COMBINED POWER SYSTEM PLANNING AND POLICY PROPOSITION FOR FUTURE ELECTRIC VEHICLE CHARGING INFRASTRUCTURE

A thesis submitted for the degree of Master of Philosophy

by

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Abstract

In order to achieve the UK Government's legally bound framework of greenhouse gas reduction targets, the transport sector is undergoing drastic changes. The key action taken by the Department of Transport in addressing the issue was the introduction of Ultra-low emission vehicles (ULEV) concept. Office for Low Emission Vehicles (OLEV) was introduced to support early market for ULEV and development of efficient recharging network through Plugged-in Places programme. The massive deployment of EV charging stations across GB will have direct impact on GB power system as they require electricity supply for their operation. It is therefore deemed necessary to carry out investigations on the capacity of the network assets to handle this load and to develop policies to manage the future EV charging infrastructure efficiently.

This thesis provides an overview of the EV technology introducing various technicalities behind EVs and the associated charging stations. The extended theory about interoperability between EVs and power networks is also presented. Investigation of an 11kV networked site and 66/11 kV networked area is performed to determine their potential in accommodating future EV charging infrastructure. A methodology has been proposed to carry out investigations in 11kV networked site. For analysis purpose both the real networks are modelled in detail using power system analysis software Electrical Transient Analyzer Programme (ETAP). Scottish and Southern Energy (SSE) and Northern Power Grid (NPG) are the owners of the distribution networks respectively. Collaboration with DNOs has taken place to collect the existing network data. Finally, a university based EV charging bays management policy has been proposed.

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I would like to extend my gratitude to a number of people who supported me along the way of this thesis. Firstly, I would like to thank my supervisor Prof. Gareth Taylor who provided careful supervision and encouragement at every stage. His support during collaboration with Distribution Network Operators (DNO's) is exceptional.

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Finally, I would like to thank my parents: Venkata Reddy and Vijaya Lakshmi for their priceless love, moral and financial support.

Dedication

For my grandfather

Chalama Reddy Butukuri

05 June 1939 – 01 November 2013

Declaration

The work described in this thesis has not been previously submitted for a degree in this or any other university and unless otherwise referenced it is the author's own work.

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List of Acronyms

AC	Alternating Current
Ah	Ampere Hours
AMI	Advanced Metering Infrastructure
BEAMA	British Electrotechnical and Allied Manufacturers Association
BEV	Battery Electric Vehicle
BEVIP	BEAMAs Electric Vehicle Infrastructure Project
BUL	Brunel University London
CD	Charge Depleting
CS	Charge Sustaining
DC	Direct Current
DNO	Distribution Network Operator
DoD	Depth of Discharge
DSM	Demand Side Management
ENEVATE	European Network of Electric Vehicles and Transferring Expertise
ER	Engineering Recommendation
ERDF	European Regional Development Fund
ESQC	Electricity Safety, Quality and Continuity
ETAP	Electrical Transient Analyzer Program
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
FCV	Fuel Cell Vehicle
FV	Front View
G2V	Grid to Vehicle
GB	Great Britain
GCV	Grid Connected Vehicle
HEI	Higher Educational Institution
HEV	Hybrid Electric Vehicle
ICT	Information Communication Technology
IEC	International Electrotechnical Commission

ISO	International Organisation for Standardization
JEVA	Japanese Electric Vehicle Association
kph	Kilometre per Hour
KW	Kilowatt
KWh	Kilowatt Hours
LCN	Low Carbon Network
LCP	Least –Cost Planning
LCTP	Low Carbon Transition Plan
LEV	Light Electric Vehicles
LTDS	Long Term Development Statement
MPV	Midpoint Voltage
NCR	National Chargepoint Registry
NEMS	National Energy Modelling System
NPG	Northern Power Grid
OFGEM	Office of Gas & Electricity Markets
OLTC	On Load Tap Changer
ONS	Office for National Statistics
PAYG	Pay As You Go
PCN	Penalty Charge Notice
PHEV	Plug-in Hybrid Electric Vehicle
PiP	Plugged in Places
PSS/E	Power System Simulation for Engineering
RCD	Residual Current Device
ResCon	Research Conference
RFID	Radio Frequency Identification
RV	Rear View
SAE	Society of Automotive Engineers
SC	Sub Committee
SNM	Strategic Niche Management
SoC	State of Charge
SoD	State of Discharge
SSE	Scottish and Southern Energy
TC	Technical Committee

UK	United Kingdom
UPEC	Universities Power Engineering Conference
V2G	Vehicle to Grid
WPT	Wireless Power Transfer

Nomenclature

M_M	Molar mass of the limiting reactant
m_R	Mass of limiting reactant
t_{cut}	Time at which the battery terminal voltage is at V_{cut}
t_o	Time at which battery is fully charged
E_c	Energy of a battery with constant current discharge
E_P	Practical available energy in a battery
E_T	Theoretical battery stored energy
F	Faraday Constant
I	Constant discharge current
$MtCO_2e$	Million metric tons of carbon dioxide equivalent
Q_P	Practical battery capacity
Q_T	Theoretical battery capacity
V_{bat}	No load terminal voltage
V_{cut}	Voltage of the battery below midpoint voltage (MPV)
M	Mass of the battery
P	Amount of power delivered
i	Discharge current
n	Number of electrons
$p(t)$	Instantaneous battery terminal power
v , V_t, v_t	Terminal voltage of the battery
λ , n	Constants in Peukert's equation

Chapter 1

Introduction

In this chapter the environmental legislation containing UK greenhouse gas emission targets are presented. Then the strategy followed by the Department of transport in encouraging the usage of Ultra-Low Emission Vehicles is described. This strategy leading to the research motivation is also explained. The principle research objectives and the research contributions that are made in this thesis are summarised. Finally, the list of publications and the way this thesis is organised is presented.

1.1 Environmental Legislation

UK and EU are at the forefront to achieve the targets in reducing the greenhouse gas emissions to prevent the adverse impacts of climate change. UK Government developed a legally binding framework by turning the Climate Change Act 2008 into a law according to which the greenhouse gas reduction of 34% by 2020 and 80% by 2050 against the 1990 emission levels must be reached. [1] [2]

Carbon dioxide (CO_2) tops the list of greenhouse gases that contribute towards global warming. Transport sector which is listed after energy sector as the highest contributor of CO_2 emissions and 24% contributor of UK greenhouse gas emissions is given serious consideration and is undergoing drastic changes. [3]

The key action taken by the Department of Transport in addressing the issue explained above was the introduction of Ultra-low emission vehicles concept.

1.1.1 Strategy to Encourage Ultra-Low Emission Vehicles

Department of Transport, UK introduced Office for Low Emission Vehicles (OLEV) which is a team supporting the early market for Ultra-Low Emission Vehicles (ULEV). The increase in the usage of BEVs, PHEVs and FCVs are expected to reduce CO_2 emissions considerably. In order to encourage people purchase these vehicles a £5,000 grant for every purchase was declared. Match funding to build an efficient recharging network for these ULEVs were in place through Plugged-in Places programme. East of England, Greater Manchester, London, Midlands, Milton Keynes, North East England, Northern Ireland and Scotland are the eight places under this programme. Additionally, several other schemes that were introduced are [4] [5]:

a) Grant scheme for the installation of plug-in vehicle charging stations on the UK government and wider public sector estate
b) Government funding for residential on-street charging for plug-in vehicles
c) Grant fund for the installation of plug-in vehicle charging infrastructure at train stations
d) Grants to provide residential on-street and rapid charging stations for plug-in vehicles

1.1.2 Charging Stations on the Wider Public Sector Estate

Universities, schools, emergency services, government departments, armed forces etc. were made eligible to obtain grant funding for up to 75% of the capital expenditure incurred as a result of purchase and installation of charge-points under this scheme. The guidance reports published for this scheme states the public sectors can get prepared for the future and demonstrate their leadership on sustainability by deploying the charging stations on their site. It was the aim of the OLEV to make workplace charging as the next option after home charging for all the EV owners. [4]

1.2 Research Motivation

Electric Vehicle (EV) charging infrastructure will be deployed extensively in the near future. This will be as a consequence of the policies approved by the UK Government. The aim of the research as presented in this thesis is to investigate the potential of existing power networks in accommodating future EV charging infrastructure.

The rise in the mass production of EVs and the associated increase in consumer demand significantly exacerbate the problems associated with the operation and management of future electric power networks. The vast EV charging infrastructure development starting from the homes, workplaces and public areas requires grid connection for their operation. It is essential for all the public and private sectors, specially the Distribution Network Operators (DNO) to analyse the ability of the existing power networks in meeting the significant demand due to EVs.

1.3 Research Objectives

The main objectives of the research requiring interaction with people and exploration of technology related to Electric Vehicles & Power Systems can be broadly summarised as:

- Carry out a review on the existing research related to the EVs and power network interoperability. Focussing on the impacts the EVs can develop on power networks.

- Learn the techniques adopted in introducing a new technology to the people and implement where necessary in terms of policy development.

- To investigate the potential of an 11kV networked site and 66kV networked area to accommodate future EV charging infrastructure.

1.4 Research Contributions

In addition to the review that was carried out related to EVs and Power Systems, the applied knowledge in this thesis resulted in the following contributions:

- A methodology has been proposed to investigate the potential of an 11kV networked site in accommodating future EV charging infrastructure.

- Detailed modelling and analysis of a real 11kV networked site and 66kV networked area using power system analysis software Electrical Transient Analyzer Programme (ETAP)

- University based "EV charging bays management local policy" has been proposed.

- Competitive Benchmarking is performed with seven UK higher educational institutions that have established EV charging facilities.

1.5 List of Publications & Presentations

The research work presented in this thesis has resulted in the following publications and presentations.

1.5.1 International Conference Publications

Y.R.Bhavanam, G.A.Taylor, P.Berresford and J.Langsman, “A Novel Policy Making Proposition for EV charging Infrastructure Management at HEI's,” in 49th International Universities Power Engineering Conference (UPEC), 02-05 September 2014, Cluj-Napoca, Romania.

Y.R.Bhavanam, G.A.Taylor, S.Bowden, M.Li and I.Pisica, “Applied Modelling and Analysis to Investigate the Potential of a 11kV Networked Site to Accommodate EV Charging Infrastructure”. (Accepted for 50th International Universities Power Engineering Conference (UPEC), 01-04 September 2015, Staffordshire, UK)

1.5.2 Research Conference Presentations

1.5.2.1 Oral Presentations

Y.R.Bhavanam, G.A.Taylor, P.Berresford and J.Langsman, “A Novel Policy Making Proposition for EV charging Infrastructure Management at HEI's,” in 7th Annual Student Research Conference (ResCon’14), 23-26 June 2014, Brunel University London, UK

1.5.2.2 Poster Presentations

Y.R.Bhavanam, G.A.Taylor, “Impact of Electric Vehicles on Network Reliability”, in IET Smart Grids Conference Poster Session, 16 October 2013, Holiday Inn Bloomsbury, London, UK

Y.R.Bhavanam, G.A.Taylor, “Policy Making Proposition for EV Charging Infrastructure Management at HEIs”, in Brunel Graduate School Research Student Conference, 11-12 March 2014, Brunel University London, UK

1.5.3 Reports

Y.R.Bhavanam, G.A.Taylor, P.Berresford and J.Langsman, “Electric Vehicle Charging Bays Management” a policy proposition developed and submitted to the Department of Operations, Brunel University London on 17 February 2014.

1.6 Organisation of the Thesis

In this section an overview of the remaining chapters of the thesis is given. The description presented here paves the way before exploration.

In chapter two: Review of EV Technology, the classification of EVs is explained. History of EVs is described along with the pictorial representation of the development of EVs since 1882. Modes and Types of EV charging infrastructure are explained with specific examples, followed by the listing of technical standards published and proposed by IEC.

In chapter three: EVs and Power Network Interoperability, insight of several researchers on the technical impacts that arise on connecting EVs to distribution networks are presented. The governing and constitutive equations associated with the battery charging parameters are mathematically explained. Importance of smart grids and smart meters for EVs is described. Additionally, some of the major low carbon projects in UK and EU are presented.

In chapter four: Network Planning for 11kV Networked Site Case Study, Brunel University London power distribution network is modelled using power system analysis software Electrical Transient Analyzer Program (ETAP). Capacity of the network is determined under four Electric Vehicle (EV) penetration levels (17%, 30%, 50% and 100%) and three (slow, fast and rapid) charging types. Transformer loading, voltage variations, real and reactive power changes in the system are observed.

In chapter five: Network Planning for 66kV Networked Area Case Study, Spennymoor power network which is located in Durham County is modelled using ETAP. Transformer loading at four (66/11) kV substations in the area are analysed under different EV penetration levels (25%, 50%, 75% and 100%) supplied by home charging infrastructure. Voltage deviations at all substations in the area are monitored and controlled using Load Tap Changers (LTC). Additionally, firm capacities of the substations are compared with load values until the year 2050.

In chapter six: Policy Making Proposition for EV Charging Infrastructure Management at HEI's, a systematic procedure that was followed in order to initiate the research and to escalate it further is explained. The strategy adopted to identify the current and prospective EV owners and the summary of the consultation process with them is presented. The PAYG usage concept of Type 2 Mode 3 charging stations that are manufactured by Pod Point Ltd is described. Key findings from benchmarking (seven HEI's) that influenced final recommendations in the policy proposition are included. Finally, current status of EV charging infrastructure at BUL is presented.

In chapter seven: Conclusions and Further Research, a final summary of the concluding remarks made at the end of every chapter in answering the principle research objectives is presented. Suggestions for future work related to the research presented in this thesis are also given.

Chapter 2

Review of EV Technology

2.1 Introduction

In this chapter an overview of Electric Vehicles (EV) in general is presented. Initially a broad classification of EVs is explained. Then the history of EVs is described along with the pictorial representation of the development of EVs since 1882. Modes and Types of EV charging infrastructure is explained with specific examples of wall mounted home charging equipment, floor mounted public charging stations and DC rapid charging stations. Finally, the list of EV standards that are already published and under development by IEC Technical Committee (TC) 69 and subcommittee (SC) 23H are presented.

2.2 Electric Vehicles

Vehicles relying on electric motors to drive their wheels are termed as Electric Vehicles (EV). EVs are broadly categorised as

a. Battery electric vehicles or All- electric vehicles
b. Hybrids and Plug-in Hybrids
c. Fuel cell vehicles
d. Grid connected vehicles

Battery Electric Vehicle (BEV): These vehicles rely on on-board large, rechargeable batteries for storage of electricity which are supplied by plugging into the power grid when stationary. The Internal Combustion Engine (ICE) is absent. At present the basic models of EVs in the market have a range between 80 to 120 miles with the battery capacities ranging between 18kWh to 35kWh. [6] [7]

Examples : Nissan Leaf, Mitsubishi iMiEV, BMW i3, Citroen C Zero, Ford Focus Electric, Peugeot iOn, Renault Fluence Z.E. and Volkswagen Golf Blue-e-motion

Hybrid Electric Vehicle (HEV): Both ICE and Electric Motor (EM) is present in HEVs which can propel the car. Battery is recharged with the help of ICE and regenerative braking when in motion. EM is used to drive the wheels from stationary up to 65kph and ICE is used for greater speed. There is no option to recharge the battery by plugging into electric grid when stationary.

Examples: Toyota Prius and the Ford Fusion

Plug-in Hybrid Electric Vehicle (PHEV): It is similar to HEV consisting of both ICE and EM but with an added feature of plug-in facility where battery can be recharged from the power sockets when stationary. The battery capacity is bigger when compared to HEVs due to multiple options available for recharging. The battery powered range lies between 10 and 40 miles. The overall range of a PHEV is equivalent to ICE alone powered vehicle. [8]

Examples: Chevrolet Volt, Mitsubishi Outlander and Toyota Prius Plug-In Hybrid

Fuel Cell Vehicle (FCV): The EM present in FCV is powered by fuel cell which generates electricity on-board. Fuel cell uses oxygen from air and hydrogen to generate power. The hydrogen can be refilled into fuel cell. The rate of use of energy to move the vehicle is higher in FCV when compared to BEV. [9]

Example: Honda ZC2, Toyota Mirai and Hyundai ix35 FCEV

Grid Connected Vehicle (GCV): These types of vehicles are connected to electric power grid directly when they are in motion. GCVs do not carry on-board large, heavy batteries. The efficiency of the vehicle is higher when compared with a BEV. For the same amount of electricity generated, a BEV travels 81km for every 100km travelled by GCV. [9]

Examples: Electric trams, trains and trolley bus systems

Although EV is a generalised term for car, bike, truck, bus, train etc. powered by EM, in this thesis EV is totally referred to electric road car.

2.3 EV History with Pictorial Representation

Authors such as Michael H. Westbrook and Iqbal Husain mentioned several interesting facts and developments regarding the history of EVs in their books up to late 1990s. In addition to this the current market is explained in this section. Table 2.1 summarizes the major events occurred along with its associated year.

Table 2. 1: History of EV in a nutshell [10] [11]

Year	Major events in the development of EVs
1800	Alessandro Volta successfully stored electrical energy in Italy
1821	Michael Faraday demonstrated the principle of EM
1831	Discovery of electromagnetic induction by Faraday
1832	Invention of DC motor
1835	Demonstration of an operating motor by Francis Watkins in London Prof.Stratingh in Holland built a model non rechargeable battery car and was demonstrated for a short distance
1834-1836	Thomas Davenport built an EV
1837	R.Davidson built a carriage which is powered by battery in Aberdeen
1838	M.Jacobi, a German physicist developed a battery powered paddle boat
1851	Development of 19mph non rechargeable EV

1859	Invention of lead-acid battery
1861	Electromechanical generator is invented by Antonio Pacinotti
1870	Invention of Double T Iron Armature motor/generator by Siemens brothers
1879	Invention of filament lamp in America by Thomas Alva Edison
1881	G.Trouve developed an electric tricycle powered by Siemens motors
1882	Prof.William Ayrton and John Perry developed 1.5kWh capacity battery powered tricycle with a range between 16 and 40km.
1885	Development of a tricycle car powered by ICE by Carl Benz
1887	R.Ward ran an electric cab in Brighton
1896	Development of Electric Road Wagon by Morris and Salmon
1903	More EVs than ICE powered vehicles in London
1900-1912	Golden age for EVs
1920	ICE propelled vehicles become more predominant
1925-1960	Dark age for EVs
1960 – 1990	EVs development started again due to increasing carbon emissions from ICE vehicles.
1990	Vast development in power electronics leading to new battery technologies and EVs
2003	Fuel Cell Electric Vehicle (FCEV) by Toyota
2010	Nissan Leaf release in Japan and USA, the world's bestselling all electric car with 24kWh battery capacity and 120km range
2008-2012	The Tesla Roadster by Tesla motors with 320km range per charge was available in the market
2014	Tesla Model S with 85kWh battery is available in the market with 155mph top speed
2015	Tesla Model X is expected to be released, a high-performance advanced car that can go from 0 to 60mph in just 4.4 seconds with a range of 430km per charge

The development in EVs has increased vastly in its technology and outlook since 1800s. The horseless carriages turned into proper cars in 1912 which was described as golden age of EVs in [11]. Figures 2.1 to 2.13 illustrate the visual evidence of the development of EVs.

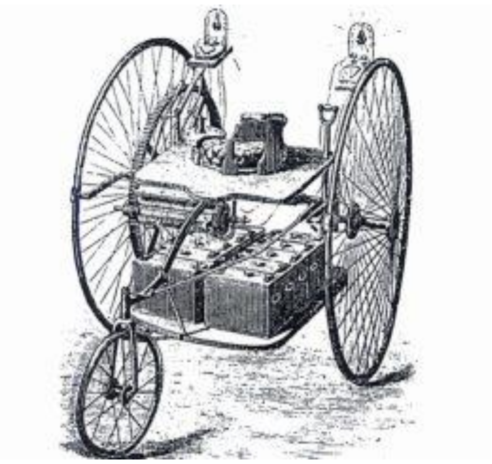


Figure 2. 1Ayrton and Perry tricycle of 1882 [12]

Figure 2. 2: Electric road wagon of 1896 [12]

Figure 2. 3: Jenatzy electric racing car of 1899 [13]

Figure 2. 4: Porsche No.1Lohner-Wagen of 1900 [14]

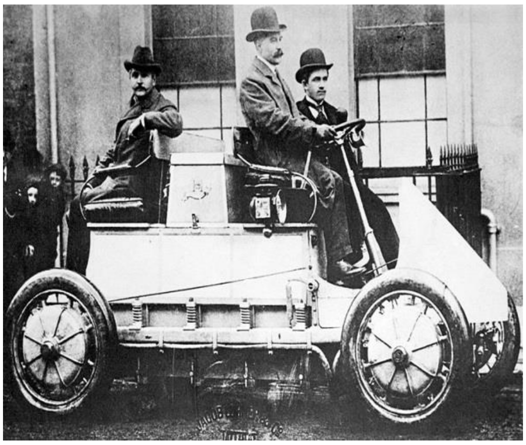


Figure 2. 5: Lohner-Porsche Rennwagen of 1902 [11]

Figure 2. 6: Century Electric Roadster of 1912 [15]

Figure 2. 7: Enfield 8000 Electric Car in 1966 [11]

Figure 2. 8: Sebring-Vanguard Citi Car of 1976 [16]

Figure 2. 9: City Stormer of 1988 by VW [17]

Figure 2. 10: Nissan Leaf of 2010 [18]

Figure 2. 11: BMW i3 of 2013 [19]

Figure 2. 12: Ford Focus Electric of 2013 [20]

Figure 2. 13: The Latest Tesla Model S in the market with 85kWh battery capacity [21]

2.4 EV Charging Infrastructure

The mass production of EVs will be started by the manufacturers, only when there is consumer demand. Consumers adopt EVs only if they find comfort zone in using them. This easy and quick adoption of EVs is possible only if there is efficient and sufficient charging infrastructure in place. Homes, public places and highways must be ready with the charging stations or Electric Vehicle Supply Equipment (EVSE).

There are several organisations such as IEC, IEEE, Society of Automotive Engineers (SAE), etc. that are focussed in the development of standards for the spread of efficient infrastructure. The British Electrotechnical and Allied Manufacturers Association (BEAMA) in UK initiated the project titled "BEAMAs Electric Vehicle Infrastructure Project" (BEVIP) in March 2011. This project recognises the need for long lasting and interoperable charging infrastructure for quicker adoption of EVs and developed a guide to EV charging infrastructure. This guide is used as standard by the EVSE manufacturers and the industry in collaboration with the UK Government for the development of legislations and standardizations.

EV Charging Infrastructure is categorised into "Types" and "Modes". Modes refer to charging modes where the amount of power supply to EV will vary accordingly. The Types are referred to the plugs and sockets that support the power transfer.

2.4.1 Modes of Charging

There are four types of Modes into which the EV infrastructure is categorised. These are mainly dependent on the output power supply, protection and communication facilities. [22]

2.4.1.1 Mode 1

In this mode, EV is connected to the normal household or industrial power sockets which are capable to supply current not exceeding 13A and 16A respectively. Here the EV is connected to 230V AC power supply that is available from the distribution feeders into the house. There is no special Residual Current Device (RCD) protection available at the connection which helps to prevent exposure to fatal shocks. The BS 1363, 13A socket and BS EN 60309-2, 16A socket are not designed for EV charging purposes which usually comprises of an in-cable control box.

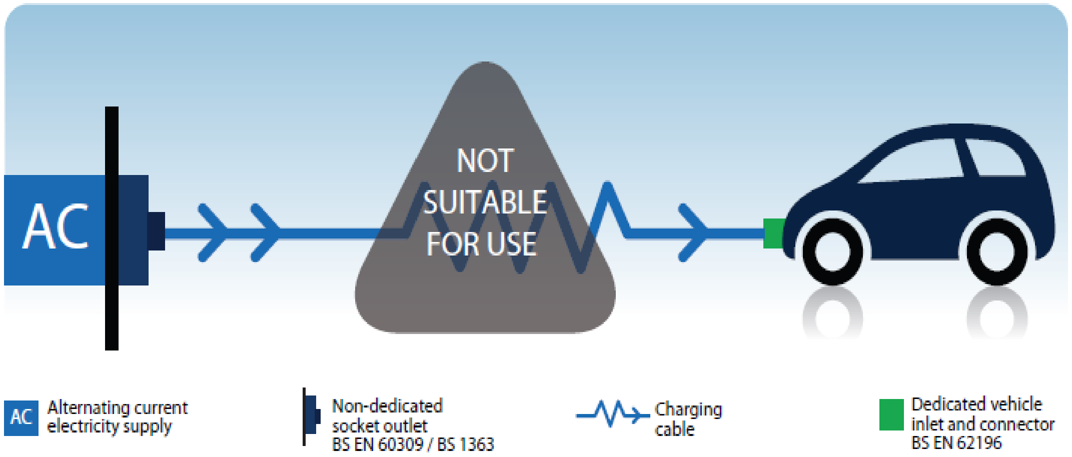


Figure 2. 14: Charging EV in Mode 1 [22]

2.4.1.2 Mode 2

In this mode EV is connected to power supply similar to Mode 1. In addition to the 13A household, 3-pin socket outlet and 16A industrial socket, this mode supports the 32A BS EN 60309-2 outlet as well. There is no dedicated charging socket installed for charging EV but the RCD protection is available in the cable supplied by the EV manufacturer. The current that is supplied to the battery of the EV is controlled or derated by the EV manufacturers to 10A or something different. The output power that is delivered from power sockets and the input power to the battery which is in EV need not be similar. Although there is benefit of minor installation costs and in-cable RCD protection, this Mode of charging takes long hours (8 to 12 hours) to charge the battery and there are no smart systems in place for effective communication.

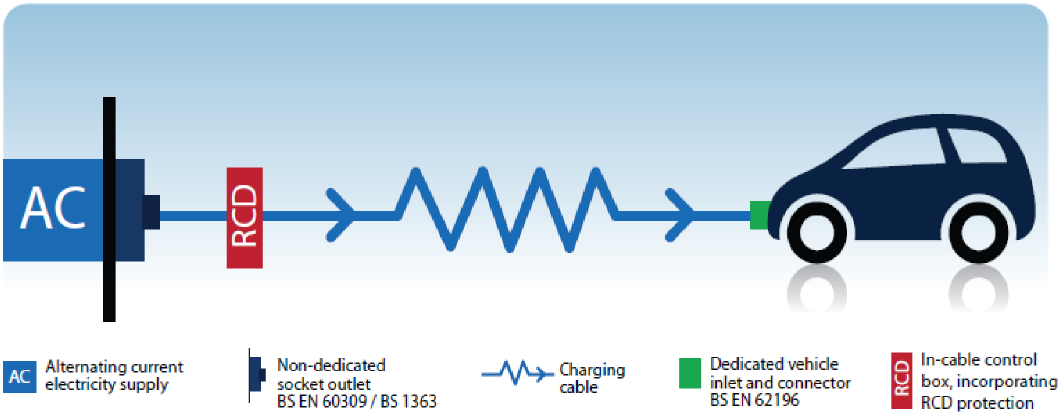


Figure 2. 15: Charging EV in Mode 2 [22]

2.4.1.3 Mode 3

In this Mode of charging there is a dedicated charge point with permanent installation of RCD and surge protection connected to mains. This mode of charging supports 16A or 32A, 1-phase AC supply. It has got the smart feature of communication with EV. The two different types in which these Mode 3 chargers are available are:

a. Charging point with a tethered cable which is usually installed in homes
b. Charging station with a dedicated socket which is commonly installed in public areas.

