Impacts and Solutions on Vehicle to Grid (V2G) Infrastructure

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ABSTRACT

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To deal with the problem of global warming and dependency on oil, the need for emmission-free transport has brought electric vehicles to life. The main aim of this thesis is to investigate, analyze and propose solutions to the impact of electric vehicles (EVs) on the smart grid. Before investigating the impacts of electric vehicles to smart grid, it is important to have a better understanding of EVs, power grids and vehicle to grid (V2G) infrastructure. The fundamentals of V2G technology are provided in the thesis to understand V2G infrastructure. A power demand study for domestic customers is carried out which asseses the best period for charging electric vehicles at home. Several domestic customer distribution feeders are studied and common observations are drawn. The number of EVs that can be connected to the distribution transformer per phase is calculated and discussed. This calculation considers three home charging levels and types of distribution transformers used by the South African utility company ESKOM together with common observations from demand studies. The electric vehicle is modelled and simulated using MATLAB. The aim of this work is to understand EV power requirements, energy requirements and EV charging times. The electric vehicle is simulated travelling at different road gradients and travelling at different speeds for each road slope. The study results in terms of the impacts of V2G infrastructure are provided and discussed systematically. It is observed that the main impacts include: overloading, under-voltage, imbalance and network instability. Possible solutions to the impacts are provided and discussed. The solutions include overnight charging, constructive charging, balanced charging, distributed controlled charging and centralized controlled charging. After careful analysis, it is observed that the charging impacts are further minimized when these solutions are combined together. Overall results, discussion and conclusion are provided. The challenges faced in this study are outlined and recommendations for future studies are given. In this thesis, it is found that EVs can be safely integrated into a power grid with intelligent charge control through V2G. V2G provides significant benefits to all stakeholders. V2G has many additional applications in the smart grid and microgrids.

Keywords: Electric vehicles, wireless charging

PUBLICATIONS ARISING

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To all of you, May God shower his blessings upon you, shows you mercy and grant you his favor always.

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Nomenclature

Abbreviations

V2G	Vehicle to Grid
G2V	Grid to Vehicle
EVSE	Electric Vehicle Service Equipment
EV	Electric Vehicle
PC	Power Converter
BC	Battery Cell
BP	Battery Pack
ICEV	Internal Combustion Engine Vehicle
HEV	Hybrid Electric Vehicle
BEV	Battery Electric Vehicle
FC	Fuel Cell
UC	Ultra-Capacitor
PHEV	Plug-in Hybrid Electric Vehicle
EM	Electric Motor
TRF	Transformer
BRK	Breaker
AC	Alternating Current
DC	Direct Current
IM	Induction Motor
EM	Electric Motor
ADMD	After Diversity Maximum Demand
ZAR	South African Currency
pu	Per Unit
pf	Power Factor
NB	Network Breaker

Technical Terminology

AC Level 2A	EV on-board single phase charger drawing up to 3.68 kW of power from the grid
AC Level 2B	EV on-board single phase charger drawing up to 6.90 kW of power from the grid
AC Level 2C	EV on-board single phase charger drawing up to 11.04 kW of power from the grid
DC Level 1	Off-board three phase charger delivering up to 34.92 kW of power to an EV
DC Level 2	Off-board three phase charger delivering up to 69.28 kW of power to an EV
Power Converter	An inverter that converts a DC voltage into the required three phase AC voltage. In this work a 1 pu power converter is taken as 5 kW
Battery Pack	Set of battery cells connected together and feeding one power converter
Power Pack	Battery pack with number of parallel battery cells required by power converter to deliver it full power
Energy pack	Battery pack with extra battery cells in parallel than in power pack, extra cells are added to meet energy requirement of an EV, which is a range of 100 km for this paper
Mostoff	Fuses in LV feeder mainly protecting distribution transformer

Technical Quantifications

CellsParallelP/PC	Battery cells in parallel per power pack
CellsParallelE/PC	Battery cells in parallel per energy pack
CellsSeriesV/PC	Battery cells in series to meet voltage requirement per power converter/ smart pack
NumberOfPCsP/EV	Number of power packs required by an EV to deliver required power
NumberOfPCsE/EV	Number of energy packs required by an EV to deliver required power and energy
BPWidthDimP/PC	Number of battery cells along the width of a power pack (for a single stack)
BPLengthDimP/PC	Number of battery cells along the length of a power pack (for a single stack)
BPWidthDimE/PC	Number of battery cells along the width of energy pack (for a single stack)
BPLengthDimE/PC	Number of battery cells along the length of energy pack (for a single stack)
BPWidthDimP/PC	Width Dimension of a battery pack to satisfy power requirement for a 1 pu power converter
BPWidthDimE/PC	Width Dimension of a battery pack to satisfy energy requirement for a 1 pu power converter
BPLengthDimP/PC	Length Dimension of a battery pack to satisfy power requirement for a 1 pu power converter
BPLengthDimE/PC	Length Dimension of a battery pack to satisfy energy requirement for a 1 pu power converter
1kWADMD5kWPP	5 kW power pack supplying power to a load with ADMD of 1 kW
1kWADMD5kWEP	5 kW energy pack supplying power to a load with ADMD of 1 kW
V2G-Hours/PP	Hours it takes for a power pack to source all of it energy to load
V2G-Hours/EP	Hours it takes for an energy pack to source all of it energy to load
Mass(kg)5kWPP	Mass of a 5 kW power pack in kg
Mass(kg)5kWEP	Mass of a 5 kW energy pack in kg
35RN	Single phase LV feeder with overall diameter of 35 mm^2
70RN	Single phase LV feeder with overall diameter of 70 mm^2
4AD	Single phase service cable with overall diameter of size 4 mm^2
10AD	Single phase service cable with overall diameter of size 10 mm^2

Chapter 1

Introduction

1.1 Preface

Electric Vehicles (EVs) are electric type vehicles designed to limit the use of Internal Combustion Engine Vehicles (ICEV). They are designed to limit dependency to oil as energy source. For EVs, the energy is stored in batteries, Fuel Cells (FCs), and or Ultra-Capacitors (UCs) instead of fuel tank. The major components of an electric vehicle system are the motor, controller, power supply, charger and drive train. There is a wide range of electric vehicles, including lower-end electric vehicles (i.e. Nissan Leaf) and higher-end electric vehicles (i.e. Tesla Model S). The advantages of electric vehicles includes efficiency, quite, cleaner, peak load shaving, reduce grid infrastructure requirements, provides mobile distributed generation or electric power, etc. EVs also has a variety of disadvantages including limited range, long charging time; require new infrastructure, adverse battery effects, and more. Charging EVs from the smart grid causes lot of issues to the smart grid including overloading, under-voltage, imbalance, etc. Many of the issues with EV charging can be addressed through control called Vehicle-to-Grid (V2G) technology [9][10][1]. V2G allows EVs to charge and provide energy and services to the grid, through an aggregator, for compensation.

Benefits of Electric Vehicles

- Energy Independent Security

  Not dependent on any one fuel, so price spikes are extremely rare

  Reduced environmental impacts

  - Higher energy conversion efficiency of the power grid to battery than an internal combustion engine
  - Easier to filter pollutants from large central plants than many smaller engines
  - Can run on clean renewable fuel (i.e., hydro, wind, solar, and nuclear)

- Improved driving experience
  - Instant torque makes EVs more responsive and provides amazing acceleration
  - No engine noise gives a much quieter drive
  - No engine vibration makes for a very smooth drive

The world will run out of oil in future. Internal combustion engine (ICE) vehicles produces carbon dioxide and carbon monoxide, which causes global warming and pollution to the environment. In ICE vehicles, most of fuel energy is converted to heat, noise and vibration, causing the vehicle to be inefficient. EVs are designed to overcome challenges associated with ICE vehicles by shifting from oil to electricity as main energy source, using efficient power electronic drivers and efficient electric motors such as induction motors.

The advantage of moving to electricity as main energy source is that the current smart grid is also moving from using coal, oil (diesel generators), fission (uranium fission), etc. to cleaner, safer, environmentally friendly and abundant energy sources such as hydro, wind, solar, fusion (deuterium and trillium fusion), etc., the world will not run out of these energy sources. EVs are used for various purposes including transportation and can be used for excess energy storage from a smart grid. EVs are more efficient, quite, and cheaper to maintain compared to ICE vehicles [11][12]. They also provide auxiliary services to smart grid that might also benefit the owner of the EV.

1.2 EV Adoption in South Africa

Data from analytics group Lightstone shows that over 400 electric vehicles have been sold in South Africa since the introduction of EVs in the country. EV penetration in South Africa is sitting at 0.3 % compared to Norway, which is currently the world leader with 6.8 % EV penetration. Nissan and BMW were the first manufacturers to introduce electric vehicles in South Africa with the Leaf in 2013 and the i3 in 2015 respectively [13][14].

The Joule from Optimal Energy was South Africa's own locally produced electric vehicle but it never formally entered the local market. The Joule project started in 2005 and ended in 2012. Currently, charging facilities are available in each province in South Africa, with Gauteng as the front-runner with over 90 stations [15].

Despite current challenges facing utility company in South Africa (ESKOM), including load shedding, electric vehicles are still motivated together with renewable energy sources. Another serious issue facing ESKOM is electricity theft (non-technical losses); in future, the company might need to consider upgrading its current power grid to smart grid and advancing its payment system to detect energy theft and adopting demand based pricing especially to EV owners to discourage them from charging during peak hours and therefore shifting the load to overnight.

1.3 Objectives of the Thesis

The need for sustainable and affordable transportation in South Africa together with variety of benefits of using electric vehicles over internal combustion vehicles is the main motivation for this research. South Africa lacks infrastructure to fully support EVs. This thesis provides a step forward towards maximizing EV penetration in South Africa. This is achieved by studying and addressing the possible impacts of electric vehicles to the current power grid. Studies and simulations are carried out in this thesis to find a better understanding of the EV-Grid system, which is useful in addressing challenges facing V2G infrastructure in South Africa.

1.4 Outline of the Thesis

This thesis presents an overview and progressive arrangement of chapters. One Publication also supports this thesis. The thesis is organized as follows.

Chapter 1 introduces the subject matter and objectives of this thesis. The major problems caused by charging electric vehicles, the reasons why electric vehicles are needed and the current EV adoption status in South Africa are outlined.

In Chapter 2, a literature review on electric vehicles and South African power grid is carried out. The fundamentals of V2G technology are provided to grasp the idea of V2G infrastructure. A short overview of V2G with renewable energy is provided and well known EV charging issues are outlined. EV-Grid system is explained and some of EV charging and discharging options are discussed. A typical procedure for installing EV Service Equipment (EVSE) for home charging is outlined.

Chapter 3 focuses on the power demand for domestic customers and finding the best period for charging electric vehicles at home. In this chapter, several distribution feeders feeding domestic customers are studied and common observations are drawn. Considering three home charging levels and types of distribution transformers used by South African utility company (ESKOM) together with common observations from demand studies, the number of EVs that can be connected to the distribution transformer per phase is calculated and discussed.

In Chapter 4 the electric vehicle is modelled and simulated using MATLAB. The aim of this chapter is to understand EV power requirements, energy requirements and EV charging times. The electric vehicle is simulated travelling at different road gradients and travelling at different speeds for each road slope.

In Chapter 5, simulation results are provided, discussed and analyzed. Here the information found in previous chapters is combined to find EV limits and boundaries for home overnight charging. The information found in this chapter is also important to people considering buying electric vehicle before adequate availability of V2G infrastructure is available in South Africa.

In Chapter 6, the study results on the impacts of V2G infrastructure are outlined and discussed. Here it is observed that the main impacts includes: overloading, under-voltage, unbalance and network instability. Possible solutions to the impacts are provided and discussed. The solutions include: overnight charging, constructive charging, balanced charging, distributed controlled charging and centralized controlled charging. After careful analysis, it is found that the charging impacts are further minimized when these solutions are combined together.

In Chapter 7, the overall results are discussed and conclusions are drawn. The challenges faced this study are outlined and recommendations for future studies are given. It is found that EVs can be safely integrated into the power grid with intelligent charge control through V2G. V2G provides significant benefits to all stakeholders. V2G has many additional applications in the smart grids and microgrids.

Chapter 2

Literature Review

Introduction

Many researchers from different countries are contributing in developing and stabilizing EV technologies. The most challenging issue that will unlock the future of EVs is the Li-ion battery price (which is projected to fall below $100/kWh by 2026 [16]) and improved battery performance. Leading countries includes China, USA and Germany. In these countries, EVs are already being used mainly for transportation. Other existing research in the field of EVs includes developing high speed/performance electric motors for EVs, and high-energy capacity battery systems and more. Different EV topologies and configurations are being researched, tested and compared to find better EV systems.

2.1 Electric Vehicles (EVs)

EVs use batteries as it main energy source and an electric motor as it main propulsion engine. Super- and ulta-capacitors are also now being used for high power regenerative braking. EVs were developed to solve the challenges of global warming, expensive fuel prices, city polution and grid distributed storage systems [17], etc. There is a wide range of electric vehicles, including lower-end electric vehicles (i.e., Nissan Leaf) and higher-end electric vehicles (i.e., Tesla Model S).

2.1.1 Types of Electric Vehicles

They are three common types of electric vehicles, battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs) and fuel cell electric vehicles (FCEVs). These types of vehicles are explained in this section.

Battery Electric Vehicles (BEVs)

BEVs use the battery as the main power source. However, some BEVs use extra storage to support the batteries, such as the ultra-capacitors and flywheels. The BEV contains an electric motor, batteries and power electronics. Several battery technologies can be used to provide different performances to the electric vehicles. The controller is the heart of an electric vehicle, and it is the key for the realization of a high-performance electric vehicle with an optimal balance of maximum speed, acceleration performance, and traveling range per charge.

Plug-in Hybrid Electric Vehicles (PHEVs)

A hybrid electric vehicle uses two or more energy supplies/sources to propel the vehicle, such as an ICE and a battery-supplied electric motor (EM). The concept of a PHEV emerged when a model similar to the hybrid electric vehicle (HEV - where the batteries are charged from the ICE and regenerative braking) was developed, and additional electrical energy is obtained from charging from the electric network [18].

Fuel Cell Vehicles (FCVs)

A fuel cell unit is used to generate power, either to supply the electric motor or to store energy in the battery. FCVs are unlikely to be competitive in a near future, when compared to BEV and PHEV, because fuel cell units are currently very expensive. In this thesis, the term EV refers to both BEV and PHEV vehicles; the FCV is not considered.

2.1.2 EV Charging Issues with the Grid

- Bulk Power Grid
  - Additional energy requirements (i.e., more fuel burned)
  - Higher load levels may require running lower efficiency plants for longer or building new power plants
- Distribution System
  - EV Charging can double a household load

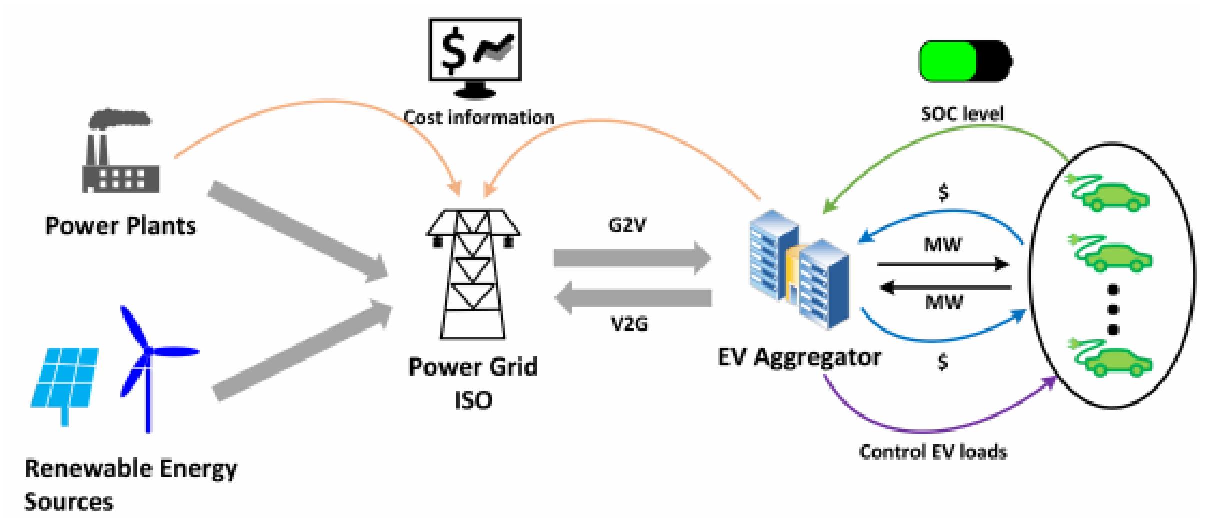

Figure 2.1 Configuration of the proposed framework. SOC: state-of-charge; G2V: grid-to-vehicle; V2G: vehicle-to-grid; ISO: independent system operator; EV: electric vehicle [1].

- Localized clustering can overload lines and transformers
- Higher loads can increase the power losses in the lines and cause low voltage problems [19]

2.2 Vehicle-to-Grid (V2G) Technology

Many of the issues with EV charging can be addressed through control called V2G. V2G allows EVs to provide energy and services to the grid, through an aggregator, for compensation. An aggregator agent for electric vehicles is a commercial intermediary between a system operator and PEVs. For the system operator perspective, the aggregator is seen as a large source of generation or load, which could provide ancillary services such as spinning and regulating reserve [20]. This is illustrated in Fig. 2.1.

2.2.1 Optimal V2G by Incremental Charge Rate Adjustment

This involves adjusting the charge rate of EVs around a fixed scheduled rate. This is called the preferred operating point (POP) [20]. This adjustment:

- Can perform regulation down and reserves by increasing above the POP.
- Can perform regulation up and reserves by decreasing from the POP.
- Does not discharge power from the EV battery into the grid.

2.2.2 Optimal V2G Scheduling

- Performed from an aggregator perspective
  - Aggregator can be a utility of a third party
- Maximizes the profits through a combined optimization of multiple V2G services [21][22]
  - Assumes revenues come from:
    - A percentage of the V2G services provided
    - Markup on the wholesale price of energy
- Considers Selling V2G
  - Regulation down
  - Regulation up
  - Responsive reserves [17]

2.2.3 V2G Optimization Constraints

- Charger limits
  - Set either by the maximum charge rate of the internal charger or the maximum charge rate of the charging station
- Battery capacity limit
  - Cannot charge beyond 90 % SOC limit for longer battery life
- EV availability
  - Forecasted transport profiles with associated probabilities
  - Uses expected values of available EVs
  - EVs can leave unexpectedly and their V2G contributions must be compensated by other EVs
- Ancillary Service Constraints
  - Regulation up and responsive reserve capacity cannot be greater than preferred operating point (POP) [23]

2.2.4 V2G with Renewable Energy

Fig. 2.2 showing two models that can be used to model and optimize the V2G optimization problem [24][25]. For the purpose of this study, these models will not be included in this thesis.

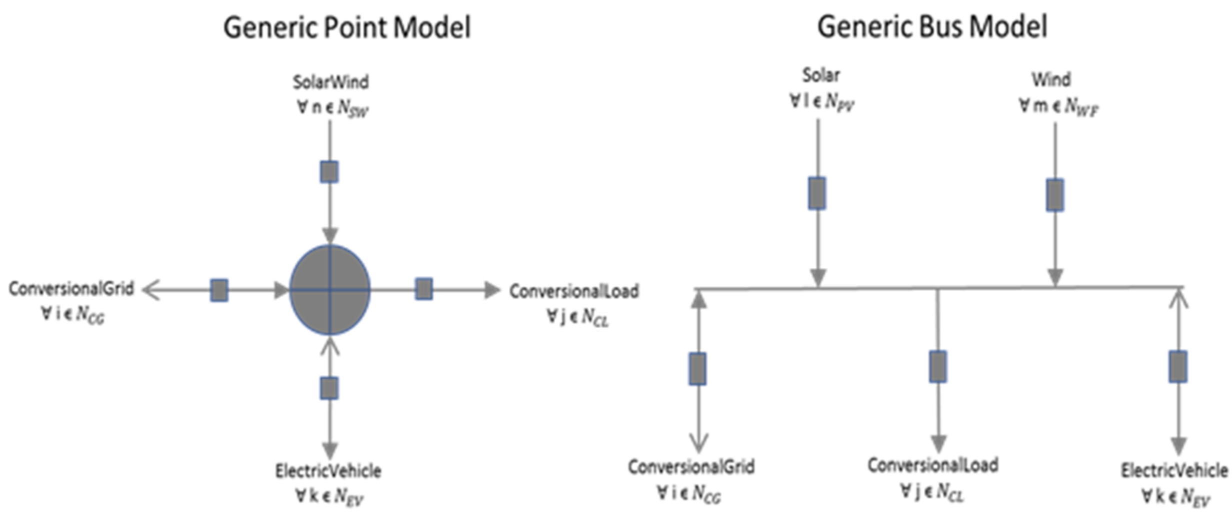

Figure 2.2 Generic Point Model and Generic Bus Model.

Some types of renewable energy, such as wind and solar, have variable uncontrolled outputs. V2G can smooth the outputs and potentially store excess energy until needed [26]. Renewable energy sources will work or perform very well with electric vehicles and power banks [27].

2.3 Unpacking EV-Grid System

Fig. 2.3 shows main components of an EV and how they are connected to the grid via EV service equipment (EVSE) devices. The following subsections further explains the overview below to give better understanding of EV-Grid system before proceeding to grid and EV analysis.

