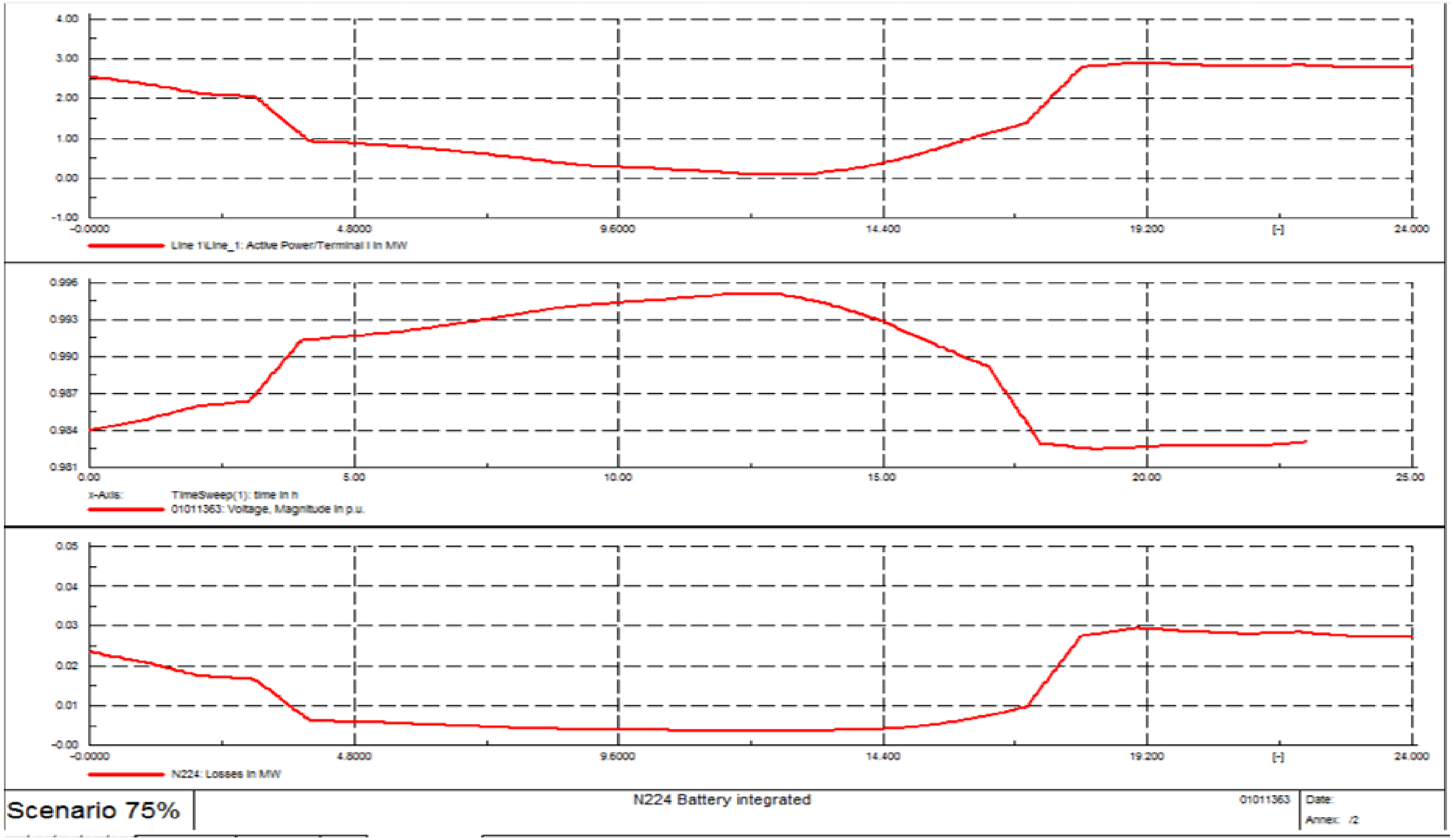
Scenario 4: Battery integrated- 50% penetration



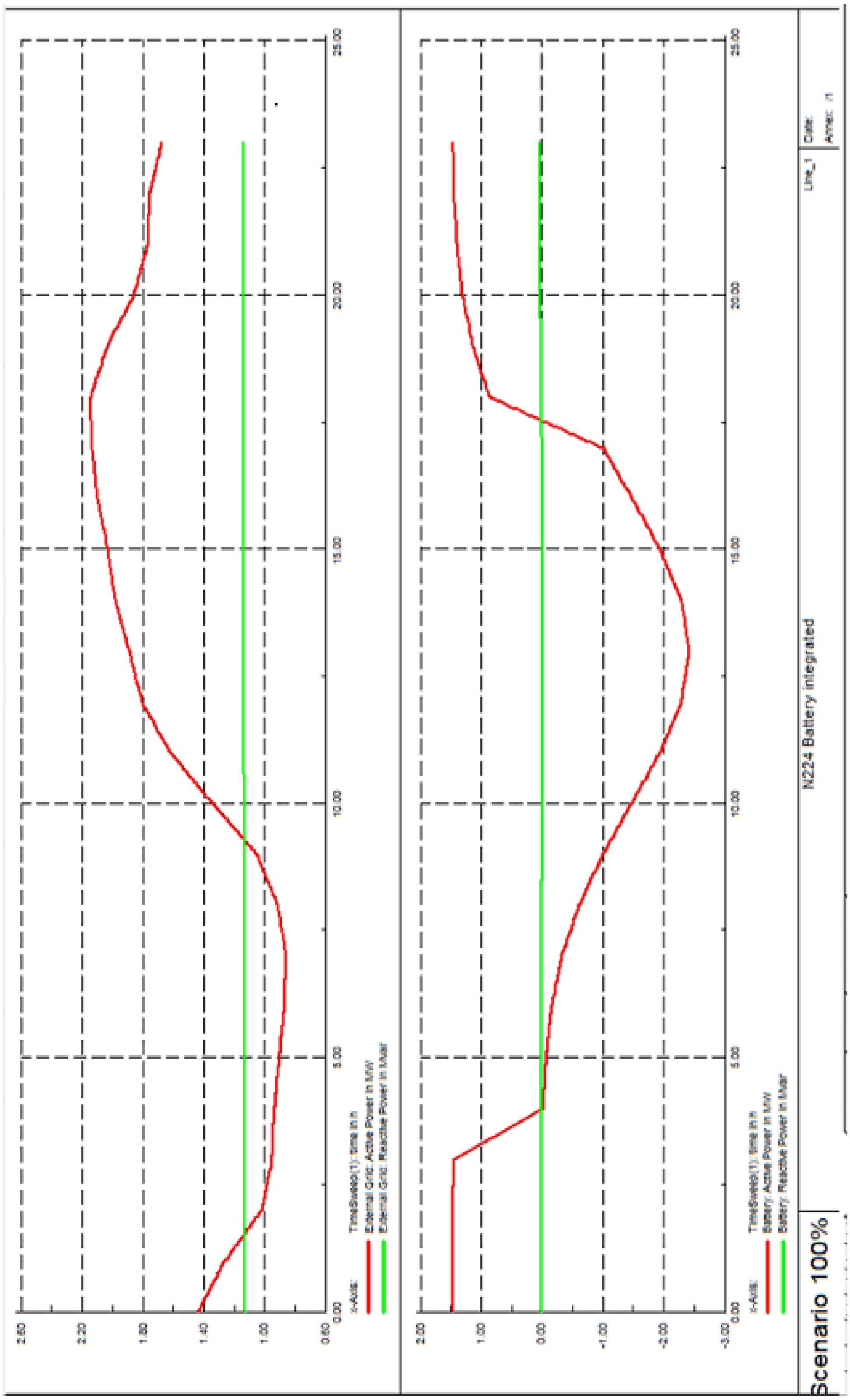

2.90
2.40
1.90
1.40
0.90
0.40
-0.0000
4.8000
9.6000
14.400
19.200
[-]
24.000
Line 1\Line_1: Active Power/Terminal i in MW
0.9955
0.9930
0.9905
0.9880
0.9855
0.9830
0.00
5.00
10.00
15.00
20.00
25.00
x-Axis: TimeSweep(1): time in h
01011363: Voltage, Magnitude in p.u.