This type of charging Mode supports in measuring the energy used by the EV owner to charge the battery of the EV. The EV owner can pay for the energy used accordingly in public areas. Mode 3 is the preferred method of charging an EV when compared to other Modes due to the communication, protection and energy measurable features.

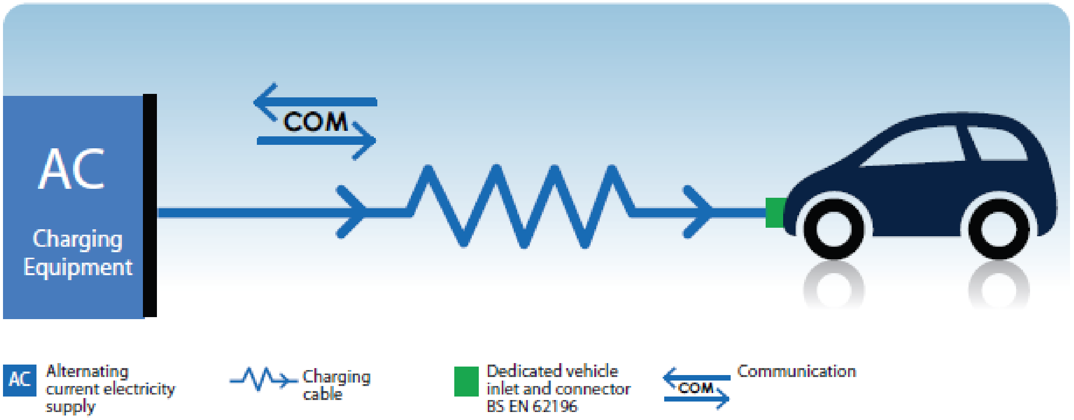


Figure 2. 16: Charging EV in Mode 3 [22]

2.4.1.4 Mode 4

In this Mode of charging EV is charged rapidly using Direct Current (DC). Rectifiers are used inside the charging station for the conversion of AC to DC. These Mode 4 charging stations are not suitable for domestic installations due to the output of high voltage and current which are up to 500V and 200A. This type of charging equipment is mainly installed in highways and service centres. In this Mode 80% of the battery of an EV can be charged in 30minutes and has got good communication facility with EV similar to Mode 3. Frequent use of DC charging stations will reduce the life of the battery. Mode 4 charging stations are expensive for installation and will cause high load on the distribution network.

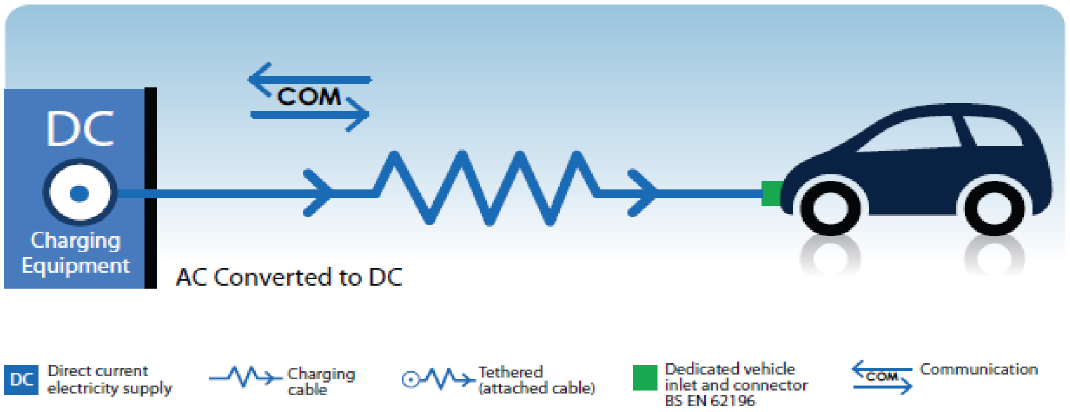


Figure 2. 17: Charging EV in Mode 4 [22]

2.4.2 Types of Charging

Three different types of plugs and sockets are available in UK for charging an EV. These types are standardised by IEC.

2.4.2.1 Type 1

This type of socket and plug is used with 1-phase supply for a maximum output of 250V and 32A. Here the charging cable and the socket has 5 pins as illustrated in Figure 2.18 and are according to the standards IEC 62196-2 (BS EN 62196-1).

Figure 2. 18: 5 pin Socket and charging plug of Type 1 [22]

2.4.2.2 Type 2

The 7 pin charging cable and socket standardised by IEC 62196-2 as illustrated in Figure 2.19 is categorised under Type 2. This type of connectors are used with 1-phase and 3-phase power supply with a maximum output voltage of 500V and maximum output current of 70A at 1-phase and 63A at 3-phase.

Figure 2. 19: 7 pin Socket and charging plug of Type 2 [22]

2.4.2.3 Type 3

The Type 3 plug and socket is developed by the EV plug alliance. It is used with single or three phase supply with maximum output voltage of 500V and maximum output current of 32A. The sockets are designed for the 5 or 7 pin plugs with shutters. It is standardized as IEC 62196-2 Type 3 plug and socket outlet.

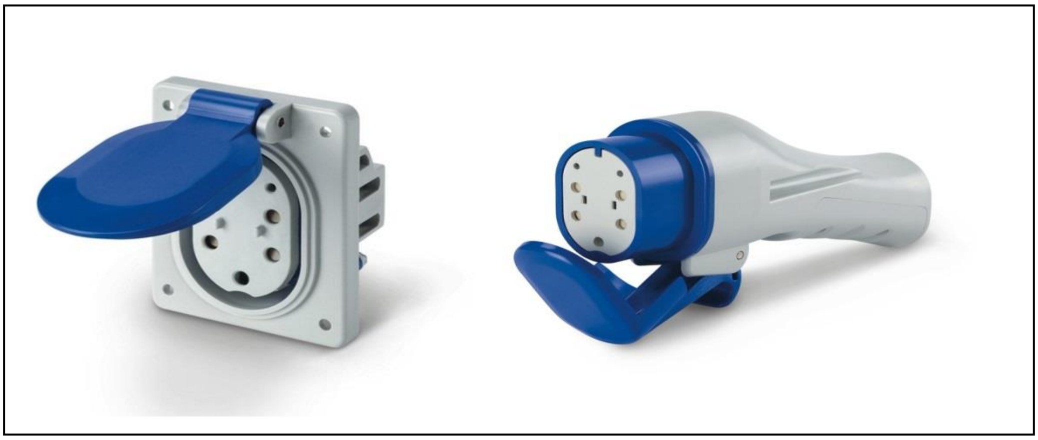


Figure 2. 20: 5 or 7 pin Socket and charging plug of Type 3 [23]

2.4.3 Infrastructure in UK

Typical UK EV infrastructure covers homes and public places. Work place charging can also be considered under public place charging. Majority of the EVs are expected to be charged at their houses due to low tariff and convenience. Public or workplace charging is used in order to top up the charge of the vehicle in general. Travelling long distances by EV can take the advantage of rapid charging stations.

2.4.3.1 Home Charging Equipment

Several EV manufacturers are in support of free installation of home charging equipment in the house of customer if an EV is purchased. UK Government also declared domestic charge point grant capped at £1,000.00 including VAT for every individual eligible EV owner [24]. Some of the home charging wall mounted installation is as illustrated in the Figure 2.21

Figure 2. 21: Domestic EV charger by Pod Point and British Gas [25] [26]

2.4.3.2 Public Charging Stations

Usually public charging stations are floor mounted and are available with twin sockets delivering the output power 3.7kW, 7kW, 22kW and 50kW. These charging stations or EVSE are classified as slow, fast and rapid charging stations depending on the output power delivered. The slow and fast charging compatible EVSE are illustrated in Figure 2.22

Figure 2. 22: Floor Mounted Slow and Fast EVSE from Pod Point and Source London [27] [28]

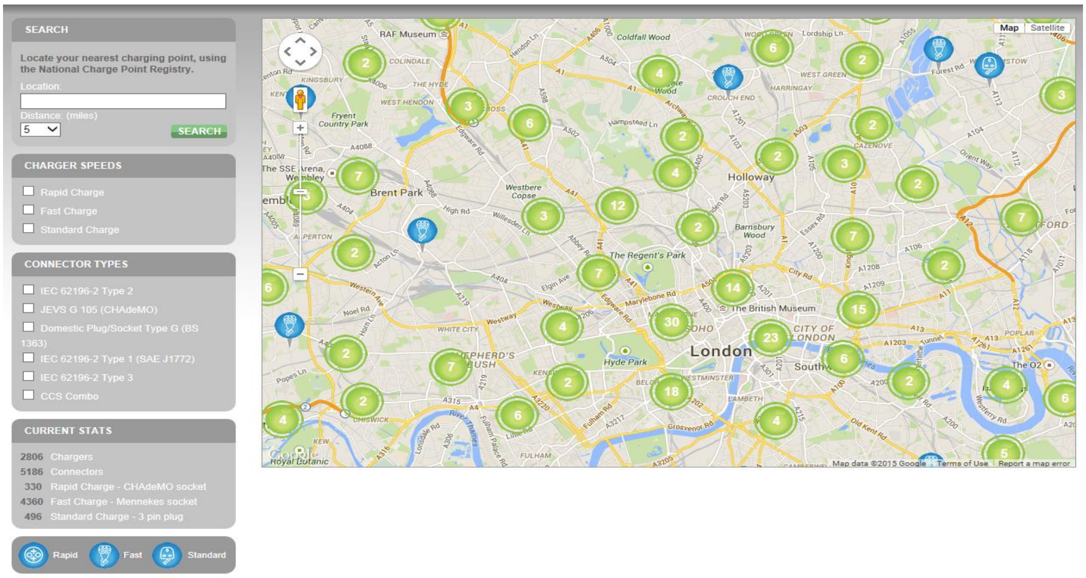
The DC fast charging stations delivering up to 50KW output power is as illustrated in Figure 2.23. These are manufactured by ecotricity and are partners of Nissan in UK.

Figure 2. 23: DC Fast Charging Station from Ecotricity connected to Nissan Leaf [29]

These rapid charging stations usually have CHAdeMO charger and are installed following IET code of practice for EV charging installation.

2.4.3.3 Location of Public Charging Stations

The public charging infrastructure can be accessed online to see the availability of charging stations in UK which are registered in the database of National Chargepoint Registry (NCR). Figure 2.24 illustrates the search criteria available on the left of the image in NCR website and the number of charging stations in the map.



SEARCH

Locate your nearest charging point, using the National Charge Point Registry.

Location:

Distance: (miles) 5

CHARGER SPEEDS

☐ Rapid Charge
☐ Fast Charge
☐ Standard Charge

CONNECTOR TYPES

☐ IEC 62196-2 Type 2
☐ JEVS G 105 (CHAdeMO)
☐ Domestic Plug/Socket Type G (BS 1363)
☐ IEC 62196-2 Type 1 (SAE J1772)
☐ IEC 62196-2 Type 3
☐ CCS Combo

CURRENT STATS

2806 Chargers
5186 Connectors
330 Rapid Charge - CHAdeMO socket
4360 Fast Charge - Mennekes socket
496 Standard Charge - 3 pin plug

Figure 2. 24: Image from NCR website with EV charging stations and search criteria [30]

There are various other websites that incorporate the EV charge point's information. Some of the popular websites are as follows:

a) https://www.zap-map.com
b) http://openchargemap.org
c) https://www.sourcelondon.net/stations
d) http://pod-point.com/products/services/live-availability-map/
e) http://www.chargemasterplc.com/index.php/live-map/

2.5 EV Standards

The acceptance of EVs in the society on a large scale is linked with the EV charging infrastructure and associated standards developed by several technical groups globally [31]. IEC has commissioned a Technical Committee (TC), TC69 titled "Electric road vehicles and industrial trucks" in 1969 in order to develop standards for EV or HEV and electric industrial trucks. The published standards and work programmes by IEC are listed in Table 2.2

Table 2. 2: Published standards and work programme references by IEC TC69 [32]

Reference, Edition, Date, Title	Status
IEC TR 60783:1984 Edition 1.0 (1984-12-30) Wiring and connectors for electric road vehicles	Published
IEC TR 60784:1984 Edition 1.0 (1984-12-30) Instrumentation for electric road vehicles	Published
IEC TR 60785:1984 Edition 1.0 (1984-12-30) Rotating machines for electric road vehicles	Published
IEC TR 60786:1984 Edition 1.0 (1984-12-30) Controllers for electric road vehicles	Published
IEC 61851-1:2010 Edition 2.0 (2010-11-25) Electric vehicle conductive charging system - Part 1: General requirements	Published
IEC 61851-21:2001 Edition 1.0 (2001-05-04) Electric vehicle conductive charging system - Part 21: Electric vehicle requirements for conductive connection to an a.c./d.c. supply	Published
IEC 61851-22:2001 Edition 1.0 (2001-05-04) Electric vehicle conductive charging system - Part 22: AC electric vehicle charging station	Published
IEC 61851-23:2014 Edition 1.0 (2014-03-11) Electric vehicle conductive charging system - Part 23: DC electric vehicle charging station	Published
IEC 61851-24:2014 Edition 1.0 (2014-03-07) Electric vehicle conductive charging system - Part 24: Digital communication between a d.c. EV charging station and an electric	Published

vehicle for control of d.c. charging	
IEC 62576:2009 Edition 1.0 (2009-08-18) Electric double-layer capacitors for use in hybrid electric vehicles - Test methods for electrical characteristics	Published
IEC TS 62763:2013 Edition 1.0 (2013-12-10) Pilot function through a control pilot circuit using PWM (pulse width modulation) and a control pilot wire	Published
IEC 61851-1 Ed. 3.0 Electric vehicle conductive charging system - Part 1: General requirements	Under Development Work Programme (UDWP)
IEC 61851-21-1 Ed. 1.0 Electric vehicle conductive charging system - Part 21-1 Electric vehicle onboard charger EMC requirements for conductive connection to a.c./d.c. supply	UDWP
IEC 61851-21-2 Ed. 1.0 Electric vehicle conductive charging system - Part 21-2: EMC requirements for OFF board electric vehicle charging systems	UDWP
IEC 61851-3-5 Ed. 1.0 Electric vehicles conductive power supply system - Part 3-5: Requirements for Light Electric Vehicles (LEV) communication - Pre-defined communication parameters	UDWP
IEC 61851-3-6 Ed. 1.0 Electric vehicles conductive power supply system - Part 3-6, Requirements for Light Electric Vehicles (LEV) communication - Voltage converter unit	UDWP
IEC 61851-3-7 Ed. 1.0 ELECTRIC VEHICLES CONDUCTIVE POWER SUPPLY SYSTEM - Part 3-7, Requirements for Light Electric Vehicles (LEV) communication - Battery system	UDWP
IEC 61980-1 Ed. 1.0 Electric vehicle wireless power transfer systems (WPT) - Part 1: General requirements	UDWP
IEC 62576 Ed. 2.0 Electric double-layer capacitors for use in hybrid electric vehicles - Test methods for electrical characteristics	UDWP
IEC 62831 Ed. 1.0 User identification in Electric vehicle Service Equipment using a smartcard	UDWP
IEC 62840-1 Ed. 1.0 Electric vehicle battery swap system Part 1: System description and general requirements	UDWP
IEC 62840-2 Ed. 1.0 ELECTRIC VEHICLE BATTERY SWAP SYSTEM - Part 2: Safety requirements	UDWP
IEC/TS 61851-3-1 Ed. 1.0 Electric Vehicles conductive power supply system - Part 3-1:	UDWP

General Requirements for Light Electric Vehicles (LEV) AC and DC conductive power supply systems	
IEC/TS 61851-3-2 Ed. 1.0 Electric Vehicles conductive power supply system - Part 3-2: Requirements for Light Electric Vehicles (LEV) DC off-board conductive power supply systems	UDWP
IEC/TS 61851-3-3 Ed. 1.0 Electric Vehicles conductive power supply system - Part 3-3: Requirements for Light Electric Vehicles (LEV) battery swap systems	UDWP
IEC/TS 61851-3-4 Ed. 1.0 Electric Vehicles conductive power supply system - Part 3-4: Requirements for Light Electric Vehicles (LEV) communication	UDWP
IEC/TS 61980-2 Ed. 1.0 Electric vehicle wireless power transfer (WPT) systems - Part 2 specific requirements for communication between electric road vehicle (EV) and infrastructure with respect to wireless power transfer (WPT) systems	UDWP
IEC/TS 61980-3 Ed. 1.0 Electric vehicle wireless power transfer (WPT) systems - Part 3 specific requirements for the magnetic field power transfer systems.	UDWP

IEC has also initiated a subcommittee (SC), SC 23H for the development of standards related to plugs and socket outlets. UK automobile and EV infrastructure development industry adopts and comply with IEC standards. Standards related to plugs and socket outlets are listed is Table 2.3.

Table 2. 3: Standards published by IEC, SC 23H [33]

Reference	**Title**
IEC 60309-1	Plugs, socket-outlets and couplers for industrial purposes - Part 1: General requirements
IEC 60309-2	Plugs, socket-outlets and couplers for industrial purposes - Part 2: Dimensional interchangeability requirements for pin and contact-tube accessories
IEC 60309-4	Plugs, socket-outlets and couplers for industrial purposes - Part 4: Switched socket-outlets and connectors with or without interlock
IEC 62196-1	Plugs, socket-outlets, vehicle connectors and vehicle inlets - Conductive charging of electric vehicles - Part 1: General requirements
IEC 62196-2	Plugs, socket-outlets, vehicle connectors and vehicle inlets - Conductive charging of electric vehicles - Part 2: Dimensional compatibility and interchangeability requirements for a.c. pin and contact-tube accessories
IEC 62196-3	Plugs, socket-outlets, vehicle connectors and vehicle inlets - Conductive charging of electric vehicles - Part 3: Dimensional compatibility and interchangeability requirements for d.c. and a.c./d.c. pin and contact-tube vehicle couplers

IEC has collaboration with other national standardization bodies located in different countries formally and informally for the development of standards associated with EVs and its infrastructure. Some of them are as follows:

a) International Organisation for Standardization (ISO)
b) CENELEC, European committee for electrotechnical standardization
c) CEN, The European committee for standardization
d) Society of Automotive Engineers (SAE), USA
e) Japanese Electric Vehicle Association (JEVA), Japan

2.6 Concluding Remarks

In this chapter, BEVs or All electric vehicles that are explained in section 2.2 will be considered as loads in chapters 4 and 5. A clear description of Modes and Types of charging that are presented in section 2.4 will be adopted as the charging infrastructure for EVs during the analysis in the following chapters. EV history describing the major events is presented in Table 2.1. The latest standards published and the ones under development by IEC are listed in section 2.5 and will be mentioned where relevant in the following chapters.

Chapter 3

EVs and Power Network Interoperability

3.1 Introduction

In this chapter insight of several researchers on the technical impacts that arise on connecting EVs to distribution networks are presented initially. Then the battery charging parameters that are the key sources in developing those impacts are mathematically explained. Importance of smart grids for EVs and benefits of smart meters are described. Finally, the EV introduction into the society through key initiatives & projects in UK and EU are presented.

3.2 Impact of EVs on Distribution Networks

Deterministic and probabilistic approaches were employed in [34] to observe the voltage variations, thermal loading and electrical line losses in a future (2030) Great Britain (GB) distribution network case study. Low (12.5%), medium (33%) and high (71%) EV penetrations were considered based on the estimations made for the year 2030 using higher order polynomial regression technique. The author concludes that reinforcing the underground cables and distribution transformers will help meeting the demand that is developed by low EV penetration. Deployment of micro generation at consumer site will solve the issues related to medium EV penetration. The 71% high EV penetration requires both micro generation deployment and upgrading the distribution transformers and cables.

Transformer loading and transformer efficiency are considered as factors for observation in the analysis of charging two PHEVs from a 25KVA distribution transformer which is supplying power to five homes in [35].

Normal charging (110V/15A) and quick charging (240V/30A) were used as the charging methods in summer and winter seasons with all PHEVs charged at 6pm and at off-peak hours. Both the cases in normal charging method did not overload the transformer. 68.5% and 63.5% loading levels are reached during winter and summer respectively. Quick charge method for cars overloaded the transformer (103.1%) when plugged in at 6pm in winter. Even charging during off-peak hours consumed lot of power which made loading levels of transformers rise and reach close to the transformer rating. From the results, transformer efficiency is better while charging during off-peak hours.

As an alternative to the generic solution of upgrading the transformer when the loading levels are high, stagger charge and household load control through advanced metering infrastructure (AMI) is suggested. Both these methods did not create overload on the transformer. Analysis of large scale electric vehicle penetration into the distribution networks is suggested as the future research.

This is an interesting paper with so simple system. Very limited factors were considered for analysis. The methods suggested for demand side management leads to additional expenditure and requires consumers to plan ahead in order to avoid situations.

An IEEE 34-node test feeder with reduced voltage level to 230V is used in [36] to represent a residential radial network in Belgium. Three charging periods between 9pm- 6am, 6pm-9pm and 10am-4pm in summer and winter seasons with EV penetration levels at 0%, 10%, 20% and 30% are considered. Voltage deviation and power losses are observed through load flow analysis. Uncoordinated charging is assumed and all EVs are expected to be charged at home. The maximum power loss and voltage deviation is declared during 6pm-9pm. In order to minimise power loss the coordinated charging method is considered as an optimization problem and is solved using quadratic and dynamic programming. The author here suggests coordinated charging of electric vehicles through advanced smart metering technology will reduce the power losses and voltage drop.

PHEV loading on Hydro Quebec distribution system is studied in [37]. The author observes thermal loading, voltage excursions, power losses and the penetration of EVs in a non-uniform manner with the help of the model developed by EPRI and its simulation package Open DSS. Various charging scenarios are considered assuming all the consumers supplied by single and three phase transformers will turn out to be the EV owners. Historical load data is used to which the additional load of 2400kWh in a year by one EV is added for the analysis purpose. The paper concludes with no significant impact on the distribution system at 25% penetration of EVs. It is also mentioned that the charging profile of an EV plays major role in affecting the distribution system.

In addition to the parameters observed in [37], transformer aging is calculated with the help of IEEE C57.91 in [38]. The author here concludes that severity of the impacts on distribution networks will rise according to the increase in the penetration of EVs and DNOs should conduct distribution feeder analysis to understand the capacity of their network assets.

Effects of PHEVs on 11kV substations in Stockholm were observed in [39]. Three areas named Nockeby, Brunkeberg and Gardet are chosen for the analysis. EVs were considered as static loads and normal home charging infrastructure was assumed for charging the battery of EVs. Load flow analysis was conducted on the existing high voltage Swedish network model using Power System Simulation for Engineering (PSS/E) software. Python scripting was used to update the load values automatically. Regulated and unregulated charging of an EV is evaluated at 20%, 40% and 100% EV penetration level percentages. The total numbers of cars present in these areas are assumed to convert to EVs. The author concludes that Voltage levels are within the limits at all substations, 11kV substation at Nockeby needs upgrading as it was pure residential area and regulated charging can be implemented in order to give access to more EVs for charging.

Axsen and Kurani conducted an extensive data collection through online survey, consumer EV buyers’ guide and driving diary which is presented in [40]. Driving diary was used to record the complete details of the travel in one day that includes trip time, distance travelled and location of the EV parked along with distance of charging station from parking. The buyers’ guide includes the price, recharge time for totally discharged EV, range in charge depleting (CD) mode, gasoline usage in CD mode and charge sustaining (CS) mode. Based on the data obtained energy usage profiles were developed and analysed. The authors conclude that if utility has no control over the timings of charging an EV then a serious issue of shoot up in peak demand will arise in addition to the regular peaks occurring between 6pm and 8pm. 12am to 6am was the time period where there was reduced amount of energy consumption in California and it was proposed by the authors to shift the charging of EVs or usage of any other electrical loads to this period.

National energy modelling system (NEMS) software is used to assess the impact of PHEV on generation expansion in [41]. Four types of charging profiles were considered for the analysis. They are uniform charging, home based charging, off-peak charging and V2G charging. The conclusions drawn by the author were that a higher penetration of EVs will require a definite expansion in the generation. Out of the four charging profiles V2G requires least generation expansion and infrastructure development.

Calculation of transformer loss of life due to increased PHEV load using IEEE C57 standard is presented in [42]. Chris Farmer says that there will be reduction in transformer life due to increased temperature, reduced wear and tear of the transformer bushings if the EVs are charged during off-peak hours and finally increased harmonic distortions because of the power electronic equipment associated with the EV charging infrastructure.

3.3 Battery Charging Characteristics

The impacts on the distribution power system due to the penetration of EVs observed by many researchers are presented in 3.2. The main sources of these disorders are the charging behaviours of the batteries that are connected to the network. Charging time and charging duration which are associated with the battery power and capacity are the significant areas that contribute to the battery charging characteristics. [10]

3.3.1 Battery Capacity

The positive and negative electrodes that are present in a battery consume and generate charge respectively. The amount of charge transfer in this phenomenon is the battery capacity. It is measured in Ampere hours (Ah). It can be represented as

$$Q_T = 0.278\ F\ \frac{m_R n}{M_M} \tag{3.1}$$

Where , Q_T = Theoretical battery capacity, F is the Faraday constant which is 96412.2C/mol, m_R is the limiting reactants mass value, n is the number of electrons generated by the negative electrode and M_M is the molar mass of the limiting reactant.

Practical capacity of the battery is lower than the theoretical value because of the limitations associated externally with it. This can be represented as

$$Q_P = \int_{t_o}^{t_{cut}} i(t)dt \tag{3.2}$$

Where, Q_P = Practical battery capacity, t_o is the time of full battery charge, t_{cut} is the time at which the voltage of the battery reaches V_{cut} value.

This Q_P value depends completely on the amount of current that is discharged. Battery capacity is said to be high if the magnitude of the discharged current is low and vice versa.

3.3.1.1 Battery Stored Energy

This term can be defined as the product of battery capacity and the voltage discharged. It applies to both theoretical and practical capacities presented in 3.3.1. The theoretical battery stored energy is represented as

$$E_T = V_{bat}\, Q_T \qquad (3.3)$$

Using equation 3.1 and 3.2 in the above equation it can be written as

$$E_T = 9.65 * 10^7 \frac{m_R n}{M_M} V_{bat} \qquad (3.4)$$

$$E_P = \int_{t_o}^{t_{cut}} vidt \qquad (3.5)$$

Where, V_{bat} is the no load terminal voltage of the battery, v is the terminal voltage of the battery and i is the discharge current of the battery and E_P is the practical available energy in a battery.

3.3.1.2 Battery Energy with Constant Current Discharge

In the above equation 3.5 if the current is considered as constant then the energy of a battery with constant current discharge can be represented as

$$E_c = I \int_{t_o}^{t_{cut}} V_t dt \qquad (3.6)$$

In general Peukert's equation is used for the representation of battery characteristics, which is related with t_{cut}. This equation can be represented as

$$t_{cut} = \frac{\lambda}{I^n} \qquad (3.7)$$

And

$$E_c = \lambda I^{n-1} \mathrm{MPV} \qquad (3.8)$$

Where, MPV is called the midpoint voltage. This is the voltage where the t_{cut} value is half and λ, n are constants.