2.3.1 Grid - LV Network

In this section, the basics of an LV Grid network is provided. This is illustrated in Fig. 2.4. This figure shows the LV network from the distribution transformer to the distribution board inside the

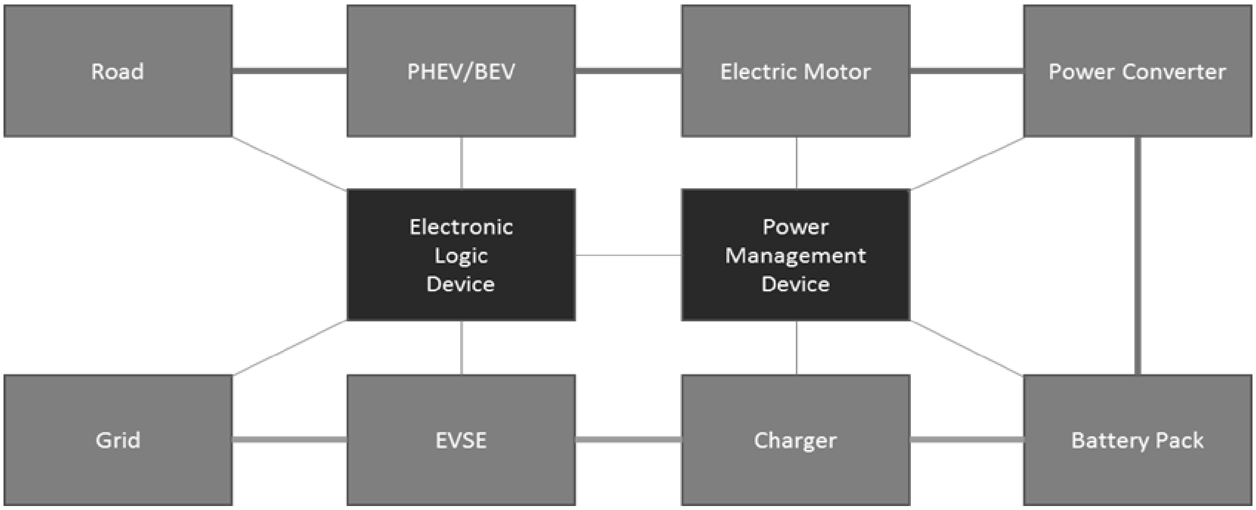

Figure 2.3 EV-Grid System/Components.

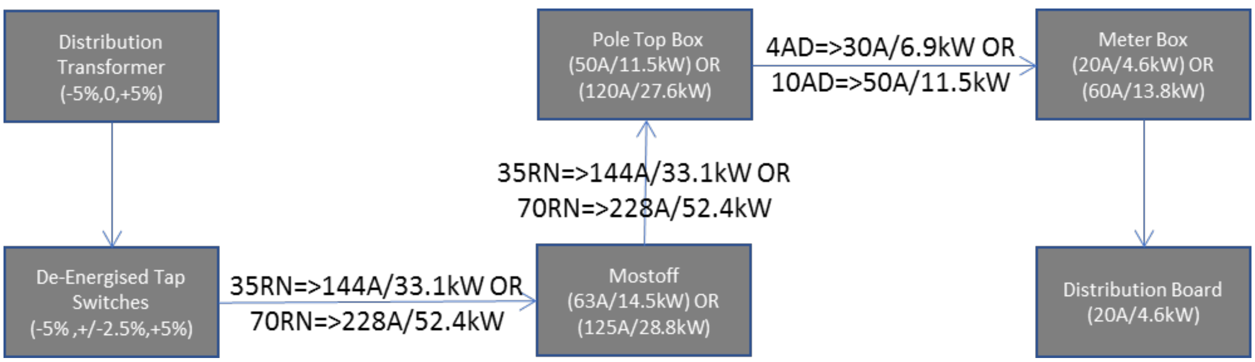

Figure 2.4 The LV Grid Network.

customer house. Here, ratings of conductors, fuses and breakers used by ESKOM [28][29][30][31] are indicated and power delivered at every point is calculated and shown in the figure. It should be noted that the maximum power per phase that can be delivered to each house is limited by service cable at 11.5 kW for a 10 mm^2 airdac. Table 2.1 shows some practical settings of a charger to avoid overloading and damage to utility equipment.

The settings (2A, 2B, 2C) in Table 2.1will be used throughout this thesis during grid and EV analysis. Charging currents are set to 80 % of grid rated current to allow few light essential appliances to connect during charging, this includes lights, fridge, etc.

Table 2.1 Charger Settings for the Grid.

Ideal Place	Protection, Voltage, Phase Technology, and Current	Power	Charging Level and Charger
Rural Domestic	20 A BRK, 230 V line-ground, Single Phase, 0.8 × 20 A = 16 A	3.68 kW	AC Level 2A, Mobile charger: 120 V - 240 V, up to 40 A
Urban Domestic	16 kVA TRF 63 A Mostoff, or 60 A BRK, 230 V line-ground, Single Phase, 0.5 × 60 A = 30 A	6.90 kW	AC Level 2B, High power wall charger: 208 V - 240 V, up to 70 A
Private Places	16 kVA TRF 63 A Mostoff, or 60A BRK, 230 V line-ground, Single Phase, 0.8 × 60 A = 48 A	11.04 kW	AC Level 2C, High power wall charger: 208 V - 240 V, up to 70 A
Public Places	50 kVA TRF 63 A Mostoff, 400 V line-line, 3-phase, 0.8×63 A = 50.4 A	34.92 kW	DC Level 1, Super charger: 480 V DC, 250 A (up to 120 kW)
Commercial Stations	100 kVA TRF 125 A Mostoff, 400V line-line, 3-phase, 0.8×125 A = 100 A	69.28 kW	DC Level 2, Super charger: 480 V DC, 250 A (up to 120 kW)

2.3.2 EV Service Equipment (EVSE)

Electric Vehicle Supply Equipment (EVSE) provides for the safe transfer of energy between the electric utility power and the EV. EVSE includes EV charge cords, charge stands (residential or public), attachment plugs, vehicle connectors, and protection. Adoption of EVSE is critical to the success of electric vehicles in South Africa. Level 1 and Level 2 EVSE convert the utility AC power into DC power through the EV's on-board charger.

- EV manufacturers provide the Level 1 EVSE consisting of a power supply cable with a standard 3-prong plug (NEMA 5-15P/20P, limited to 20 A) and a charge current interrupting device (CCID) located in the cable within 12 in. of the plug.
- Level 2 EVSE typically operate with a peak current of 32 A AC with a branch circuit breaker rated at 40 A.

The vehicle charger communicates with the EVSE to identify the circuit rating (voltage and current) and adjust the charge to the battery accordingly. Level 3 provides electricity through an off-board charger, delivering DC power directly to the vehicle. The different charging levels are given in Table 2.2.

2.3.3 EV Chargers

In this section, Table 2.3 is taken from the SAE standard for EVs. In the table some parameters are not yet finalized, they might change in the future but are used in this thesis as a guide.

Table 2.2 Charging Power Levels Based in Part on SAE Standard J17723 [3].

Power Level Types	Charger Location	Typical Use	Energy Supply Interface	Expected Power Level	Charging Time	Vehicle Technology
Level 1 (Opportunity) 120 Vac (US) 230 Vac (EU)	On-board 1-phase	Charging at home or office	Convenience outlet (NEMA 5-15R/20R	1.4 kW (12 A); 1.9 kW (20 A)	4-11 h; 11-36 h	PHEVs (5-15 kWh); EVs (16-50 kWh)
Level 2 (Primary) 240 Vac (US) 400 Vac (EU)	On-board 1- or 3-phase	Charging at private or public outlets	Dedicated EVSE	4 kW (17 A); 8 kW (32 A); 19.2 kW (80 A)	1-4 h; 2-6 h; 2-3 h	PHEVs (5-15 kWh); EVs (16-30 kWh); EVs (3-50 kWh)
Level 3 (Fast) (208-600 Vdc)	Off-board 3-phase	Commercial, analogous to a filling station	Dedicated EVSE	50 kW; 100 kW	0.4-1 h; 0.2-0.5 h	EVs (20-50 kWh)

2.3.4 Battery Pack for EVs

In this section, different types of energy sources are compared and the best battery type is selected. This uses lithium technology. Different types of lithium batteries are tabulated and associated with their applications.

Energy Sources for EVs

Fig. 2.5 shows carbon free energy storing elements; fuel cells, batteries and supercapacitors used by Electric Vehicles (EVs).

It can be seen that fuel cells have the largest energy density but low power density, which implies that they have slow dynamic properties. From Fig. 2.5, it can be seen that supercapacitors

Table 2.3 SAE J1772 Standard for EV Chargers [5].

SAE Charging Configurations and Ratings Terminology			
AC Level 1	PEV included on-board charger	*DC Level 1	*DC Level EVSE includes an off-board charge
	120 V, 1.4 kW @ 12 A		200 - 450 V up to 36 kW (80 A)
	120 V 1.9 kW @ 16 A		Est. charge time (20 kW off-board charger): PHEV: 22 min (SOC - 0 to 80 %); BEV: 1.2 h (SOC - 20 to 100 %)
	Est. charge time: PEV: 7 h (SOC - 0 % to full); BEV: 17 h (SOC - 20 % to full)		
AC Level 2 (SAE J1772)	PEV includes on-board charger (see below for different types)	*DC Level 2	EVSE includes an off-board charger
	240 V up to 19.2 kW (80 A)		200 - 450 V up to 90 kW (200 A)
	Est. Charge time (3.3 kW on-board charger): PEV: 3 h (SOC - 0 % to full) BEV: 7 h (SOC - 20 % to full)		Estimated charge time (45 kW off-board charger): PHEV: 10 min (SOC - 0 to 80 %) BEV: 20 min (SOC - 20 to 80 %)
	Est. charge time for 7 kW on-board charger: PEV: 1.5 h (SOC - 0 % to full) BEV: 3.5 h (SOC - 20 % to full)		
	Est. charge time for 20 kW on-board charger: PEV: 22 min (SOC - 0 % to full) BEV: 1.2 h (SOC - 20 % to full)		
AC Level 3 (TBD)	Less than 20 kW single phase and 3 phase	*DC Level 3 (TBD)	EVSE includes an off-board charger
			200 - 600 V DC (proposed), up to 240 kW (400 A)
			Est. charge time (45 kW off-board charger: BEV (only): less than 10 min (SOC - 0 to 80 %)
*Not finalized			
Voltages are nominal configuration voltages, not coupler ratings			
Ideal Charge times assume 90 % efficient chargers, 150 W to 12 V loads and no balancing of Traction Battery Pack			
Ideal Charge times assume 90 % efficient chargers, 150W to 12V loads and no balancing of Traction Battery Pack			
Notes:			
1) BEV (25 kWh usable pack size) charging always starts at 20 % SOC, faster than a 1C rate (total capacity charged in one hour) will also stop at 80 % SOC instead 100 %			
2) PEHV can start from 0 % SOC since hybrid mode is available. **Developed by the SAE Hybrid Committee ver. 031611**			

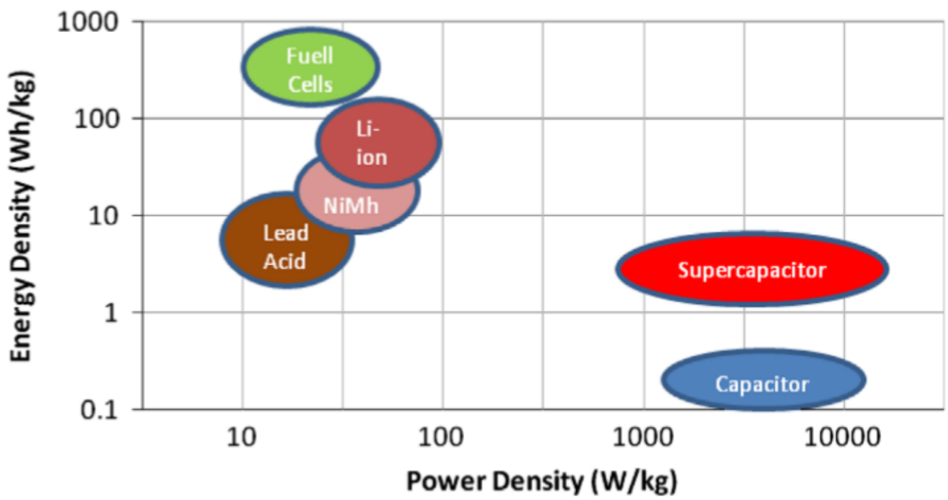

Figure 2.5 Comparison between various energy states in terms of power and energy density [2].

have large power density but low energy density meaning they are perfect sources/banks during acceleration and deceleration periods. Batteries tend to provide average performance between fuel cells and supercapacitors. When two or three sources are integrated or hybridized together, excellent performance is obtained. Fuel cells are very expensive so their future in EV applications is very narrow. From Fig. 2.5, it can be seen that lithium type batteries seem to be providing better performance (energy and power).

Lithium Technology for EVs

Table 2.4 gives the different types of lithium batteries and their applications. Lithium technology is a very good energy storage solution and used extensively in the EV industry and they lead other battery technologies [23]. From Table 2.4 it can be noted that NCA and LTO lithium types are used in EVs although LTO chemistry is still being developed and improved for future use. Currently NCA lithium types are used in most lithium battery EVs. Table 2.5 shows the properties of NCA lithium battery types.

From Table 2.5 the battery cell parameters, such as cell mass, rated voltage, rated capacity and rated energy, will be utilized during the simulation stage.

Table 2.4 Lithium-Ion Battery Technology [6].

Li-Ion Battery Chemistries		Chemical Formula	Application
Lithium Cobalt	LCO	Li-CoO2	Cellphones, laptops, and cameras
Lithium Nickel Manganese Cobalt Oxide	NMC	Li-NiMnCoO2	Power tools, medical, hobbyist
Lithium Iron Phosphate	LFP	Li-FePO4	Power tools, medical, hobbyist
Lithium Manganese Oxide	LMO	Li-Mn2O4	Power tools, medical, hobbyist
Lithium Nickel Cobalt Aluminum Oxide	NCA	Li-NiCoAlO2	Electric vehicles and grid storage
Lithium Titanate	LTO	Li4Ti5O12	Electric vehicles and grid storage

2.3.5 Power Converters for EVs

The power converter converts a DC voltage (which could be low in a small vehicle, such as 24 V in a scooter, to a DC bus of several hundred volts for a high performance EV) into a balanced 3-phase voltage set (if a 3-phase motor is used) which has variable frequency and voltage magnitude, and vice-versa for bidirectional converters. Usually, more than one power converter is used in an electric vehicle. Typical ratings of power converters are typically from about 5 kW for a very partial hybrid vehicle or small electric scooter into several hundred kW for a high performance EV. The converters are voltage source inverters that use pulse wave modulation to control the conversion. These are bidirectional. Wide voltage and frequency ranges are required because of the wide speed range required. A DC-to DC converter may also be required to control the DC bus voltage and battery charging. This should be bidirectional too.

In this work the concept of multiple power converters is used where the base power converter is 5 kW. So an EV taken as having 10 power converters will mean the vehible is rated at 50 kW

Table 2.5 NCA Li-ion Battery Cell Properties [7][8].

Li-Ion Battery Chemistries			Chemical Formula	Application	
Lithium Nickel Cobalt Aluminum Oxide		NCA	Li-NiCoAlO2	Electric vehicles and grid storage	
Cell name		Cell shape	Cell Dimension (mm)	Cell Volume (cm^3)	
21700		Cylindrical	Height=70, Width=21	0.024245	
Energy Density (Wh/cm^3)	Specific Energy (Wh/kg)	Cell Mass (g)	Cell Capacity (Ah)	Charge Power (W)/Discharge Power (W)	Charge/Discharge Rate (A)
877.5	300	65 - 75	3 - 4.8	2.8; 7; 17; 25	I = 0.2 C; 0.5 C; 1 C; 1.5 C
Cell Voltage (V)	3	3.3	3.6	3.9	4.2
Cell Capacity (Ah)	0.217	0.73	2.9	5	5.07
Cell Charging Cycles ($N \times 10^3$)	*	*	*	2.4 - 4	0.3 - 0.5
Cell Life Time (Years) - For single daily charged cells		*	*	6.56 - 11	0.82 - 1.37
Cell Energy (Wh)	0.651	2.41	10.44	19.5	21.275
Rated Voltage (V)	Rated Temp (°C)	Rated Cycles ($N \times 10^3$)	Rated Life (Years)	Rated Capacity (Ah)	Rated Energy (Wh)
3.6	T = -20; 0; 40; 60	2.4	6.56	4.27	17.1

and the main power converter will be a 3-phase PWM inverter, using devices such as IGBTs.

2.3.6 Electric Motors for EVs

Most EV manufacturers prefer 3-phase brushless permanent magnet AC motors (BPMs) or possibly induction motors (IMs) as the main motor(s) for propelling the car [32]. The traditional commutator DC machine is a very old technology and not considered for automotive applications because it large, heavy and not efficient. The commutator and brushes need maintenance. Automotive drive motors run into a high transient region during high acceleration and braking. This region is only sustainable for short periods and their thermal operation is key. For instance, the machine may only be rated at 100 Nm continuous but will operate up to 300 Nm during hard braking. The machines are often liquid cooled.

BPM machines use rare earth magnets (usually sintered Neodymium Iron Boron) which are high energy magnets. These are expensive but the machines can be very efficient - the highest of any automotive drive motor. They have no brushgear and the rotor has magnets so there is no rotor current. They can operate into several tens of rpm. For instance, the 3rd generation Toyota Prius has an 8 pole BPM machine which runs up to 14500 rpm. They are expensive and the magnet material mostly comes from China and the supply chain can be difficult. However, they are the main preference in motor choice.

The IM is widely found in many industrial applications due to its advantages over other types of motors. However, the demands for an automotive application is somewhat different. Below are some advantages [33].

- The IM has no brushes so it needs less maintenance.
- The cost of IM is less than cost of an BPM motor of the same nominal power.

- The IM is robust and can work in abnormal ambient conditions for short periods.
- The IM can be manufactured for nominal voltage up to 25 kV (though not needed for EVs).
- The IM can be manufactured for high power - their speed is limited by the inverter supply voltage but they can run at reduced voltage at high speed - the BPM can be field weakened to reduce the voltage but not to the same extent as the IM.

A review of EV drive motors is given in [34].

2.3.7 Some Existing EVs and their ratings

Table 2.6 shows a list of some EVs already in the market. This information is very useful to endure that simulations are within the boundaries of existing EV systems.

The average modern BEV has a battery capacity of 31 kWh and level 2 charging infrastructure capable of delivering 7 kW at 86 % efficiency. The range is increasing with new BEVs, allowing more batteries to be committed to V2G service provision.

Table 2.6 Existing electric vehicles in the market.

Make	Model	Battery Capacity (kWh)	Range (km)	Grid Connection Power (kW Rated)	EV charging Level
BMW	i3	19	130	7.4	AC Level 2B
Chevrolet	Spark	19	132	3.3	AC Level 2A
Fiat	500e	24	140	6.6	AC Level 2B
Ford	Focus	23	122	6.6	AC Level 2B
Honda	Fit	20	132	6.6	AC Level 2B
Kia	Soul	27	150	6.6	AC Level 2B
Mercedes	B-Class	28	140	10	AC Level 2C
Mitsubishi	iM IEV	16	100	3.3	AC Level 2A
Nissan	Leaf	24	135	6.6	AC Level 2B
Tesla	S-70	66	v386	10	AC Level 2C
Tesla	S-85	78	435	10	AC Level 2C
Volkswagen	eGolf	24	134	7.2	AC Level 2B

2.3.8 Road (Standard)

Before simulating an EV using MATLAB, it is very important that the road standard be reviewed to find the maximum road gradient/slope. In the standard, road gradients are given in percentage and Fig. 2.6 illustrates the relationship between road gradient in percent and in degrees.

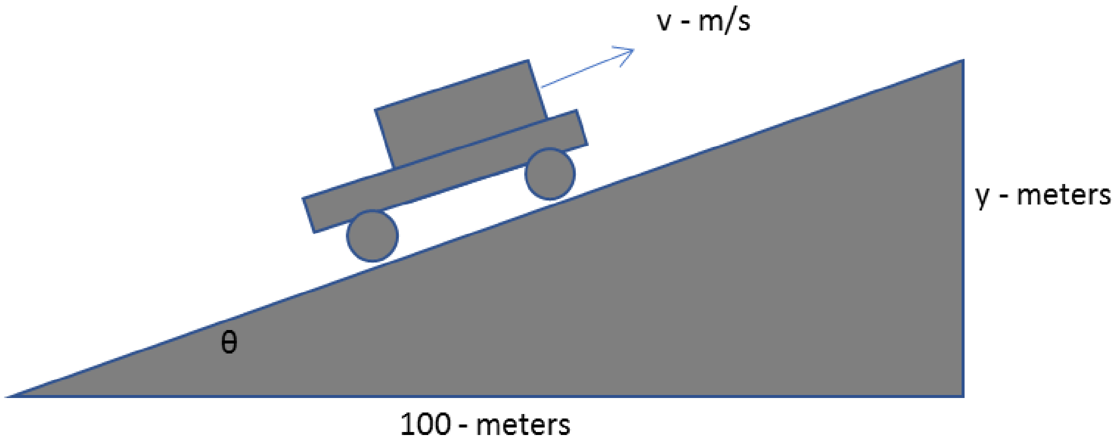

Figure 2.6 Road Gradient standard and calculation.