0.028
0.023
0.018
0.013
0.008
0.003
-0.0000
4.8000
9.6000
14.400
19.200
[-]
24.000
N224: Losses in MW
Scenario 50%
N224 Battery integrated
01011363
Date: 4/30/2015
Annex: /1

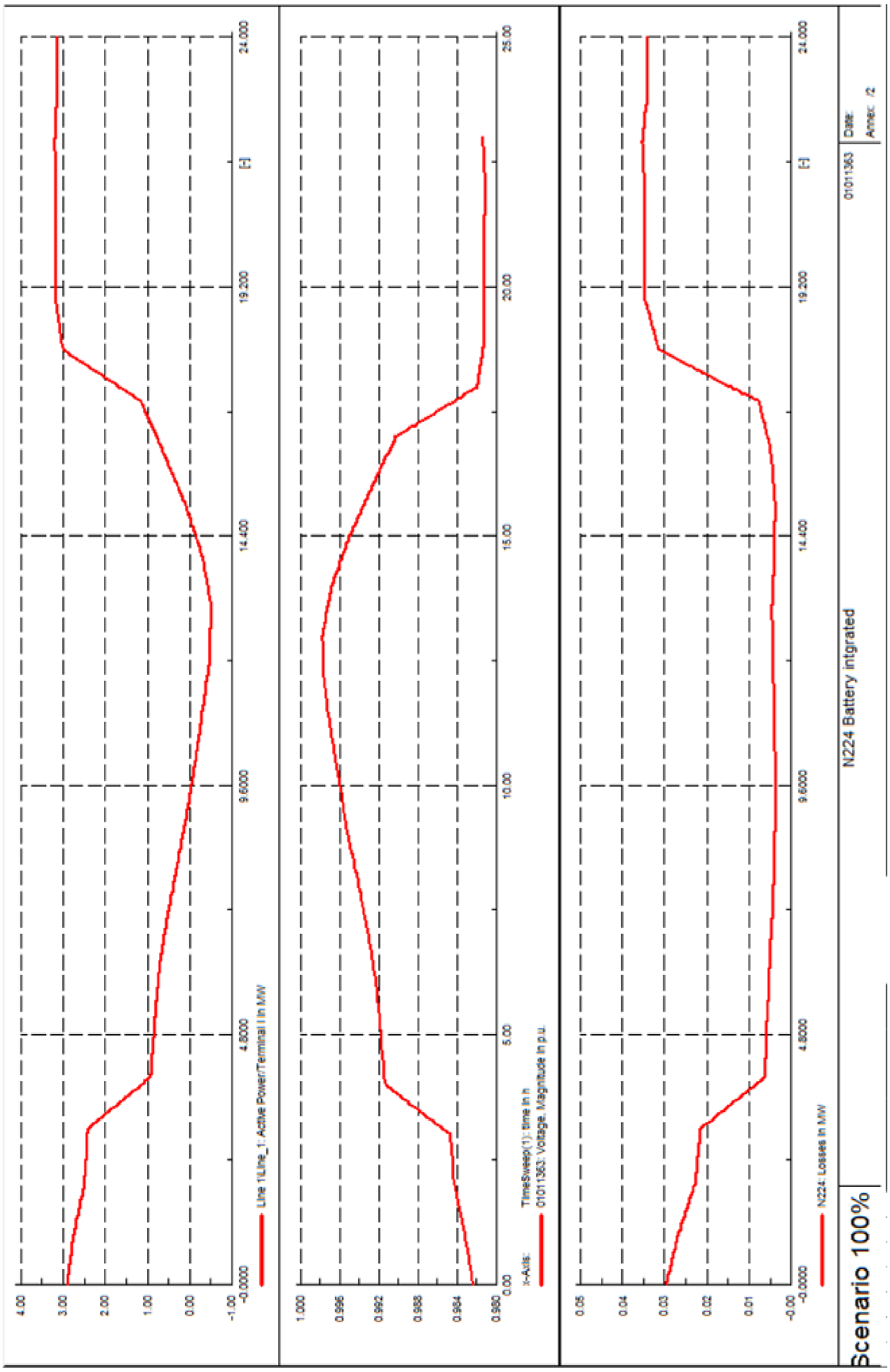
Scenario 4: Battery integrated- 75% penetration




4.00
3.00
2.00
1.00
0.00
-1.00
-0.0000
4.8000
9.6000
14.400
19.200
[-]
24.000
Line 1\Line_1: Active Power/Terminal i in MW
0.996
0.993
0.990
0.987
0.984
0.981
0.00
5.00
10.00
15.00
20.00
25.00
x-Axis:
TimeSweep(1): time in h
01011363: Voltage, Magnitude in p.u.
0.05
0.04
0.03
0.02
0.01
-0.00
-0.0000
4.8000
9.6000
14.400
19.200
[-]
24.000
N224: Losses in MW
Scenario 75%
N224 Battery integrated
01011363
Date:
Annex: /2

Scenario 4: Battery integrated- 100% penetration




4.00
3.00
2.00
1.00
0.00
-1.00
-0.0000
4.8000
9.6000
14.400
19.200
24.000
[-]
Line 1\Line_1: Active Power/Terminal i in MW
1.000
0.996
0.992
0.988
0.984
0.980
0.00
5.00
10.00
15.00
20.00
25.00
x-Axis:
TimeSweep(1): time in h
01011363: Voltage, Magnitude in p.u.
0.05
0.04
0.03
0.02
0.01
-0.00
N224: Losses in MW
Scenario 100%
N224 Battery intgrated
01011363
Date:
Annex: /2

Appendix -4

Nedlands real-time 30-minute load data

Time Start	1/1/2012									
Time End	1/1/2013									
Time Interval	30m									
Time stamp	N T1 LV MVAR	N T1 LV MW	T1 MVA	N T2 LV MVAR	N T2 LV MW	T2 MVA	N T3 LV MVAR	N T3 LV MW	T3 MVA	**Sum Sub Load**
25-Jan-12 00:00:00	-1.799999952	-4.314844575	4.675241548	-2.211924994	-5.105386319	5.563953778	-1.885311949	-4.135146794	4.54465	14.78384494
25-Jan-12 00:30:00	-1.680266628	-4.187399994	4.51194134	-2.170708284	-4.877444235	5.338673686	-1.896705147	-3.983487153	4.411991	14.26260554
25-Jan-12 01:00:00	-1.679999948	-4.023733421	4.36037045	-2.103196544	-4.712930708	5.160925456	-1.801672244	-3.814698962	4.218762	13.7400577
25-Jan-12 01:30:00	-1.679999948	-4	4.338478976	-2.062123005	-4.55661582	5.001509674	-1.780350308	-3.697169945	4.1035	13.44348872
25-Jan-12 02:00:00	-1.679999948	-3.962800051	4.304205393	-2.065873839	-4.428678729	4.886822076	-1.757820797	-3.605602419	4.011272	13.20229943