3.3.2 Battery Power

The product of terminal voltage of the battery (v_t) and discharge current (i) is the power of the battery that can be supplied instantaneously. This relation can be represented as

$$p(t)= v_t * i \tag{3.9}$$

Rated continuous power and rated instantaneous power are the two specifications that are observed to identify the performance of the battery. The maximum power that the battery can deliver over long discharge periods without any effect on the life of the battery is called as rated continuous power. Maximum power that the battery can deliver over short discharge periods without any effect on the life of the battery is called as rated instantaneous power. When leasing the battery from the manufacturer in order to use in an EV, these specifications are very important.

3.3.2.1 Specific Power of a Battery

It is denoted with the units W/Kg. It is represented as

$$SP = \frac{P}{M} \tag{3.10}$$

Where, P is the amount of power delivered by the battery and M is the mass of the battery.

3.3.2.2 Battery Configuration

Batteries are designed according to the output voltage and the discharge power requirements. The modules are arranged in series, parallel or in combination of both internally. The electrodes and electrolyte which are enclosed in a casing is connected to the electronic system that powers the wheels. This power electronic equipment controls the discharge and charge cycles improving the life of the battery.

3.3.3 Technical Parameters

Some of the technical words associated with the batteries are defined as below.

State of Charge (SoC): It is the current capacity of a battery to supply the given load. Once the battery is fully charged and it is used to power the wheels of an EV for certain time, there will be reduction in the battery capacity. Now, the measured amount of the capacity of the battery is its SoC.

State of Discharge (SoD): The amount of charge that is delivered by the battery in supplying a load. It is the difference between the Full charge and SoC of a battery.

$$\text{SoD} = Q_P - \text{SoC} \tag{3.11}$$

Where, Q_P is the practical capacity of the battery

Depth of Discharge (DoD): It is defined as the percentage a battery SoC to which the battery is discharged.

$$\text{DoD} = \frac{Q_P - SoC}{Q_P} * 100\% \tag{3.12}$$

Where, the term Q_P in the equation is defined in section 3.3.1

3.4 GHG Emissions & Importance of Smart Meters

According to the 2008 Climate Change Act the Green House Gas (GHG) emissions for the year 2050 must be reduced by 80% to that of the year 1990 in UK.

Table 3. 1: UK greenhouse gas emissions from 1990-2013 in $MtCO_2e$ [3]

Greenhouse Gas	1990	1995	2000	2005	2010	2012	2013
Net CO_2 emissions (emissions minus removals)	597.9	562.0	559.5	557.8	500.8	476.3	467.5
Methane (CH_4)	136.9	129.9	113.9	92.1	67.0	61.2	56.2
Nitrous Oxide (N_2O)	57.1	47.2	36.6	32.2	28.9	27.7	27.6
Hydrofluorocarbons (HFC)	14.6	19.6	10.5	13.1	15.7	16.2	16.2
Perfluorocarbons (PFC)	1.7	0.6	0.6	0.4	0.3	0.3	0.3
Sulphur hexafluoride (SF_6)	1.3	1.3	1.8	1.1	0.7	0.6	0.6
Nitrogen Trifluoride (NF_3)	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total greenhouse gases	809.4	760.6	722.8	696.6	613.3	582.2	568.3

Figures of greenhouse gas emissions in UK are presented in Table 3.1. In order to meet the legislation target set by the UK Government, the secretary of the state has brought in strict measures to control the carbon emissions from transport sector which is standing second in the list presented in Table 3.2.

Table 3. 2: CO_2 emissions by sector in the year 2013 [3]

Sector	CO_2 ($MtCO_2e$)
Energy Sector	180.8
Transport	115.7
Business	75.5
Residential	74.7
Agriculture	4.9
Waste Management	0.3
Industrial Process	12.2
Public	9.5

Transformation in using ICE vehicles to EVs in the society can help achieve targets. This transformation requires a well-established infrastructure. The power required for EVs to run must be generated from renewable energy sources in order to contribute to the CO_2 reduction. When to use renewable energy or low carbon energy to top up the batteries of an EV is a challenging task. Many researchers have studied the driving habits and charging patterns of the public. The results revealed that the plug in timing is during the peak load times of the day i.e. once the EV owner reaches home in the evening. To utilize the energy sources and EVs in reducing the carbon dioxide emissions a proper Information Communication Technology (ICT) infrastructure or a Smart Grid is mandatory.

UK Government's vision for a smart Grid by 2050 has kicked off with the plan to install smart meter in every home across UK by 2020. This roll out plan was included in the UK Low Carbon Transition Plan (LCTP) approved by the parliament. Department of Energy & Climate Change (DECC) and Office of Gas & Electricity Markets (OFGEM) are jointly leading the smart meter installation programme. The necessity of smart meters to develop smart grid in the words of DECC are as follows

"Building a smart grid is an incremental process of applying information and communications technologies to the electricity system, enabling more dynamic real-time flows of information on the network and greater interactivity between suppliers and consumers. These technologies help deliver electricity more efficiently and reliably from a more complex network of generation sources that it does today" [43]

Real time information obtained through these smart meters will be useful for both consumers and suppliers for Demand Side Management (DSM) and Least –Cost Planning (LCP) [44]. They are:

a. Disconnection of power supply to particular electrical appliance in consumer house
b. Send low tariff information and timings when to use large non critical loads.

c. Information on the availability of charging stations to the EV owners (Public Charging) regarding power supply
d. Control Grid to Vehicle (G2V) & Vehicle to Grid power transfer (V2G)
e. Control small scale generation (wind, solar) connected to grid
f. Transmit information on incentives for the consumer to decide
g. Can balance demand and supply efficiently
h. Reduce peak demand and avoid load shedding
i. Smarter use of network capacity by increasing the load factor
j. Efficient load forecasting
k. Avoid new investments for transmission and distribution

3.5 EV Adoption & Initiatives

For the successful interoperability between the power networks and EVs the barriers that arise need breaking. The increase in the uptake and complete adaptability of EVs by end users in future is one of the considerations for the concept of introducing ICTs and building Smart Grids. The barriers are not always technical. They can be social, economic and psychological etc.

To introduce new sustainable technologies such as solar PV, wind energy generation, electric vehicles and its infrastructure into the society the Strategic Niche Management (SNM) method is followed. The main characteristics of this method are: [45] [46]

a) That technology or innovation that is planned should match with the needs of the people in the society.
b) Experimental based learning to identify the possibilities and constraints of the new concept. Its acceptability, policy and standards development for its regulation purposes.

c) End users cooperation and active involvement are crucial. Their vision, belief, practices, expectations etc. must all go in the same direction with regards to the new technology.

The first and last characteristic of the SNM method are out of the scope of this thesis. The second characteristic which requires experimental study has been implemented and the evidence is presented in Chapter 6.

In meeting the UK and EU targets of reducing carbon dioxide emissions in several sectors including transportation, various initiatives were taken by the respective governments and their associated organisations. The following sections summarise some of the important projects and their aims.

3.5.1 ENEVATE

It is abbreviated as European Network of Electric Vehicles and Transferring Expertise. This project was partly funded through the INTERREG IVB programme by European Regional Development Fund (ERDF) which has plans to invest €355 million over seven years period. This project has 14 partners from six countries (Netherlands, Belgium, Germany, UK, Ireland, and France). Cardiff University from UK was looking at E-mobility energy management, vehicle structures & materials and E-mobility impact assessment. [47]

3.5.2 MERGE

It is a European project which was part of Seventh Framework Programme for Research and Technological Development. The aim of the project was to evaluate the impacts of EVs on EU electric power systems in terms of planning, operation and market functioning. [48]

3.5.3 Customer-led Network Revolution

This was a UK based project hosted by CE Electric UK in the north-east England region. This project was awarded £26.8 million by Ofgem from the Low Carbon Network (LCN) fund to explore the Time of Use Tariffs and DSM concept among the customers. It aims to monitor 14,000 customers with smart meters. [49]

3.5.4 Low Carbon London

A £21.7 million project by UK Power Networks is a UK based project funded through Low Carbon Network (LCN) fund. The key concept of this project was to develop a network that serves a low-carbon city. With 17 key partners the main focus was to implement new tariffs for EV charging stations that are publicly available. [50]

3.6 Concluding Remarks

In this chapter the technical barriers that arise on connecting EVs to power distribution networks is explored. Section 3.2 formed a substantial base and helped in the development of chapters 4 and 5. The necessity of smart grids for complete adoption of EVs and the advantages of ICT infrastructure requirement in the form of smart meters for both supplier and consumer are described. Some of the key EU & UK projects and their aims in better understanding the introduction of EV technology into the society are presented. The methods of customer interaction i.e. by conducting online surveys, focus groups and personal interviews is followed in the development of a policy proposition for the EV infrastructure users which is presented in chapter 6.

Chapter 4

Network Planning for 11kV Networked Site Case Study

4.1 Introduction

In this chapter Brunel University London power distribution network is modelled using power system analysis software Electrical Transient Analyzer Program (ETAP). Peak load values at the substations in a year are evaluated under four different Electric Vehicle (EV) penetration levels and three different charging types.

Transformer loading of all the twenty substations on site is carefully observed in all simulations under different scenarios.

Initially ETAP 12.0.0 is employed to conduct power flow analysis and study the existing network conditions and later the voltage variations, real and reactive power changes in the system due to the uptake of EVs

4.2 Description of the Case Study

Brunel University London is a campus based university. It is categorised into three research institutes, three colleges and 34 halls of residence. There are 2,492 staff and 13,504 students [51]. The electricity to the whole campus is supplied from 11kV HV ring which is owned by Scottish and Southern Energy (SSE), a Distribution Network Operator (DNO). There are totally 21, 11/0.433 kV substations that supply power, out of which 20 substations are inside the campus connected to HV ring and 1 substation is fed from different supply line. In this chapter only 20 substations which are inside the campus are considered for modelling and analysis purpose.

4.3 Data Collection

Collaboration with SSE has taken place in order to obtain the data required for network modelling. Substations inspection is carried out for collecting majority of the information. SSE Long Term Development Statements (LTDS) for the year 2013 and 2014 are used to input the data in ETAP for 66/11kV substations.

Energy consumption or load data is received from Department of Estates in kilowatt hours (kWh) at 30 minute intervals which date between 01/02/2013 to 31/01/2014.

Information regarding number of car parking spaces is obtained from Department of Operations.

Names of the substations according to SSE are different in small number to that of Brunel's estates. The internal naming of the substations is given according to the metering points located in the buildings. These metering points are used to record the energy consumed.

Table 4. 1: Substation naming according to Brunel and SSE

Name of S/S according to SSE	Name of S/S according to Brunel Estates	Meter Serial Number
Brunel No.6 Board B	Isambard A	03C05191
Brunel No.5	Fleming	03C05197
Brunel No.6 Board A	Galbraith	03C05199
Brunel Boiler House	Boiler House	03C05632
Brunel Bio Science	Bio Science	03C06019
Brunel Physics	Physics	03C06761

Brunel Tower D	Tower D	03C06765
Brunel Sports Hall	Sports Hall	03C06767
Brunel Towers B&C	Towers B&C	03C06769
Brunel Tower A	Tower A	03C06771
Brunel CSB Board B	CSB 2	03C08047
Brunel CSB Board A	CSB 1	03C08049
Brunel Cleveland Road	Cleveland Road	03C08893
Brunel Chepstow	Chepstow	03C08901
Brunel Health Building	Health	04C01012
Brunel F	Bannerman	04C01591
Brunel F	John Crank	04C01593/ 11C06294
Brunel F	CLB	04C01595
Brunel Energy Centre	Wilfred Brown	05C05039
Brunel No.7	Isambard B	06C00917
Brunel Data Centre	Data Centre	07C00437
Brunel University Science Park	Eastern Gate Way & St Johns	By name

4.4 Network Modelling

A very effective graphical user interface and well defined output reports generated through load flow result analyzer are the key reasons to choose ETAP 12.0.0 for modelling purpose. Features like alerts and warning report, automatic power system equipment condition monitoring, colour codes differentiating the loading levels of the busbars and finally the onscreen result appearance along with the model made the decision firm. Simulated model at 100% EV penetration undergoing fast charging along with the results display following colour codes is presented in Appendix A.

4.4.1 AC Elements Naming & Numbering

During the construction process several buses and other AC elements are added and deleted. The element ID has to be unique in the project and therefore the count has gone up very high. There is no sequence in the numbering. System Dumpster in ETAP is similar to Recycle Bin in Windows operating system. This is the place where all deleted elements remain and will continue to carry the elements ID. The same number or name of the element which is deleted cannot be used during the construction in the study space.

To overcome this problem, Dumpster has been emptied completely after the construction phase of one line diagram. A fresh naming and numbering has been given to the elements for clear understanding.

4.4.2 Assignment of Engineering Properties

AC elements in the single line diagram are assigned with engineering properties. This data entry process took place by giving a double click on the element with the help of mouse. The Info page of the Device Property Editor is where the required information is given as input.

4.4.3 Overview of BUL Power Distribution Network Model

There are two supply points from which the BUL power network is fed. One feeder entering into Brunel University Board A from Uxbridge and the other into Brunel University Board B from Yiewsley. The two supply feeders are coming out of 66/11 kV substations located in the places mentioned previously. This formed an 11kV HV ring to which the 11/0.433 kV substations are connected supplying the loads.

Breakdown of elements that compose BUL power distribution network are as below:

Table 4. 2: Voltage ratings of elements in the network

Voltage Rating (kV)	**Element**	**Number of Elements**
66	Power Grid	1
66	Bus	1
66/11	Transformer, 2-Winding	4
11	Bus	4
11	Cable	2
11/0.433	Transformer, 2-Winding	20
0.433	Bus	20
0.433	Load	20

Substations and its kVA ratings are as below:

Table 4. 3: Apparent power rating of substation

Name of S/S according to SSE	**Rating (kVA)**
Brunel No.6 Board B	500
Brunel No.5	500
Brunel No.6 Board A	500
Brunel Boiler House	750
Brunel Bio Science	800
Brunel Physics	1000
Brunel Tower D	800
Brunel Sports Hall	1000
Brunel Towers B&C	800
Brunel Tower A	800
Brunel CSB Board B	800
Brunel CSB Board A	800
Brunel Cleveland Road	750
Brunel Chepstow	800
Brunel Health Building	500
Brunel F	800
Brunel Energy Centre	800
Brunel No.7	500
Brunel Data Centre	800
Brunel University Science Park	800

The complete BUL power distribution network modelled using ETAP is illustrated in Figure 4.1

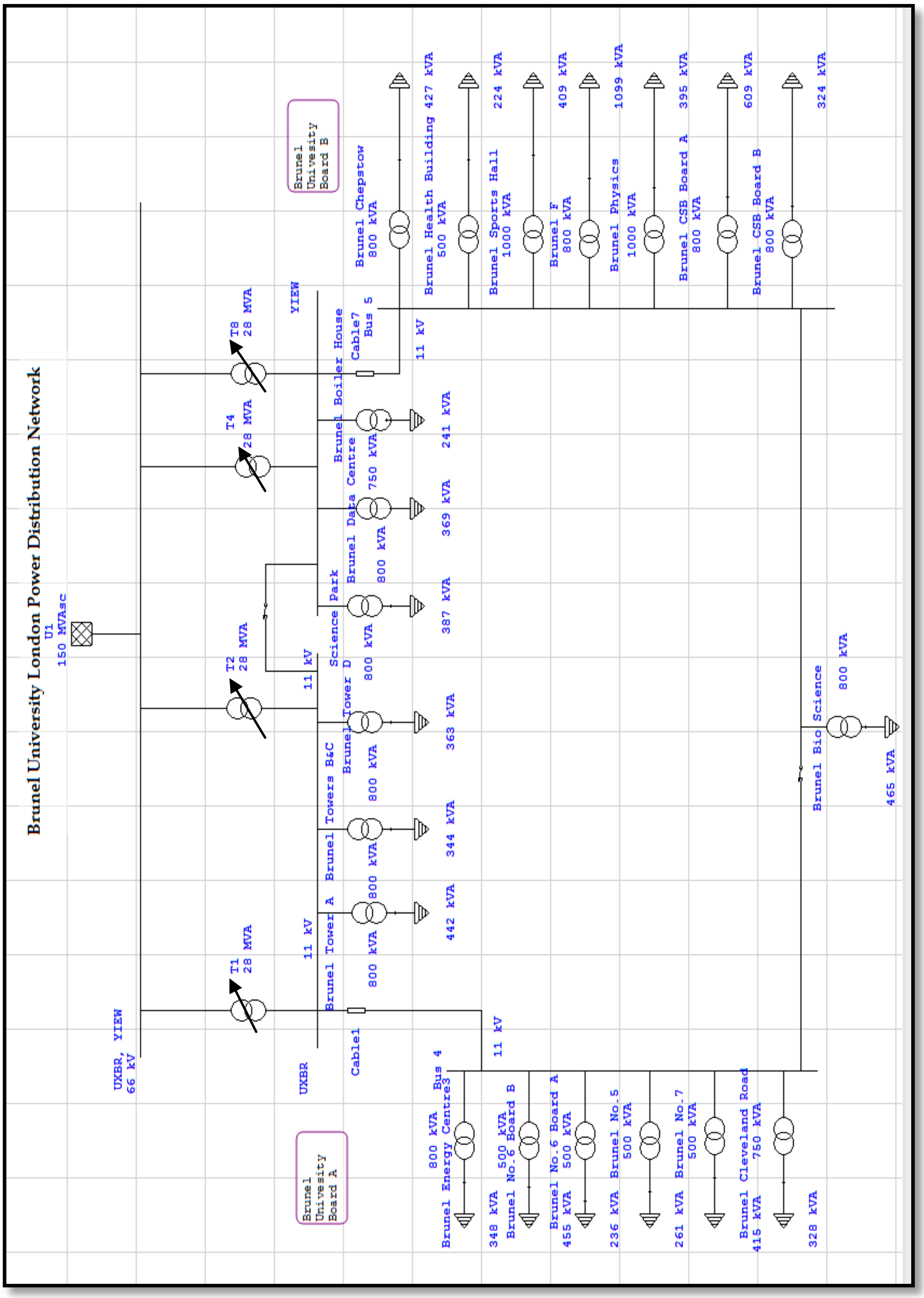


Figure 4. 1: BUL Power Distribution Network Modelled using ETAP

4.5 Scenario Planning

A strategic planning process is deployed in evaluating the additional load of EV penetration into the existing network. The recorded load data obtained between the dates 01/02/2013 to 31/01/2014 from the metering points is used to figure out the peak load value on the system. Total numbers of car parking spaces at BUL are 1955. There are 7 people driving EV to the university and 10 are planning to purchase in next 12 months. It is assumed that all 17 people are driving EV to university. This total is used as the initial EV penetration on site at each substation in test case 1. A steady increase of 30% EV load is assumed in test case 2. Half capacity of the site (50%) and full capacity of the site i.e. 100% EV penetration is considered in test cases 3 and 4 for the investigation of transformer loading levels and voltage variations. A total of four different EV penetration levels are considered based on number of car parking spaces (equivalent to cars) assumed to be supplied with power from each substation. Slow, fast and rapid charging are the types under which EVs will be charged. BUL has fast charging infrastructure for its EV community. In this chapter all 3 types of charging infrastructure are considered in analysing different scenarios presented in Table 4.4

Table 4. 4: Various scenarios including load developed due to EV penetration percentage

Test Case	EV Penetration (%)	Scenario	Charging Type	Load (kW) due to EV penetration	Total No. of EVs
1	17	Assumed initial EV penetration on site	Slow	62.9	340
			Fast	119	
			Rapid	850	
2	30	Steady Increase	Slow	111	600
			Fast	210	
3	50	Half capacity of the site	Slow	185	1000
			Fast	350	
4	100	Full Capacity of the site	Slow	370	2000
			Fast	700	

4.5.1 Peak Load Value Extraction from Database

Microsoft Excel workbook containing 72 sheets of recorded information is used to extract the peak load values at each substation between the dates mentioned above. The table below shows the extracted peak load value, data set used for each substation and the date it occurred.

Table 4. 5: Peak load values and data set chosen from the database for each substation

Substation	Data Set	Peak Load (kWh)	Date
Brunel No.6 Board B	E750 : AZ1125	174	05-02-2013
Brunel No.5	E751 : AZ1126	61.8	11-03-2013
Brunel No.6 Board A	E751 : AZ1126	43.2	13-02-2013
Brunel Boiler House	E751 : AZ1126	46.5	23-08-2013; 03-12-2013
Brunel Bio Science	E751 : AZ1126	179	27-02-2013
Brunel Physics	E751 : AZ1126	142.2	13-02-2013
Brunel Tower D	E751 : AZ1126	124.2	12-03-2013
Brunel Sports Hall	E751 : AZ1126	149.5	28-02-2013
Brunel Towers B&C	E751 : AZ1126	113.5	05-02-2013
Brunel Tower A	E751 : AZ1126	167.5	15-05-2013
Brunel CSB Board B	E751 : AZ1126	101.5	22-07-2013
Brunel CSB Board A	E747 : AZ1122	253.5	12-02-2013
Brunel Cleveland Road	E751 : AZ1126	104	13-02-2013
Brunel Chepstow	E751 : AZ1126	159	25-02-2013
Brunel Health Building	E751 : AZ1126	33.4	07-03-2013
Brunel F	E751 : AZ1126	191.1	11-02-2013
Brunel F	E751 : AZ1126	98.3	05-02-2013
Brunel F	E751 : AZ1126	88.5	13-02-2013
Brunel Energy Centre	E751 : AZ1126	115.8	5-12-2013
Brunel No.7	E751 : AZ1126	153	12-01-2014
Brunel Data Centre	E751 : AZ1125	127.1	13-05-2013
Brunel University Science Park	E601: AZ976	137.4	22-07-2013

4.5.2 Nissan Leaf as Load

An EV consumes 200Wh/km and runs on an average 40km/day which is equal to 8kWh/day [52]. The battery of an EV is different in size varying with the manufacturers. Nissan Leaf, a popular EV has 24 kWh lithium-ion battery [53] . Initially, the battery is charged full and topped up thereafter. According to [54] the lifetime of the battery reduces if the state of charge (SoC) goes below 20% or overcharged above 90% repeatedly. With this fact in mind the EV owners are expected to maintain the battery levels within the range of 20% to 90% SoC.

Either a staff member or a student driving an EV to university is expected to park their EV for at least 8 hours. EV owners living in the university halls of residence will have their EV parked on site more than 8 hours. There are 20 substations and 1955 parking spaces in total. For economic purposes equal load sharing concept between the substations is assumed.

$$\frac{1955}{20} = 97.75 \tag{4.1}$$

An approximation of 100 vehicles charging capacity at a time from each substation is the base for further analysis. From Chapter 6, section 6.1.2 it is found that 80% of EV community owns Nissan Leaf. Therefore, Nissan Leaf is considered for evaluating the additional load on transformers at the substations.

Nissan Leaf or any other EV in UK can be charged using different charging infrastructure available. The Kilowatt (kW) rating of the single or dual outlet charging unit gives choice to EV owners to plug in. Higher the kW rating quicker the charge. The available AC/DC charging outlets in the market are the following: [25]

Table 4. 6: Mileage from variety of charging stations

Load (kW)	**AC/DC**	**Supply**	**Number of miles for 1 hour charge**
3.7	AC	1-Phase	15
7	AC	1-Phase	30
11	AC	3-Phase	50
22	AC	3-Phase	100
50	DC	n/a	100 (in 0.5 hours)

The popular ones from the above table are 3.7 kW, 7 kW and 50kW charging units. These three charging varieties are considered as methods to charge the batteries of EVs (loads) in different scenarios to examine transformer loading.

4.6 Scenario Testing and Data Analysis

Each substation is assumed to be capable enough to supply 100 EVs. Number of charging stations is set up according to the increasing percentage of EVs. Slow, fast and rapid charging is used to plug in. Percentage increase in EVs and the total load values are mentioned in Table 4.7

Table 4. 7: Load on substations due to increase in EVs at charging stations

% Increase in EV	Slow Charging Load(kW)	Fast Charging Load(kW)	Rapid Charging Load (kW)
17%	62.9	119	850
30%	111	210	1500
50%	185	350	2500
100%	370	700	5000

The additional loads from EVs are added to the peak load values extracted and presented in section 4.5.1. This new load values are entered in the simulation model to observe the transformer loading levels and voltage variations.

4.6.1 Test Case 1: 17% EV connected to slow, fast & rapid charging stations

This test case involves the connection of EV's to slow, fast and rapid charging stations. 17% EV connected will act as load for each substation in addition to the existing load. Each substation is added with 62.9 kW to the existing load during slow charging.

On performing the power flow analysis, the transformer loading results obtained are illustrated in Figure 4.2. Majority of the substations can accommodate the slow charging stations. Brunel F got overloaded even during the slow charging process. This is due to the existing transformer loading which is 0.732MVA. There is very less scope to accommodate the extra load. The transformer rating is 0.8MVA. During slow charging the total apparent power required is 0.895MVA which is 111.9% operating value. Brunel No.6 Board B and Brunel No.7 substations are operating close to the transformer rated values. 80.4% and 72.3% are the respective loading percentages for the substations.

While fast charging the EV's, 119kW is added to the substations. Brunel F is overloaded as the loading input is 1.040MVA. The other significant observations are the transformer loading values of Brunel No.6 Board B and Brunel No.7. The transformers are loaded at 90.8% and 82.6% respectively. Fast charging stations can be powered by majority of the substations.

850kW is the excess load at each substation for rapid charging to take place at 17% EV uptake. Brunel Physics and Brunel Sports Hall are the two substations that can accommodate rapid charging stations. The transformer loading is 89.3% and 90.4% respectively. This mentioned values are close to the transformer rated values.

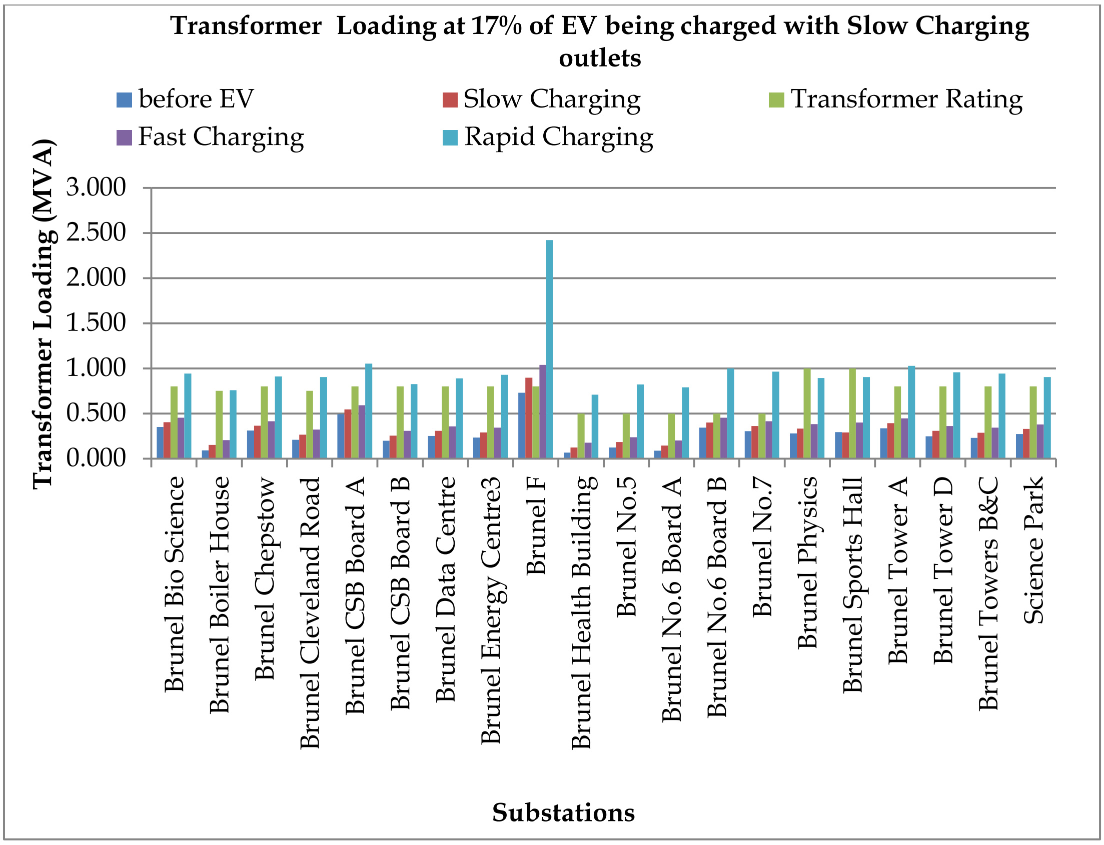


Figure 4. 2: Transformers Loading at 17% EV Charging

Voltages at substations tend to fall due to increase in load. The voltages at the secondary of the 11/0.433kV transformers which is less than or equal to 1kV must be maintained within the statutory limits of +10%/-6% in order to comply with the distribution code. Therefore, the critical voltage limits are set at 94% and 110% for under voltage and over voltage identification of the buses that are connected to respective substations in ETAP project settings. There is also a percentage marginal setting for bus voltages which is set at 98% and 102% for under and over voltage identification. The critical voltage limit violations are observed at various charging methods. The results obtained are illustrated in Figure 4.3.