With reference to Fig. 2.6, the road slope or gradient $= y/100 = y\% = \tan(\theta)$ do that

$$\theta = \arctan(y\%) = \arctan(y/100) \quad (2.1)$$

From the SA roads standard, gradients should preferably not exceed 14 % and in no circumstances exceed 20 % [35]. From this information, the electric vehicle will be studied travelling along four different roads with the following gradients:

1. 0 % = 0.0 °
2. 7 % = 4.0 °
3. 14 % = 7.97 °
4. 21 % = 11.86 °

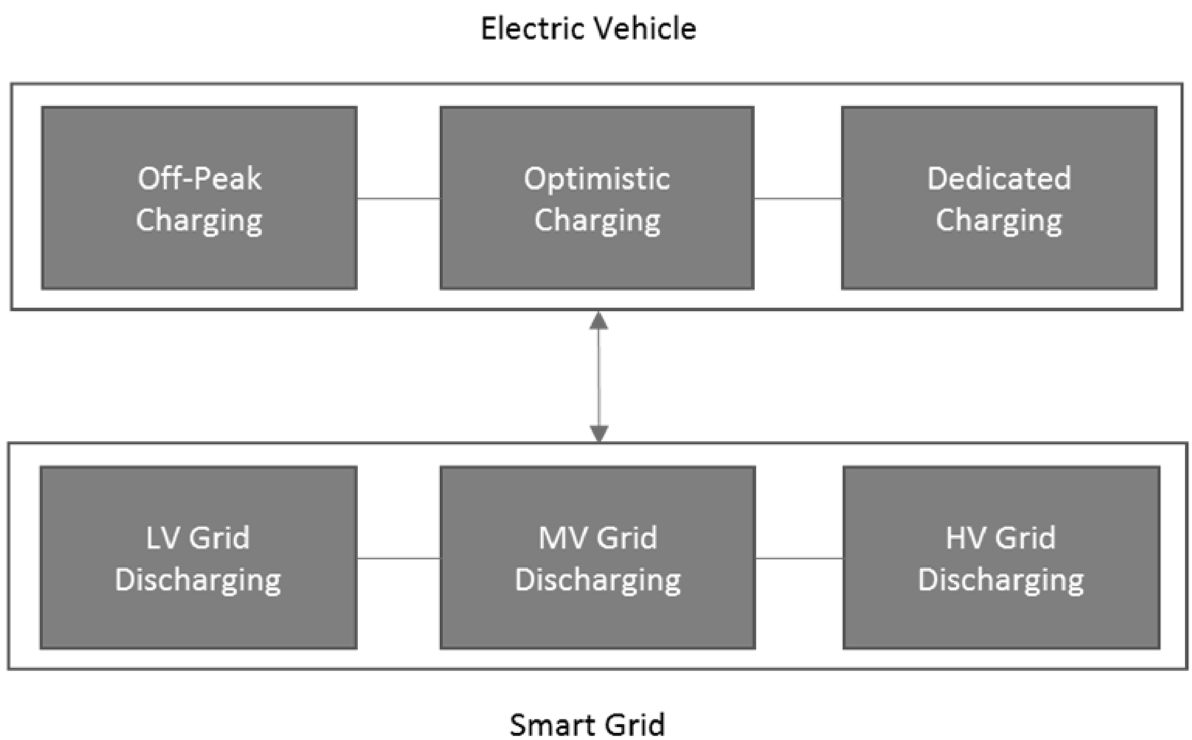

Figure 2.7 Charging and discharging EV battery packs to and from the smart grid.

2.4 EV Basic Charging Options and Discharging Levels

Fig. 2.7 shows three common charging options including off-peak charging, optimistic charging and dedicated charging. There are also three EV discharging levels including LV grid, MV grid and HV grid.

2.4.1 Charging Options for EVs

As can be seen from Fig. 2.7 there are three basic charging options that can be adopted for charging EVs.

- **Off-peak charging:** This is the simplest and cheapest method when applied properly. It does not require any upgrade of the smart grid. This method is sometimes called overnight charging because most networks have lower overnight loading.

- **Optimistic charging:** This method can be used to improve the flexibility of EV charging and therefore improving customer satisfaction. Here more smart devices are required to control charging process.

- **Dedicated charging:** This method requires a dedicated transformer/capacity for charging EVs only. It provides maximum flexibility and reliability although it might be expensive and difficult for domestic customers.

2.4.2 Discharging Levels for EVs

Apart from charging from the grid, EVs may possibly be used for peak shaving in future by providing electrical energy back to the grid. There are three main levels of discharging battery-stored energy back to the grid:

- **LV Grid Discharging:** This level is useful during peak times to relief over-loading distribution transformers. Here an EV is used as a house backup during contingencies and provides a short time alternative to grid electricity.

- **MV Grid Discharging:** Here a fleet of EVs is used instead of a single EV to discharge their energy back to MV grid system during peak hours. This can save power transformers from overloading and hence improving their lifespan.

- **HV Grid Discharging:** This level is not likely to be adopted in future but can improve end voltages during peak hours mainly at a sub-transmission level. This method can help avoid tap-changer lockout due to low voltages in distribution substations.

2.5 Integrating EV for home charging

In this section, EV considerations for home charging are discussed. Fig. 2.8 helps demonstrate the concept. Here, the customer buys an EV together with EVSE V2G device. Then the next step is for the EV owner to contact the utility to notify them that they want to install the EVSE for home charging. The utility then visits the EV owner house to mainly check the conditions of the source distribution transformer and how much power can the EV draw from the transformer without damaging utility equipment (transformer, fuses and Arial Bundle Conductors - ABC) [36]. However, this might not be a one day process since the utility may want to install a data logger (i.e., temperature logger) to download a 24-hour data to check how much the transformer is loaded during the day. From that information, and other projections, the utility can tell whether the EV can be charged from the transformer or not and under what conditions, if any. If charging is not possible, a schedule can be drawn up in order to implement network upgrades, such as installing a new transformer or upgrading the LV feeders, fuses and circuit breakers.

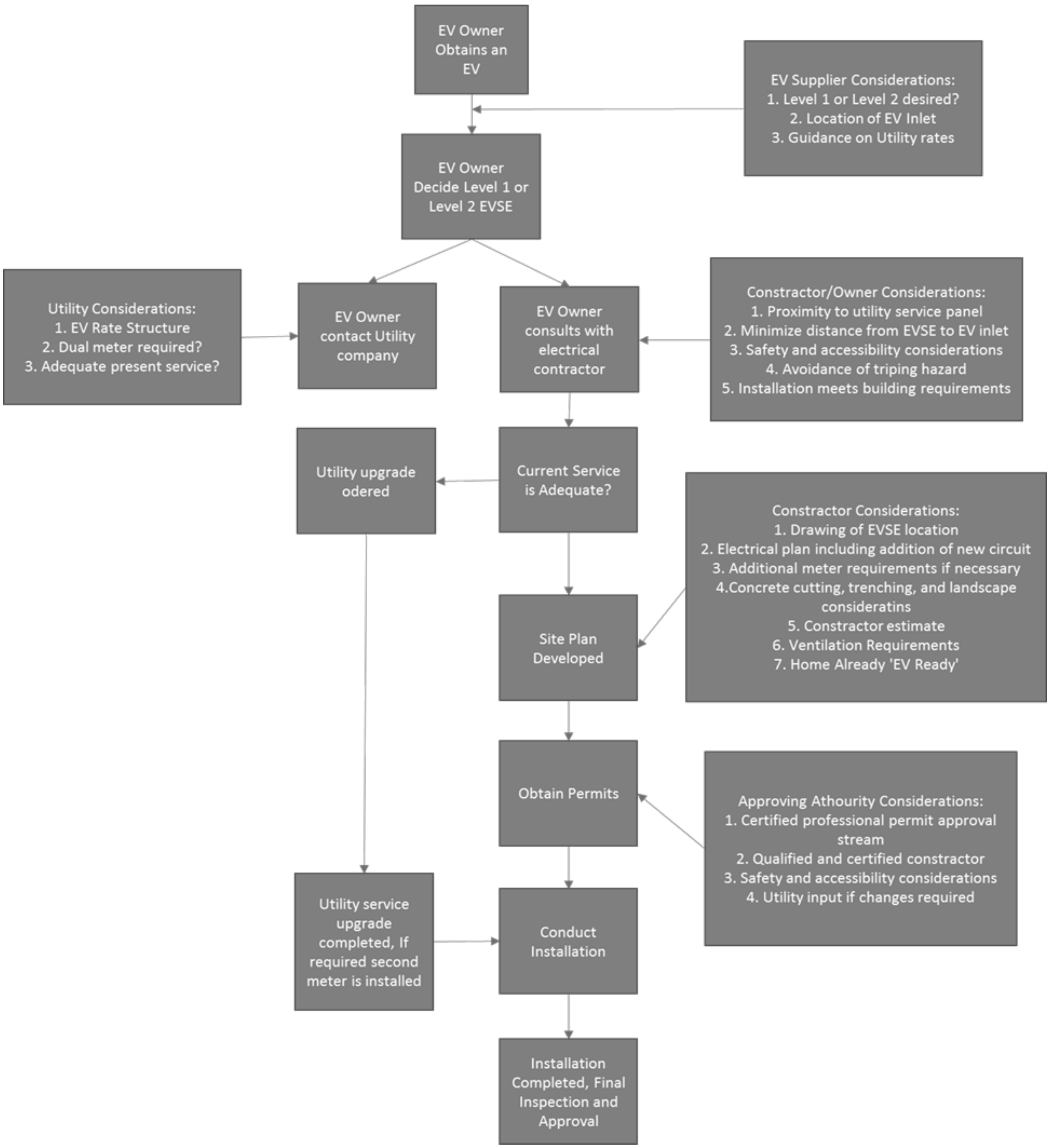

Figure 2.8 Procedure for installing EVSE for home charging [3].

Chapter 3

Power Grid Study

3.1 Demand Study

In this section, the grid is analyzed to understand its behaviour during the year and during the day. This information is very useful in finding the best charging time and period for different types of feeders. For the purpose of this study, only feeders feeding domestic customers are analyzed. To obtain accurate results from the analysis it is important that multiple distribution transformers feeding domestic customers are analyzed and the average of the results is taken at the end. Here, instead of analyzing the distribution transformers one by one, the feeders of most importance to the domestic customers (>90 %) were selected, scaled and analyzed. The reason for this approach is to save time, increase accuracy (since the feeder is feeding lot of distribution transformers) and the availability of the statistical data (from substation meters which supply the MV90 database). The following steps were followed during analysis and repeated in all collected networks to find a common point of the study:

1. **Find domestic feeder:** To find a domestic feeder, Spaceman software can be used although this may take a little longer, or feeders can be requested from Geo-Load Forecast (GLF) engineers/technicians since they know their networks much better. In this work, the EDENDALE Substation NBEC and ESTON Substation NB13 are included to demonstrate the analysis and common point results. ESTON NB13 can be found in appendix A.

2. **Download one-year feeder statistics:** Statistical data is requested from MV90 or by using ADS software to download the statistics from the MV90 database into an excel spreadsheet.

3. **Scale feeder apparent power:** In this analysis, the main aim is to observe the trend for how the domestic feeder load varies over the year and during the day. So the apparent power of the network is scaled to unity by diving all apparent power data by the maximum normal apparent power. For domestic networks, the maximum normal apparent power occurs in mid-winter which is 6.25 MVA for EDENDALE NBEC and 2.1 MVA for ESTON NB13. After doing this, the yearly graph in Fig. 3.1 is plotted together with power factor.
   Fig. 3.1 shows how the load changes from 01 January 2017 to 31 December 2017. Analyzing 2016 and 2015, it was observed that the pattern is almost identical.

4. **Pick one day in the middle of winter:** Before picking a day, a month in the middle of winter is picked which is July, and then a day in the middle of July is picked. For the purpose of this study, the best day to pick is a working day (not holiday or weekend). For this network, 18 July 2017 was chosen and plotted with power factor as shown in Fig. 3.2.
   From the above plot, it can also be seen how the load was varying during the day in winter. The network is least loaded from 22:30 to 04:30 (below 40 % of peak load for 6 hours). It should also be noted that in winter the morning peak is around 8:00 am with evening peak at 18:00 pm.

5. **Pick one day in the middle of summer:** Before picking a day, a month in the middle of

summer is picked which is January, and then a day in the middle of January is picked. For the purpose of this study, the best day to pick is working day (not holiday or weekend). For this network, 18 January 2017 is picked and plotted with power factor as shown in Fig. 3.3.

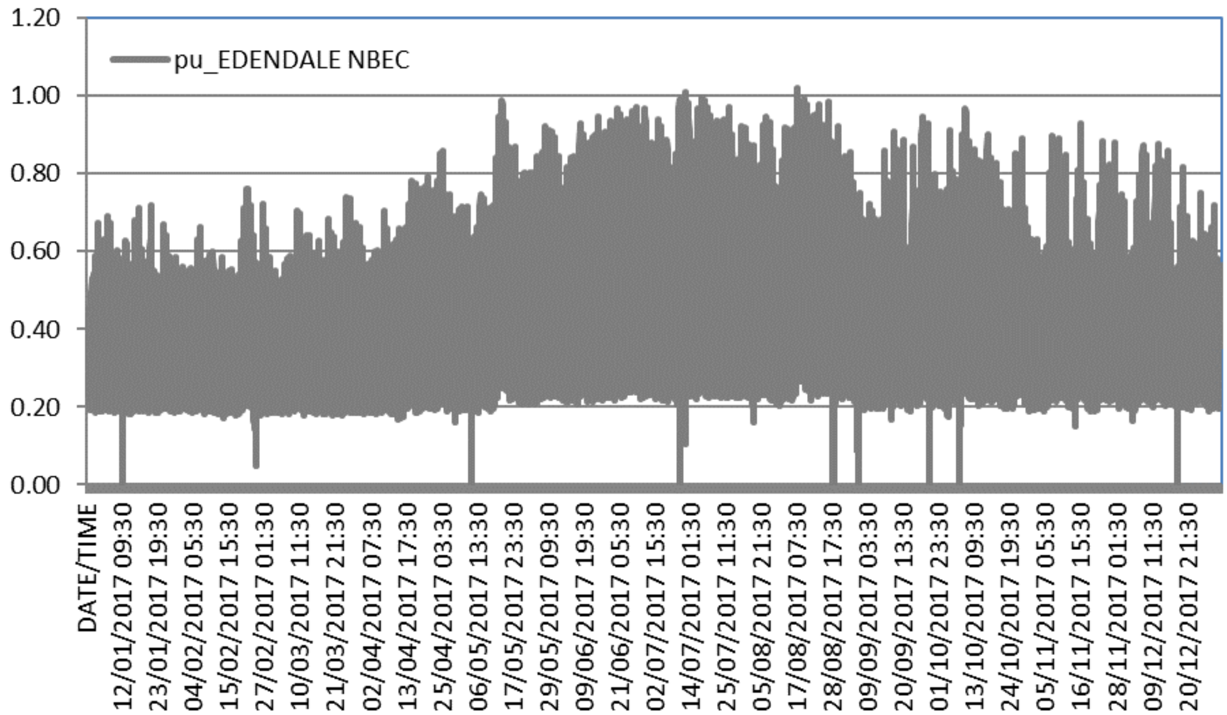

Figure 3.1 Statistical data for EDENDALE Substation NBEC.

The network is designed and analyzed under extreme conditions which happens in winter, as can be seen in Fig. 3.2, in summer the network is less loaded compared to winter, but for completion purpose, the summer load is also analyzed in this study. It should be noted that in summer the morning peak is around 6:00 am with evening peak at 20:00 pm.

It very important to remember that the power factor of the network can be used to tell what type of a feeder the network is. Good power factor (> 90 %) means less inductive load and less non-linear loads injecting harmonics into the network and therefore such a feeder and network is dominated by domestic customers.

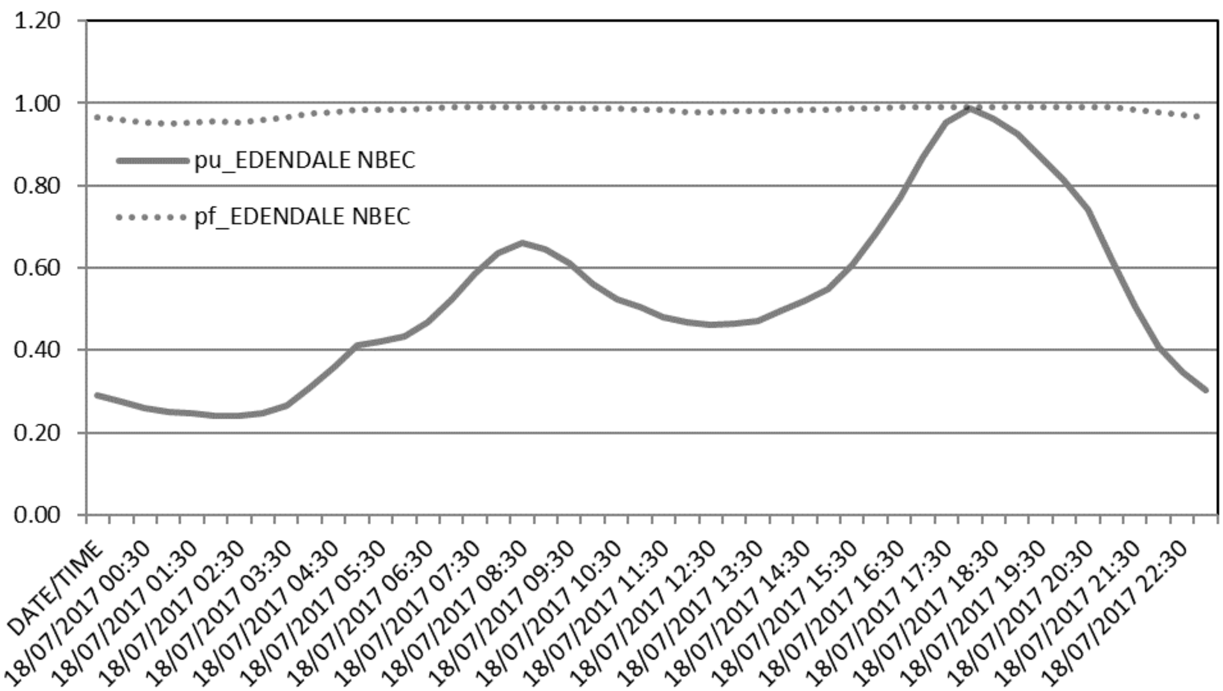

Figure 3.2 Scaled Daily Load during winter.

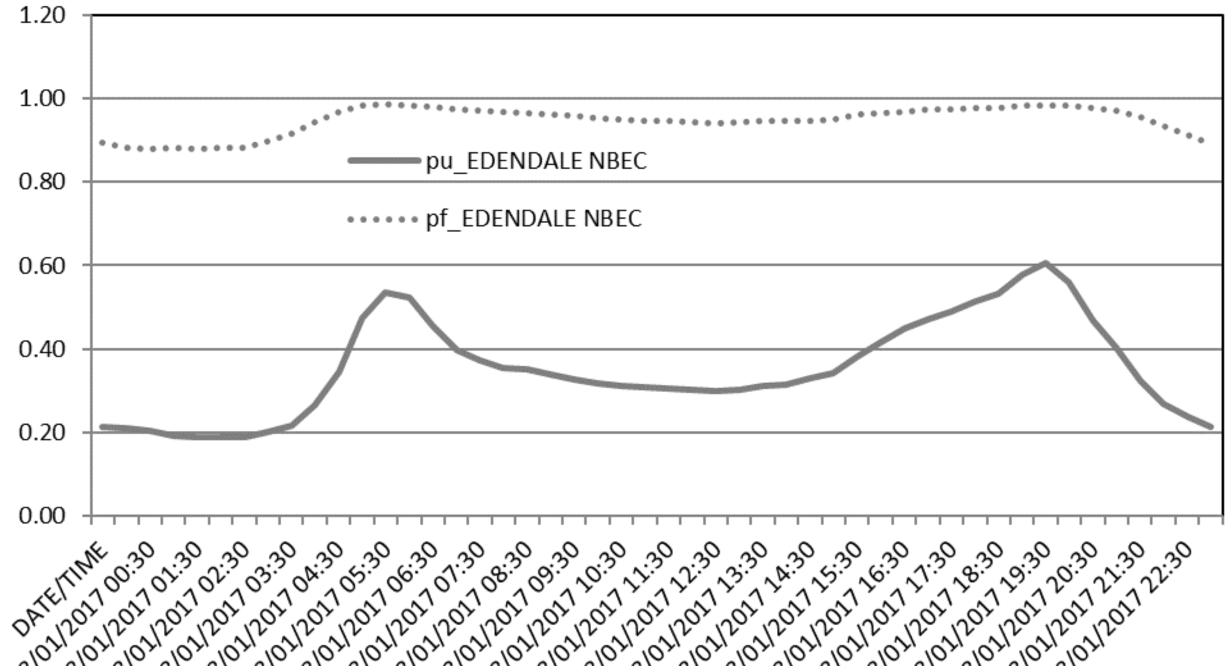

Figure 3.3 Scaled Daily Load during summer.

3.2 Observations from Demand Study/Grid Study

Table 3.1 summaries the results found from grid/demand study. Here under yearly load characteristic; sunrise, sunset and electricity demand is summarized. Sunrise and sunset information can be very useful when designing and dealing with solar assisted EV-Grid systems like solar roof EVs, solar roof houses, and or grid-tied, off-grid and hybrid solar systems. Under the daily load characteristics, electricity demand is summarized as a function of time of the day in hours.
From the grid daily load characteristics results, it can be observed that the network feeding domestic load has more excess capacity from around 22h30 to 04h30 which is a duration of 6 hours. This means EVs charging overnight are limited to a charging period of 6 hours. From grid statistical data, it is observed that during overnight the grid is loaded below 40 % of its peak, which happens at around 18h00 during winter and around 20h00 during summer.

3.3 Design for Overnight Charging

Using the information, we have obtained so far from the demand/grid study together with a couple of electricity delivery standards, the number of EVs that can be connected to each distribution transformer per phase during overnight period can be determined for all three charging levels, AC level 2A, AC level 2B and AC level 2C. During electrification design, transformers are loaded up to 80 % of their rated capacity for overhead networks (up to 50 % for underground networks), so here it is assumed that every distribution transformer peak is at 80 % of it rated capacity in mid-winter at 18:00 pm (highest peak of the year). From this information it not difficult to see that the distribution transformer during mid-winter overnight is expected to be loaded below 40 % of its highest peak of the year (80 %), therefore below 40 % $\times$ 80 % = 32 % of it rated capacity.