25-Jan-12 02:30:00	-1.679999948	-3.91753295	4.262565452	-2.03085389	-4.306079951	4.760954953	-1.719717804	-3.52334555	3.920637	12.94415724
25-Jan-12 03:00:00	-1.679999948	-3.820866557	4.173897588	-2.005512755	-4.241125486	4.691399237	-1.735955875	-3.42875976	3.843167	12.70846431
25-Jan-12 03:30:00	-1.679999948	-3.846422233	4.197304352	-1.888712194	-4.125104963	4.536928995	-1.624670432	-3.352714405	3.72562	12.45985382
25-Jan-12 04:00:00	-1.679999948	-3.706066714	4.069069957	-1.970095226	-4.159393158	4.60237185	-1.6290553	-3.314088499	3.692831	12.36427321
25-Jan-12 04:30:00	-1.638933328	-3.66886644	4.018293594	-1.961197776	-4.104433975	4.548920198	-1.568900325	-3.179223292	3.545266	12.1124795
25-Jan-12 05:00:00	-1.606534388	-3.657601103	3.994871534	-1.965297082	-4.084111985	4.532368401	-1.549738726	-3.197941163	3.553663	12.08090252
25-Jan-12 05:30:00	-1.629799843	-3.691334259	4.035120338	-1.875460663	-3.929672007	4.354270867	-1.478809697	-3.176378807	3.503749	11.89314069
25-Jan-12 06:00:00	-1.719798834	-3.87328825	4.237932267	-1.893844297	-4.063296876	4.482970859	-1.583312306	-3.51560723	3.855693	12.57659659
25-Jan-12 06:30:00	-1.785757464	-4.101952217	4.473806178	-2.155447241	-4.653685364	5.128619725	-1.638313267	-3.643269376	3.994682	13.59710763
25-Jan-12 07:00:00	-1.867533221	-4.459422189	4.834679575	-2.296596152	-5.123782452	5.614935485	-1.812730841	-4.113012538	4.49476	14.94437481
25-Jan-12 07:30:00	-2.184042889	-4.992953709	5.449736698	-2.570630771	-5.800587998	6.344679951	-2.012962697	-4.550894123	4.976209	16.77062566
25-Jan-12 08:00:00	-2.443310865	-5.679532331	6.182787032	-2.838708549	-6.451809779	7.048696025	-2.142838274	-4.993797709	5.43413	18.66561329
25-Jan-12 08:30:00	-2.725733164	-6.278064938	6.844247267	-2.344999809	-7.20708748	7.578992944	-2.419082929	-5.620313052	6.118814	20.54205391
25-Jan-12 09:00:00	-2.922266522	-6.876044049	7.471253134	-1.019016657	-8.11982404	8.1835162	-2.521979873	-6.149571605	6.646624	22.30139354