During the slow charging process the voltages are maintained within the statutory limits. Bus 16 connected to secondary of Brunel F is operating at under voltage while fast charging. The rapid charging of EV does violate the voltage conditions. All buses numbered from 6 to 25 that are connected to substations are in under voltage condition.

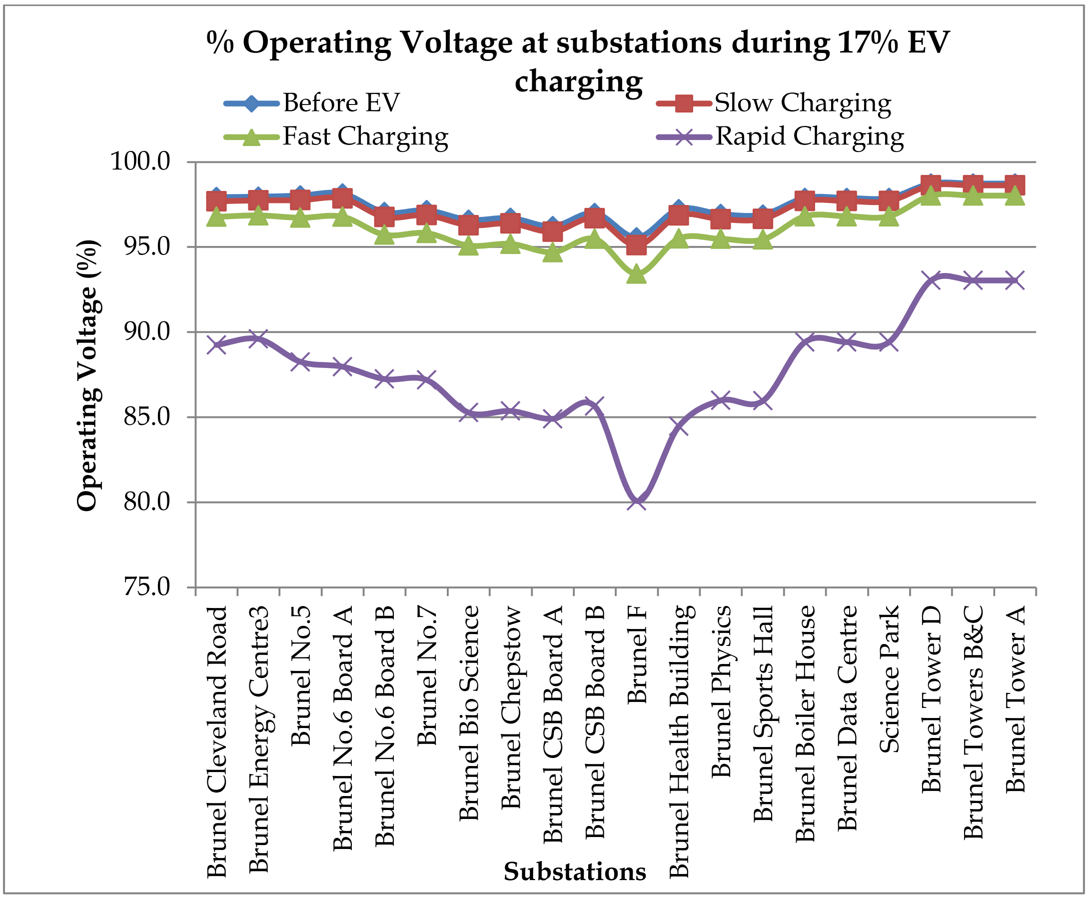


Figure 4. 3: Operating voltage variations at substations during different charging methods

The Real and Reactive Power at all 20 substations before EVs are connected and while EVs are connected through different charging methods are illustrated in Figure 4.4. The slow and fast charging curves of real and reactive power follows the same trend of the curves where the EVs are not connected except at Brunel F. This is due to the high amount of load that is added which is 850kW in addition to the existing load mentioned in 4.4.1. Rapid charging curves are at 0.666 MW at Brunel Health Building with least real power and 2.195MW at Brunel F as highest. The reactive power values with least 0.199Mvar at Brunel Boiler House and highest at 1.025Mvar at Brunel F

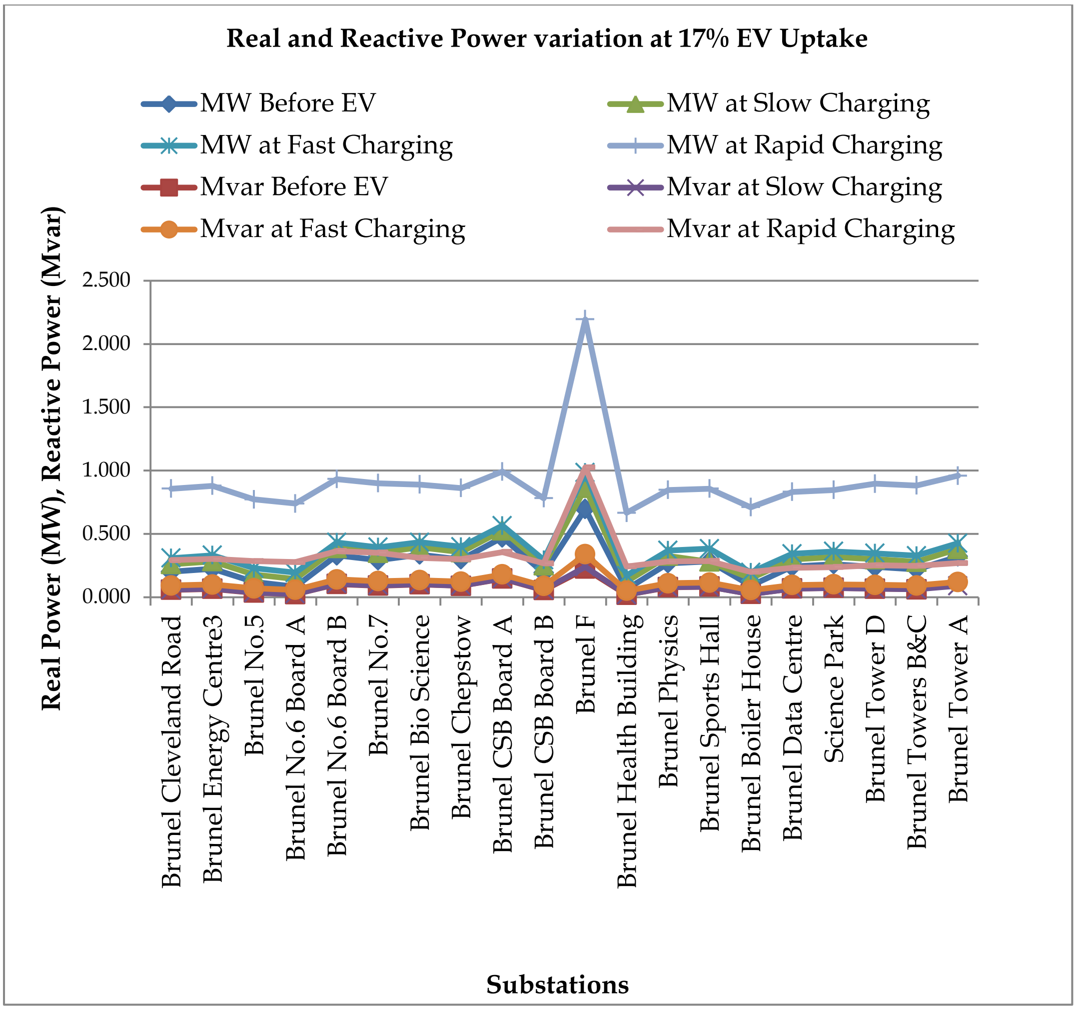


Figure 4. 4: Real and Reactive power flows at 17% EV charging

4.6.2 Test Case 2: 30% EV connected to slow and fast charging stations

This test case involves only slow and fast charging infrastructure for the assessment of transformer loading. Rapid charging is not taken into consideration here, in test case 3 and test case 4. This decision is made based on the results obtained from test case 1. The percentage of electric vehicles on site is expected to increase gradually. This increase is assumed to be very limited and therefore 30% is taken into consideration. The transformer loading results obtained on performing the simulation are illustrated in Figure 4.5

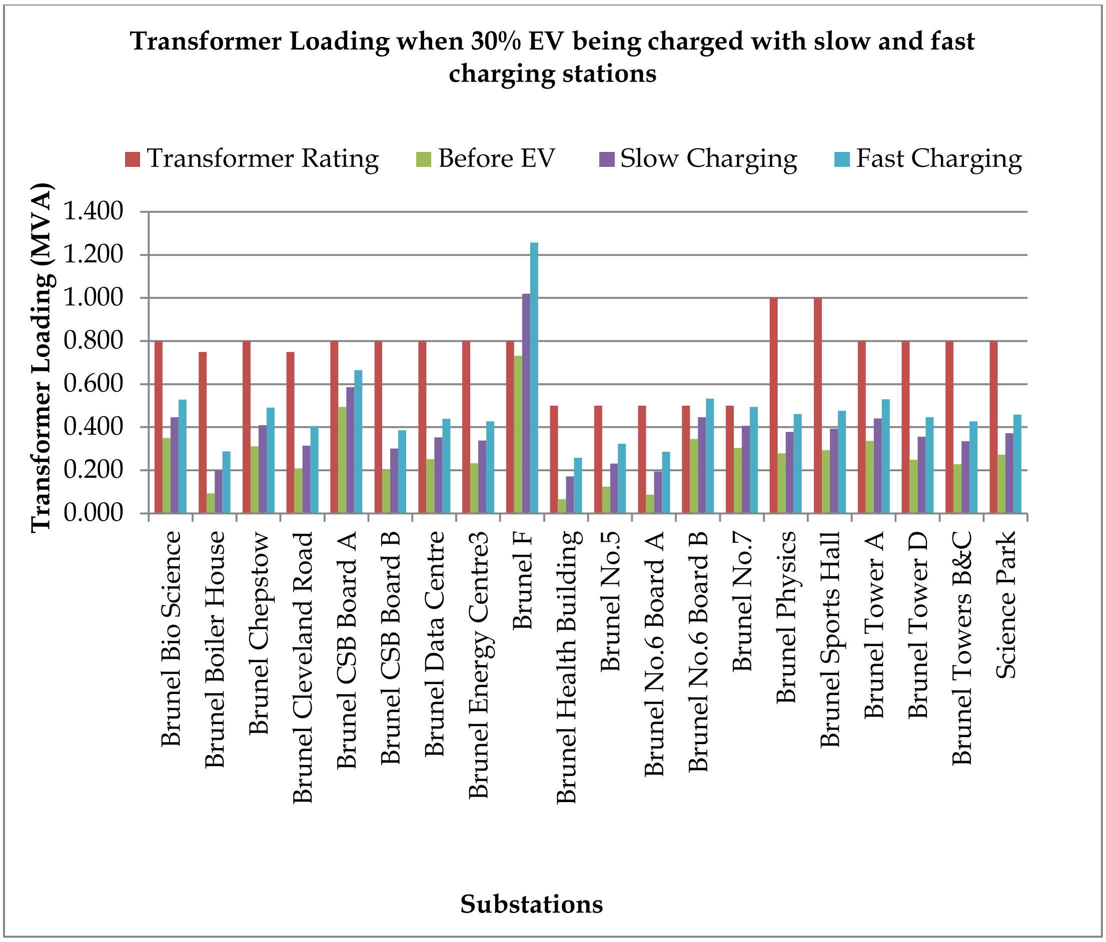


Figure 4. 5: Transformers Loading at 30% EV Charging

During slow charging, substation Brunel F is loaded at 1.020MVA where its rating is limited to 0.8MVA. The transformer at this substation is operating at 127.5% exceeding the branch capability. Other 19 substations are within the rated MVA. Fast charging infrastructure is also possible to adopt at this rate of EV penetration except at the substations Brunel F and Brunel No.6 Board B. The later substation is operating just above the capability of the transformer at 106.5%.

Voltage variations at the peak load values of all the substations are illustrated in Figure 4.6. Bus 16 which is connected to Brunel F is operating at under voltage while slow charging. It is operating at 93.6% where the lower statutory limit is 94%. Due to fast charging of EV's four buses are operating at under voltage condition. The bus numbers are 12, 14, 16 and 19. These buses are connected to the substations named Brunel Bio Science, Brunel CSB Board A, Brunel F and Brunel Chepstow. Voltage regulation is required as an immediate solution.

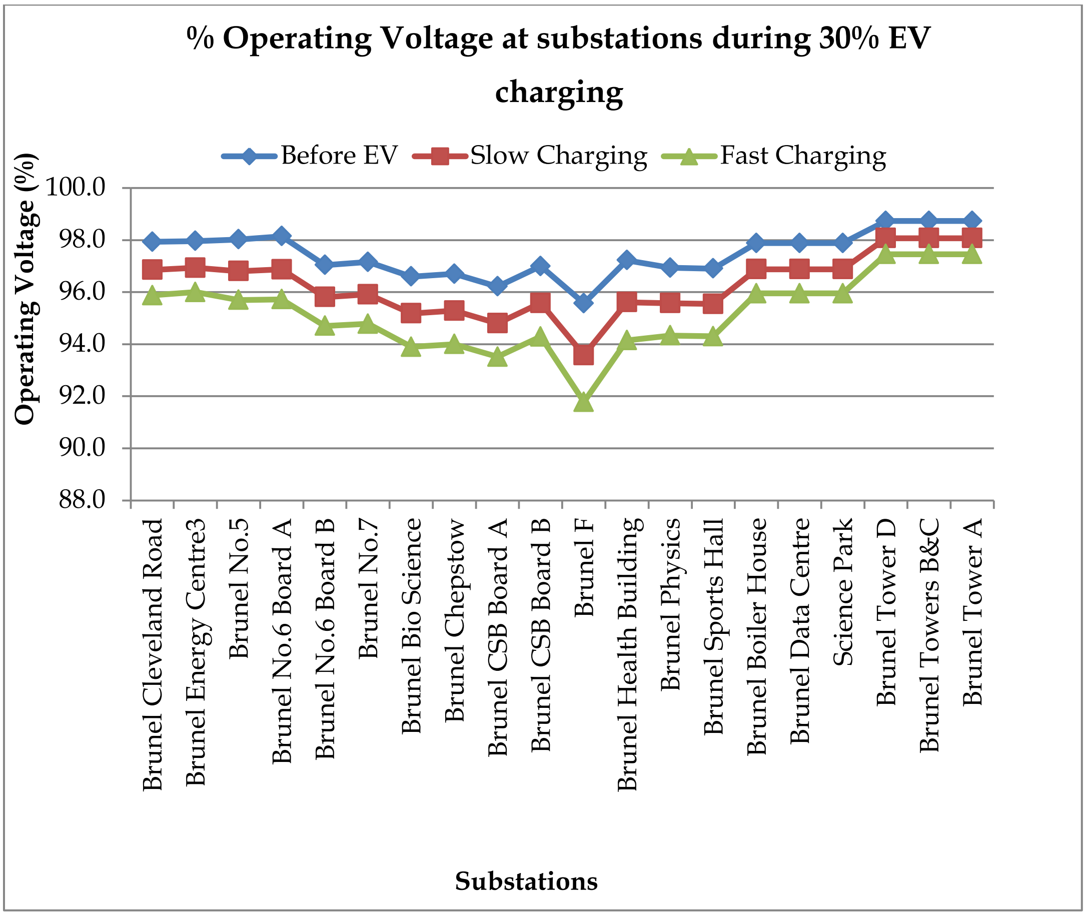


Figure 4. 6: Voltage variations at 30% EV Charging

Real and Reactive Power flows that are delivered are illustrated in Figure 4.7. The measurements are higher compared to 4.5.1 as the amount of load on the substations increased. The losses at Brunel F are 11.1kW+64kvar and at Brunel No 6 Board B are 3.8kW+19.2kvar

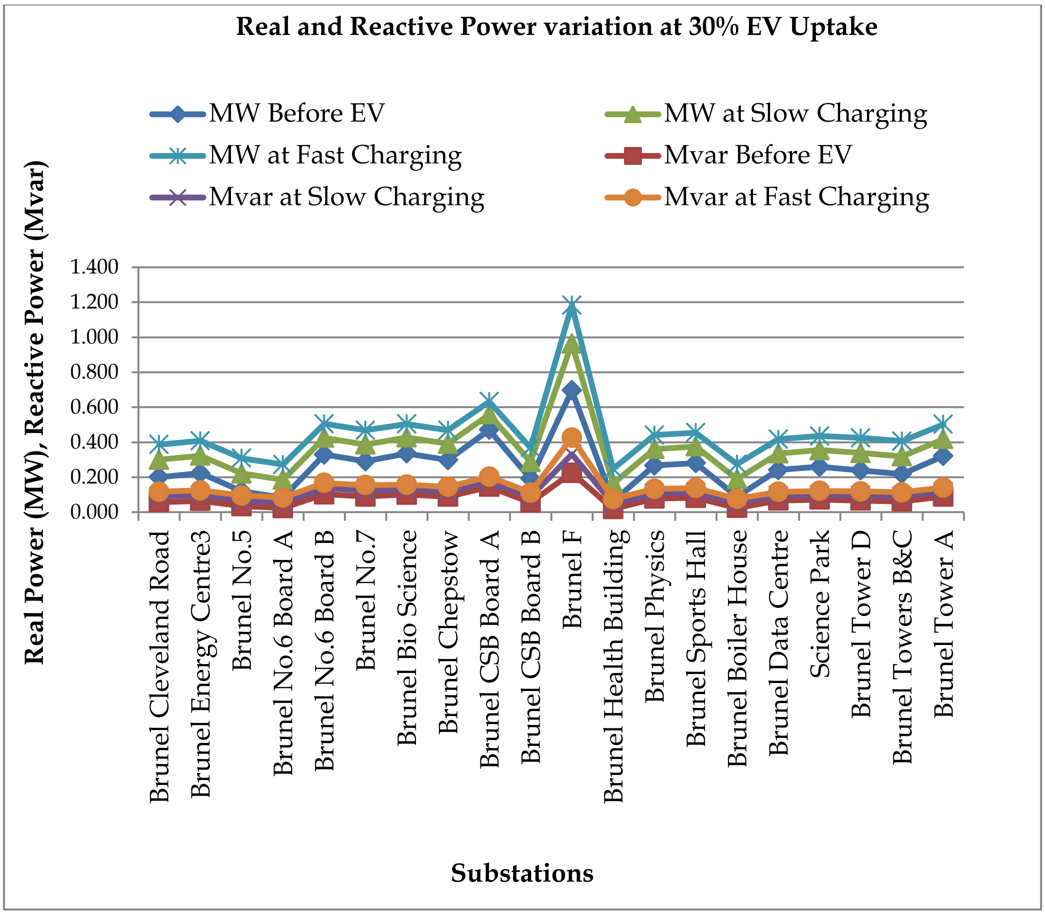


Figure 4. 7: Real and Reactive power flows at 30% EV charging

4.6.3 Test Case 3: 50% EV connected to slow and fast charging stations

This test case involves only slow and fast charging infrastructure for the assessment of transformer loading. Rapid charging is not taken into consideration here. This decision is made based on the results obtained from test case 1. The percentage of electric vehicles on site is increased to 50%. This is equal to 50 electric vehicles being able to charge from each substation which in total 1000 electric vehicle charging capacity on site. The transformer loading results obtained on performing the simulations are illustrated in Figure 4.8. Operating voltages at all 20 substations are illustrated in Figure 4.9. Real and Reactive Power delivered are illustrated in Figure 4.10.

On adding 185kW to the peak base load the slow charging simulation is performed. Two transformers named Brunel F and Brunel No.6 Board B are operating at overload condition. They are operating at 1.2MVA and 0.512MVA. Bus 14, 16 connected to Brunel CSB Board A and Brunel F respectively are operating at under voltage condition. The real and reactive power losses at Brunel F are 15.6kW and 90.1kvar. Losses at other over loaded transformer are 5kW and 25.4kvar.

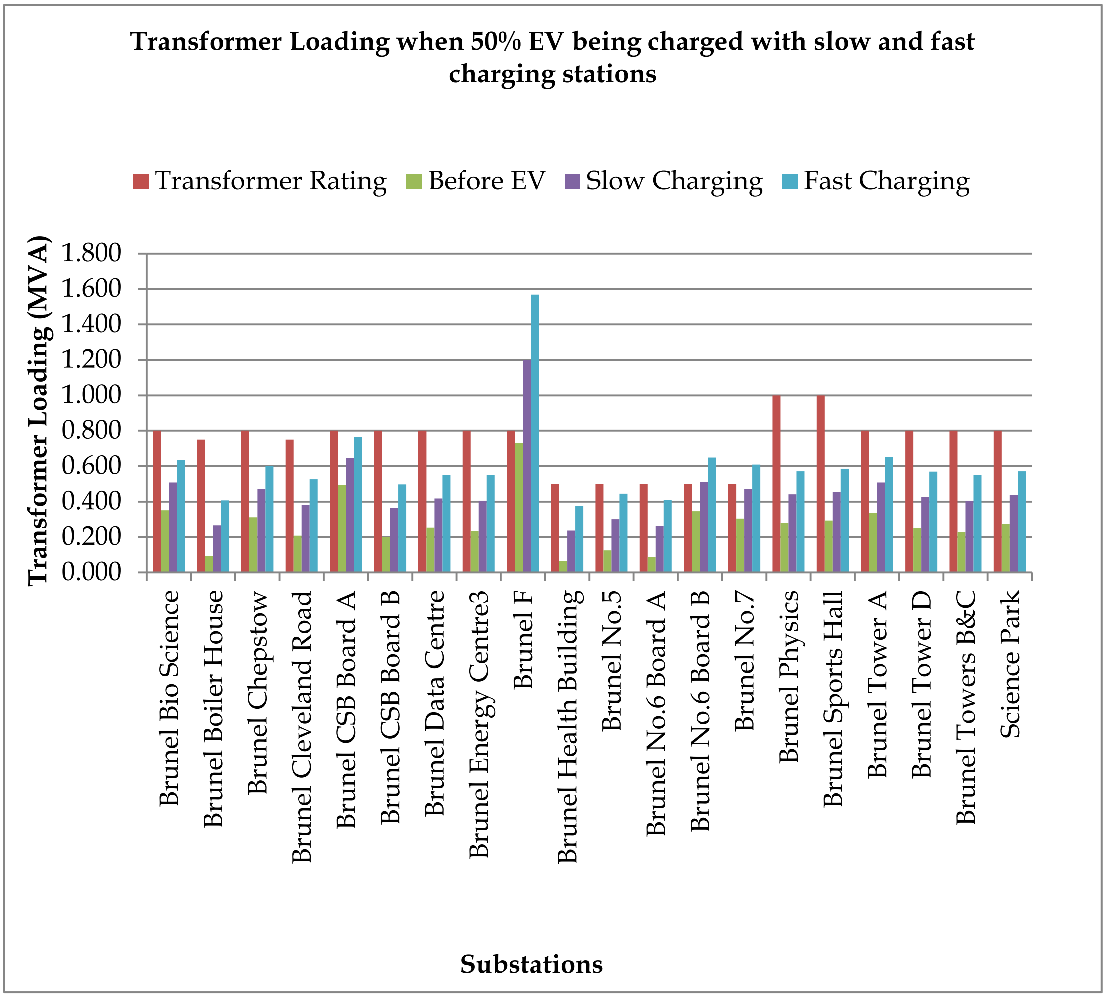


Figure 4. 8: Transformers Loading at 50% EV Charging

The fast charging simulation in this test case is performed after adding 350kW to the base peak load. The critical report shows 3 overloaded transformers and 12 buses operating at under voltage. The report is stated in Table 4.8

Table 4. 8: Condition of transformers and buses while 50% EV undergoes fast charging

Critical Report

Device ID	**Type**	**Condition**	**Rating/Limit**	**Unit**	**Operating**	**% Operating**	**Phase Type**
Brunel F	Transformer	Overload	0.80	MVA	1.57	196.1	3-Phase
Brunel No.6 Board B	Transformer	Overload	0.50	MVA	0.65	129.7	3-Phase
Brunel No.7	Transformer	Overload	0.50	MVA	0.61	121.9	3-Phase
Bus 10	Bus	Under Voltage	0.43	kV	0.40	93.2	3-Phase
Bus 12	Bus	Under Voltage	0.43	kV	0.40	92.0	3-Phase
Bus 13	Bus	Under Voltage	0.43	kV	0.40	92.4	3-Phase
Bus 14	Bus	Under Voltage	0.43	kV	0.40	91.7	3-Phase
Bus 15	Bus	Under Voltage	0.43	kV	0.40	92.5	3-Phase
Bus 16	Bus	Under Voltage	0.43	kV	0.39	89.2	3-Phase
Bus 17	Bus	Under Voltage	0.43	kV	0.40	92.5	3-Phase
Bus 18	Bus	Under Voltage	0.43	kV	0.40	92.1	3-Phase
Bus 19	Bus	Under Voltage	0.43	kV	0.40	92.1	3-Phase
Bus 20	Bus	Under Voltage	0.43	kV	0.40	93.3	3-Phase
Bus 21	Bus	Under Voltage	0.43	kV	0.40	93.1	3-Phase
Bus 22	Bus	Under Voltage	0.43	kV	0.40	93.0	3-Phase

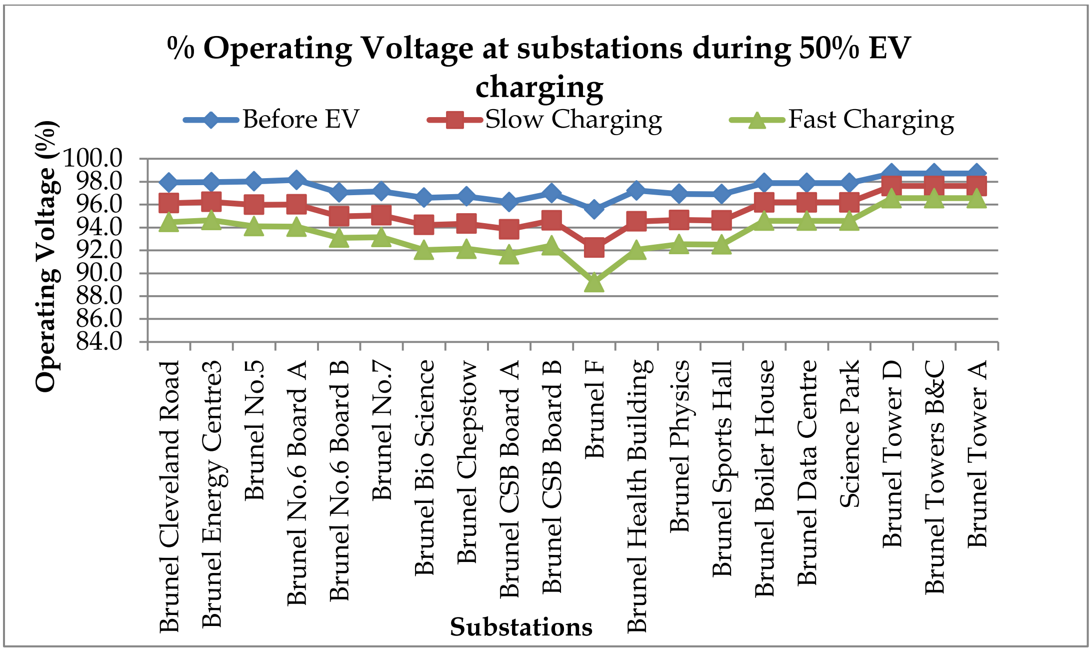


Figure 4. 9: Voltage variations at 50% EV Charging

Real and Reactive Power flows that are delivered are illustrated in Figure 4.10. The measurements are higher compared to previous test cases as the amount of load on the substations increased. The losses at Brunel F are 27.6kW+159.9kvar, Brunel No 6 Board B are 8.2kW+41.8kvar and Brunel No.7 are 7.6kW+38.7kvar. Brunel F has the highest real power flow as 1.465MW and the reactive power flow as 0.562Mvar.