Table 3.1 Daily Load (Domestic) Characteristic

Yearly Load Characteristics												
Season	Summer		Autumn			Spring			Winter			Summer
Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Sunrise	05h00		06h00			07h00			06h00			05h00
Sunset	19h00		18h00			17h00			18h00			19h00
Demand	Minimum		Rising			Peak			Falling			Minimum

Daily Load Characteristics																								
Session	Night			Morning						Day						Afternoon						Night		
Hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Demand	Night Min			Rising			Morning peak			Falling			Day min			Rising			Evening peak			Falling		

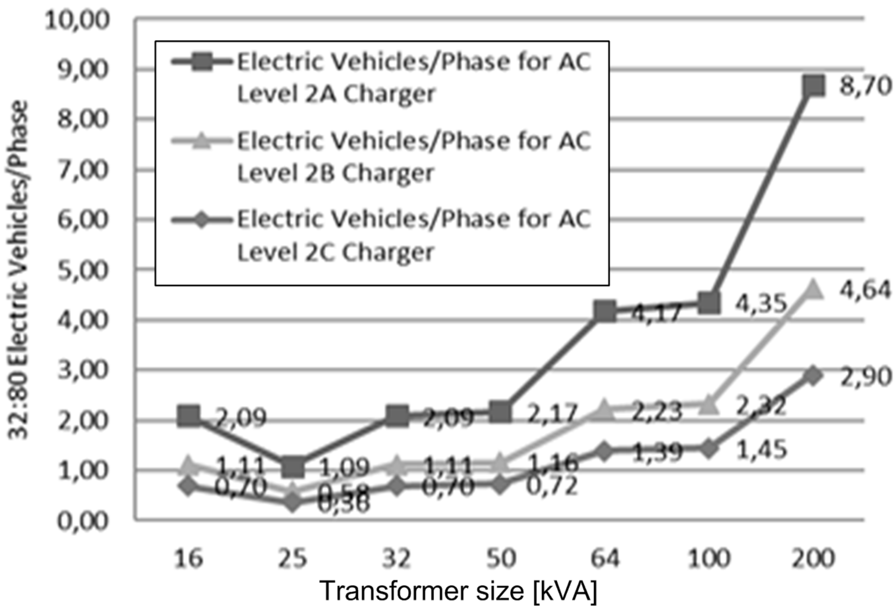

Figure 3.4 32:80 EVs per phase against transformer kVA during winter off-peak period.

Therefore, during overnight the majority of distribution transformers are expected to be loaded below 32 % of their rated capacity. At night, (off-peak) more load (EVs) can be connected to distribution transformers to increase overnight load from 32 % to 80 % of their rated capacity (design limit). Table 3.2 shows the calculated number of EVs that can be connected to each phase of the distribution transformer using the above information.

Plotting the results in Table 3.2 from a transformer size of 16 kVA to 200 kVA, the plot in Fig. 3.4 is obtained. The figure shows results for pole mounted distribution transformers only. From 350 kVA to 5000 kVA distribution transformers, the results can be read direct from Table 3.2

Design Analysis

Here most distribution transformers are assumed to have at least 48 % (80 % - 32 %) of normal excess capacity during the overnight charging period. It should be noted that this design should

Table 3.2 Number of EVs/ Phase during Winter Off-Peak Period.

Transformer Capacity (kVA)	Phase Technology	Winter Peak Load = 80 % of TRF Capacity (kVA)	Winter Mid-Night Load = 40 % of Winter Peak (kVA)	Winter Midnight Excess Capacity/ TRF (kVA)	Winter Midnight Excess Capacity/ Phase (kVA)	EVs/Phase for AC Level 2A Charger	EVs/Phase for AC Level 2B Charger	EVs/Phase for AC Level 2C Charger
16	1-Phase	12.8	5.12	7.68	7.68	2.09	1.11	0.70
25	3-Phase	20.0	8.00	12.00	4.00	1.09	0.58	0.36
32	Dual Phase	25.6	10.24	15.36	7.68	2.09	1.11	0.70
50	3-Phase	40.0	16.00	24.00	8.00	2.17	1.16	0.72
64	Dual Phase	51.2	20.48	30.72	15.36	4.17	2.23	1.39
100	3-Phase	80.0	32.00	48.00	16.00	4.35	2.32	1.45
200	3-Phase	160.0	64.00	96.00	32.00	8.70	4.64	2.90
350	3-Phase	280.0	112.00	168.00	56.00	15.22	8.12	5.07
500	3-Phase	400.0	160.00	240.00	80.00	21.74	11.59	7.25
1000	3-Phase	800.0	320.00	480.00	160.00	43.48	23.19	14.49
1500	3-phase	1200.0	480.00	720.00	240.00	65.22	34.78	21.74
2500	3-Phase	2000.0	800.00	1200.00	400.00	108.70	57.97	36.23
5000	3- Phase	4000.0	1600.00	2400.00	800.00	217.39	115.94	72.46

never lead to damage of distribution transformer due to overloading during overnight charging period of 22:30 pm to 04:30 am if the actual load of the distribution transformer is not more than 102 % (150 % - 48 %) of its capacity/size. This is because distribution transformers are designed to withstand an ultimate load of up to 150 % of their rated capacity. Therefore, this is not a sensitive design since the actual load of the distribution transformer during overnight charging period can increase from 32 % to 102 % of its rated capacity without damaging the transformer. Concluding, if this method for overnight charging is applied correctly and leads to damage of a distribution transformer due to overloading, that will mean that distribution transformer was already overloading by at least 2 % (making 102 %) of its rated capacity during overnight charging period, which rarely happens.

Chapter 4

Modelling and Simulating EV System

Introduction

The physical model of the vehicle system is developed based on the applied load during motion. The characteristics of the vehicle and the parameter coefficients that concern the vehicle varies, depending on the vehicle design and the movement situation. Forces that occur during the movement of the vehicle, including the motor torque and speed, are evaluated. The motor speed and torque are not directly linked to the linear movement of the vehicle but instead through the gears with a gear ratio of $1/G$ and a radius r of the vehicle drive wheel.

4.1 Modelling the Electric Vehicle

Generally, the modelling of an EV involves the balancing of the forces acting on a running vehicle. The forces are categorized into road load and tractive forces. The road load consists of the gravi-

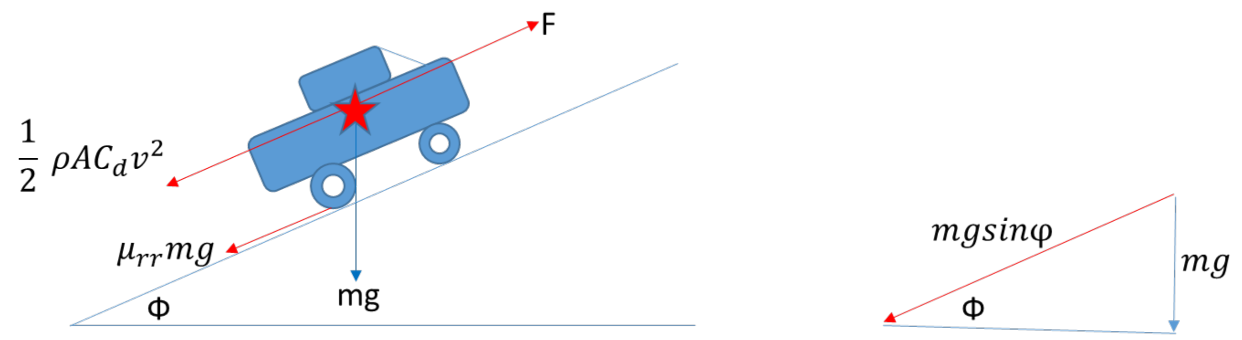

Figure 4.1 Modelling the Electric Vehicle.

tational force, hill-climbing force, rolling resistance of the tires and the aerodynamic drag force as shown in Fig. 4.1.

In Fig. 4.1, the momentum is conserved and it rate of change with time is equivalent to the sum of all forces acting on the electric vehicle. The momentum is defined as:

$$P = mv \tag{4.1}$$

so that

$$\frac{dP}{dt} = m \times \frac{dv}{dt} = F - \mu_{rr}mg = \frac{1}{2}\rho AC_d v^2 - mg\sin(\phi) \tag{4.2}$$

Re-arranging terms we get

$$F = \mu_{rr}mg + \frac{1}{2}\rho AC_d v^2 + mg\sin(\phi) + m\frac{dv}{dt} \tag{4.3}$$

where m is the mass of the electric vehicle; g is the gravity acceleration; v is the driving velocity of the vehicle; μ_{rr} is the rolling resistance coefficient; ρ is the air density; A is the frontal area of the vehicle; C_d is the drag coefficient; and ϕ is the hill climbing angle. The rolling resistance is produced by the flattening of the tyre at the contact surface of the roadway. The main factors affecting the rolling resistance coefficient μ_{rr} are the type of tyre and the tyre pressure. It is generally obtained by measurement in a field test. The typical range is 0.005 to 0.015 depending on the type of tyre [37]. The rolling resistance can be minimized by keeping the tyres inflated properly.

In eqn. (4.3), the first term corresponds to the rolling resistance force; the second term corresponds to the aerodynamic drag force; the third term corresponds to the hill climbing force; and the forth term corresponds to the acceleration force. This resultant force F, will produce a counteractive torque to the driving motor, i.e., the tractive force.

4.2 Modelling the Gear Ratio

For vibration study, the connection between the driving motor and the tyre should be modelled in detail. In this work, a simplified model is used. With this simplified model, the relationship between the tractive force and the torque produced by the motor can be obtained from

$$T_L = rGF \tag{4.4}$$

where r is the tyre radius (m) of the electric vehicle, $G = \frac{r1}{r2}$ is the gearing ratio, and T_L (Nm) is the torque produced by the driving motor. Fig. 4.2 shows a diagram representation of the gear ratio. Here a set of primary and secondary gears are working together to transfer power from primary gear (with radius $r1$) to secondary gear (with radius $r2$).

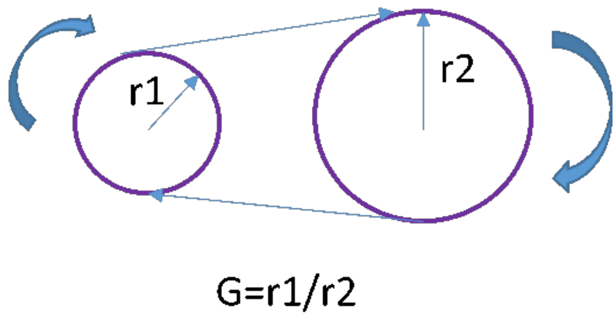

Figure 4.2 The gear ratio of the electric vehicle.

4.3 Power Flow Diagram

To analyze how the wheels of the electric vehicle are linked to the electric motor inside the EV, a single line diagram is used as shown in Fig. 4.3. This diagram is useful in developing the EV model that is used to analyze and understand the behaviour of EVs under various conditions.

4.4 Assumptions and Parameters

In this section, a list of assumptions to be used for simulations are provided. Here assumptions including the road, EV, electric motor, power converter, battery pack, charger, EV supply and service equipment (EVSE), grid, and travel pattern are provided below. Table 4.1 shows the assumptions to be used in the simulation model. Here parameters that have been outlined in previous sections are not included in this table, such as the Li-ion battery cell rated values.

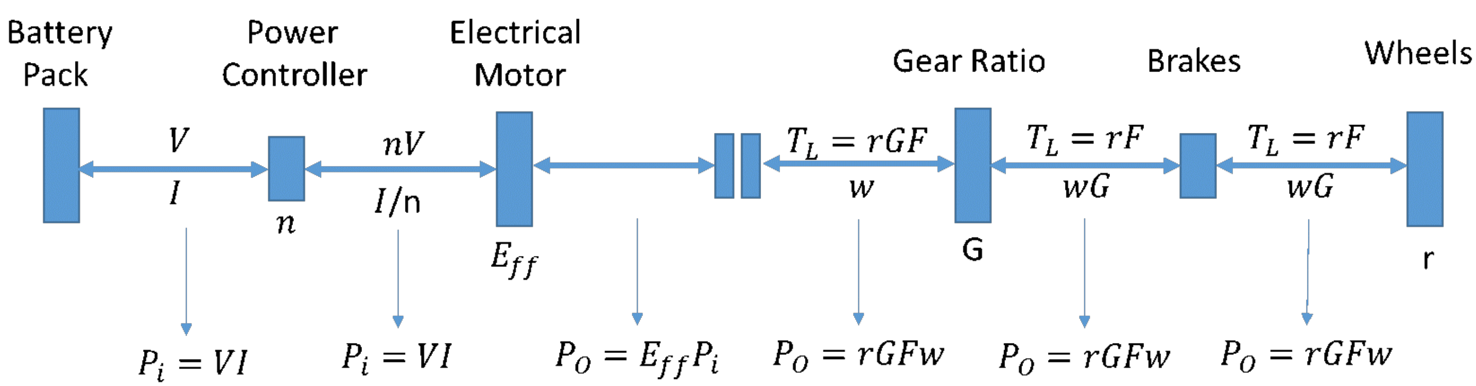

Figure 4.3 The power flow diagram of an electric vehicle.

Table 4.1 Assumption and parameters for simulations.

Road Parameters	
Parameter	Value
Air density	$d = 1.25$ kg m^{-3}
gravity	$g = 9.81$ ms^{-2}
Road gradient	0 % = 0.0°
	7 % = 4.0°
	14 % = 7.97°
	21 % = 11.86°
EV Parameters	
Parameter	Value
Drive Train Efficiency	$TC = 0.92$, $SC = 0.97$
Tire Radius	$r = 0.26$ m
Gear Ratio	$G = 0.5$
Vehicle mass + Passengers	$M = 2000$ kg
Frontal Area	$A = 1.2$ m^2
Drag coefficient	$cd = 0.75$
Rolling coefficient	$U_r = 0.009$
Minimum Range	100 km
Electric Motor Parameters	
Efficiency	EM_Eff = 0.95
Power Converters	
Efficiency	PC_Eff = 0.93
Rated Power for 1 pu Converter	5 kW
Input Voltage for 1 pu Converter	30 V
Battery Pack	
Efficiency	BP_Eff = 0.98
Cell Type	21700 NCA
Cell Rated Voltage	3.6 V
Battery Pack Output Voltage	30 V
Charger	
Efficiency	Ch_Eff = 0.90
EVSE	
Efficiency	EVSE_Eff = 1.00
Smart Grid	
Transformers peak in winter	80 % of their capacity
Tariff	1.50 ZAR/kWh
Mostoff Sizes	63 A/125 A
House CB Ratings	20 A/60 A

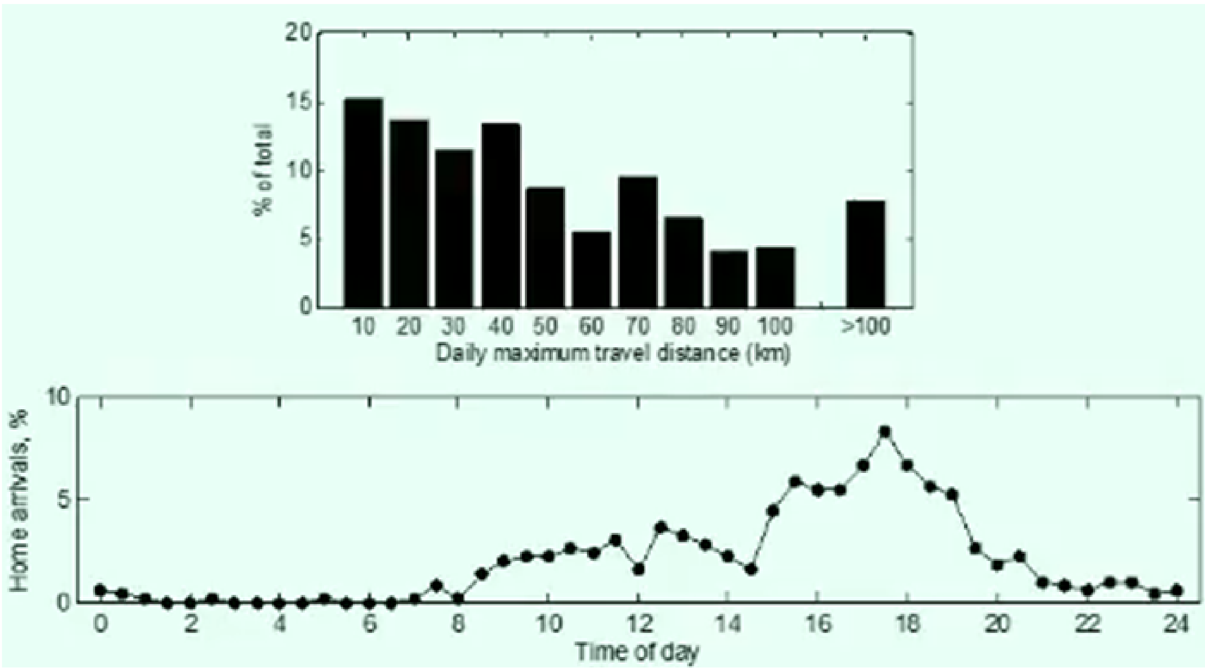

Figure 4.4 Average daily travel pattern of electricity customers [4].

Travel Patterns for EV Customers

Here it is assumed that the potential or majority of EV customers are employed who leave their houses early in the morning and come back late afternoon. Fig. 4.4 shows the Vista Travel Survey conducted in 2009 by the Victoria Department of Transport. In this survey, 13000 records of 24-hour vehicle travel profiles were recorded, daily distances travelled by working class people versus the percentage of total number of records are shown.

This survey shows that most people are working close to where they live to minimize travelling expenses and the graph decreases almost linear as the travel distance increases. From this survey results it is good to assume that people are travelling 100 km every day although the majority of them are travelling between 10 km to 50 km. Fig. 4.4 shows that the majority of people return home from 16h00 to 19h00.

4.5 EV Simulation Diagram

Using previous models and assumptions, the simulation diagram is constructed; this show in Fig. 4.5. The EV simulation diagram is used to simulate the vehicle under various conditions, i.e., travelling along the roads of different slopes. The aim for this is to investigate and analyse the behaviour and requirements of the EV at different road gradients and at different speeds. The equation inside the MATLAB function $f(u)$ is

$$= u(7)u(8)u(9) + 0.5u(4)u(5)u(6)u(1)^2 + u(8)u(9)\sin(u(3)) + u(8)u(2) \tag{4.5}$$

The MATLAB model in Fig. 4.6 for EV battery pack belongs to the subsystem in Fig. 4.5. This model is very useful in determining power and energy requirements from the battery pack.

In addition to the battery power and battery energy results, more parameters are modelled by the above model including number of required battery cells in series and parallel, battery pack dimensions and battery pack weight.

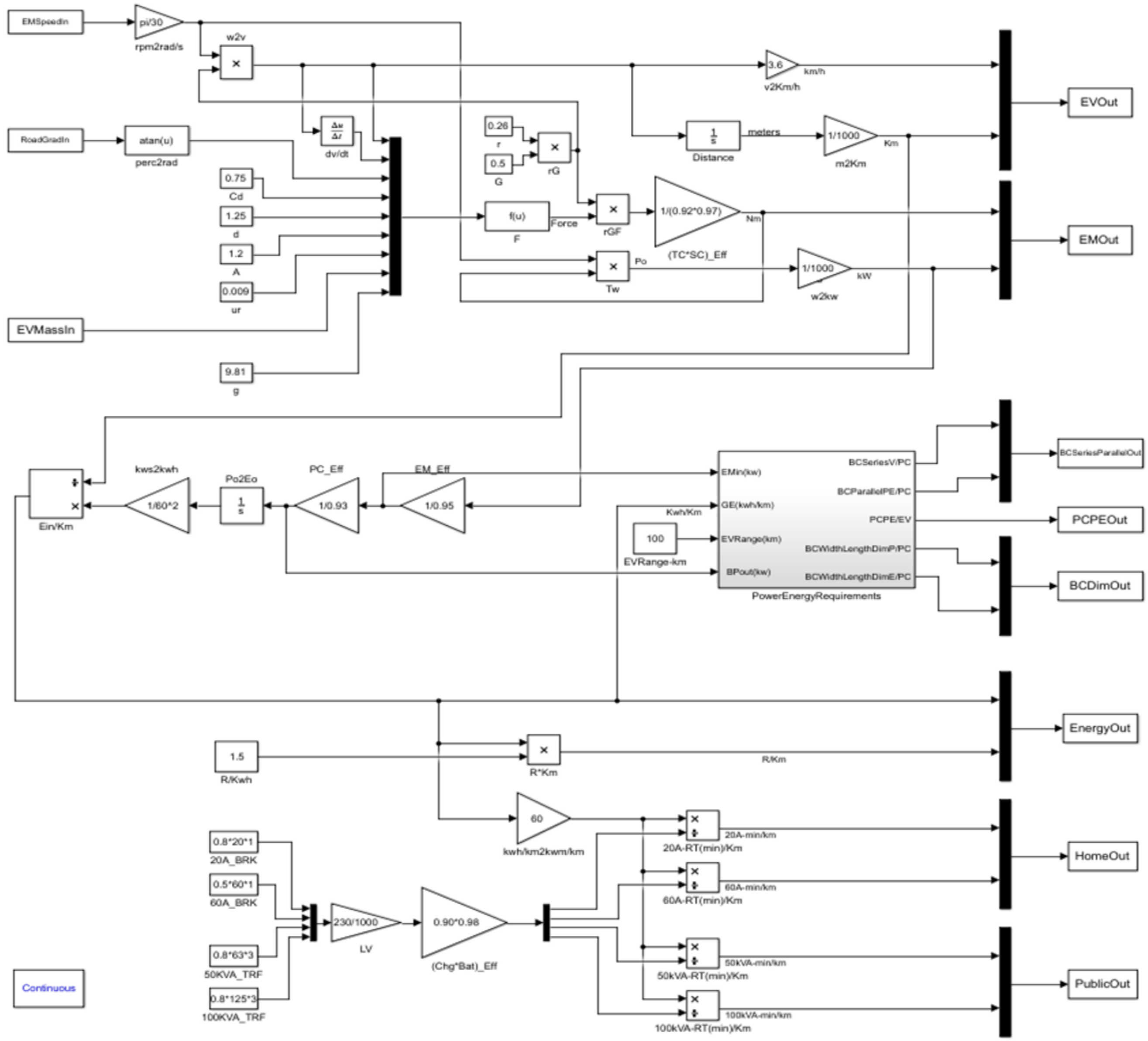

Figure 4.5 MATLAB EV Model.