25-Jan-12 09:30:00	-3.012733201	-7.371576464	7.96346036	-1.121596261	-8.508989708	8.582591917	-2.613753791	-6.394911496	6.908444	23.45449653
25-Jan-12 10:00:00	-3.119999886	-7.635777816	8.248606073	-1.183530929	-8.799932783	8.879164513	-2.701476213	-6.591425968	7.123543	24.25131395
25-Jan-12 10:30:00	-3.175400064	-7.857777152	8.47512993	-1.198244732	-8.979573555	9.059168376	-2.920630685	-6.865270897	7.460699	24.99499721
25-Jan-12 11:00:00	-3.192466834	-7.999844365	8.613324233	-1.209064542	-9.060495028	9.140809987	-2.988016689	-6.977779001	7.590629	25.34476289
25-Jan-12 11:30:00	-3.359999895	-8.100622852	8.769816981	-1.299234803	-9.234511083	9.325460097	-3.07875838	-7.134397116	7.770352	25.86562941
25-Jan-12 12:00:00	-3.437665423	-8.376107778	9.054099904	-1.374388849	-9.457635693	9.556977431	-3.106594889	-7.350945575	7.980434	26.5915117
25-Jan-12 12:30:00	-3.36440002	-8.512333013	9.153086956	-1.463239208	-9.724031939	9.833507316	-3.09278909	-7.477056757	8.09146	27.0780541
25-Jan-12 13:00:00	-3.360533181	-8.593266487	9.22699367	-1.495907124	-9.858467494	9.971314831	-3.095854747	-7.654186752	8.256567	27.45487507
25-Jan-12 13:30:00	-3.393727736	-8.721541034	9.358561105	-1.586422139	-10.04394596	10.16846033	-3.090620736	-7.729438447	8.324431	27.85145266
25-Jan-12 14:00:00	-3.493139907	-8.867689954	9.530894582	-1.80302493	-10.34427891	10.50023833	-3.180481326	-7.754127404	8.381047	28.41218018
25-Jan-12 14:30:00	-3.548933456	-8.883133443	9.565823981	-1.752385113	-10.41175171	10.55819242	-3.196367684	-7.782346652	8.413185	28.53720164
25-Jan-12 15:00:00	-3.60519946	-9.021575557	9.715260607	-1.769752598	-10.50286039	10.65092018	-3.199974008	-7.846649112	8.474063	28.84024333
25-Jan-12 15:30:00	-3.639999866	-9.093868114	9.795306851	-1.785371704	-10.52536929	10.67571781	-3.234787624	-7.906676875	8.542798	29.01382222
25-Jan-12 16:00:00	-3.639999866	-9.056865417	9.76096359	-1.792463459	-10.65666505	10.80636087	-3.263513909	-7.976541242	8.618337	29.18566149