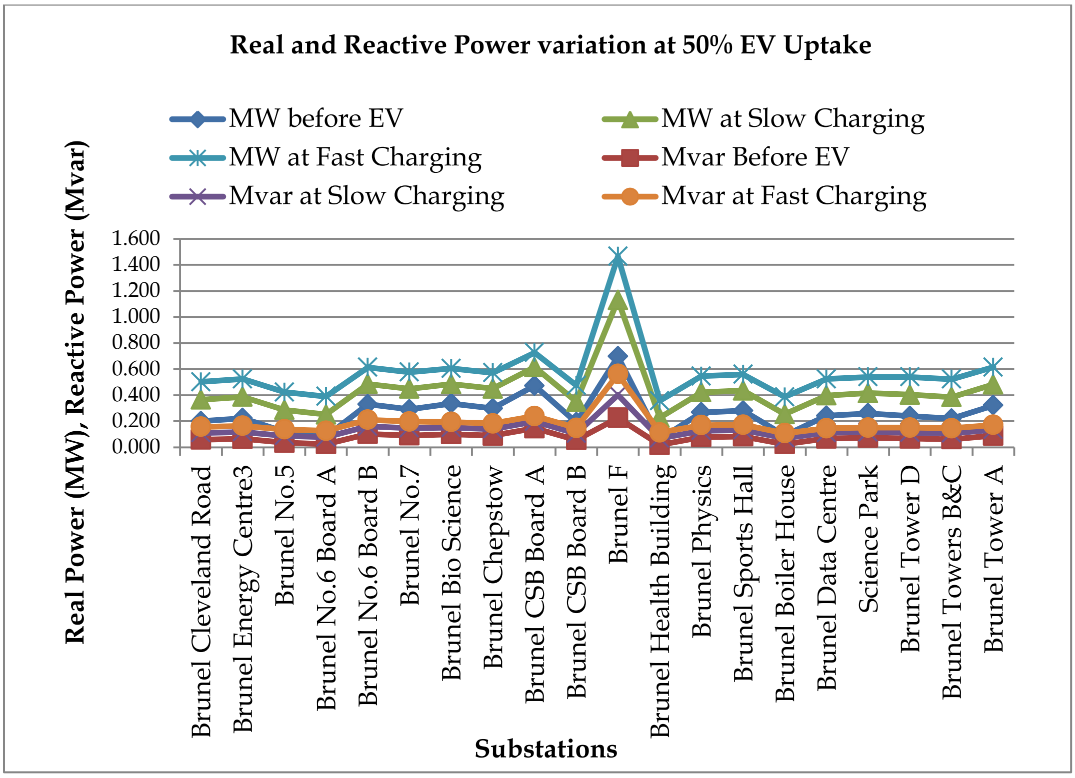


Figure 4. 10: Real and Reactive power flows at 50% EV charging

4.6.4 Test Case 4: 100% EV connected to slow and fast charging stations

In this test case the full potential of site is tested to accommodate 2000 electric vehicles at a time for charging. Slow charging infrastructure is possible on site except at three substations. Brunel F, Brunel No.6 Board B and Brunel No.7 are operating at 201.4%, 132.8% and 125.2% respectively. The results obtained are illustrated in Figure 4.11. 15 buses that are connected to substations are operating at under voltage which is below 94% of the rated value. Although the transformers are capable to supply the load at most substations, voltage regulation is an issue. Operating voltages at buses connected to respective substations and real, reactive power flows into the substations are illustrated in the Figures 4.12, 4.13.

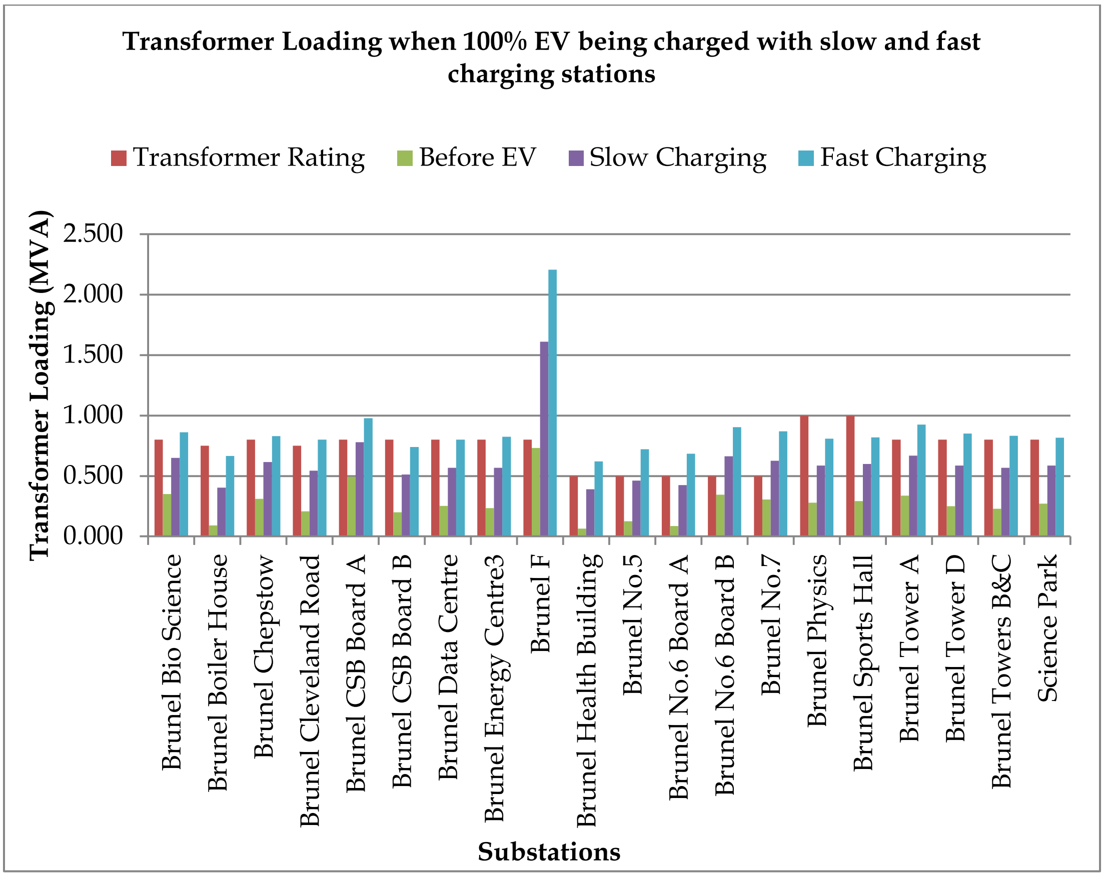


Figure 4. 11: Transformers Loading at 100% EV Charging

Fast charging infrastructure deployment at 100% EV penetration on site is possible only if reinforcement of the transformers and cables take place. 15 transformers are overloaded in this scenario and all the buses connected to the substations are operating at under voltage condition. Real and reactive power values are extremely high when compared to previous test cases and are illustrated in the Figures 4.12 and 4.13 respectively.

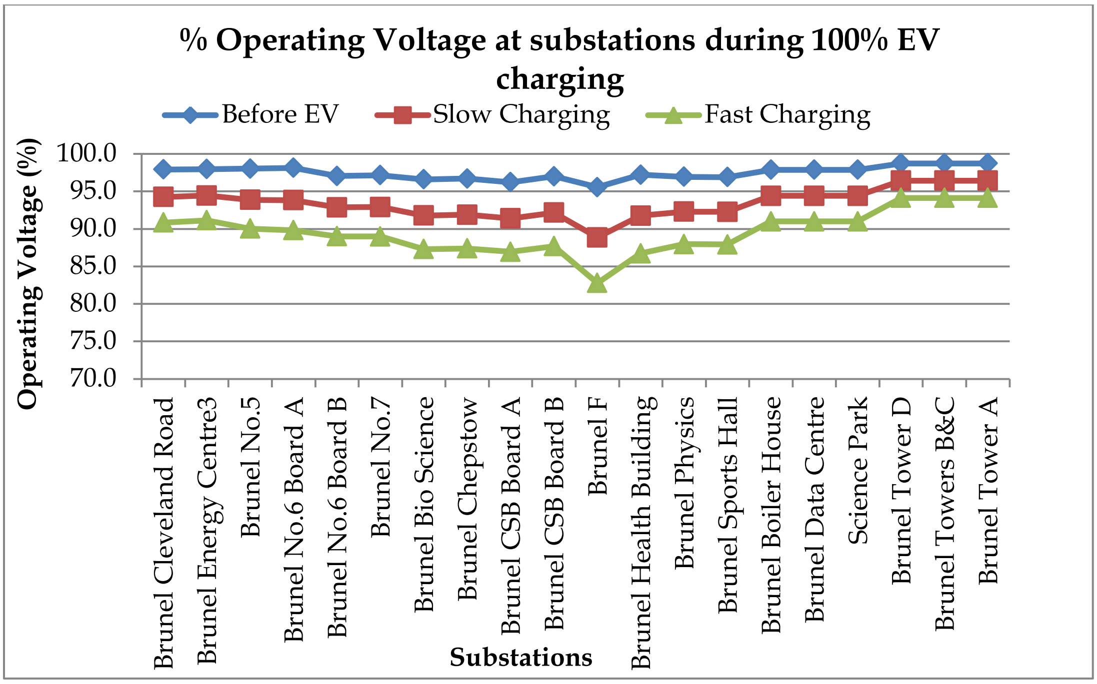


Figure 4. 12: Voltage variations at 100% EV Charging

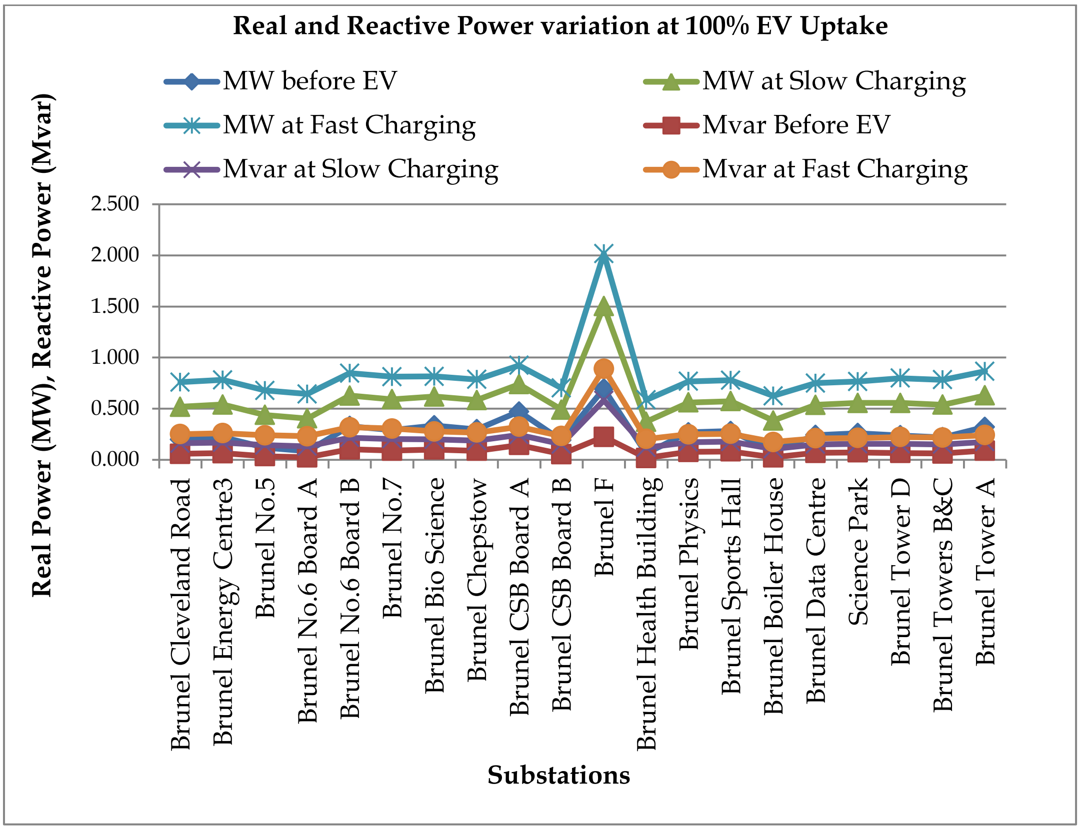


Figure 4. 13: Real and Reactive power flows at 100% EV charging

4.7 Data Verification and Validation

At every stage of simulation all the input data is checked. Data checking is one of the major phases during scenario testing. There are different scenarios under four test cases that are mentioned in section 4.5. On completing each power flow simulation mismatches between supply, load and losses are checked through load flow result analyzer. The output mismatch value should be zero where supply (MW) = load (MW) + losses (MW) to indicate a balanced steady state condition. List of bus results, branch results and load flows are also generated as reports for verification.

The results obtained in the base case are compared with the actual measured values to scan for any potential data issues across the power network. Real Power, Reactive Power, Apparent Power and Voltage measurements in the substation Tower A/Howell Building and Kilmorey Hall (Brunel Sports Hall) are compared with the actual measured values from a thesis [55]. The electrical network instrument named "C.A 8335 QUALISTAR PLUS" was used to measure the actual values at the point of common coupling by the author.

The measured voltages in the reference thesis at substation Tower A on 25/10/2010 was mentioned as 427.4V whereas the supply voltage according to ETAP is 427.371Volts. Measured voltage from the reference thesis at Kilmorey Hall which is a residence hall is part of substation named Brunel Sports Hall. The voltage recorded is 420V on 1/11/2010 in the reference and it is 419.577V in the present ETAP simulation. Voltages are always maintained within the statutory limits and at a constant rate on the site.

The power supply values seem to have increased slightly since 2010. There is 22kW increase in the real power supply which was 300kW in 2010 and 322kW in 2013. There is 34kvar decrease in the reactive power supply which was 130kvar in 2010 and 96kvar in 2013. These changes not only depend on the amount of load increase but also on the time the values are recorded and the usage.

4.8 Concluding Remarks

In this chapter a solid methodology is proposed in the assessment of deploying 20 EV charging parks with the maximum capacity of 2000 EVs at BUL. Different simulations under four test cases with realistic increase in the uptake of EVs and various charging patterns are analysed.

Slow, fast and rapid charging is considered in test case 1. The transformers are overloaded due to rapid charging, therefore it is not considered in further test cases.

The capacity of BUL power distribution network in accommodating EVCS to supply the EV penetration levels depending on transformer loading condition is as follows:

- At 100%: Slow charging infrastructure deployment to supply 1700 EVs or fast charging stations establishment to supply 500 EVs on site is possible.
- At 50%: 900 EVs can undergo slow charging or 850 EVs can plug in to the fast charging stations.
- At 30%: 570 EVs can power up their batteries with the help of slow charging infrastructure or 540 EVs with the help of fast charging stations.
- At 17%: 323 EVs can undergo slow or fast charging while 34 EVs can undergo rapid charging.

34 single outlet rapid charging stations deployment is possible at the compromise of no slow or fast charging stations. OLTC facility is not currently available for the transformers on site. Voltage regulation has to be carried out at the primary substations where violations are observed.

Chapter 5

Network Planning for 66kV Networked Area Case Study

5.1 Introduction

In this chapter an area based power network Spennymoor (132/66/20/11) kV which is located in Durham County under Northern Power Grid (NPG) electricity distribution network operator (DNO) is modelled using power system analysis software ETAP 12.0.0. NPG has undertaken Customer Led Network Revolution (CLNR) project to assess new technology and customer flexibility to increase their network capacity. Four types of DSR are being trialled such as time of use tariff, restricted hours tariff, direct load control and within premises balancing. One of the areas under this DNO is chosen to study the impacts of EV penetration and future load planning with an aim to contribute to the learning outcomes of the ongoing research. Following substations are investigated for their capacity to withstand the additional load that will occur due to uptake of electric vehicles.

a) Belmont
b) Low Spennymoor
c) Meadowfield
d) Fylands Bridge

Initially ETAP 12.0.0 is employed to conduct power flow analysis and study the existing network conditions and later the voltage variations of busbars and transformer loading conditions due to the uptake of EVs. Estimated load using linear regression until 2050 with the help of data obtained from NPG are compared with the substation firm capacities.

5.2 Geographical Area Description

Spennymoor is located in Durham, which is in north of England. It is a town that has an approximate population of 20,000. In this area there are four 132/66 kV substations, seven 66/20 kV substations, five 66/11kV substations and one 132/25kV substation. The licensed distribution network operator for this area is Northern Power Grid (NPG). Entire network is modelled in ETAP 12.0.0. Due to insufficient data at one of the 11kV substations only four are considered in the analysis.

5.3 Data Collection

Collaboration with Northern Power Grid (NPG) has taken place in order to obtain the data required for network modelling. Detailed schematic and geographical diagrams are used for the initial modelling purposes. From the database Appendix 3 for circuit data, Appendix 4 for transformer data and Appendix 5 for load data are used to input the values for the elements in the network. NPG Long Term Development Statement (LTDS) for the year 2013 is studied to get an overview of the voltage limits that are followed. Information regarding usual resident population, area in hectares, population density, total number of cars & vans and percentage change in population is obtained from Office for National Statistics (ONS) and Durham County Council.

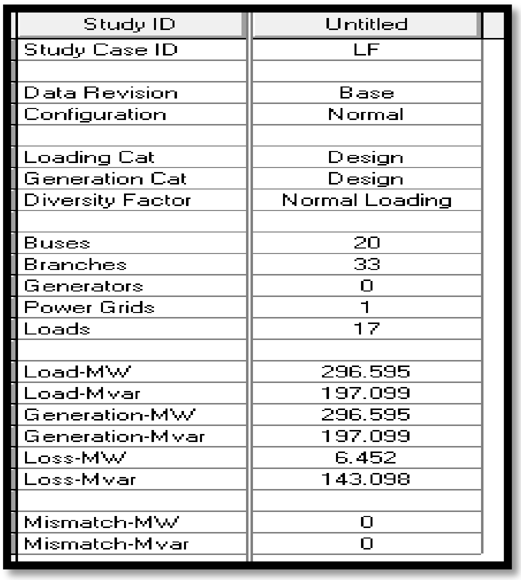
Necessary data required for scenario planning is obtained through email communication and from the websites directed by Durham County Council. [56] and [57] are the web pages of Neighbourhood Statistics and Nomis Web respectively. The detailed statistics within specific geographic area and official labour market statistics obtained are as described in Table 5.1.

Table 5. 1: Geographical area, vehicle and population statistics in the substation areas

Area/Substation Name	Usual resident population	Area (hectares)	Population density	Sum of cars and vans	% change in population
Belmont	3492	114	30.63	2109	-6.1
Low Spennymoor	1519	172	8.83	555	2.7
Meadowfield	3497	2139	1.63	2194	-4.4
Fylands Bridge	1338	139	9.62	748	-2.4

5.4 Spennymoor Network Modelling

A new project is created in ETAP 12.0.0 in the similar way as described in 4.4 of the thesis. The "General Info" report in the load flow result analyser window gives an overall summary of the modelling. It also shows the power mismatches and the number of elements used in the project as illustrated in Figure5.1. Simulated model at 100% EV penetration at all four substations along with the results display following colour codes is presented in AppendixB.



Study ID	Untitled
Study Case ID	LF
Data Revision	Base
Configuration	Normal
Loading Cat	Design
Generation Cat	Design
Diversity Factor	Normal Loading
Buses	20
Branches	33
Generators	0
Power Grids	1
Loads	17
Load-MW	296.595
Load-Mvar	197.099
Generation-MW	296.595
Generation-Mvar	197.099
Loss-MW	6.452
Loss-Mvar	143.098
Mismatch-MW	0
Mismatch-Mvar	0

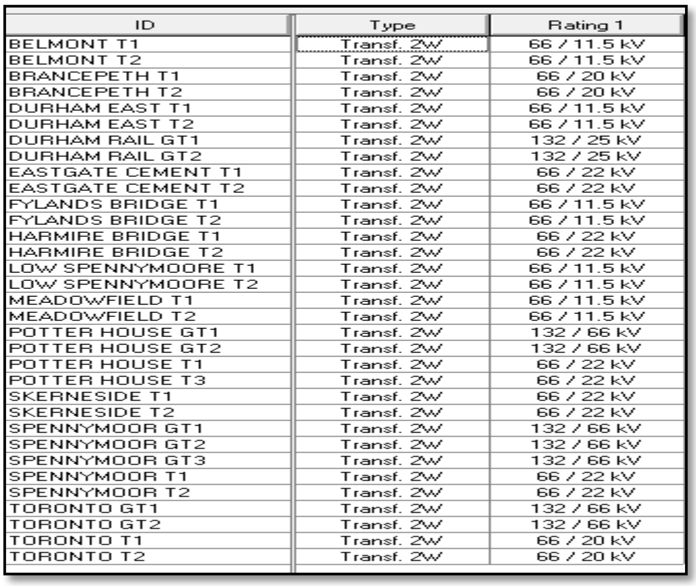
Figure 5. 1: General Information regarding Spennymoor project

5.4.1 Assumptions and Limitations

The license type of ETAP is an "Educational License for Colleges, Universities and Educational Institutions". A maximum of 25 buses can be used in the project. Usage of number of buses is reduced where possible in order to comply with the limitation. The area based network has a distributed generation which is operating at 30MVA, 33/66kV and is connected to Toronto 66kV bus. This Stonefoot wind farm which is consumer owned and maintained is not considered in this project. This decision is made in order to assess the capability of the substations and loads purely based on the power grid supply and not with the help of distributed generation. Similarly the Chilton Biomass generation connected to Spennnymoor 66kV bus is not considered. Fishburn 66kV primary and the two 25MVA, 66/20kV substations connected to it are also not considered in this area based network analysis. Fishburn 66kV bus does not have any supply or connection from the Spennymoor 66kV buses or any other substations. Annfield south tyne load connected to Potter House 66kV busbar is not considered in the analysis due to insufficient data. Durham East substation is modelled in ETAP but it is not considered for analysis purpose due to insufficient data regarding number of cars & vans in that area. The red and green buses at each 66kV substation are modelled as single busbar due to the limitation of the buses. Only 66/11kV substations in the area are considered because most of the lower order distribution voltages i.e. 230V and 433V are stepped down from 11kV feeders. This is a different voltage level where the EV charging impacts can be noticed.

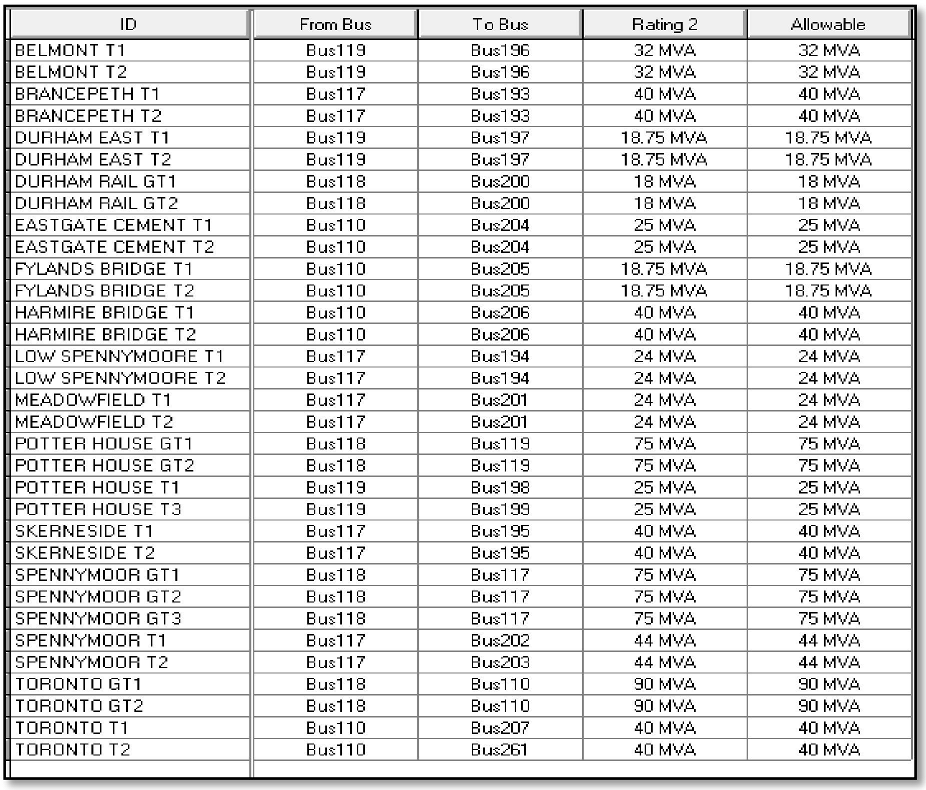
5.4.2 Voltage and Power Rating Assignment to the Transformers

The Spennymoor area is supplied with power from Spennymoor 275 kV supergrid transformers which from then are lowered to 132kV. Power Grid in the network model is rated at 132kV. The busbar connected to the power grid is the common point for the 132/66kV substations. From here other lower voltage substations are connected. The overall voltage and MVA ratings of the transformers are illustrated in Figure 5.2 and Figure 5.3.