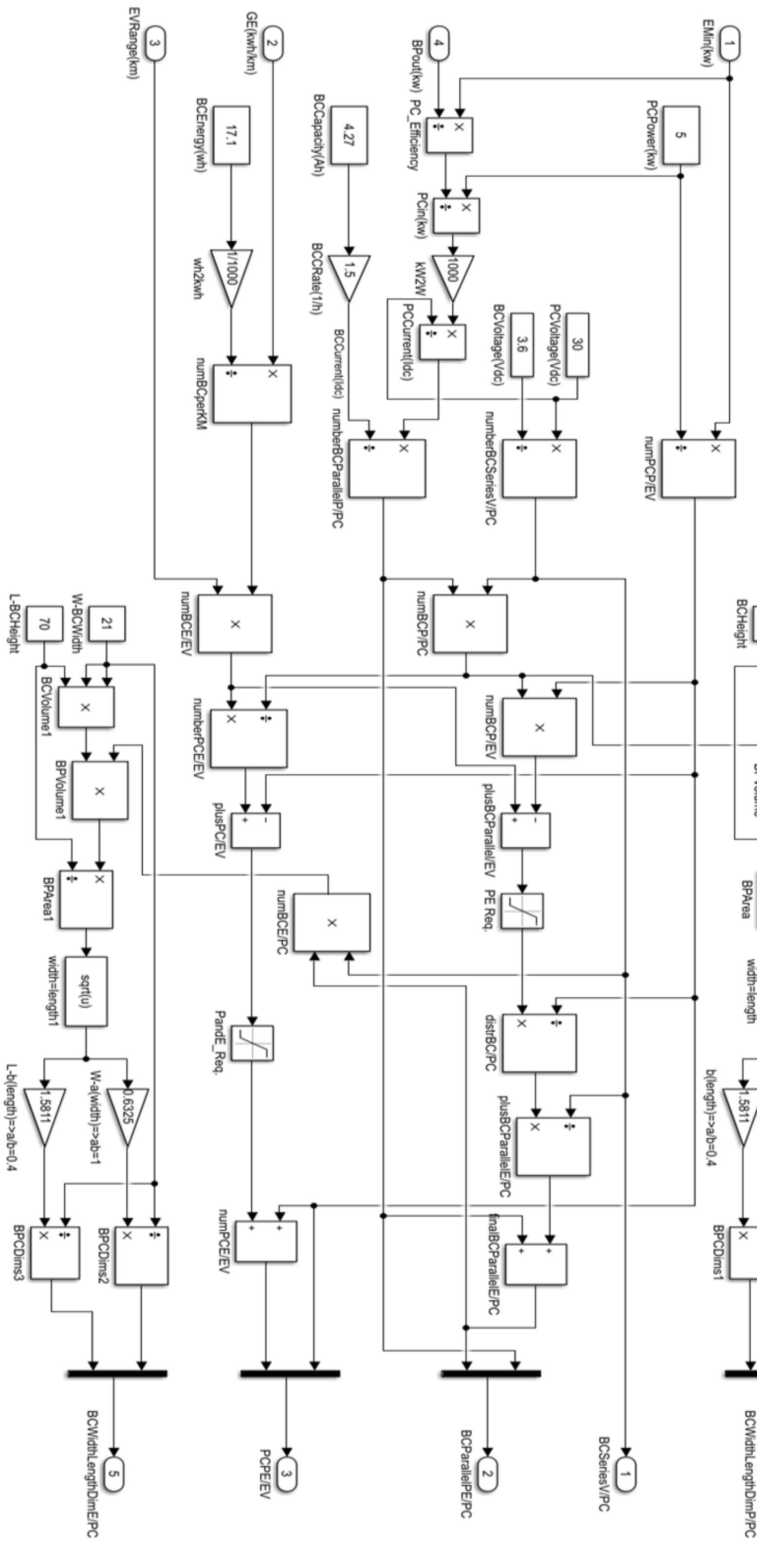

Figure 4.6 MATLAB Battery Pack Model.

Chapter 5

Simulation Results and Analysis

Introduction

Using the MATLAB models developed, the EV system is simulated at various conditions (i.e., various road gradients and various EV speeds for each road gradient). This can easily be seen from Table 5.1. In this model, there are three controlled parameters, which are EV mass, road gradient and EV speed. Then the rest are outputs from the model. To maximize accuracy of results, a MATLAB script was developed to read inputs from excel, simulate the model and read model outputs back to excel. This helps eliminates human reading error, improve reliability of results and greatly improves simulation time for all of these outputs for every single set of input parameters.

5.1 Grid to EV (Charging) Analysis

Table 5.1 summarizes the electric vehicle simulation results. This simulation is for electric vehicles with total mass from 1000 kg to 2000 kg, which is the range of most EVs.

Using the simulation results in Table 5.1 and the fact that for overnight charging, there are 6 hours available for all overnight home charging levels 2A, 2B and 2C, the results in Table 5.2 (daily limits and boundaries) in the next section are calculated and tabulated. These results are more accurate for a journey with a total average road gradient of 0 %. For graphical representation of the results, refer to appendix A (for G2V simulation results) and appendix B (for V2G simulation results).

5.1.1 Daily Limits of Overnight Charged EVs

In this section, the daily G2V limits are analyzed for overnight home charged EVs. These limits are set by the 6 hour availability for uncontrolled overnight charging. Table 5.2 summarizes these limits including maximum daily range (km), maximum daily energy (kWh) and maximum money spending (ZAR) assuming an EV tariff of ZAR1.5/kWh.

Using the fact that there are six hours available for overnight charged EVs for all charging levels, the daily travelling range limit can be calculated for a 2000kg EV having a road journey with a total average road gradient of 0 %. Using the simulation results above of recharge time (RT) in mins per km travelled, the daily range limit can be calculated and plotted as shown in Fig. 5.1.

In Fig. 5.1 it should be noted that the daily travelling range limit depends to the travelling speed of an EV and the overnight charging level. It should also be noted that the lower the trav-

Table 5.1 EV and Grid Simulation Results for EVs with mass 1000 kg to 2000 kg.

EV mass	1000 kg < mass <= 2000 kg											
EV Speed	40 km/h				80 km/h				120 km/h			
Road gradient	0 %	7 %	14 %	21 %	0 %	7 %	14 %	21 %	0 %	7 %	14 %	21 %
Electric Motor and Energy Consumption												
N (rpm)	816.18				1632.36				2448.54			
T (Nm)	36	235	432	623	66	266	462	654	117	316	513	704
P (kW)	3.063	20.12	36.93	53.27	11.31	45.43	79.05	111.72	29.94	81.12	131.55	180.56
kWh/km	0.087	0.569	1.045	1.507	0.160	0.643	1.118	1.581	0.282	0.765	1.241	1.703
R/km	0.13	0.85	1.57	2.26	0.24	0.96	1.68	2.37	0.42	1.15	1.86	2.55
Grid Recharge Time per Kilometer Travelled - RT(min)/km												
20 A Breaker (A)	1.60	10.53	19.32	27.86	2.96	11.88	20.68	29.22	5.22	14.14	22.94	31.48
60 A Breaker (B)	0.85	5.61	10.30	14.86	1.58	6.34	11.03	15.58	2.78	7.54	12.23	16.79
60 A Breaker (C)	0.53	3.51	6.44	9.29	0.99	3.96	6.89	9.74	1.74	4.71	7.65	10.49
50 kVA TRF (DC1)	0.17	1.11	2.04	2.95	0.31	1.26	2.19	3.09	0.55	1.50	2.43	3.33
100kVA TRF (DC2)	0.09	0.56	1.03	1.49	0.16	0.63	1.10	1.56	0.28	0.75	1.22	1.68

Table 5.2 Daily limits Simulation Results for EVs with mass 1000 kg to 2000 kg.

1000 kg < mass <= 2000 kg						
Range(Km) Limits for Home/AC Charging Levels	RT(min)/km for a 0 % Road slope			Range Limit a Day (km)		
	40 km/h	80 km/h	120 km/h	40 km/h	80 km/h	120 km/h
AC Level 2A	1.60	2.96	5.22	224.677	121.657	68.959
AC Level 2B	0.85	1.58	2.78	421.269	228.108	129.298
AC Level 2C	0.53	0.99	1.74	679.245	363.636	206.897
kWh Limits for Home/AC Charging Levels	kWh/km for a 0 % Road slope			Energy Limit a Day (kWh)		
	40 km/h	80 km/h	120 km/h	40 km/h	80 km/h	120 km/h
AC Level 2A	0.087	0.160	0.282	19.475	19.475	19.475
AC Level 2B	0.087	0.160	0.282	36.515	36.515	36.515
AC Level 2C	0.087	0.160	0.282	58.876	58.210	58.429
Rand Limits for Home/AC Charging Levels	R/km for a 0 % Road slope			Cost Limit a Day (Rands)		
	40 km/h	80 km/h	120 km/h	40 km/h	80 km/h	120 km/h
AC Level 2A	0.13	0.24	0.424	29.21	29.21	29.21
AC Level 2B	0.13	0.24	0.42	54.77	54.77	54.77
AC Level 2C	0.13	0.24	0.42	88.31	87.31	87.64

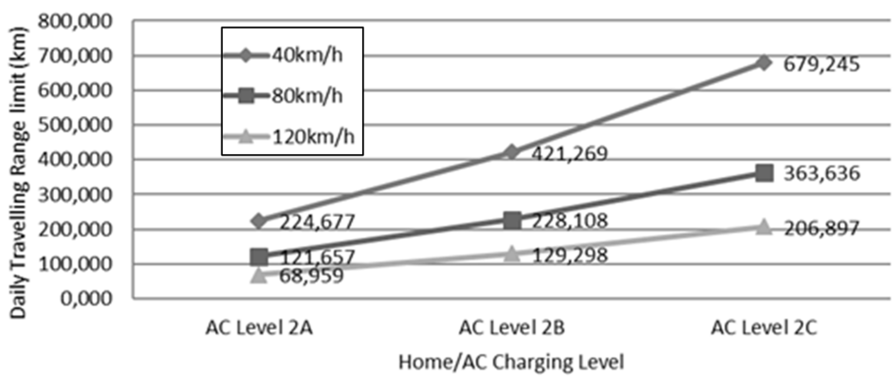

Figure 5.1 Daily range limit against Home/AC charging level for an average road gradient of 0 %.

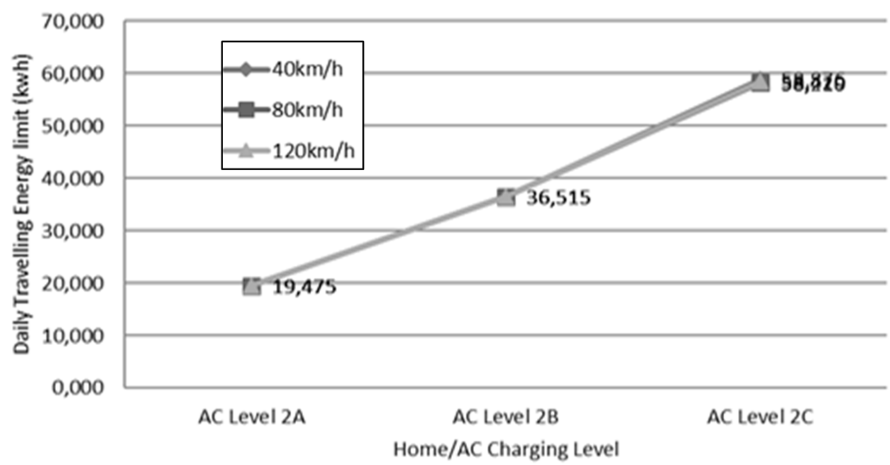

Figure 5.2 Daily Energy Limit against Home/AC charging level for an average road gradient of 0 %.

elling speed, the longer the daily range limit (km). Using a higher-level charger extends the daily travelling range limit. Here a balanced choice from Fig. 5.1 could be AC Level 2B and a travelling speed of 80 km/h, yielding daily range limit of 228.1 km for overnight home charged EVs.

Since there are six hours available for overnight charged EVs for all charging levels, it can be noted that level 2A (3.68 kW) draws just over 19.475 kWh of energy from the grid for the duration of six hours. Level 2B (6.90 kW) draws just over 36.515 kWh of energy from the grid for the duration of six hours. Finally level 2C (11.04 kW) draws just over 58.826 kWh of energy from the grid for the duration of six hours. From this information, Fig. 5.2 can be plotted.

Fig. 5.2 shows the maximum overnight energy that the grid can provide for the duration of six hours for AC Level 2A, AC Level 2B and AC Level 2C chargers. This means that if an EV has energy capacity greater than 60 kWh then the EV cannot be charged overnight from empty to full in one day using any of the above charging levels. Using the above results and the assumption that the tariff is 1.50 ZAR/kwh, the daily travelling cost limit is plotted (in ZAR) is plotted in Fig. 5.3.

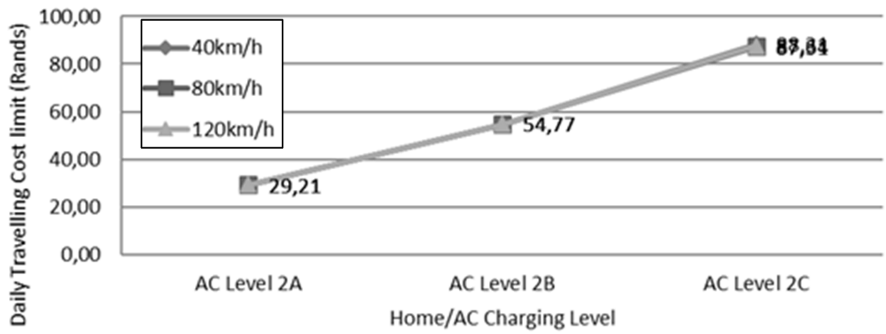

Figure 5.3 Daily Cost Limit against Home/AC charging level for an average road gradient of 0 %.

In Fig. 5.3, it can be seen that for AC Level 2A charger the owner of the EV can spend a maximum of ZAR 29.21 on overnight charging per day. With AC Level 2B charger can spend a maximum of ZAR 54.77 on overnight charging per day. In addition, with AC Level 2C charger can spend a maximum of ZAR 88 on overnight charging per day. This assumes the same tariff for all charging levels 2A, 2B and 2C, which might not be the case in future.

5.1.2 EV to Grid (Discharging) Analysis

In this section, it is assumed that the EV battery system consists of several battery packs, with every battery pack connected to a single 1 pu "power converter" such that the number of battery packs in an EV is equivalent to the number of power converters. Table 5.3 contains various information about every battery pack in an EV including cells connected in series for power converter input voltage requirement, cells connected in parallel for EV power and energy requirements, number of 1 pu power converters (which will be connected in series and parallel to define the real power converter) required by an EV and battery pack dimensions. All this information is put together to find the V2G capabilities of each EV battery pack when used as power wall or household battery bank.

In Table 5.3, the number of battery cells in series and parallel (for power and energy pack) required per converter were recorded during every simulation. In addition, the dimensions of each battery pack and number of battery packs were recorded for every simulation. The information about battery cells and battery packs required by an EV for every road gradient and every travelling speed recorded above plays an important role when talking about vehicle to grid (V2G) capabilities.

5.1.3 V2G Capabilities per Battery Pack

Assume one 5 kW battery pack is removed from an EV and used as a power wall or battery bank for household appliances, and assume that the battery pack is connected to a 1 kW load. Then Table 5.4 shows the results for the duration it will take each battery pack to run out of its rated energy. Here, the EV power pack and energy pack are analyzed. The weight of each battery pack is also calculated and shown in the table for portability analysis.

In this section, each battery pack (single unit) is analyzed to find out it capability of being used as a source of electricity at least at home to power essential appliances like lights, fridge, stove, etc. Table 5.4 tabulates the results and these are plotted in the following sections to visualize the results.

Battery Pack to Load (Hours)

Fig. 5.4 shows the duration in hours each EV power pack (PP) can last when delivering a power of 1 kW to the load (assuming constant power load).

It should be remembered that one power pack (PP) used in this study is rated at 5 kW. From the

Table 5.3 Power Pack and Energy Pack Simulation Results.

EV mass	1000 kg < mass <= 2000 kg											
EV Speed	40 km/h				80 km/h				120 km/h			
Road gradient	0 %	7 %	14 %	21 %	0 %	7 %	14 %	21 %	0 %	7 %	14 %	21 %
Battery Cells Connection and Power Controllers												
CellsParallelP/PC	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0
CellsParallelE/PC	94.3	94.3	94.3	94.3	47.2	47.2	47.2	47.2	31.4	31.4	31.4	31.4
CellsSeriesV/PC	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3
NumberOfPCsP/EV	0.6	4.2	7.8	11.2	2.4	9.6	16.6	23.5	6.3	17.1	27.7	38.0
NumberOfPCsE/EV	2.2	14.3	26.2	37.8	4.0	16.1	28.1	39.6	7.1	19.2	31.1	42.7
Battery Cells Arrangement												
BPWidthDimP/PC	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7
BPLengthDimP/PC	24.1	24.1	24.1	24.1	24.1	24.1	24.1	24.1	24.1	24.1	24.1	24.1
BPWidthDimE/PC	17.7	17.7	17.7	17.7	12.5	12.5	12.5	12.5	10.2	10.2	10.2	10.2
BPLengthDimE/PC	44.3	44.3	44.3	44.3	31.3	31.3	31.3	31.3	25.6	25.6	25.6	25.6

Table 5.4 V2G Duration (Hours) for Power Pack and Energy Pack.

Load (kW)	Vehicle to Grid Duration (Hours) Per Battery Pack											
1kWADMD5kWPP	3.99	3.99	3.99	3.99	3.99	3.99	3.99	3.99	3.99	3.99	3.99	3.99
1kWADMD5kWEP	13.44	13.44	13.44	13.44	6.72	6.72	6.72	6.72	4.48	4.48	4.48	4.48
Mass(kg)5kWPP	17.49	17.49	17.49	17.49	17.49	17.49	17.49	17.49	17.49	17.49	17.49	17.49
Mass(kg)5kWEP	58.95	58.95	58.95	58.95	29.48	29.48	29.48	29.48	19.65	19.65	19.65	19.65

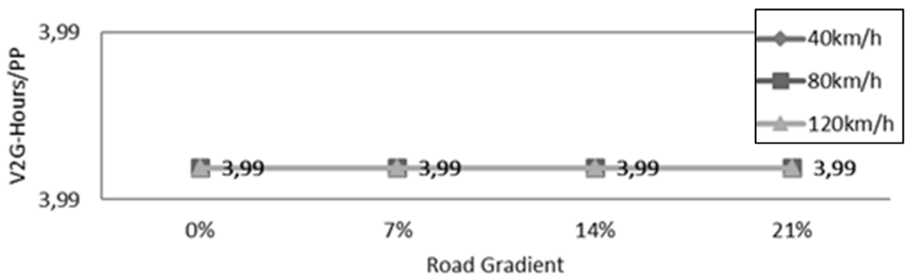

Figure 5.4 Using EV power pack for powering the house (Duration in Hours) – V2G-Hours/PP against road gradient.

above graph, it can be seen that one power pack of 5 kW is capable of delivering 1 kW of power for the duration of 4 hours (3.99 hours). Fig. 5.5 shows the duration (in hours) at which each energy pack (EP) can deliver 1 kW of power to the load (assuming constant power load).

From Fig. fig:5.5, it should be noted that the duration now depends to the travelling speed of an EV. The simulations assume constant speed so at high speeds the vehicle requires many power

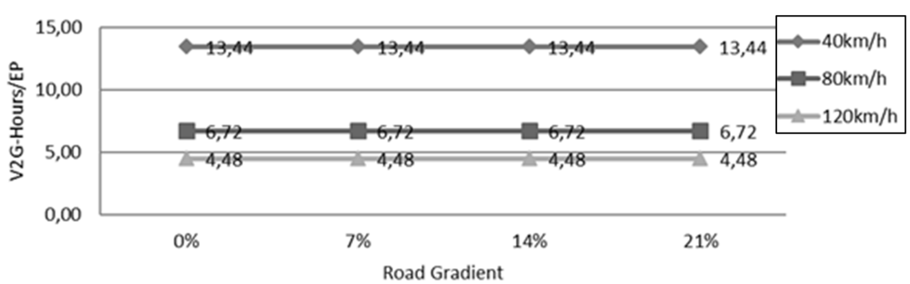

Figure 5.5 Using EV energy pack for powering the house (Duration in Hours) – V2G-Hours/EP against road gradient.

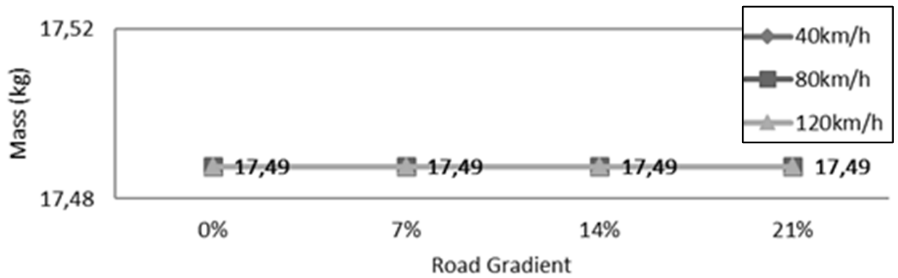

Figure 5.6 Mass in kg per (smart) power pack – mass (kg) against road gradient.

converters to satisfy the energy requirement of the EV, particularly on inclines. Since the energy is required for transporation then less energy is available for the power bank. At low travelling speeds, the vehicle needs less energy to travel 100 km so that more energy is available discharging back to the grid. The simulations here are simplified. A further development would be to use the standard driving cycles in the calculations [38].