25-Jan-12 16:30:00	-3.528733552	-8.8851319	9.560205508	-1.76957815	-10.63120811	10.77747617	-3.177396452	-8.027210036	8.633189	28.9708705
25-Jan-12 17:00:00	-3.370577674	-8.601067345	9.237919318	-1.662295869	-10.3760319	10.50834267	-3.137706213	-7.928792613	8.527072	28.27333373
25-Jan-12 17:30:00	-3.208266662	-8.244045212	8.846313155	-1.472264582	-9.838082394	9.947634302	-3.081061974	-7.640854642	8.238665	27.03261255
25-Jan-12 18:00:00	-3.001200158	-7.865999947	8.419094818	-1.209335336	-9.344526363	9.422455355	-2.945514428	-7.428198865	7.990882	25.83243208
25-Jan-12 18:30:00	-2.960000038	-7.771134307	8.315775889	-1.950534431	-9.190912093	9.395607999	-3.00991103	-7.250641866	7.850565	25.56194896
25-Jan-12 19:00:00	-2.861533319	-7.474266232	8.003313604	-3.585169035	-8.77098519	9.475421796	-2.834768892	-6.991158762	7.544019	25.02275393
25-Jan-12 19:30:00	-2.693866581	-7.462533555	7.933871956	-3.503547022	-8.806481104	9.477813629	-2.77213496	-7.039792588	7.565938	24.97762319
25-Jan-12 20:00:00	-2.679999828	-7.417487114	7.886793655	-3.543412838	-8.976267957	9.650345122	-2.787672689	-6.954138025	7.492073	25.02921157
25-Jan-12 20:30:00	-2.679999828	-7.349866211	7.823230305	-3.544398506	-8.914414462	9.593203113	-2.808456485	-6.786129401	7.344316	24.76074959
25-Jan-12 21:00:00	-2.5560665	-7.082237473	7.529380026	-3.515617894	-8.768266879	9.446802275	-2.794029646	-6.621269024	7.186641	24.16282304
25-Jan-12 21:30:00	-2.395933438	-6.532579078	6.95809503	-3.444393391	-8.408208722	9.08635349	-2.600058565	-6.171421146	6.696771	22.74121965
25-Jan-12 22:00:00	-2.197733387	-6.085999986	6.470658998	-3.238124625	-7.884322413	8.523379083	-2.442726626	-5.823231376	6.314819	21.30885693
25-Jan-12 22:30:00	-2.119999886	-5.69422217	6.076064979	-3.044883363	-7.287758409	7.898274326	-2.42079913	-5.494410151	6.004066	19.97840554
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25-Jan-12 23:30:00	-2	-5.031044413	5.414001097	-2.58258018	-5.952136918	6.488270515	-2.10890046	-4.820466418	5.261593	17.1638643