ID	Type	Rating 1
BELMONT T1	Transf. 2W	66 / 11.5 kV
BELMONT T2	Transf. 2W	66 / 11.5 kV
BRANCEPETH T1	Transf. 2W	66 / 20 kV
BRANCEPETH T2	Transf. 2W	66 / 20 kV
DURHAM EAST T1	Transf. 2W	66 / 11.5 kV
DURHAM EAST T2	Transf. 2W	66 / 11.5 kV
DURHAM RAIL GT1	Transf. 2W	132 / 25 kV
DURHAM RAIL GT2	Transf. 2W	132 / 25 kV
EASTGATE CEMENT T1	Transf. 2W	66 / 22 kV
EASTGATE CEMENT T2	Transf. 2W	66 / 22 kV
FYLANDS BRIDGE T1	Transf. 2W	66 / 11.5 kV
FYLANDS BRIDGE T2	Transf. 2W	66 / 11.5 kV
HARMIRE BRIDGE T1	Transf. 2W	66 / 22 kV
HARMIRE BRIDGE T2	Transf. 2W	66 / 22 kV
LOW SPENNYMOORE T1	Transf. 2W	66 / 11.5 kV
LOW SPENNYMOORE T2	Transf. 2W	66 / 11.5 kV
MEADOWFIELD T1	Transf. 2W	66 / 11.5 kV
MEADOWFIELD T2	Transf. 2W	66 / 11.5 kV
POTTER HOUSE GT1	Transf. 2W	132 / 66 kV
POTTER HOUSE GT2	Transf. 2W	132 / 66 kV
POTTER HOUSE T1	Transf. 2W	66 / 22 kV
POTTER HOUSE T3	Transf. 2W	66 / 22 kV
SKERNESIDE T1	Transf. 2W	66 / 22 kV
SKERNESIDE T2	Transf. 2W	66 / 22 kV
SPENNYMOOR GT1	Transf. 2W	132 / 66 kV
SPENNYMOOR GT2	Transf. 2W	132 / 66 kV
SPENNYMOOR GT3	Transf. 2W	132 / 66 kV
SPENNYMOOR T1	Transf. 2W	66 / 22 kV
SPENNYMOOR T2	Transf. 2W	66 / 22 kV
TORONTO GT1	Transf. 2W	132 / 66 kV
TORONTO GT2	Transf. 2W	132 / 66 kV
TORONTO T1	Transf. 2W	66 / 20 kV
TORONTO T2	Transf. 2W	66 / 20 kV

Figure 5. 2: Name (ID), Type and Voltage Rating of the Transformers



ID	From Bus	To Bus	Rating 2	Allowable
BELMONT T1	Bus119	Bus196	32 MVA	32 MVA
BELMONT T2	Bus119	Bus196	32 MVA	32 MVA
BRANCEPETH T1	Bus117	Bus193	40 MVA	40 MVA
BRANCEPETH T2	Bus117	Bus193	40 MVA	40 MVA
DURHAM EAST T1	Bus119	Bus197	18.75 MVA	18.75 MVA
DURHAM EAST T2	Bus119	Bus197	18.75 MVA	18.75 MVA
DURHAM RAIL GT1	Bus118	Bus200	18 MVA	18 MVA
DURHAM RAIL GT2	Bus118	Bus200	18 MVA	18 MVA
EASTGATE CEMENT T1	Bus110	Bus204	25 MVA	25 MVA
EASTGATE CEMENT T2	Bus110	Bus204	25 MVA	25 MVA
FYLANDS BRIDGE T1	Bus110	Bus205	18.75 MVA	18.75 MVA
FYLANDS BRIDGE T2	Bus110	Bus205	18.75 MVA	18.75 MVA
HARMIRE BRIDGE T1	Bus110	Bus206	40 MVA	40 MVA
HARMIRE BRIDGE T2	Bus110	Bus206	40 MVA	40 MVA
LOW SPENNYMOORE T1	Bus117	Bus194	24 MVA	24 MVA
LOW SPENNYMOORE T2	Bus117	Bus194	24 MVA	24 MVA
MEADOWFIELD T1	Bus117	Bus201	24 MVA	24 MVA
MEADOWFIELD T2	Bus117	Bus201	24 MVA	24 MVA
POTTER HOUSE GT1	Bus118	Bus119	75 MVA	75 MVA
POTTER HOUSE GT2	Bus118	Bus119	75 MVA	75 MVA
POTTER HOUSE T1	Bus119	Bus198	25 MVA	25 MVA
POTTER HOUSE T3	Bus119	Bus199	25 MVA	25 MVA
SKERNESIDE T1	Bus117	Bus195	40 MVA	40 MVA
SKERNESIDE T2	Bus117	Bus195	40 MVA	40 MVA
SPENNYMOOR GT1	Bus118	Bus117	75 MVA	75 MVA
SPENNYMOOR GT2	Bus118	Bus117	75 MVA	75 MVA
SPENNYMOOR GT3	Bus118	Bus117	75 MVA	75 MVA
SPENNYMOOR T1	Bus117	Bus202	44 MVA	44 MVA
SPENNYMOOR T2	Bus117	Bus203	44 MVA	44 MVA
TORONTO GT1	Bus118	Bus110	90 MVA	90 MVA
TORONTO GT2	Bus118	Bus110	90 MVA	90 MVA
TORONTO T1	Bus110	Bus207	40 MVA	40 MVA
TORONTO T2	Bus110	Bus261	40 MVA	40 MVA

Figure 5. 3: Name (ID), From and To buses & MVA Rating of the Transformers

The simplified model of the network is illustrated in Figure 5.4.

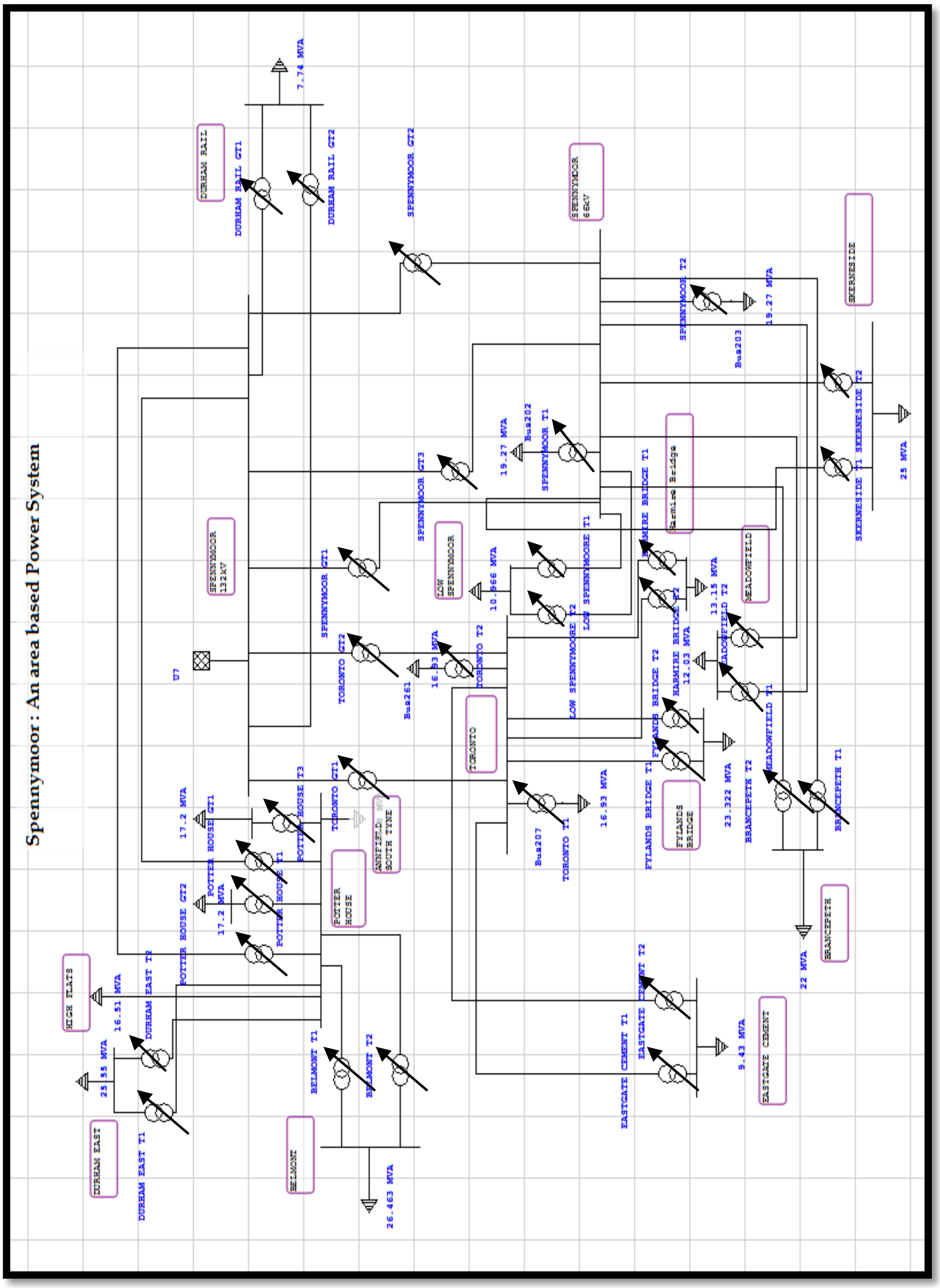


Figure 5. 4: Spennymoor Network Modelled in ETAP 12.0.0

5.5 Scenario Planning

A valid methodology presented in [39] has been used for scenario planning. Initially 11kV substations are identified in Spennymoor area and peak loads are assessed at each substation. Table 5.2 indicates the peak load at each substation along with the season, date and time it occurred. The demand data that is considered for the analysis is from 01/04/2013 to 02/04/2014. Accurate season's classification in UK is studied from Met Office website [58].

Four different EV penetration levels are considered based on number of cars & vans available in each area. A 25% increase in each step is assumed to evaluate the loading on the transformers in regular intervals. In Chapter 4 the EV penetration levels are considered with respect to number of car parking spaces available on site. In site based analysis there is limit on number of car parking spaces whereas there is no limit in area based analysis. Here existing number of cars and vans in the areas are taken as base values, predicting them to convert to electric vehicles in future. The penetration percentages considered are as follows:

- 25%: Assumed initial EV penetration at 66/11kV substations
- 50%: Penetration of half of the total vehicles at each 66/11kV substation
- 75%: A periodic step increase of 25% EV penetration at 66/11kV substations
- 100%: Full penetration of EVs at all four 66/11kV substations

A standard home charging is considered as the charging infrastructure available for EV owners to charge the batteries of the cars.

5.5.1 Peak Load Day in a Year

Microsoft Excel workbook containing recorded information is used to extract the peak load values at each substation between the dates mentioned above. Table 5.2 indicates the extracted peak load value at each substation, season, date, time it occurred and the dataset chosen from database.

Table 5. 2: Peak load values and data set chosen from the database for each substation

Substation	Peak Load (MVA)	Season	Date	Time	Dataset
Belmont	25.75	Winter	21/1/2014	17:30	B10:B17577
Low Spennymoor	10.1	Autumn	19/11/2013	17:30	E10:E17577
			20/11/2013	17:30	
		Winter	16/12/2013	17:00	
			17/12/2013	17:00,17:30	
		Winter	13/1/2014	17:30	
			14/1/2014	17:30	
			28/1/2014	17:30	
Meadowfield	11.3	Spring	10/4/2013	11:30	F10:F17577
Fylands Bridge	23.07	Autumn	20/11/2013	16:30	D10:D17577

Load curves are illustrated in Figure 5.5, Figure 5.6, Figure 5.7 and Figure 5.8 for the substations in the areas of Belmont, Meadowfield, Fylands Bridge and Low Spennymoor respectively.

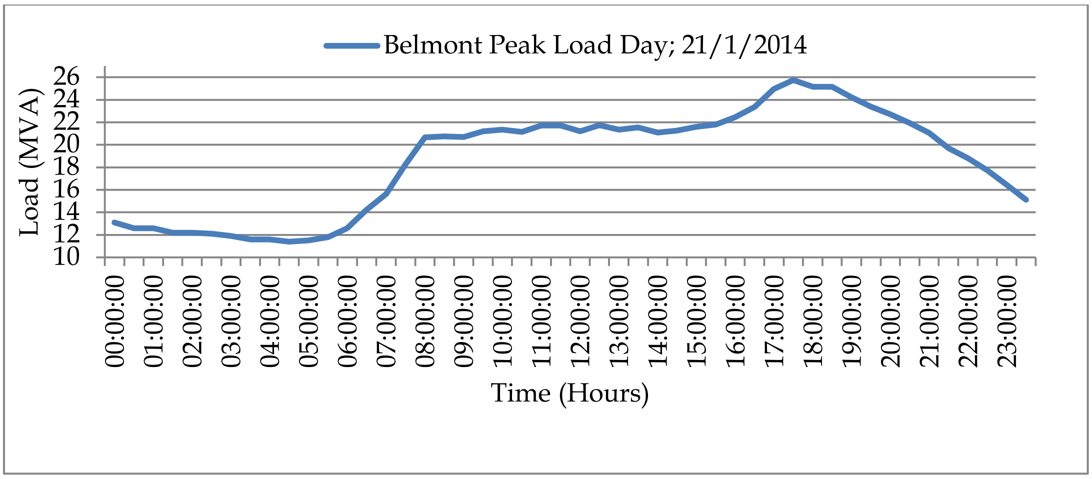


Figure 5. 5: Load Curve of Belmont on a Peak Load Day

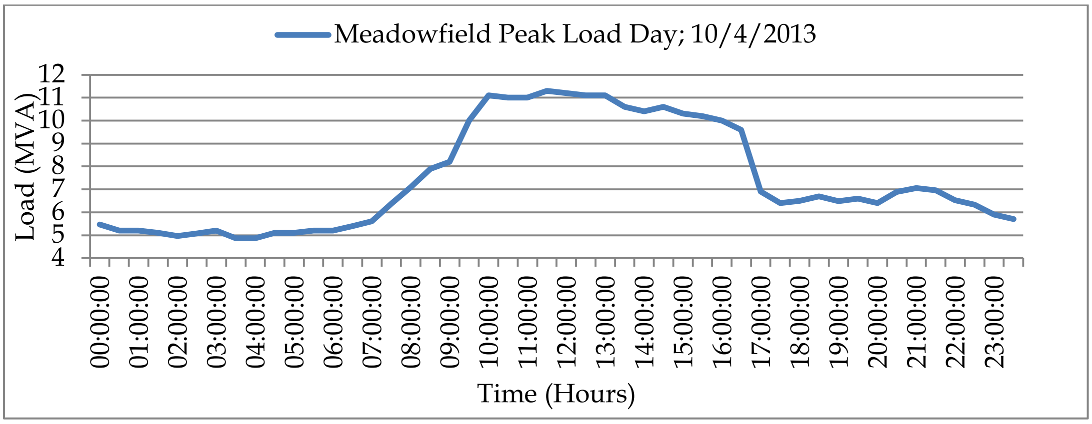


Figure 5. 6: Load Curve of Meadowfield on a Peak Load Day

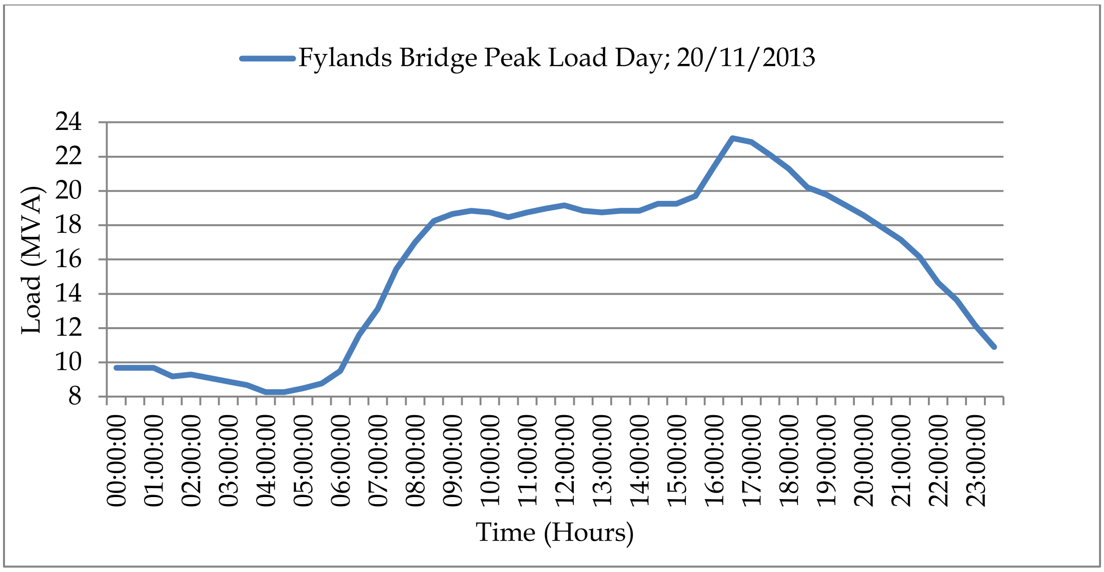


Figure 5. 7: Load Curve of Fylands Bridge on a Peak Load Day

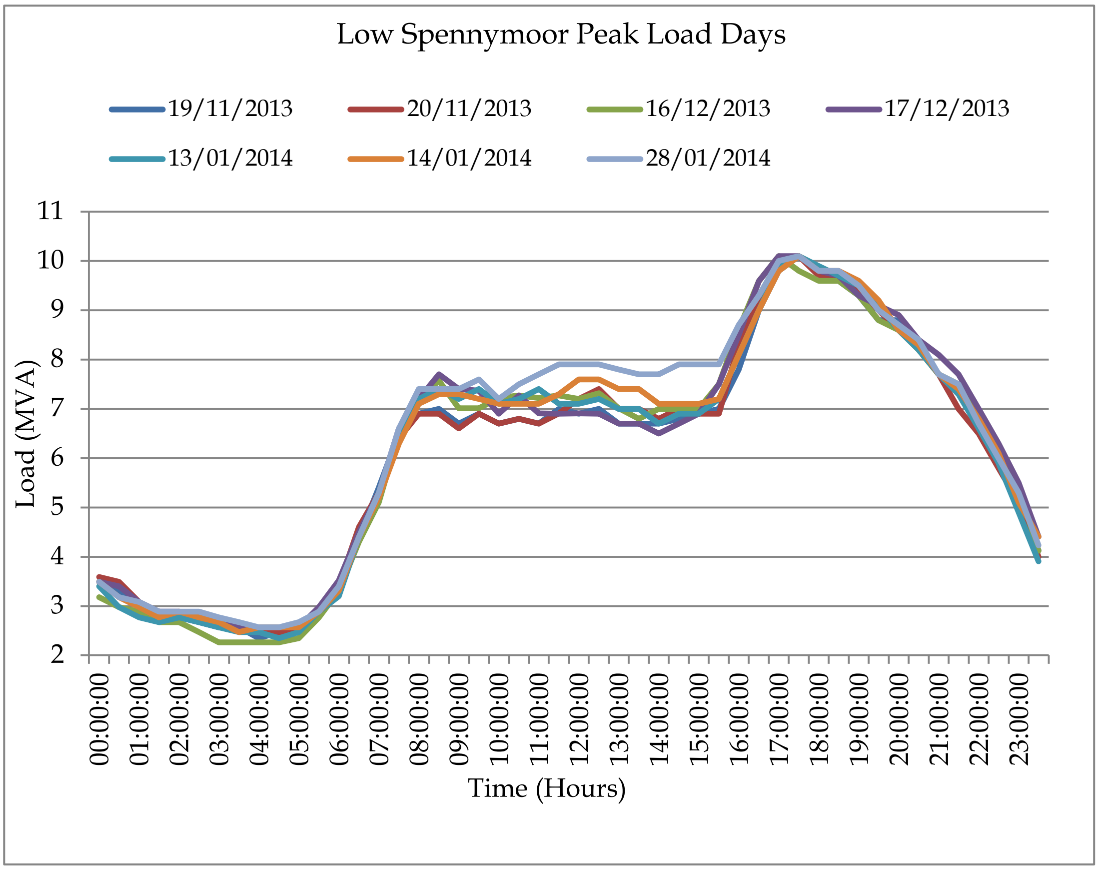


Figure 5. 8: Load Curves of Low Spennymoor on a Peak Load Day

5.5.2 Additional Demand in the Areas due to Uptake of EVs

An EV consumes 200Wh/km and runs on an average 40km/day. Therefore 8kWh/day energy is required [52]. The required energy is obtained by charging EVs at home. The time at which the EVs are charged is an important factor. Peak load demand occurrence and the transformers capability to supply the demand are the relevant subjects. The data available from Office of National Statistics regarding the availability of cars & vans in each area is taken as the base which would eventually become EVs and creates additional demand. Total energy and power requirement for cars & vans available in Belmont area, Low Spennymoor, Meadowfield and Fylands Bridge are given in Table 5.3, Table 5.4, Table 5.5 and Table 5.6 respectively.

Table 5. 3: Energy and power demand with % increase in cars at Belmont

Substation: Belmont; Total number of cars & vans =2109		
% of total cars & vans change to EVs	Energy (kWh/day)	Power (kW)
25	4218	175.75
50	8436	351.5
75	12654	527.25
100	16872	703

Table 5. 4: Energy and power demand with % increase in cars at Low Spennymoor

Substation: Low Spennymoor; Total number of cars and vans = 555		
% of total cars & vans change to EVs	Energy (kWh/day)	Power (kW)
25	1110	46.25
50	2220	92.5
75	3330	138.75
100	4440	185

Table 5. 5: Energy and power demand with % increase in cars at Meadowfield

Substation: Meadowfield; Total number of cars & vans = 2194		
% of total cars & vans change to EVs	Energy (kWh/day)	Power (kW)
25	4388	182.83
50	8776	365.6
75	13164	548.5
100	17552	731.3

Table 5. 6: Energy and power demand with % increase in cars at Fylands Bridge

Substation: Fylands Bridge; Total number of cars & vans = 748		
% of total cars & vans change to EVs	Energy (kWh/day)	Power (kW)
25	1496	62.3
50	2992	124.6
75	4488	187
100	5984	249.3

5.6 Simulation Results and Analysis

The load values are updated prior to each simulation at individual substations with the real power values calculated in 5.5.2. The percentage increase in EVs creates excess load and is added to the peak load value.

The MW value of the load is updated with new value and then the load flow simulation is carried out. Once the simulation is performed the impact of load increase is observed on whole area. If the voltages at the busbars are operating beyond the statutory limits of ±6% at 66/11kV transformers, transformer taps are used to maintain the desired voltage levels. Initially transformers overloading is observed and later the load values are forecasted until 2050 to compare with the firm capacities in order to understand where the uprating is necessary.

5.6.1 Substation 1: Belmont

Belmont is a coal mining village situated in County Durham. At this substation the EV owners are expected to plug in their electric vehicles during the peak load time which is at 5:30pm. Results obtained at Belmont are shown in Table 5.7

Table 5. 7: Results at Belmont during different EV penetration levels

Case	Ratings					Operating Load		Operating Voltage
	MVA	MW	Mvar	%PF	Amps	P (MW)	Q(Mvar)	kV
Base Load (No EV)	22.11	21.892	3.1	99.01	1160	23	3.3	11.285
Peak Load (PL) (No EV)	25.75	25.496	3.61	99.01	1352	25.3	3.6	10.965
PL + 25%	25.924	25.671	3.61	99.03	1361	25.5	3.6	10.954
PL+ 50%	26.098	25.847	3.61	99.04	1370	25.6	3.6	10.941
PL + 75%	26.272	26.023	3.61	99.05	1379	25.4	3.5	10.874
PL + 100%	26.447	26.199	3.61	99.06	1388	25.5	3.5	10.861

Bus 196 in the modelled network which is connected between Belmont substation and load was initially within the limits. On reaching the peak load value of 25.75MVA the bus bar started operating at under voltage. With the help of On Load Tap Changer (OLTC) on the primary side of the transformer at that particular substation the voltage is brought back to stay within the limits at the tap position 4.375%. The minimum and maximum % values of the transformer tap positions are -15 and 6. There is no other effect on the remaining network. On conducting different scenarios where the penetration of EV increases at 25%, 50%, 75% and 100% based on the existing number of cars present in this area, there is no significant effect on busbars or transformers. The firm capacity of the substation is 32MVA where in the analysed worst case scenario considering 100% of the vehicles present in this area change to complete electric mode, the load on the substation is expected to reach 27.074MVA at 99% power factor. There will not be any requirement in the uprating of the transformers or busbars at Belmont substation.

With the help of given forecast load information from NPG until 2018, a further forecast has been made until 2050 with the help of linear regression technique in Microsoft excel. The given load is in the units of MVA and is converted to real power by using the following equation:

$$P\ (MW) = S\ (MVA) * \text{Power Factor}$$

The estimated load at different EV penetration levels is added with the forecast load.

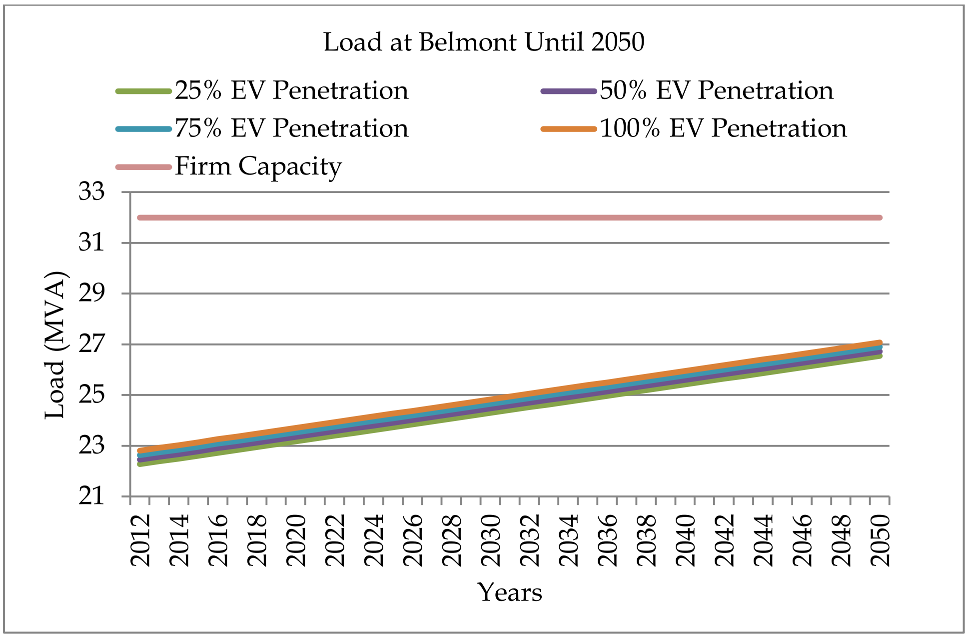


Figure 5. 9: Forecast Load Vs Firm Capacity at Belmont

The load values even at 100% EV penetration did not reach the firm capacity of the substation. The maximum load that is calculated is 27.07458 MVA in 2050 when all the cars & vans are EV's. There will not be any issue with the transformer loading but the peak demand value in this area will be very high where the generation of power will play a significant role.

5.6.2 Substation 2: Low Spennymoor

At this substation the EV owners are expected to plug in their electric vehicles in the evening at 5:00pm or 5:30pm. This is the time the peak demand values are recorded at this substation. Load values are updated as explained in 5.6 of this chapter and simulations are performed. Table 5.8 shows the operating load values along with the voltages for the given input values.