Battery Pack Weight

Fig. 5.6 shows the mass of a single power pack delivering power to the grid or load. This includes battery cells only (not cooling and electronic systems).

From Fig. 5.6 the mass of a power pack, delivering power to the grid or load is expected to be around 17.49 kg, which is portable (if each power pack was made removable from an EV). Fig. 5.7 is a graph showing expected weight of each energy pack at all road gradients and all EV travelling speeds.

From Fig. 5.7, it should be noted that the weight of each energy pack (EP) varyies from 19.65 kg to 58.95 kg. If in future EVs, manufacturers decide to make removable battery packs that can be used as individual battery banks or power walls, it is very important that a portable pack size be

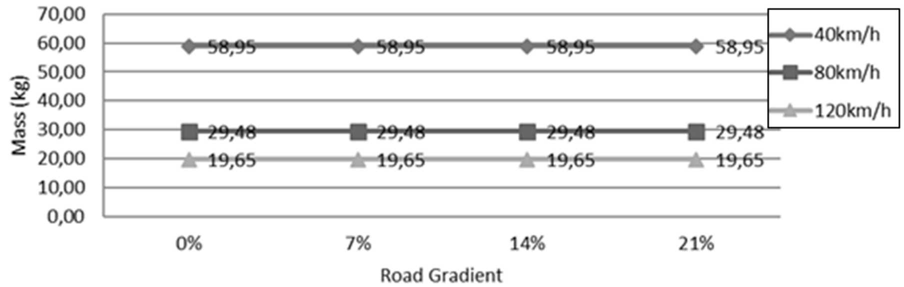

Figure 5.7 Mass in kg per (smart) energy pack– mass (kg)/EP against road gradient.

chosen to make it easy to handle. Removable battery packs can solve the issue of long charging times because at charging stations, the EV can exchange empty packs with charged ones.

Chapter 6

Impacts and Solutions on V2G Infrastructure

6.1 Impacts of V2G Infrastructure

The following impacts can affect network performance, reliability and quality of electricity significantly if not managed properly. Temperature loggers can be useful to detect overloaded transformers while vecto-graph can be used to monitor voltage drop and unbalance in the network.

6.1.1 Overloading

Normally distribution transformers are designed to be operated up to 100 % of their capacity. To increase reliability and lifetime of the transformer, they are loaded up to 80 % of their capacity. Distribution transformers can be loaded up to 150 % of their capacity especially during contingency situations.

6.1.2 Voltage Drop

Electricity standards requires that the voltage along all parts of the network be kept within +/- 10 % of the nominal voltage. Actually -10 % is the worst-case scenario, this scenario is avoided by limiting the minimum voltage to 93 %. When the network operates close to this limit, the electricity company must fix the problem as fast as possible.

6.1.3 Phase Unbalance

Phase unbalance causes significant current to flow through neutral conductor to earth via earth resistance increasing neutral voltage to unacceptable limits resulting to phase to neutral voltage drop.

6.1.4 Network Instability

This problem is observed when EV are discharging the power back to the grid. This impact affects the quality of electricity delivered to customers.

6.2 Solutions on V2G Infrastructure

The previous section outlined the impacts of electric vehicles on the grid. The day to day demand pattern showed that the distribution transformers are more loaded around 20h00 pm. In this section, possible solutions to the impacts are provided and discussed.

6.2.1 Uncontrolled Charging

In this approach, EV charging is not controlled either locally or centrally; it is the simplest charging system. Here the electric vehicle is connected to the network or charge point and charging starts immediately.

Overnight Charging

Previous investigations and analysis has shown that transformers operate under high load stress after work hours. When people arrives to their houses, they start using electricity and those with electric vehicles suddenly start charging to keep their EVs ready for the next day. In addition, the morning peak, but evening peak is worst. Early observations proved that the LV network start to relax/ cool down after 22h30 pm until 04h30 am next day. This 6-hour time of flexibility can be used to charge electric vehicles. By doing this the load due to electric vehicles charging has been shifted to overnight avoiding transformer over-loading and voltage drop.

Constructive Charging

Constructive charging is when a load is connected to the least loaded phase which can help balance the network and therefore boosting the network voltage up. This can be done using automatic phase selector charger. It should be noted that constructive charging does not solve the problem of transformer overloading, but load shifting does.

Balanced Charging

There are two main issues that cause voltage drop to customer houses. The first one is high current flowing through the phase conductor due to heavy load and the second one is the current flowing through neutral conductor due to unbalance loading. Therefore, to minimize significant drop in voltage at least two phases must be balanced.

6.2.2 Distributed Controlled Charging

This approach does not need any utility operator; it simplifies the system. Here the electric vehicle is connected to the network/ charge point and the charger itself takes the decision. Although this approach may result to lower charging costs due to the fact that there is no middle man (aggregator), it might not be reliable enough to ensure safety to utility equipments and quality of supply to all customers in the network, especial voltage sensitive customers.

Distributed Local Charging

This is the simplest approach that can be used, here no communication required between the EV and the charge point. It simplifies the charge point complexity since no communication is required. This uses a simple principle, Low voltage means high load, and high voltage means low load. If low voltage is detected then the device will not charge the EV, else it will start charging instantly if the device measures high voltage. This approach should be applied when charging downstream the network since upstream voltages are usually always within the standard, unlike downstream where voltages are the lowest.

Distributed Central Charging

In this approach, the charge point request and verify the vehicle information including voltage, temperature, etc. The charge point then measures the voltage and the current of the transformer. Using this vehicle, transformer and network information, it then decides if the network has necessary capacity to charge the vehicle or not. If the network is able to charge the vehicle, it then starts the charging process, else it rejects the vehicle with a relevant message. This approach can more effective if applied in a modernized network with real time network information.

6.2.3 Centralized Controlled Charging

This approach involves the utility operator; it is a bit complicated system. Here the electric vehicle is connected to the network or charge point and the utility operator or aggregator takes the decision. These charging schemes are more reliable then distributed schemes except that the charging cost might be higher due the presence of a middle man called aggregator. The distribution network in its current state in South Africa is not capable of supporting these charging schemes. The network needs to be modernized using smart metering devices at all strategic positions on the network to avoid phase imbalance, over currents, over voltages (upstream) and under voltages (downstream). New database centers for information storing and processing might need to be built to support these charging schemes.

Centralized exclusive Charging

Here the vehicle is connected to the network or charge point. The charge point collects network and vehicle information such as voltage, temperature, etc. Then the charge point sends all this information to the utility operator where the final decision is taken and response is given back to the charge point. The charge point gives feedback to the vehicle as to whether it can charge or not, if it can charge, under what constraints must it charge and then start charging if the vehicle owner agrees to the constraints if there are any.

Centralized inclusive Charging

In this approach, charging one EV stops the charging of another EV. This allows large number of EVs into the network at the same time but increases battery recharging time. Using this approach helps to make sure that the maximum loading of distribution transformer does not exceed maximum limit.

Centralized Price-Based Charging

Here electric vehicle owners are not limited to charging overnight but they charge their EVs on a varying electricity price/tariff. During peak hours the electricity price increases rapidly to discourage EV owners from charging during this time. Only those who are willing to pay more will charge from the network. This approach enables utility companies to generate more profit during peak hours. It will also ensure continuous service to its customers.

Chapter 7

Discussion and Conclusions

7.1 Discussion

The focus for this work was to address challenges associated with vehicle to grid (V2G) and grid to vehicle (G2V) technologies. A number of challenges including insufficient information regarding EV technology faced this study. This might be because this technology is still being developed by various companies including TESLA, Chevrolet, Mercedes, BMW, etc., so they still lot of competition in this industry leading to less technical information available to public. To get better understanding, an EV had to be modelled, simulated and analyzed. The other challenge is that this technology is not mature yet leading to lot of changes/new solutions being implemented by EV designers/manufactures. Despite all challenges, this study continued, using all available resources and solving all arising challenges.

Uncontrolled charging is found to cause overloading, voltage drop and phase unbalance, with EV discharging causing network instability. These impacts can be minimized using overnight charging, constructive charging, balanced charging, distributed controlled charging, and centralized controlled charging methods.

For single-phase distribution transformers, there are two possible impacts that can be caused by charging EV, which is overloading and voltage drop. Overnight charging can be used to solve the problem of transformer overloading and voltage drop by keeping the length of LV feeder as short as possible such that the end voltage to EV service equipment (EVSE) is within the standard (i.e. within 10 % of 230 V).

For three phase distribution transformers with single-phase supply to the house, the problem of phase imbalance has to be addressed to avoid/ limit under voltage due to excessive current flowing through neutral conduct to ground. This impact can be limited by using constructive charging if the load is not balanced. Therefore, for better charging at night, it is a good idea that overnight charging is used together with constructive charging. For three phase transformers with three-phase supply to houses, the problem of phase imbalance is solved by adopting balanced charging (i.e., using a three-phase EV charger).

Other solutions including distributed controlled charging and centralized controlled charging need to be considered and implemented especially as the number of EVs increases overtime. These solutions are reliable than uncontrolled solutions but expensive. Controlled charging methods will also improve customer satisfaction, flexibility since EV customers will no longer be limited to overnight charging, and hence no daily limits (i.e., daily travelling range limit) will apply to EV owners. For best control of EV charging, it is recommended that more solutions are used together, i.e. uncontrolled solutions together with distributed and centralized controlled charging. Off-board charging stations (i.e. DC Level 1 and DC Level 2) need to be constructed to support home charging, solve the problem of street charging, and maximize charging flexibility and satisfaction. Renewable energy sources including solar and wind farms shall be used especially in EV fleets to support conventional grid. In South Africa, the sun's irradiance is stronger, so PV farms seems to be promising renewable energy source.

7.2 Conclusions

The basics of V2G and G2V technology has been provided to familiarize the reader with the concept of V2G technology. An overview of the EV-Grid system is given and explained component by component. Due to circuit breaker and mostoff fuse ratings used by ESKOM, an EV on-board charger connected to the grid via EV service/supply equipment (EVSE) is limited to three possible charging levels, AC Level 2A, AC Level 2B, and AC Level 2C.

The impacts of V2G technology are listed, including overloading, voltage drop, phase unbalance (for dual and three phase transformers), and network instability. The solutions to the impacts are proposed including overnight charging, constructive charging, balanced charging, distributed controlled charging, and centralized controlled charging methods.

The smart grid has been studied to understand how domestic load varies over the year and during the day. From the yearly load profile, it is observed that the feeder/network feeding domestic load is more loaded in winter (i.e. June to August) implying the majority of distribution transformers are more loaded during winter period. From mid-winter (July) daily load profile, it is observed that the majority of domestic distribution transformers are least loaded (below 32 % of their rated capacity) from 22:30 pm to 04:30 am which is the duration of six hours. Using the information observed from grid/demand study, the number of EVs that can be connected to each transformer per phase are calculated, tabulated (for 16 kVA to 5000 kVA distribution transformers), and plotted (for 16 kVA to 200 kVA distribution transformers).

An EV model has been developed from conservation of momentum, gear ratio model, and power flow diagram. This model is useful for analysing the behaviour of an EV at different conditions (i.e., at different road gradients and at different travelling speeds). Before applying the model to MATLAB, all model parameters had to be assigned practical values. All assumed parameter values are tabulated and discussed.

A MATLAB model was developed for an EV-Grid system (for G2V analysis) and Power-Energy pack system (for V2G analysis). The model is simulated using developed MATLAB script to avoid human reading error, improve reliability of results, and speed up simulation time for every set of input parameters. The script reads inputs from excel, assign them to the MATLAB model, run the model, wait for the simulation to complete and read model outputs, writes them back to excel spreadsheet where further processing of model results is done. See MATLAB script in appendix G.

From the grid study results (the available charging period is six hours for overnight home charged EVs) and EV-Grid model simulation results (battery pack recharge time per kilometre travelled (min/km)), the limits/ boundaries (daily travelling range limit, daily energy limit, and daily travelling cost limit) are calculated, tabulated and plotted for analysis. These results are for an EV with a journey average road slope of 0 %.

From the results, it is seen that the daily travelling range limit depends to the level of overnight charger and EV travelling speed. The higher the level of overnight charger (i.e. AC Level 2C), and or the slower the travelling speed of an EV, the greater the daily travelling range limit. For medium speed (80 km/h) and medium overnight charger (AC Level 2B), the daily travelling range limit is 228.108 kilometres (which is considered as the average daily travelling limit for overnight home charged EVs of mass from 1000 kg to 2000 kg).

Using kilowatt-hour per kilometre travelled (kwh/km) results from EV-Grid simulation results together with daily travelling range limit results, the daily energy (kWh) limit is calculated, tabulated and plotted for analysis. The average daily energy limit is 36.515 kWh. From daily energy (kWh) limit and the EV tariff assumption of 1.50 (ZAR/kwh), the daily cost (ZAR) limit is calculated, tabulated, and plotted for analysis. The average daily cost limit is 54.77 ZAR.

EVs whose owners are using one EV for daily travelling purpose (i.e., going to work every day) and whom do not have other charging options (i.e., optimistic and dedicated charging) except overnight home charging cannot exceed daily limits.

The EV-Grid (V2G) system capabilities are analysed to see if EV battery packs are capable of being used as distributed generators (DGs), grid alternative for home electricity (especially during contingencies and load shedding) and power/energy banks (for future EVs with removable battery packs). Each power pack rated at 5 kW is found to be capable of delivering 1 kW of power to the load for the duration of 4 hours and weighs 17.5 kg. For energy packs, the discharge duration and pack mass are dependent to the speed at which the vehicle is travelling. Each energy pack can deliver 1 kW of power for the duration of 4.5 hours (4 hour 30 minutes) to 13.4 hours, and weighs 19.7 kg to 59 kg. The discharge duration and mass of energy packs increases with decreasing travelling speed of an EV.

Future EVs are likely to have removable portable battery packs as one technique to solve the problem of long charging times (instead, in charging stations, an EV can just exchange empty battery packs with full packs without waiting any time). Removable battery packs in EVs will greatly improve their flexibility and will solve lot of problems. Indeed this option is being used for scooters in Taiwan.

Under discussion section, findings in this paper are discussed and recommendations are given. This includes for best control of EV charging, it is best to use multiple solutions together (i.e. uncontrolled charging together with distributed and centralized controlled charging methods), controlled charging methods are expensive than uncontrolled charging solutions but they provide better control, reliability and customer satisfaction. To improve flexibility and charging time, off-board charging stations (DC Level 1 and DC Level 2) needs to be considered.

Finally, EVs can be safely integrated into the power grid with intelligent charge control through V2G. V2G provides significant benefits to all stakeholders. V2G has many additional applications in the smart grid and microgrids [39]. This thesis provided a step forward to current impacts. There is more research still to do before fully integrating EVs to the grid in South Africa.

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Appendix A

Smart Grid Analysis

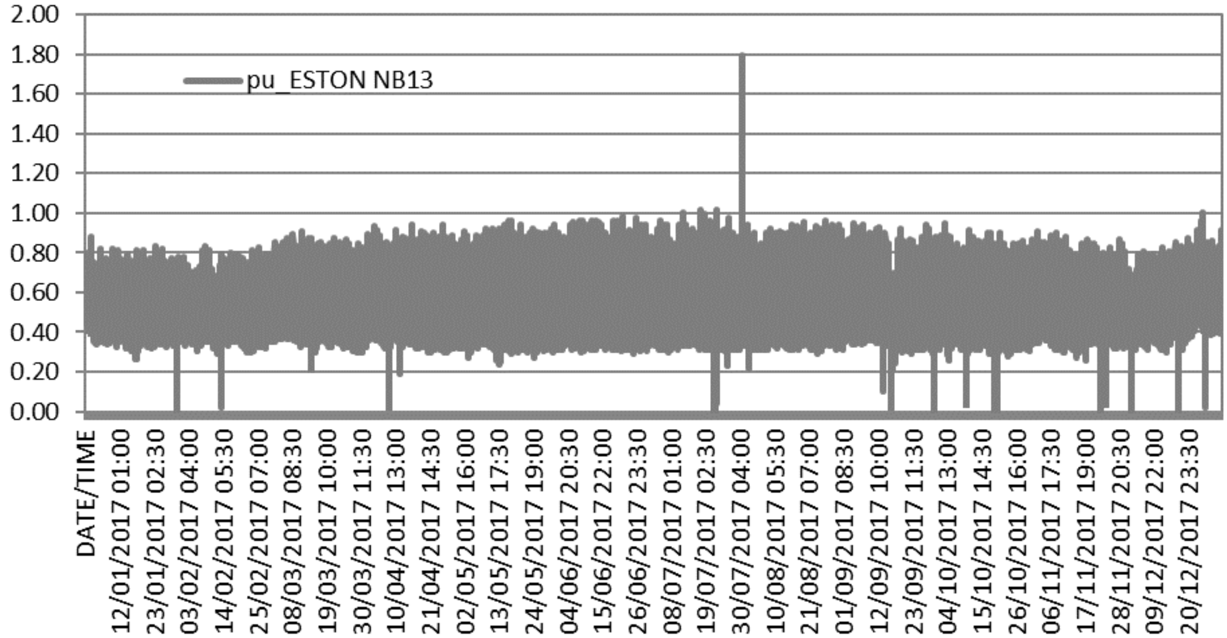

Figure A.1 Stats Data for ESTON Substation NB13 (p.u.).

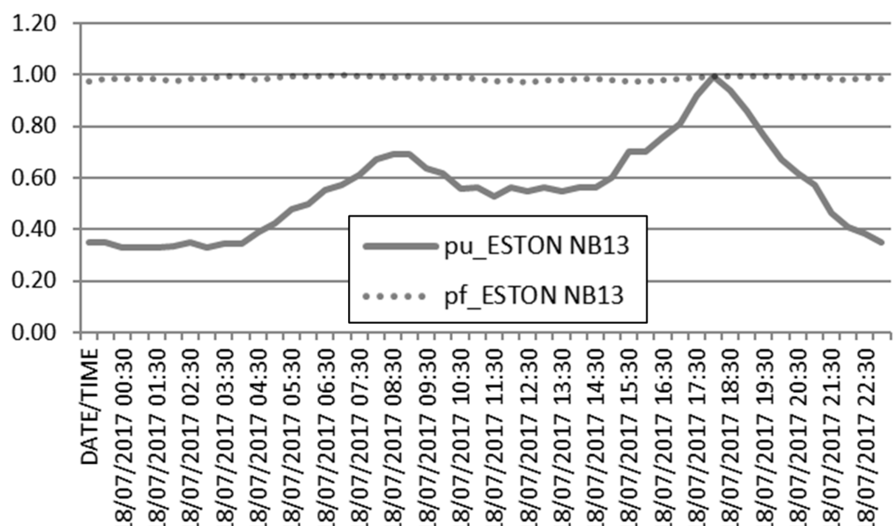

Figure A.2 Scaled Daily Load during winter (p.u.).

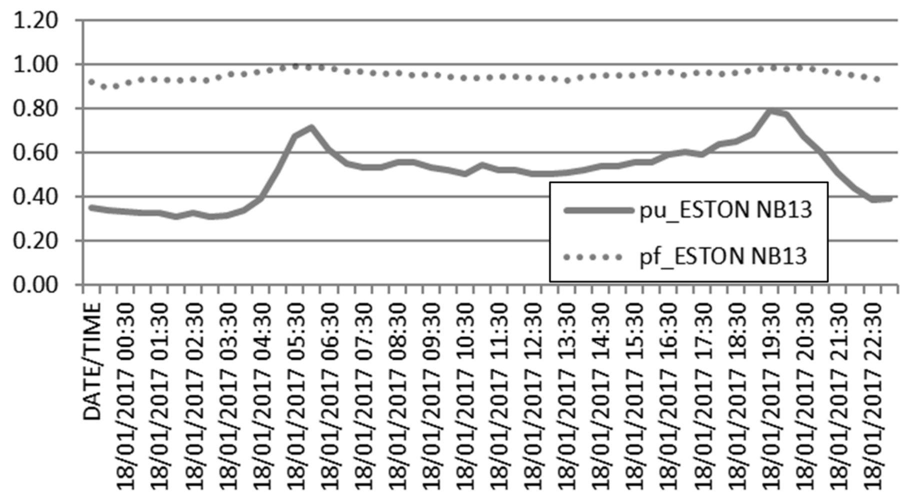

Figure A.3 Scaled Daily Load during summer (p.u.).

Appendix B

Grid-EV (G2V) Simulation Results

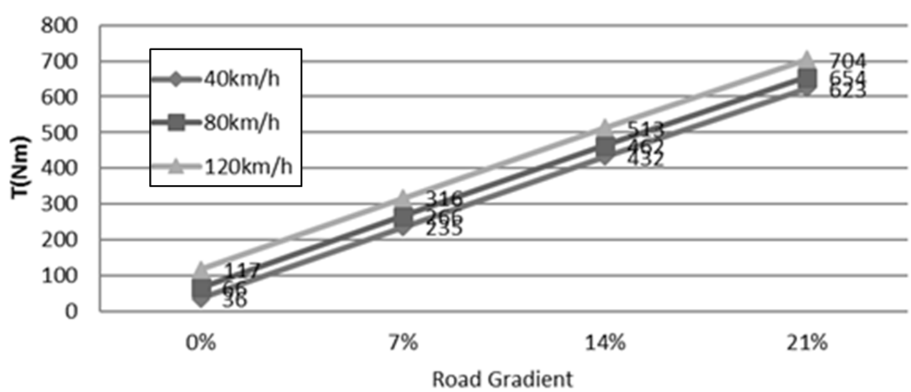

Figure B.1 Torque experienced by Electric Motor(s) – T(m) against road gradient.

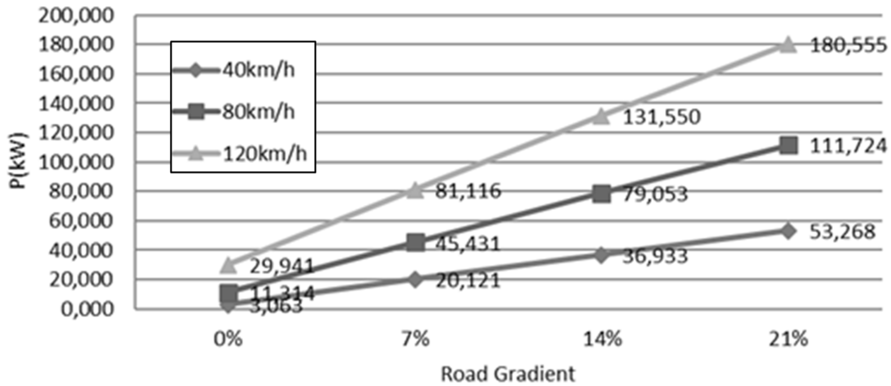

Figure B.2 Power delivered by electric motor(s) – P(kW) against road gradient.

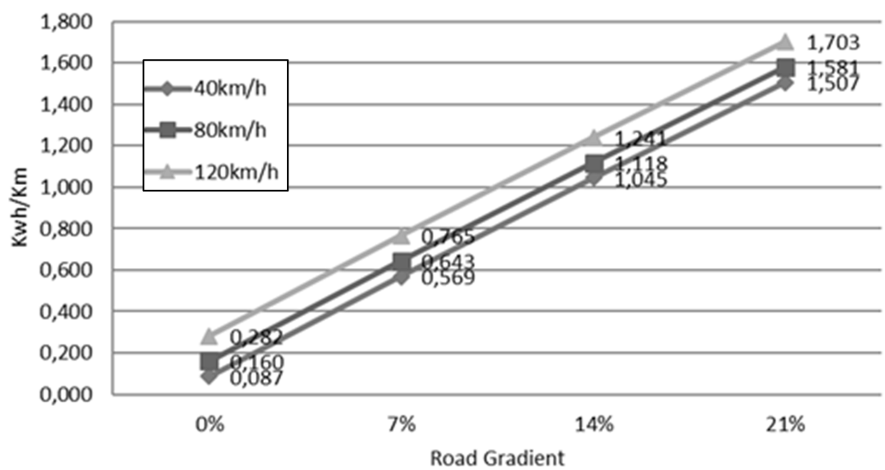

Figure B.3 Energy Consumed per kilometer travelled – kWh/km against road gradient.

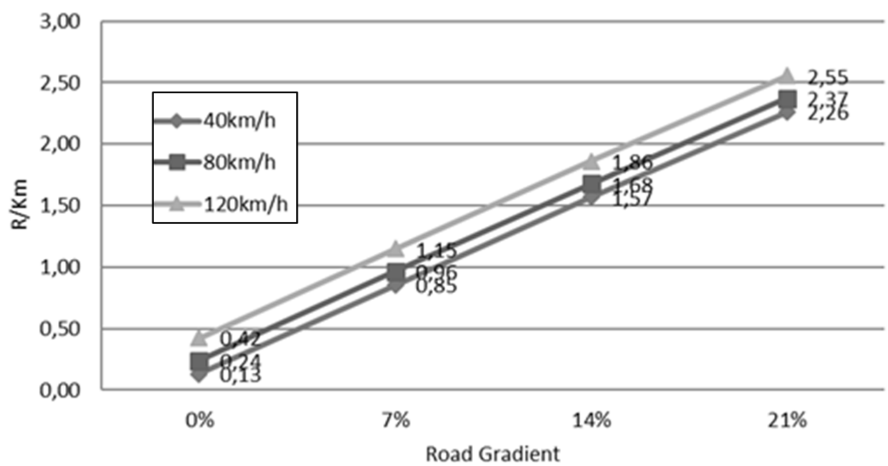

Figure B.4 Travelling Cost per kilometer (ZAR/km) – R/km against road gradient.

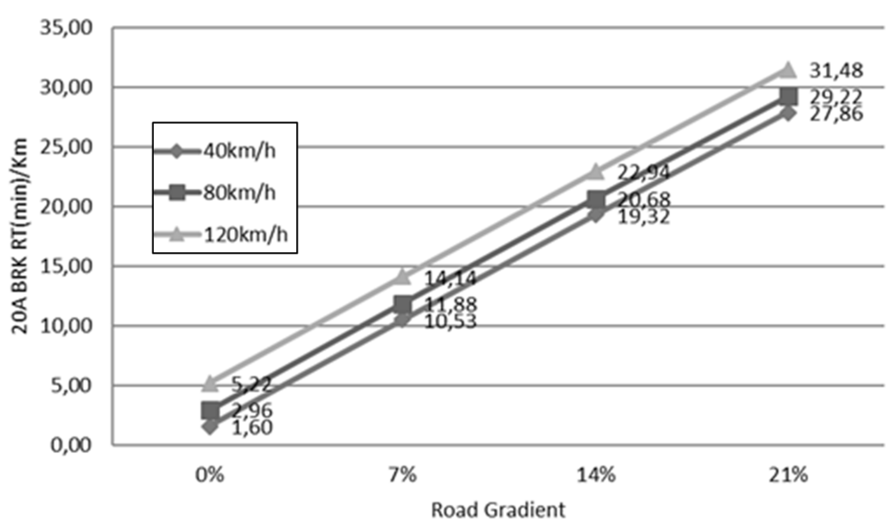

Figure B.5 Battery Recharge Time from a 20A BRK per kilometer travelled (AC Level 2A).

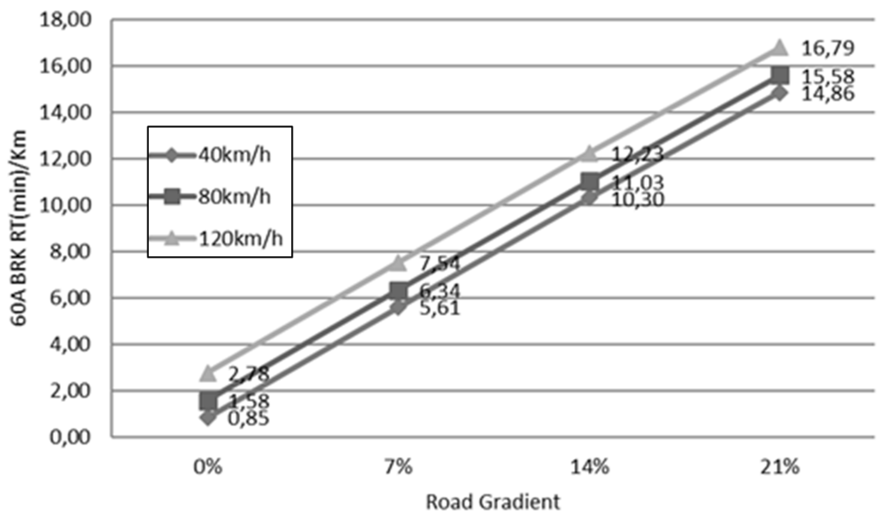

Figure B.6 Battery Recharge Time from a 60A BRK per kilometer travelled (AC Level 2B).

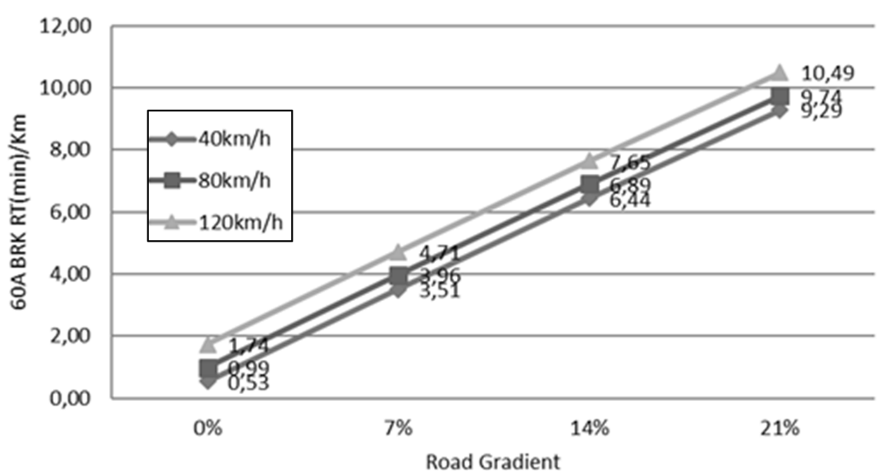

Figure B.7 Battery Recharge Time from a 60A BRK per kilometer travelled (AC Level 2C).

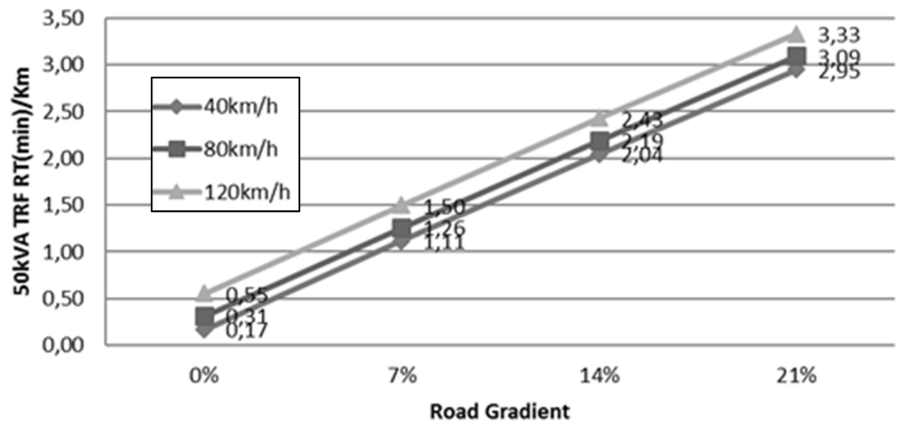

Figure B.8 Battery Recharge Time from a 50kVA TRF per kilometer travelled.

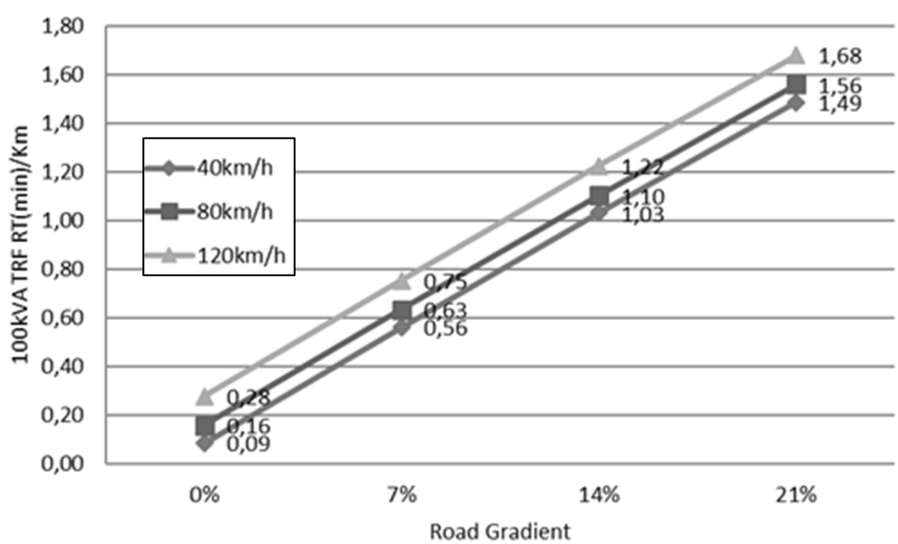

Figure B.9 Battery Recharge Time from a 100kVA TRF per kilometer travelled.

Appendix C

EV-Grid (V2G) Simulation Results

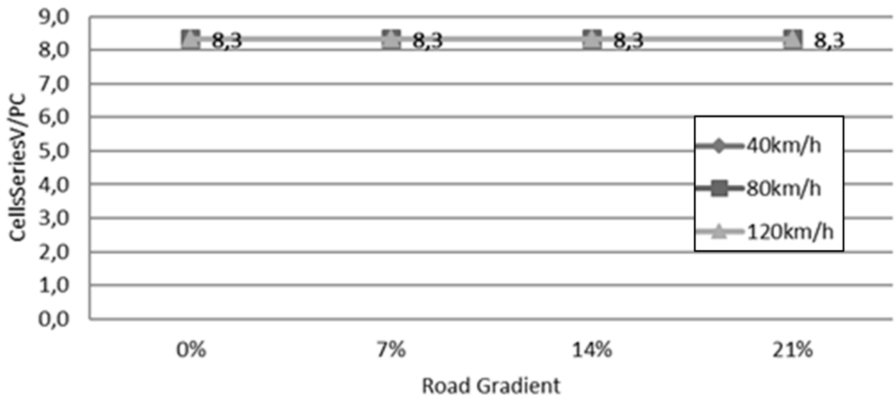

Figure C.1 Battery cells connected in series to satisfy voltage requirement per battery pack– CellsSeriesV/PC against road gradient.

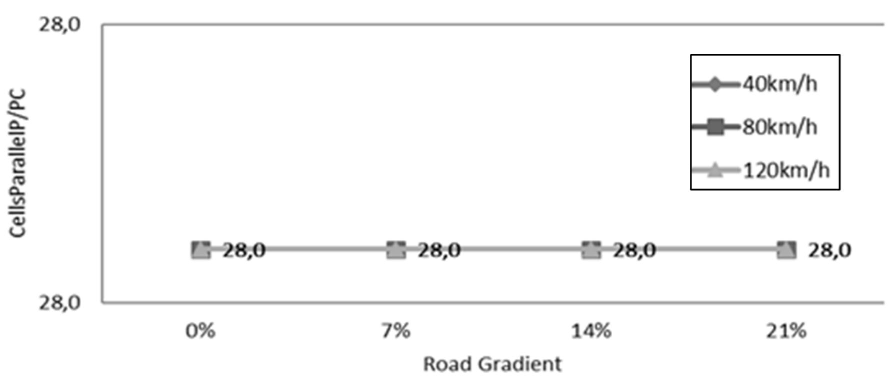

Figure C.2 Battery cells connected in parallel to satisfy power requirement per battery pack – CellsParallelP/PC against road gradient.

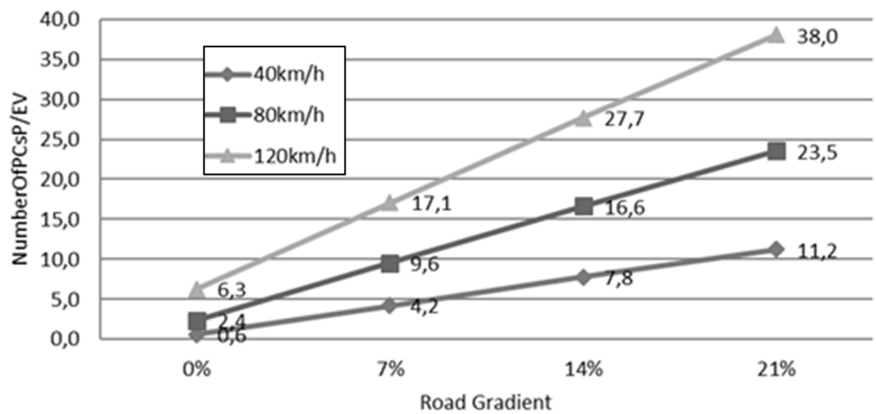

Figure C.3 Power Converters required to satisfy power requirement per EV – NumberOf-PCsP/EV against road gradient.

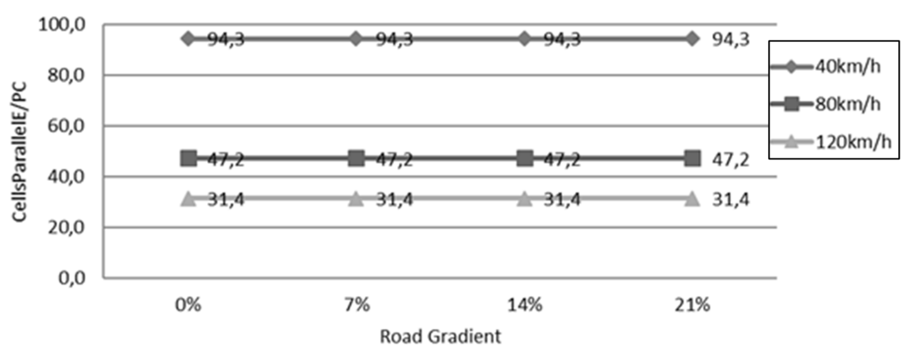

Figure C.4 Battery cells connected in parallel to satisfy energy requirement per battery pack – CellsParallelE/PC against road gradient.

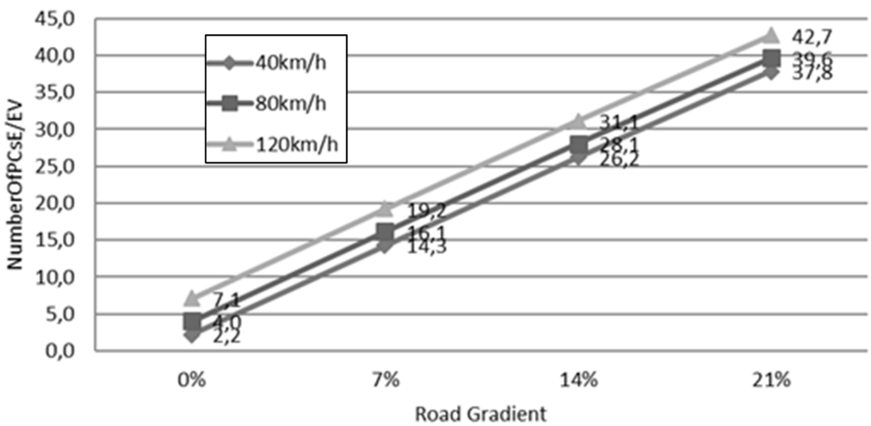

Figure C.5 Power Converter required to satisfy energy requirement per EV – NumberOfPCsE/EV against road gradient.

Appendix D

Battery Pack Dimensions

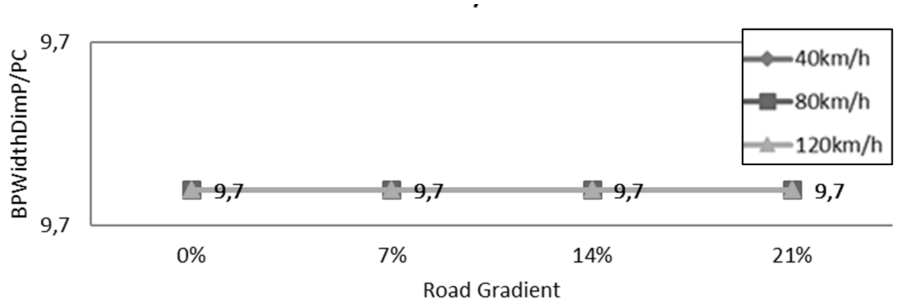

Figure D.1 Number of Battery cells along the width of battery pack to satisfy power requirement per battery pack – BPWidthDimP/PC against road gradient.

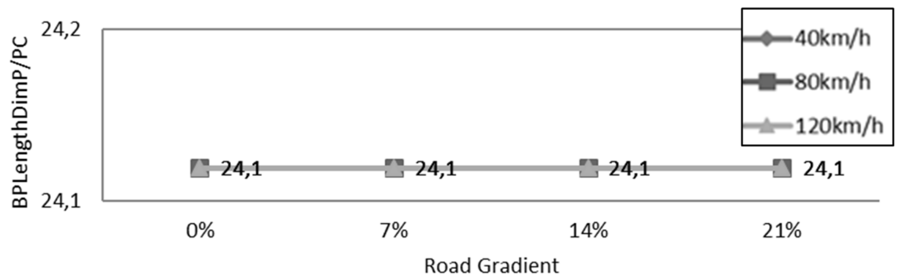

Figure D.2 Number of Battery cells along the length of battery pack to satisfy power requirement per battery pack – BPLengthDimP/PC against road gradient.

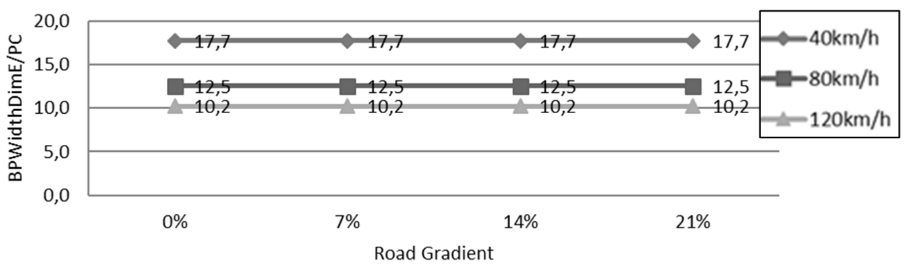

Figure D.3 Number of battery cells along the width of battery pack to satisfy energy requirement per battery pack – BPWidthDimE/PC against road gradient.

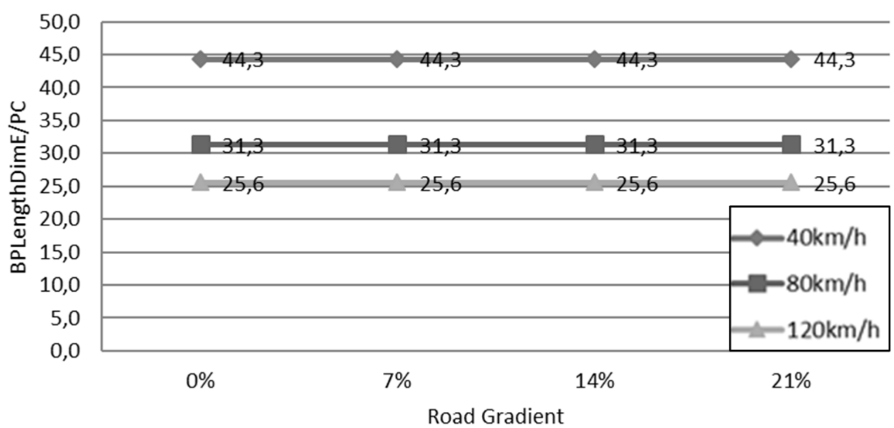

Figure D.4 Number of battery cells along the length of battery pack to satisfy energy requirement per battery pack – BPLengthDimE/PC against road gradient.