Table 5. 8: Results at Low Spennymoor during different EV penetration levels

Case	Ratings					Operating Load		Operating Voltage
	MVA	MW	Mvar	%PF	Amps	P (MW)	Q(Mvar)	kV
Base Load	10.1	9.999	1.425	99	530.1	12.3	1.7	12.189
Peak Load (PL)	10.78	10.672	1.521	99	565.8	12.8	1.8	12.032
PL + 25%	10.812	10.718	1.425	99.13	567.5	11.88	1.57	11.581
PL+ 50%	10.858	10.764	1.425	99.14	569.9	11.93	1.57	11.578
PL + 75%	10.904	10.81	1.425	99.14	572.3	11.967	1.578	11.573
PL + 100%	10.95	10.857	1.425	99.15	574.7	12.011	1.576	11.57

At this substation the peak load from the data is 10.1MVA. From historical data it shows that the maximum load connected was 10.78MVA. Therefore the higher value among the both is considered as the peak load to carry out scenarios. Initially the substation was loaded at 10.78MVA and the settings of the transformer taps were such that the voltage is within the limits. Load is reduced to 10.1MVA to check the operating voltage, real and reactive power variations. Buses numbered 194, 195 & 201 which are connected to the loads at substations Low Spennymoor, Skerneside and Meadowfield respectively are operating at over voltage which is beyond the limits. Using OLTC which is connected to the primary of the Skerneside the voltage is brought back to normal by reducing two taps which is -3.125%. Once the voltage is set back to the limits at Skerneside, bus bar 203 connected to Spennymoor T2 got affected and it started operating at under voltage. Here again two taps were adjusted at the primary of the substation. Again, Busbar 193 connected to Brancepeth substation operating on under voltage is brought back to limits with one tap adjustment at the primary. Bus 201 at Meadowfield substation operating at under voltage is brought back to normal adjusting four tap positions i.e. to -2.5%. On further penetration of EV in different scenarios there is no significant effect on the buses or transformers.

The firm capacity of the substation is 24MVA. According to the forecasted information in 2050 the load will increase to 13.01MVA at 99% power factor and 100% EV penetration. Hence no significant changes will be required to make at this substation.

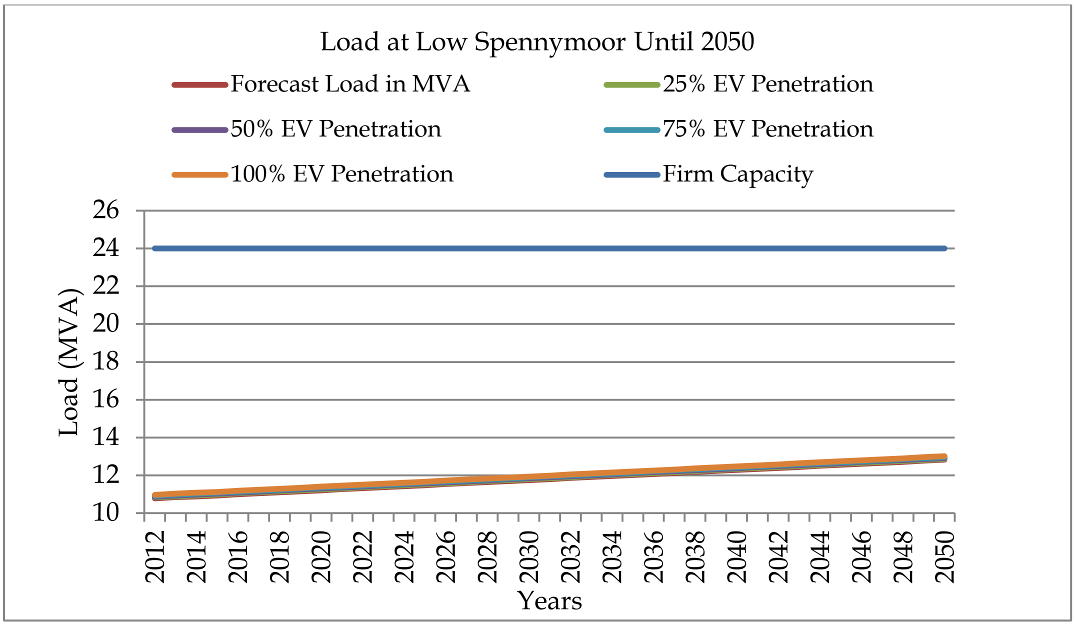


Figure 5. 10: Forecast Load Vs Firm Capacity at Low Spennymoor

The blue legend used for firm capacity is 24MVA load level in the Figure 5.12. The forecast load in 2050 with 555 cars fully electric will not have any significant effect on transformer loading levels. The uprating of the transformers is not required because of the additional load level.

5.6.3 Substation 3: Meadowfield

Medowfield has an industrial estate. The recorded peak load demand in this village is at 11:30am. It is planned to analyse the worst case scenario regarding the demand at the substation. The EV owners are expected to plug in their vehicles during this time. The industrial load along with the residential load will add up to the peak load values in addition to the EV penetrations. The simulations performed and the results obtained are shown in Table 5.9.

Table 5. 9: Results at Meadowfield during different EV penetration levels

Case	Ratings					Operating Load		Operating Voltage
	MVA	MW	Mvar	%PF	Amps	P (MW)	Q(Mvar)	kV
Base Load	9.78	9.78	0	100	513.3	11.506	0	11.931
Peak Load (PL)	11.3	11.3	0	100	593.1	13.045	0	11.819
PL + 25%	11.483	11.483	0	100	602.7	13.224	0	11.804
PL+ 50%	11.666	11.666	0	100	612.3	13.402	0	11.79
PL + 75%	11.849	11.849	0	100	621.9	13.579	0	11.776
PL + 100%	12.03	12.03	0	100	631.4	13.752	0	11.761

No major changes are observed in the voltage levels and transformer loading. The whole network seems to operate in steady condition. NPG has designed the equipment which can support future load increments. All buses are operating within the limits.

The firm capacity of the substation is 24MVA. On forecasting the load through linear regression at 100% EV transformation, it is observed that the load increases to 12.59MVA by 2050. There will be no requirement of reinforcement at this substation. The demand values are plotted against the firm capacity of the substation in the Figure 5.13

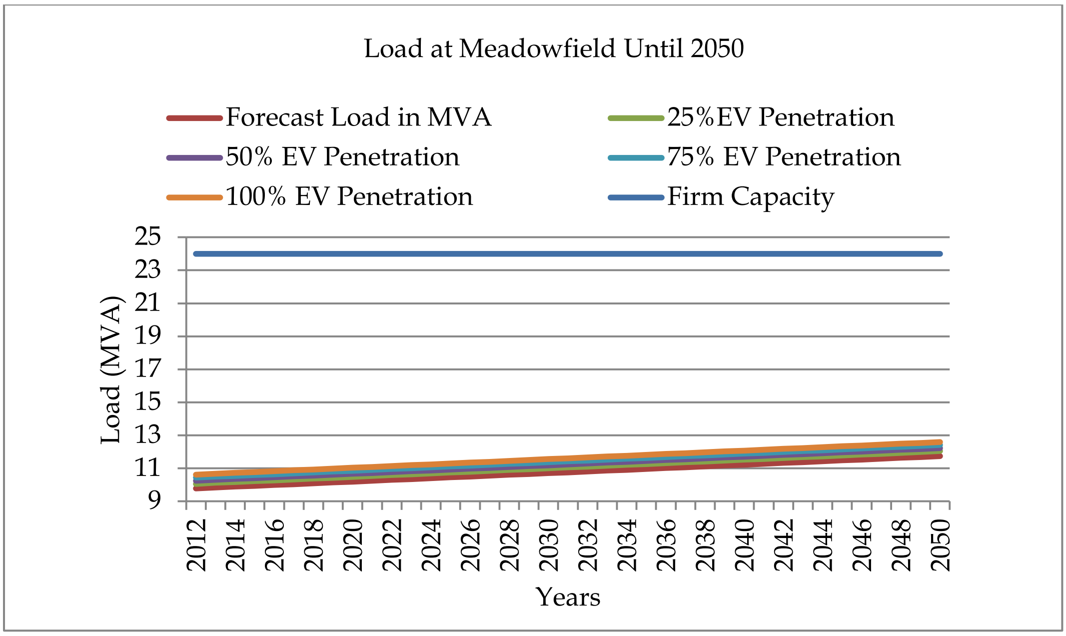


Figure 5. 11: Forecast Load Vs Firm Capacity at Meadowfield

5.6.4 Substation 4: Fylands Bridge

It is an area spread in 139 hectares with 748 cars & vans. EV owners in this area are expected to plug in their EV at 4:30pm. The peak demand value occurred in autumn is obtained from recorded data which is 23.07MVA. The simulations performed and the results obtained are shown in Table 5.10.

Table 5. 10: Results at Fylands Bridge during different EV penetration levels

Case	Ratings					Operating Load		Operating Voltage
	MVA	MW	Mvar	%PF	Amps	P (MW)	Q(Mvar)	kV
Base Load	21.77	21.335	4.332	98	1143	21.609	4.388	11.07
Peak Load (PL)	23.07	22.609	4.591	98	1211	21.905	4.448	10.827
PL + 25%	23.131	22.671	4.591	98.01	1214	22.527	4.562	10.965
PL+ 50%	23.193	22.734	4.591	98.02	1217	22.55	4.555	10.955
PL + 75%	23.254	22.796	4.591	98.03	1221	22.573	4.548	10.946
PL + 100%	23.314	22.858	4.591	98.04	1224	22.596	4.541	10.937

No major changes are observed in the voltage levels and transformer loading. The whole network seems to operate in steady condition. NPG has designed the equipment which can support future load increments. All buses are operating within the limits.

Firm capacity of the substation is 25.2MVA, whereas at the 100% EV penetration the load demand reached to 25.177MVA in 2043. The additional load cannot be connected to the substation which it can withstand. The substation has to be uprated in the year 2043 or even before in order to comply with the ER P2/6: security of supply standards [59]. The forecast loads and firm capacity are illustrated in Figure 5.14.

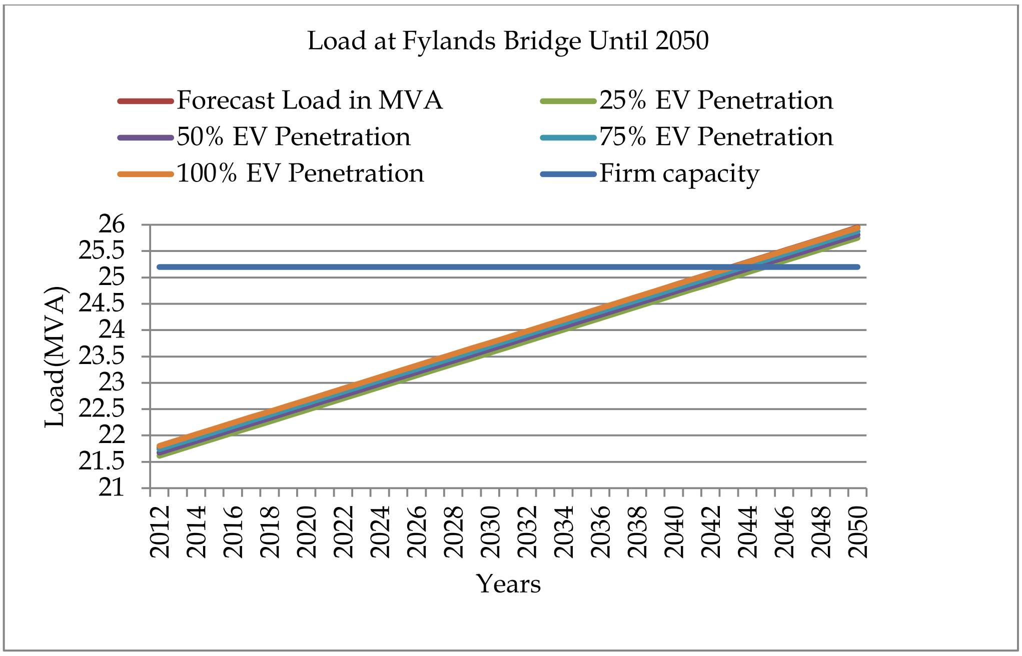


Figure 5. 12: Forecast Load Vs Firm Capacity at Fylands Bridge

5.7 Concluding Remarks

In this chapter 66/11kV networked area Spennymoor, located in Durham is modelled and analysed. Four 66/11kV substations at four different EV penetration levels considering home charging as the EV charging infrastructure present is assumed for research. The impact of EV penetration is observed at busbars operating voltage. The busbars that are not directly connected to the selected substations also experienced the change in voltage. Voltage levels are brought back to operate within the limits with the help of OLTC connected on the primary side of the transformers.

The transformer loading levels are well under the firm capacity value at all substations even at 100% EV penetration. Further analysis of estimating the future load until 2050 based on the data provided by NPG is compared with the firm capacity of the substations. Transformers at Fylands bridge substation are the only among other substations which met the firm capacity in the year 2044 at 75% EV penetration in addition to the existing peak demand value. Reinforcement should take place before the firm capacities are reached to comply with ESQC and ER P2/6: Security of Supply regulations.

Chapter 6

Local Policy Making Proposition for EV Charging Infrastructure Management at HEI’s

6.1 Introduction

In this chapter a systematic procedure that has been followed in order to initiate the research is explained. The strategy that has been followed to identify the current and prospective EV users is mentioned. Summary of the consultation process with EV owners is discussed. The identification process of the availability of the Pod Point’s in order to charge an EV, charging cable compatibility, electrical properties of the charging stations, first time ever PAYG concept to use Type 2 Mode 3 charging stations that are manufactured by Pod Point Ltd are also explained. Key findings from benchmarking (seven Higher Educational Institutions (HEI’s)) with several learning outcomes are stated. Final recommendations that were made based on the learning outcomes of the research are included. Most of the content in this chapter is published in the proceedings of an international conference. [60]

6.2 Local Policy Development Strategy

With the help of government funding from Office of Low Emission Vehicles (OLEV), Department of Transport and the associated company Pod Point Ltd that installs the electric vehicle charging stations, it is really important to develop a reasonable and acceptable policy for the present and future EV community at Brunel University London.

6.2.1 Student, Staff Interest Survey

Annual travel survey is conducted every year by the department of operations in order to improve the travel and parking arrangements at BUL. Two questions were made part of that survey to identify the existing and future EV users. The questions are:

1. Do you drive an electric vehicle to Brunel?
2. Do you have any plans to purchase an electric vehicle in the next 12 months?

Out of 15,996 Brunel's staff and students 4,452 members participated in the annual travel survey. Out of which seventeen people positively responded for the above questions. Seven are driving an EV to BUL and ten have plans to purchase an EV in the next 12 months.

6.2.2 Discussion with Present and Prospective EV Owners

As part of the consultation process, open discussion and personal interviews were conducted with people identified. Topics discussed were regarding availability, usage, compatibility of charging cable, electricity tariff, hours of operation of Pod Point, enforcement and incentives. Additional questionnaire was developed to further understand the EV community. The questions are:

1. What made you to buy or consider to buy an EV
2. Please specify the make and model of the EV you wish to recharge.
3. Does the charging cable become barrier to use the charging facility
4. How much time you think you need to top up the charge of your vehicle
5. If you are an existing user of EV, what is the nearest public charging station to university that you are using in case you need to. Please mention the location along with postcode.

6. Do you think you should be eligible for any incentive because of driving a zero carbon emission vehicle into university
7. What incentive you prefer

Summary: Novelty, reducing carbon emissions, tax avoidance, cutting costs are responses to the first question. 80% of Brunel's EV community responded that they are owners of Nissan Leaf. Charging cable does seem to be a barrier in utilising the facility of charging stations at Brunel University because the domestic cable that is supplied during the purchase of the vehicle is not compatible with the charging stations that are available on campus. Compatibility of charging cable with charging stations is discussed in 6.3.2 in detail. 60% of the EV owners need at least three hours of charging for their EV's while they are at university. All the present and prospective EV owners responded that they should be eligible for incentives. 100% of EV community at Brunel University are worried about the parking space to park their EV after charging it.

6.2.3 Competitive Benchmarking

Seven UK HEI's which has established EV charging stations for its users are considered to compare and draw conclusions on various aspects [61]. Universities considered are:

1. Kingston University, London
2. University of Bath
3. Homerton University Hospital
4. National Oceanography Centre, University of Southampton
5. Nottingham Trent University
6. Northumbria University, Newcastle
7. Teesside University

Learning outcomes and key findings from benchmarking are discussed in Section 6.4.

6.3 Using Type 2 Mode 3 Charging Stations

EVSE are manufactured, supplied and installed by a company named "Pod Point". Pod Point is a wholly owned brand of Pod Point Ltd. This company is responsible for the overall user experience at BUL. BUL takes major decisions such as, tariff for the PAYG users (staff, students and the visitors of the university) and the hours of operation of the Pod Points. This helps to ensure that the service being provided is usable and within the reach of everyone.

Brunel's commitment to show impact on the environmental priorities such as climate change, air quality, decarbonisation, green growth and green travel will remain focussed and every development and decision in its progress will be taken on their own merit. This new establishment of Pod Points in the long term will have positive mark in reducing the carbon emissions within the campus, improves the air quality and gives strength to the green travel.

6.3.1 Pod Point Status

The blue, green and red highly visible status lights present along the side of the Pod Point will allow the EV drivers to understand from distance whether the unit is available for use, already in use (vehicle is being charged) or out of service. In addition to this the live availability map on Pod Point website will help to know the status of the nearest Pod Point. Live availability map can be accessed with this web link: http://www.pod-point.com/live-availability [62]

Figure 6. 1: Pod Point's highly visible status lights [25]

6.3.2 Pod Point Socket, Compatible Cable

The Pod Point twin Mennekes 32-32 post delivers 32 A of output current or 7kW of output power from each socket. Two electric vehicles can undergo fast charge simultaneously from a single post. The Pod Point pillar has Mennekes sockets and therefore one end of the cable that needs to be connected to the Pod Point should be compatible to them. The standard domestic lead supplied with the electric car is not useful to plug in. 7 pin Type 2 Mode 3 (Mennekes) cable is required. [63]

Figure 6. 2: Mennekes socket and one end of the charging cable [64]

6.3.3 Technical Specifications of the Pod Point

Pod Point has several electrical properties and the important ones in a nutshell are as below:

Table 6. 1: Electrical Properties of Pod Point [65]

Charge Type	Mode 3
Number of Charge Sockets	2 per each pillar
Rated Voltage	240V
Rated Output Current	2*32A
Rated Output Power	7kW
Rated Frequency	50Hz
Over current Protection	32A per door
Ground fault protection	32mA RCD
Socket Electrical Compliance	IEC 62196-2
RFID Reader Compliance	ISO 14443 Mifare
RFID Reader Frequency	13.56MHz
Standby Power consumption	5W

6.3.4 Usage of Pod Point

It is necessary to follow sequence of steps in using the charging infrastructure. The following subsections explains in detail on how to use the pay as you go Pod Point charging stations starting from registration through to payment. [66]

6.3.4.1 Sign up/ Registration

Electric vehicle owners must get registered by calling the Pod Point's call centre to use the charging facility. The telephone number to be contacted on is 0207 247 4114. The free registration process securely collects and stores the following data:

- Name and Address
- Mobile Telephone Number
- E-mail address
- A method of payment :credit or debit card details

A small initial balance (say £10) is taken and the users account balance is updated in the user login account page where they can view their usage profile.

6.3.4.2 Pricing/ Tariff at a Charging Station

Pricing at a charging station is not same at all places. Every charging station has an identification number (example: 9422134). User may wish to check the price before charging the EV; this can be done by texting (standard network texting charges may apply) a given number in the similar manner below:

Example:

SMS to 6####: "TARIFF 9422134"

Response to user: "Site A 9422134: £0.71 per hour. Text START 9422134 to begin charging".

6.3.4.3 To Start Charging

In order to start charging the electric vehicle after parking in a dedicated bay, user will need a compatible charging cable and a mobile phone.

Step 1: Plug one end of the cable to the vehicle

Step 2: Trigger the socket to open and the charge cycle to start by sending a text message to the system message centre.

SMS to 6####: "START 9422134"

Step 3: The available socket door will be released

Step 4: Plug the other end of the cable into the socket which will be locked

Response to user: "Site A 9422134 Charging. To end Text STOP 9422134".

Step 5: Highly visible status lights change colour from blue to green on the corresponding socket to indicate that charging has started.

6.3.4.4 To Stop Charging

Step 1: The user stops the charge cycle and release their cable by sending a text message to the system message centre.

SMS to 6####: "STOP 9422134"

Step 2: The highly visible status lights change colour from green to blue on the corresponding socket to indicate that charging has stopped and it is available for the next user.

Step 3: The lock will be released and the cable can be removed from the socket.

Response to user: "Site A 9422134 stopped. 24 kWh delivered over 4 hours. Total cost £ 2.83. Login for more details. Thank you."

Step 4: Close the socket door firmly

Step 5: Unplug cable from car

6.3.4.5 PAYG (Pay As You Go)

During the process of registration, user debit or credit card details are taken as a method of payment. Minimum amount (say £10) is charged and the user's account balance is updated to £10. A dedicated user account page is set up after the registration process for every individual end user. Account can be credited by dialling 0207 247 4114 when required. After each usage (sending START and STOP text message) an entry is made on the user account page recording the number of kilowatt hours delivered, usage time (charging cycle) and the users balance is updated.

6.4 Key Findings from Benchmarking

6.4.1 Learning Outcome 1: Public and PAYG Charging Networks

There are public and PAYG charging networks in UK, where a public charging network is one where EV drivers join a public network (usually by paying annual membership fee), and that gives them access to all charge points on that particular network using an RFID tag. There are two types of public charging networks:

1. "Government Plugged in Places networks:
Plugged in Places (PiP) is a government initiative in regions across the UK. Figure 6.3 shows the five currently active regions in green, and three further regions expected to be active in grey.

2. The Pod Point Open Network

For areas not covered by a Plugged in Places network, the Pod Point Open Network provides a public charging network for EV drivers and for businesses who want their charge points to be included in a public charging network." [67]

"The Pod Point PAYG Network is Europe's first pay as you go electric vehicle charging network. It allows anyone with a mobile phone to access charging points across the UK. There is no membership fee – anyone can use the charge points.

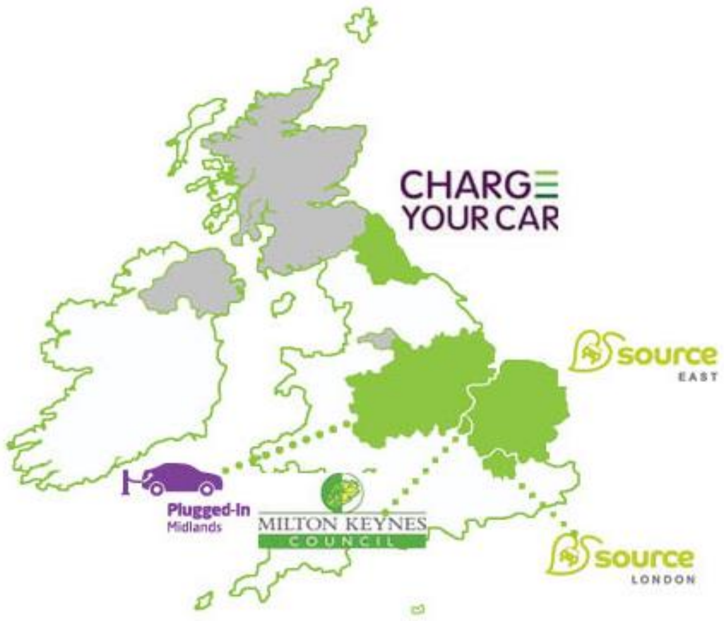


Figure 6. 3: EV public charging networks in UK [67]

The benefits of using PAYG network are:

1. EV drivers pay no yearly membership fees, instead they pay only for what they use
2. No RFID tags are needed – just a mobile phone, so drivers don't need to pre-register and wait for a tag to arrive in the post before using a charge point
3. A user login account where they can view their usage profile
4. Call centre support line in case of any charging problems." [68]

6.4.2 Learning Outcome 2: Status of EV Infrastructure at HEI's

Table 6.2 shows how the 25% funding was made available by the universities, what type of network the universities are with, whether the usage of RFID card is required for access to charging stations and how much membership fees is being paid by the EV users for the usage of those charging networks at respective universities. Most of the universities funded the 25% of investment from their own budgets. Other than Brunel all HEI's are part of public charging networks. Southampton University has unique feature where a pre booking of space, time are required and payment has to be made in advance (before 48 hours). Though RFID card is required to access the EV charging station like all other public charging networks, the prepaid process made it likely to fall under PAYG network. HEI's except Brunel requires RFID cards/tags in order to get access to EVSE and pays the membership fee as mentioned in Table 6.2. Electricity is provided free of cost for the EV users who are part of public charging networks. PAYG users will pay for what they use and the tariff is set up by the facility providers (university management).

Table 6. 2: Comparison of Various Parameters at HEI's

University	Funding	Public/ PAYG	Network	RFID tags/cards	Annual Membership fee
University of Bath	Self	Public	Pod Point	Required	£12.50
University of Southampton	Self	PAYG	Plugged in Places	Required	Not Applicable
Northumbria University Newcastle	Self	Public	Charge Your car	Required	£10.00
Teesside University	Self	Public	Charge your car	Required	£10.00
Homerton University Hospital	Self	Public	Source London	Required	£10.00
Kingston University	Council	Public	Source London	Required	£10.00
Nottingham Trent University	Self	Public	Plugged in Midlands	Required	£20.00
Brunel University	Self	PAYG	Pod Point	Not Required	Not Applicable

6.4.3 Learning Outcome 3: Annual Parking Permit Fee

Other parameter that was considered for the study is the amount of parking permit fee paid by the students and staff annually at the universities where there is parking facility. Staff at universities pays the parking fee according to their salary (0.3% of the salary of the staff member at Brunel University). Parking permit fee paid by staff who earns £25k per annum at HEI's are considered in this research. Figure 6.4 shows the graphical representation of student staff annual parking permit fee paid. Although parking fee is charged there is no guarantee of parking space and the process of hunting is required. This drawback gave scope for incentivising (concession in parking permit fee) EV users which in turn makes others motivated to use EV

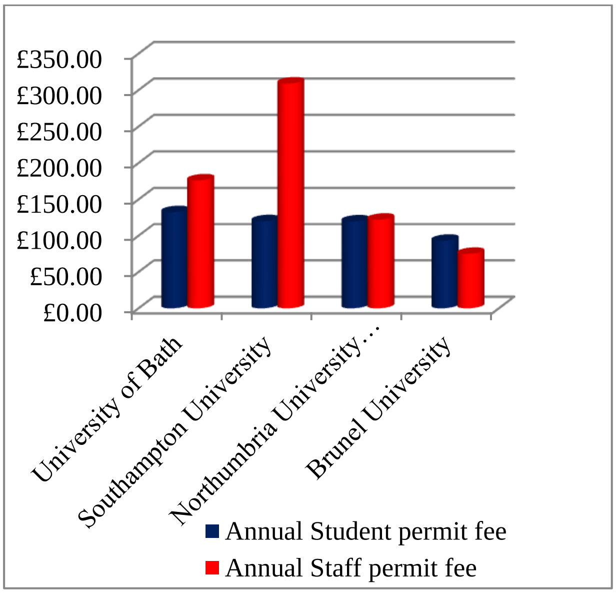


Figure 6. 4: Annual student & staff parking permit fee at HEI's

6.4.4 Learning Outcome 4: No. of Charging Bays and Stations

Figure 6.5 depicts the number of charging stations and dedicated charging bays at HEI's. Only two ports EVSE are installed under this government grant. It can be observed that the charging bays are twice to that of the charging stations. Once the EV's are charged they have to be moved to normal parking bays giving opportunity for other EV users to charge. This finding also gave scope to include in recommendations the provision of reserved parking spaces and access to both student and staff parking areas as an incentive to EV users.

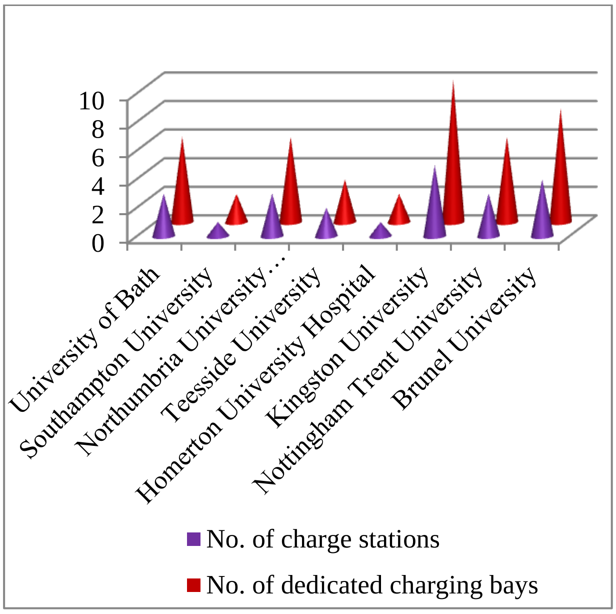


Figure 6. 5: Number of charging stations and dedicated charging bays at HEI's

6.5 Recommendations

6.5.1 Tariff and Hours of Operation

To help Brunel students, staff and visitors continue to get the most from their electric vehicles -for less- a special tariff is introduced. With this special rate of 11.8p/ kWh an EV can be charged at a cheaper rate. This finalised tariff is what exactly the university pays to the electricity providers.

Example: Nissan Leaf has 24kWh battery which when connected to 32A socket takes 4 hours to fully charge. For every 1 hour, 6kWh is delivered and 6*0.118 = £ 0.708 is payable. Fully charging a Nissan Leaf costs £ 2.832 at 11.8p/kWh

This charging facility on campus can be made available 24/7. There is a customer support line for all EV drivers using these posts at all times and the user can call on 0207 247 4114 if they have any charging problems.

6.5.2 Effective Operation of Parking and Identification of EV

A specially designed sticker must be issued to the EV owners to be displayed along with the parking permit in the windscreen of the car or a parking permit with a colour different to that of existing permit colours which are used to differentiate students and staff. Following one of the above mentioned phenomena it will be easy to identify an EV and an effective operation of parking can take place.

6.5.3 Incentive

Brunel University is extremely proactive in encouraging the usage of Electric Vehicles. The strong indication of Brunel's commitment to zero carbon emission vehicles is the establishment of Pod Points. Brunel University also encourage the EV owners through incentives. The incentives recommended were as follows:

a. 50% concession in the parking permit fee and provide few reserved parking spaces for Electric vehicles in addition to the dedicated charging bays. These reserved parking spaces must be made available only for EV's of Brunel students & staff during business hours.
b. 50% concession in the parking permit fee and allow the EV to be parked in both standard white bays (allotted for students to park their cars) and the bays marked with a red dot (reserved for staff).
c. No concession in the parking permit fee. Allow the EV to be parked in both standard white bays and the bays marked with a red dot. All the EV owners can be invited for lunch and award them with a certificate of appreciation once annually.

In addition to the above, free loan of charging cable to the EV owners is suggested to be made available.

6.5.4 Enforcement

EV owners who use the parking while charging facility at the university must obey the terms mentioned below else penalty charge notice (PCN) will be issued.

a. For any non-electric vehicles parked within the designated bays for the purpose of charging an electric vehicle.
b. For the electric vehicles if they are not being charged when parked in the designated bays.
c. If every part of the vehicle is not within the charging bay.
d. For the non-compliance of existing Traffic, Parking and Permit regulations of the university.

6.6 Current Status of EV Charging Infrastructure at BUL

Two PAYG (Pay As You Go) electric vehicle charging stations (EVCS) which are manufactured by Pod Point Ltd, facilitating four EVs to charge at the same time are made available on BUL campus. These Type 2 Mode 3 charging stations are received through grants from OLEV (Office for Low Emission Vehicles) in order to develop the EV infrastructure. EV owners will require registration with Pod Point Ltd prior to usage of EVCS through appropriate web links expected to be made available on IntraBrunel. One of the EVCS is installed in Elliott Jaques building's car park and the other in West Spur road car park. The third EVCS is expected to be installed either in front of Wilfred Brown building or in St. John's car park in near future. The installed charging station and the charging bays marked "Electric Vehicle Charging Only" at both the locations are illustrated in the Figures 6.6 and 6.7

Figure 6. 6: FV of EVCS & reserved charging bays at Elliot Jaques car park

Figure 6. 7: RV of EVCS & reserved charging bays at West Spur road car park

Two charging bays at each charging station are reserved for EVs. In Figure 6.7 it can be clearly seen that the other parking bays are not marked with similar sign instead they are marked with a red dot. The red dot denotes reserved parking for BUL staff. A white dot denotes parking for students. The EV charging bays can be used by staff, students and public although usage by public is not the priority. Appendix C includes revised parking plan by Department of Estates.

The tariff proposed in section 6.5.1 is revised and the value is rounded off to a £1 per hour (7kW * 1 hour * 11.8p/kWh ≈ 82.6 pence). The 30% handling fee charged by Pod Point Ltd (30pence) and 20% VAT on the whole (26pence) which is summed to £1.56 ≈ £1.60 per hour is payable by EV owners at the university to Pod Point Ltd. Non- university EVCS users (public) are subjected to £2.50 per hour. The mode of usage and payment is according to the procedure explained in sections 6.3.5 & 6.3.4.5 respectively. Incentives are yet to be finalised.

The EVCS are expected to be fully operational by the end of February 2015 with a view to "Go Live" in the first week of March 2015.

6.7 Concluding Remarks

In this chapter the online survey method is used to identify the EV community. The consultation process with the present and prospective EV owners through personal interviews and group discussions gave wide opportunity to discuss and debate regarding the usage of EV charging stations. Benchmarking helped to compare various parameters at several universities. Finding the parking space to park the car after charging and compatibility of the charging cable with charging stations are the most worried subjects by the EV community. The concerns rose during the consultation process and the key findings from benchmarking are given serious consideration while framing the recommendations. According to section 6.6, the EVCS at BUL are expected to "Go Live" in the first week of March 2015. This research is part of travel plan implementation promoting sustainable mode of transport to and from the university.

Chapter 7

Conclusions and Further Research

In this chapter a summary of the concluding remarks made at the end of every chapter in answering the principle research objectives is presented. The wide spread of the subjects, EVs and power systems offer several potential extensions to the work presented in this thesis. Finally, suggestions for further research are described.

7.1 Conclusions

The motivation for the research developed from the UK Government's environmental legislation containing legally binding targets towards greenhouse gas reduction is presented in chapter 1. The transport sector which is contributing 24% of UK greenhouse gas emissions is undergoing a transition from the usage of ICE powered vehicles to EVs. The supporting infrastructure deployment of charging or recharging stations requires policy by which the users can be administered. The mass deployment of charging stations and public adoption of EVs will develop significant amount of electrical load on the power networks.

In order to maintain the security of power supply by balancing the generation and demand, it is necessary to gain an evidenced understanding of the capacity of the present power networks. This will ensure proper power system planning to accommodate future EV charging infrastructure.

The power system engineer, analyse the applications for new load or generation connections to the existing networks. This is something routine in the offices of DNOs. The predictable load management is an easier and efficient task when compared to the complicated and less predictable mass adoption of EVs. In chapter 2 a review of EV technology is presented introducing various technicalities behind EVs and its associated charging stations. The extended theory about interoperability between EVs and power networks presented in chapter 3 is the area where the challenges are identified. Section 3.2 formed a substantial base and helped in the development of chapters 4 and 5. The methods of customer interaction in taking new technology into the society i.e. by conducting online surveys, focus groups and personal interviews is implemented in the development of a policy proposition for the EV infrastructure users which helped to write chapter 6.

7.1.1 Investigation of a 11kV Networked Site Capacity

A methodology is proposed in the assessment of deploying 20 EV charging parks with the capacity of 100 cars in each park at Brunel University London. Various simulations in four test cases with realistic increase in the uptake of EVs by 17% (Assumed initial EV penetration on site), 30% (Steady increase), 50% (Half capacity of the site) and 100% (Full capacity of the site) under various charging patterns are analysed.

Slow, fast and rapid charging is considered in test case 1. The transformers are overloaded due to load created by rapid charging of EVs; therefore it is not considered in further test cases.

The capacity of BUL power distribution network in accommodating EVCS to supply the EV penetration levels depending on transformer overloading condition is as follows:

- At 100%: Slow charging infrastructure deployment to supply 1700 EVs or fast charging stations establishment to supply 500 EVs on site is possible.

- At 50%: 900 EVs can undergo slow charging or 850 EVs can plug in to the fast charging stations.
- At 30%: 570 EVs can power up their batteries with the help of slow charging infrastructure or 540 EVs with the help of fast charging stations.
- At 17%: 323 EVs can undergo slow or fast charging while 34 EVs can undergo rapid charging.

A very minimum number of buses are operating at under voltage condition during 17% and 30% EV penetration at slow and fast charging. Deployment of rapid charging stations requires up grading the substations as the number of EVs increase. 34 rapid charging stations can be installed on site as discussed in section 4.6.1 at the compromise of no slow or fast charging stations.

OLTC facility is not available for the transformers on site. Voltage regulation has to be carried out at the primary substations. Out of 21 substations supplying the whole campus only 20, 11/0.433 kV substations that are inside the campus connected to 11 kV HV ring are considered for the analysis.

7.1.2 A Wider Context: 66/11kV Networked Area

For a wider context, 66/11kV networked area, Spennymoor in Durham is considered in which four substations Belmont, Low Spennymoor, Meadowfield and Fylands Bridge under four different EV penetration levels (25%, 50%, 75% and 100%) are analysed. Home/slow charging is assumed in this case study. The impact of EV penetration is observed at busbars operating voltage. The busbars that are not directly connected to the substations mentioned also experienced the change in voltage in this interconnected network. Voltage levels are brought back to operate within the limits with the help of On Load Tap Changer (OLTC) connected on the primary side of the transformers. This voltage regulation facility is not available for the substations that are present on site discussed in chapter 4.

The transformer loading levels are well under the firm capacity value at all substations even at 100% EV penetration. Further analysis of estimating the future load based on the data provided by NPG is compared with the firm capacity of the substations. Transformers at Fylands bridge substation are the only among other substations which met the firm capacity in the year 2044 at 75% EV penetration in addition to the existing peak demand. Reinforcement should take place before the firm capacities are reached to comply with ESQC and ER P2/6: Security of Supply regulations.

7.1.3 EV Charging Bays Management Local Policy Proposition for a University based EV Community

BUL has obtained grant funding that is declared by the OLEV for the establishment of charging stations. Two charging stations are set up, one in the car park of Elliot Jaques building and the other in the west spur road car park. Prior to being fully operational an EV charging bays management policy is required for smooth running of the facility. A systematic procedure is followed where initially an online survey is conducted to identify the EV community. Focus groups and personal interviews are conducted to discuss debate and obtain feedback from the EV community at BUL. The identification process of the availability of the Pod Point's in order to charge an EV, charging cable compatibility, electrical properties of the charging stations, first time ever PAYG concept to use Type 2 Mode 3 charging stations that are manufactured by Pod Point Ltd are also explained to EV users. Benchmarking (seven HEI's) is an important task performed where several learning outcomes are obtained.

Recommendations that are made based on the learning outcomes of the research are that an 11.8 p/kWh tariff should be declared as this is what exactly the university pays to the electricity providers. EV charging infrastructure must be seen as a facility provided to the EV owners in order to reduce the CO_2 emissions and support the uptake of EVs giving strength to the UK Government legislation. Otherwise it must not be considered as a business or profit making scheme at this stage.

There is security available on campus 24/7. The customer service call centres of Pod Point Ltd, who are the manufacturers of the charging stations, are also available 24/7. In the interest of EV owners who are living on campus and to reduce the charging traffic during the day time a 24/7 charging facility is recommended.

For the effective operation of parking and easy identification of EV by the parking attendants, a sticker that needs to be different to the existing stickers which are used to differentiate between students and staff must be issued to the EV owners to place in the windscreen of the EV. Rules for enforcement are also recommended where PCN must be issued if an ICE powered car is parked in the charging bays and if an EV is not being charged and just occupying the charging bay.

The proposed incentives which are presented in section 6.5.3 in detail will help increase the uptake of EVs and obtain carbon free environment. Most of the content related to this section is published in the proceedings of an international conference. [60]

The EVCS are expected to be fully operational by the end of February 2015 with a view to “Go Live” in the first week of March 2015.

7.2 Further Research

The potential extensions arose throughout the thesis. In this section summary of the further research is presented.

7.2.1 Advanced Metering Infrastructure Analysis

At present the Advanced Metering Infrastructure (AMI) is limited. In order to reduce the impacts of EVs on power networks and to postpone the reinforcement of assets, AMI deployment on a large scale is essential. Many researchers proposed it is important to identify the charging behaviour and driving patterns of EV owners to shift their usage to low energy consumption periods [69]. The most commonly observed plug in timing is in the evening after the end of business day. EVs at the moment are expensive in the market. Do people who are able to afford an EV really bother about demand side management?

Once the mass production and adoption by public starts, AMI plays a crucial role [70]. It is very straight forward, where the energy requirement is minimised the strain on the network assets also minimise. As an alternative to the generic solution of upgrading the transformer when the loading levels are high, stagger charge and household load control through advanced metering infrastructure (AMI) is suggested in [35]. Both these methods did not create overload on the transformer, however only two PHEVs are considered for analysis by the author. But the practicality of this concept needs exploration requiring large scale electric vehicle penetration into the distribution networks. AMI deployment, data monitoring & analysis, incentives, special contracts between DNOs & customers and finally the chances of customer binding to the contract where one needs to plan ahead in order to avoid situations is worth a research. Indeed, pilot projects are underway by the DNOs in UK.

7.2.2 Power Electronics

The bridge between the grid and EVs are the power electronic devices. Usually EVs consists of an on board AC to DC converter connected to the distribution network through a 1-φ or 3- φ connector. Diode bridge rectifiers are used for charging the battery i.e. during grid to vehicle (G2V) mode and switch mode converters to control the operation of both V2G and G2V [71] [72] [73]. EVs in this thesis are considered as normal static loads lumped together. Actual battery models can be developed, interfacing with the power electronic converters connecting to the distribution network.

Transformer loading and voltage variations are the impacts observed in chapters 4 and 5. With the modelling of power electronics, harmonic analysis and power quality investigation for the networks designed can be performed. A significant amount of research is possible in investigating the impacts of improved battery SoC on the electricity power networks. This includes reduced connection time of EV to the grid.

7.2.3 Optimization

The research can be taken to the next level by considering the EV charging in a specified area as an optimization problem. To reduce overloading on the grid, optimization algorithms can be used to generate the charging schedules for EV owners to follow. Researchers have used linear and quadratic programming and particle swarm optimization methods etc. to address the EV owner requirements [74] [75] [76] [77] [34]. The validation of the results obtained is a challenge.

7.2.4 EV Charging Bays Management Local Policy

As the number of EV owners increases at the university, further research on electrical vehicle charging times will be possible. AMI deployment and charging schedule generation for optimal usage of EVCS to overcome the adverse impacts on BUL 11kV HV network is a viable research option [35] [69] [70] [77]. The policy propositions with specific regard to tariff and incentives can be reviewed at regular intervals. In the future more quantitative research with large number of EV owners will help to improve the operation and management of the EV infrastructure and the management policy at BUL using advanced statistical analysis.

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Appendices

Appendix A: BUL Power Network Simulated Model

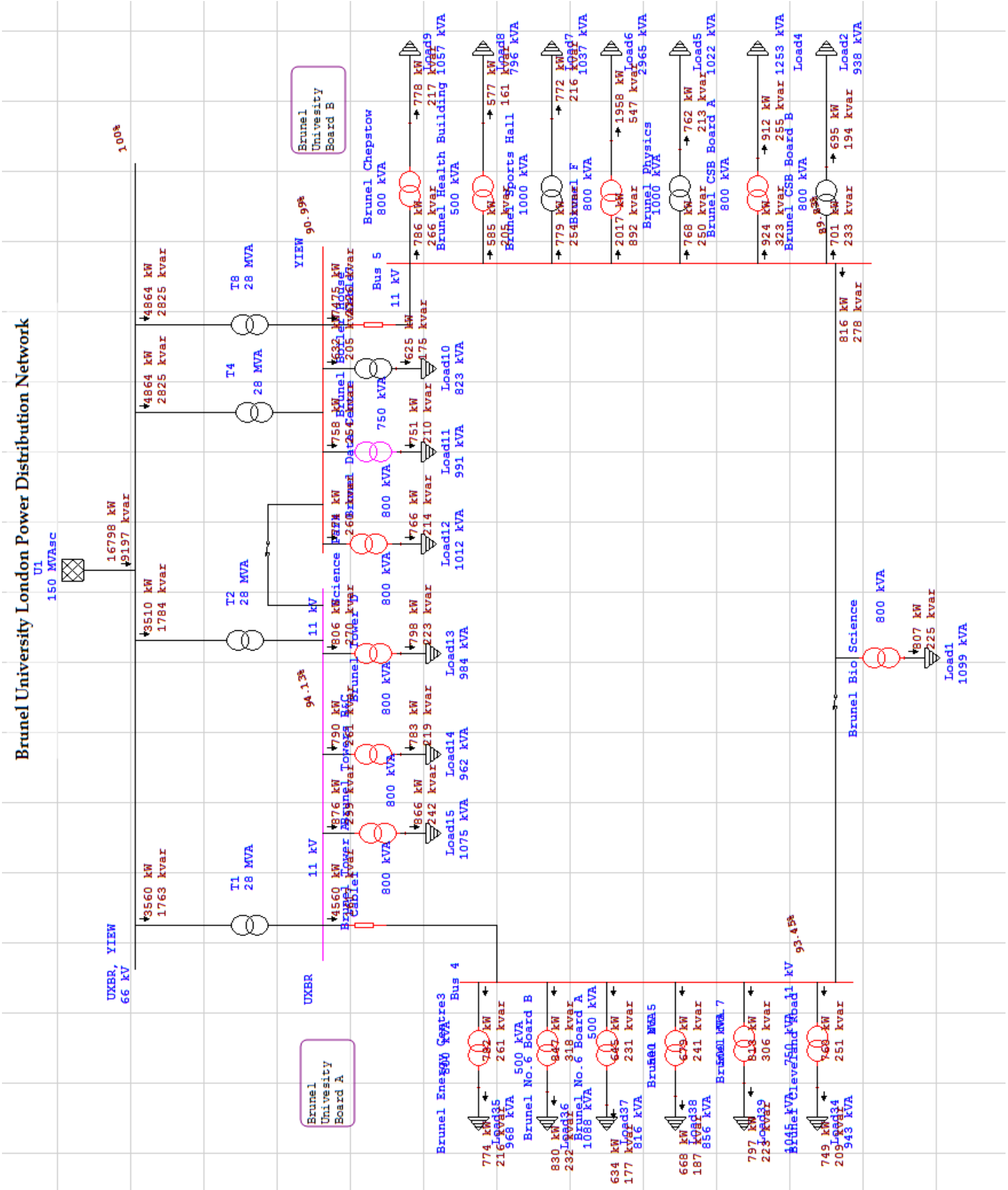

Figure A 1: BUL power network simulation at 100% EV penetration while fast charging

Fifteen transformers in red colour represent the critical overloading condition. Substation named Brunel data centre which is in pink colour represents the marginal overloading condition. Remaining transformers in black colour are able to withstand the additional load.

Appendix B: Spennymoor Power Network Simulated Model

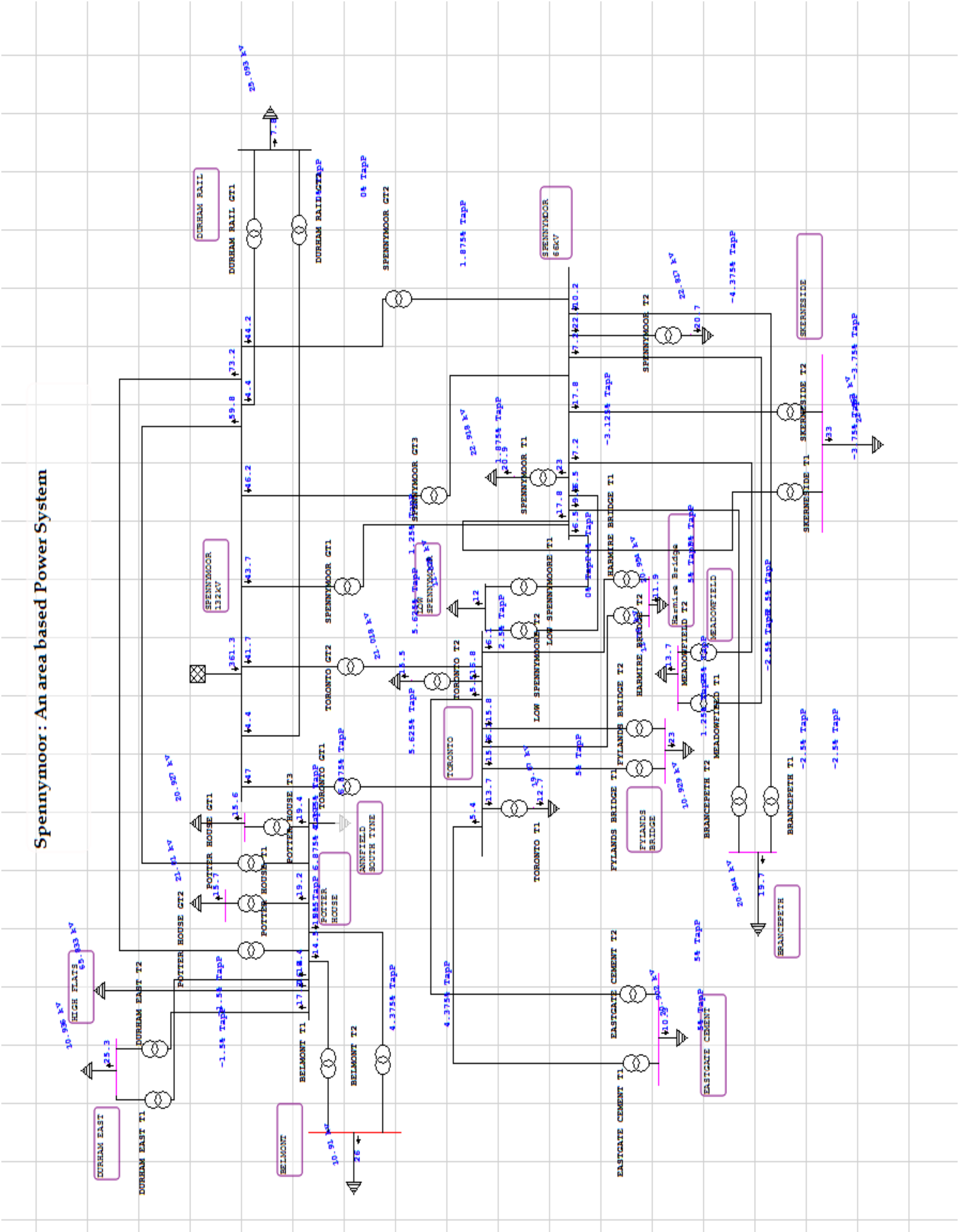

Figure B 1: Spennymoor power network simulation at 100% EV penetration in all four substations

No transformer is overloaded even during 100% EV penetration. They are all represented in black colour. Voltage deviation beyond the limits was encountered at every stage. OLTC's are used for voltage regulation.

Appendix C: Parking Plan Including Two EV Charging Bays

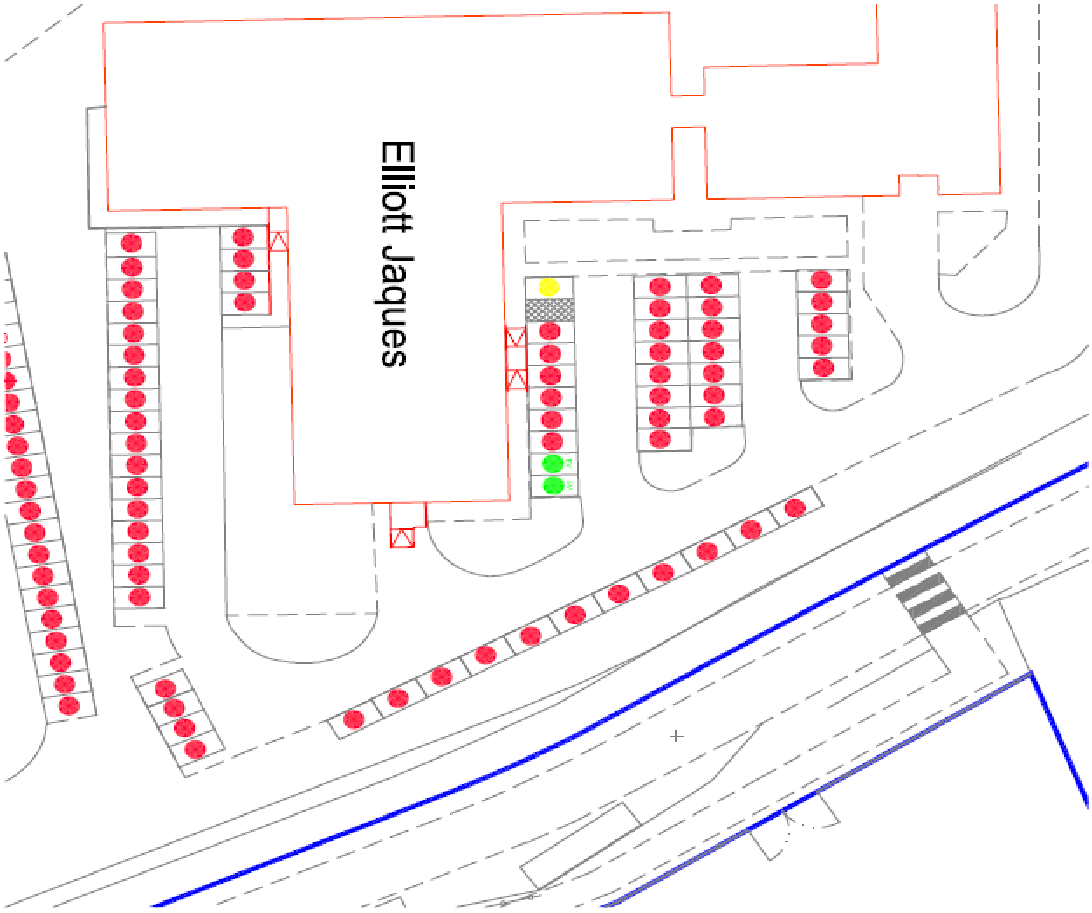

Figure C 1: Revised parking plan for Elliot Jaques car park

Department of Estates, BUL has revised the existing parking plan at Elliot Jaques car park to accommodate EV charging bays which are displayed in green colour dots. Similar work was carried out in parallel to the policy development process even at West Spur road car park.