Appendix E

Potential Revenue for Home Charging

Table E.1 Potential Revenue for night charging.

Stats Data		Home Charging Night Energy (GWh)/annum			Home Charging Night Revenue (million Rand)/annum		
Year	No. of Cars	AC Level 2A	AC Level 2B	AC Level 2C	AC Level 2A	AC Level 2B	AC Level 2C
2003	1081	5.67	10.61	17.01	8.49	15.94	25.48
2004	1193	6.26	11.71	18.77	9.37	17.59	28.13
2005	1352	7.09	13.27	21.28	10.62	19.93	31.87
2006	1667	8.74	16.37	26.23	13.09	24.57	39.30
2007	1905	9.99	18.70	29.98	14.96	28.08	44.91
2008	2432	12.76	23.88	38.27	19.10	35.85	57.33
2009	2781	14.59	27.31	43.76	21.84	41.00	65.56
2010	3392	17.79	33.30	53.38	26.64	50.00	79.97
2011	5411	28.38	53.13	85.15	42.50	79.76	127.57
2012	9588	50.29	94.14	150.88	75.31	141.34	226.04
2013	13607	71.38	133.60	214.13	106.88	200.58	320.79
2014	18626	97.70	182.88	293.11	146.30	274.57	439.11
2015	24595	129.01	241.49	387.04	193.19	362.56	579.83
2016	31514	165.31	309.42	495.92	247.54	464.55	742.95
2017	39383	206.58	386.68	619.75	309.35	580.55	928.46
2018	48202	252.84	473.27	758.53	378.62	710.56	1136.37
2019	57021	299.10	559.86	897.31	447.89	840.56	1344.28
2020	65840	345.36	646.45	1036.09	517.16	970.56	1552.19

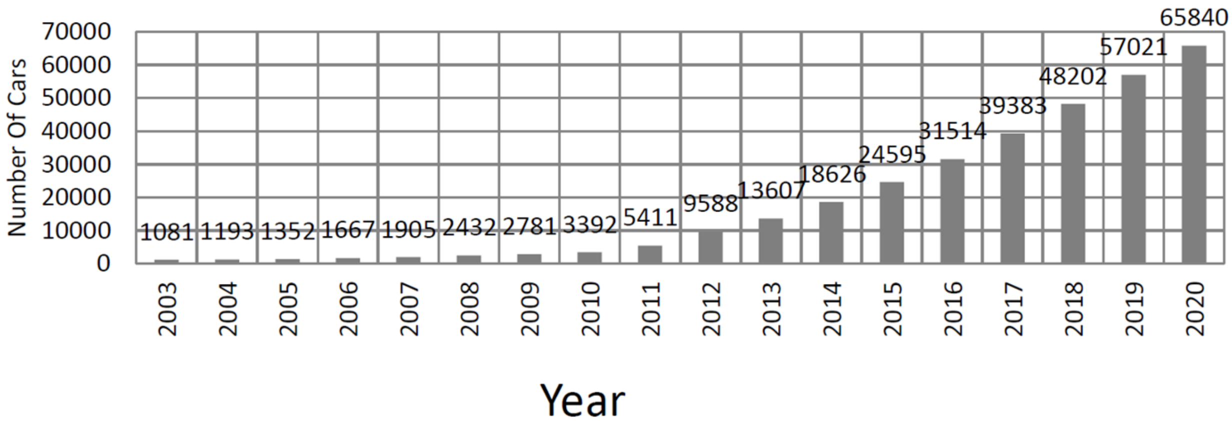

Figure E.1 Number of Cars Sold in Norway per year and Projected/Predicted Future Growth.

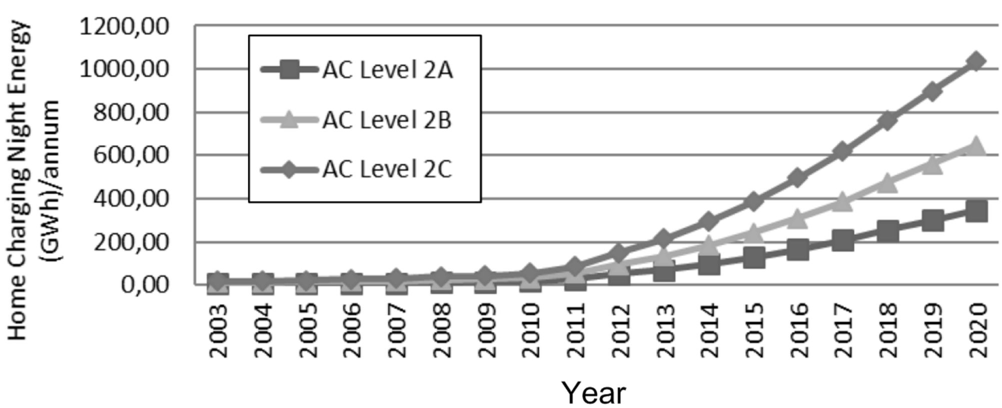

Figure E.2 Norway's Potential Energy that could be sold to EVs for Home charging AC Level 2A, 2B, and 2C.

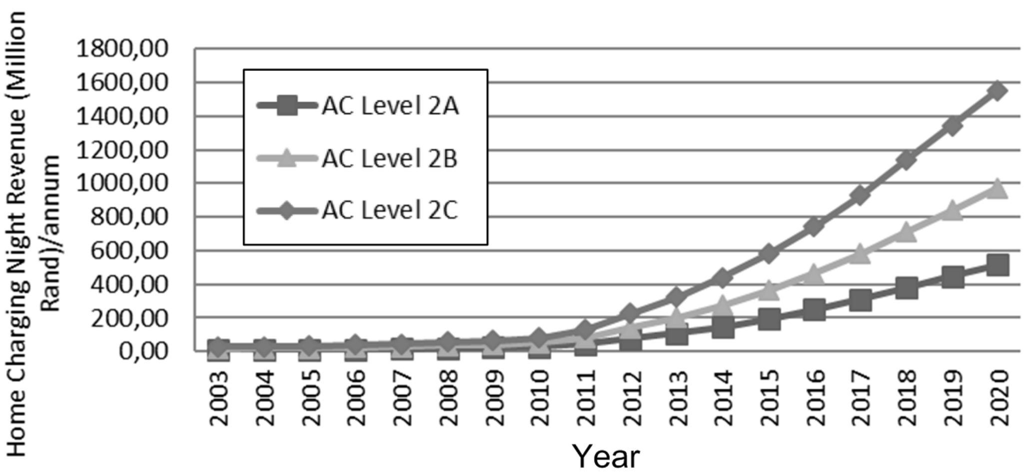

Figure E.3 Norway's Potential Revenue that could be collected from EVs for Home charging AC Level 2A, 2B, and 2C.

Appendix F

Procedures for Load/Network Studies

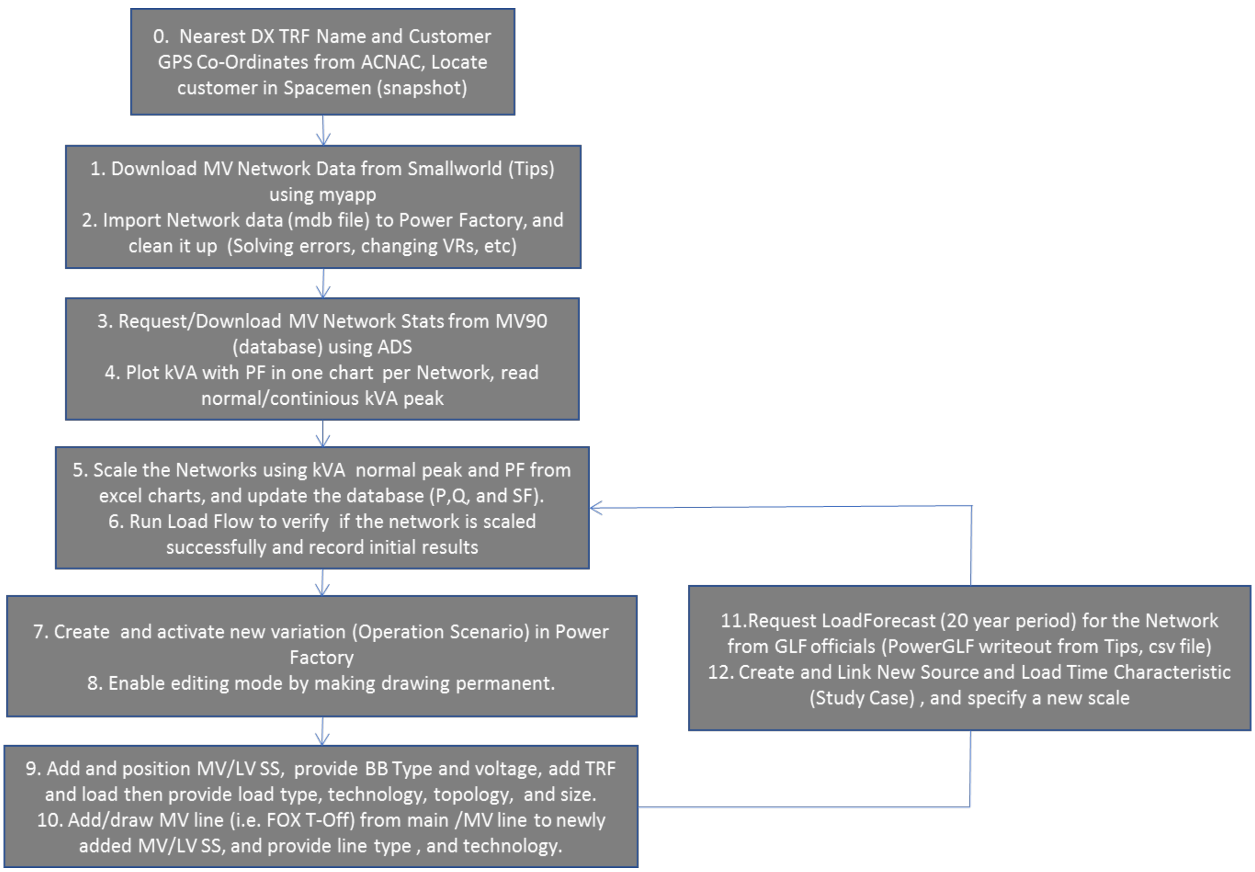

Figure F.1 Procedure for customer application study.

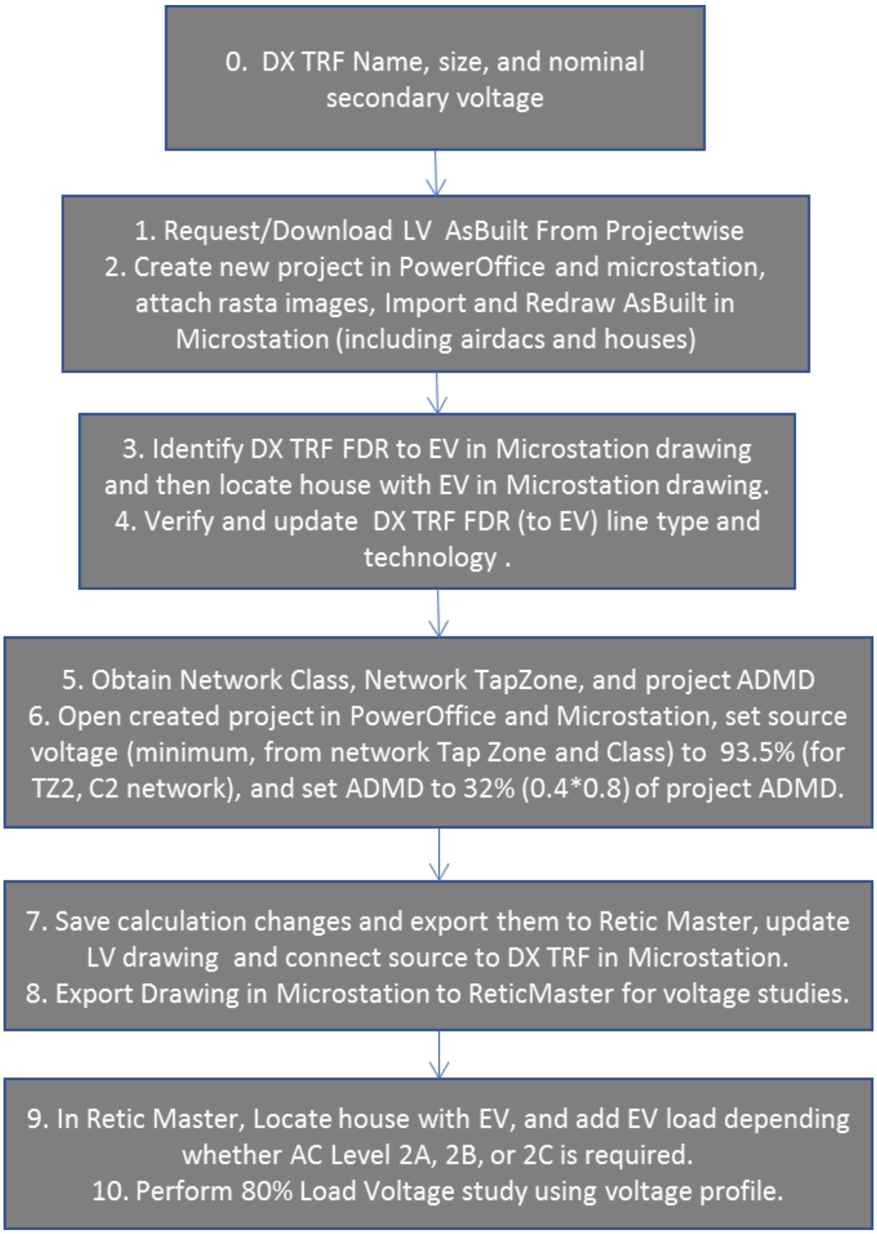

Figure F.2 Procedure for solving under voltage for EVs.

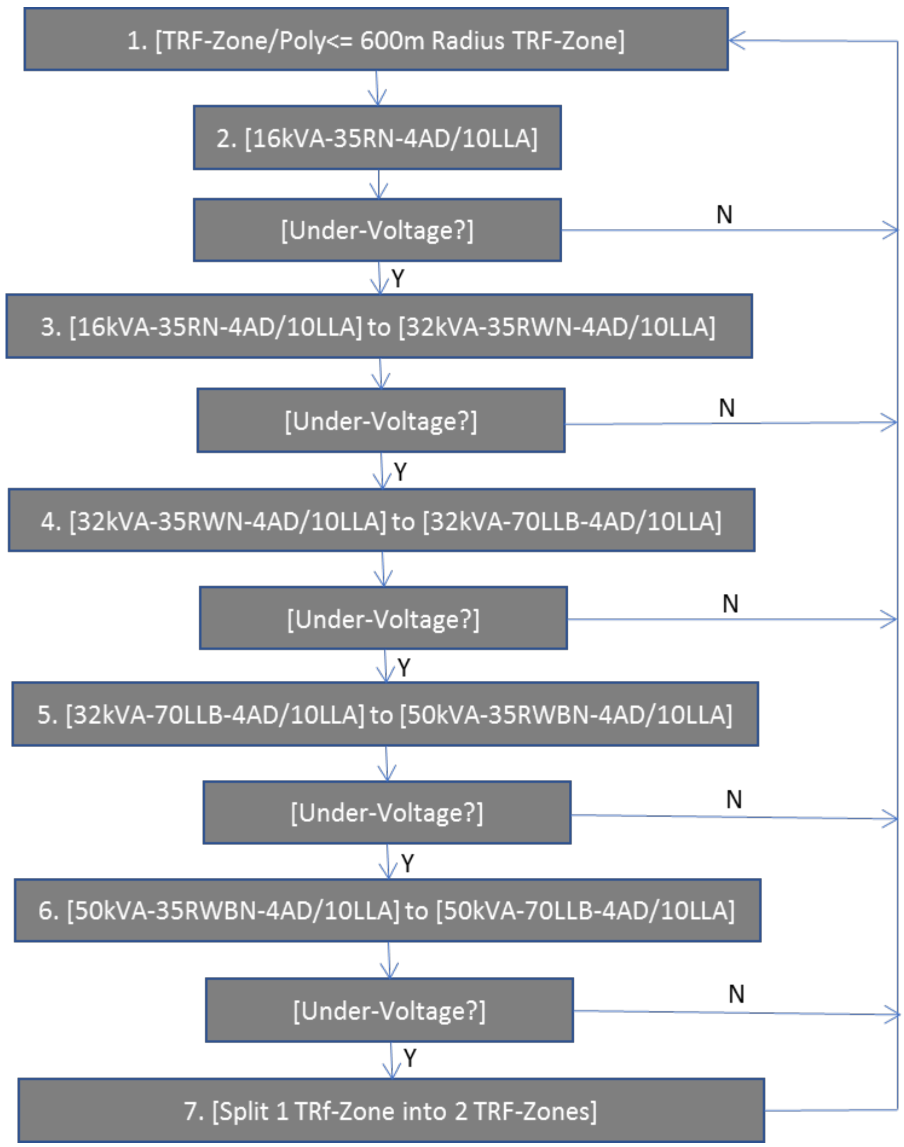

Figure F.3 Typical Algorithm for solving under voltage (for ABC OH LV).

Appendix G

MATLAB Script for MATLAB Model

```
%——Clearing Command window screen and all workspace variables———
clc
clear all
%————————————————————————————————-

% —————————————Excel File——————————————-
Workbook='EV Analysis.xlsx';
Worksheet='EVSimResults';
Range=strcat(xlRange(14,1),':',xlRange(15,2)); % returns 'N1:O2'
%Column=number2letter(1); % returns 'A'
%————————————————————————————————-

%————————————Simulink Model—————————————
Model='EV-COMPLETEMODEL-v2017b';
%————————————————————————————————-

%————–Creating Row time values for input data———————
tin=0:2:1*5*60;
tin=transpose(tin);
%————————————————————————————————-

try
```

```
for i=0:1:2

icMergedCells=4;
istartCol=2;
iCol=istartCol+i*icMergedCells;

istartRow=5;
iRow=istartRow;

iCell=xlRange(iCol,iRow);

%-Reading 2-D Array data from Excel,and converting it into 2-D timeseries-
EMSpeedIn=xlsread(Workbook,Worksheet,iCell);
EMSpeedIn=repmat(EMSpeedIn,length(tin));
EMSpeedIn=[tin EMSpeedIn(:,1)];

for j=0:1:3

jcMergedCells=1;
jCol=iCol+j*jcMergedCells;

jstartRow=3;
jRow=jstartRow;

jCell=xlRange(jCol,jRow);

RoadGradIn=xlsread(Workbook,Worksheet,jCell);
RoadGradIn=repmat(RoadGradIn,length(tin));
RoadGradIn=[tin RoadGradIn(:,1)];

[num,txt]=xlsread(Workbook,Worksheet,'B1');
[D,S]=regexp(txt,'\d+','match','split');
EVMassIn=repmat(str2double(D12),length(tin));
EVMassIn=[tin EVMassIn(:,1)];
%——————————————————————-

% ———-Runing Simulink with input data from Excel——————
```

```
opt=simset('solver','ode4','SrcWorkspace','Current');
[tout,xout,yout]=sim(Model,[0 10],opt);
% ------------------------------------------------------------


%———Writing 2-D Array Simulation Results to Excel Spreadsheet———
EVSpeedOut=EVOut(:,1);
EVSpeedOut=cellstr(sprintf('%.0f%s',EVSpeedOut(1:1),'km/h'));
xlswrite(Workbook,EVSpeedOut, Worksheet,xlRange(iCol,2));


EMTorqueOut=EMOut(:,1);
EMPowerOut=EMOut(:,2);
xlswrite(Workbook,EMTorqueOut(2:2);EMPowerOut(2:2), Worksheet,xlRange(jCol,6));


BUnitEnergyOut=EnergyOut(:,1);
TUnitCostOut=EnergyOut(:,2);
xlswrite(Workbook,BUnitEnergyOut(3:3);TUnitCostOut(3:3), Worksheet,xlRange(jCol,8));


RT20ABrkOut=HomeOut(:,1);
RT60ABrkOut=HomeOut(:,2);
v xlswrite(Workbook,RT20ABrkOut(3:3);RT60ABrkOut(3:3), Worksheet,xlRange(jCol,11));


RT50KvaTrfOut=PublicOut(:,1);
RT100KvaTrfOut=PublicOut(:,2);
xlswrite(Workbook,RT50KvaTrfOut(3:3);RT100KvaTrfOut(3:3), Worksheet,xlRange(jCol,13));


BCSeriesVOut=BCSeriesParallelOut(:,1);
BCParallelPOut=BCSeriesParallelOut(:,2);
BCParallelEOut=BCSeriesParallelOut(:,3);
xlswrite(Workbook,BCParallelPOut(3:3);BCParallelEOut(3:3);BCSeriesVOut(3:3), Worksheet,xlRange(jCol,16));


PCPOut=PCPEOut(:,1);
PCEOut=PCPEOut(:,2);
xlswrite(Workbook,PCPOut(3:3);PCEOut(3:3), Worksheet,xlRange(jCol,19));


BPWidthDimPOut=BCDimOut(:,1);
BPLengthDimPOut=BCDimOut(:,2);
BPWidthDimEOut=BCDimOut(:,3);
BPLengthDimEOut=BCDimOut(:,4);
xlswrite(Workbook,BPWidthDimPOut(3:3);BPLengthDimPOut(3:3);BPWidthDimEOut(3:3);BPLengthDimEOut(3:3),
Worksheet,xlRange(jCol,22));
```

```
end
end


catch


        myTextMessage='Please close EV Analysis Workbook and try again!';
        fig = figure;
        tx = uicontrol('style','text','position',[ 3 40 540 320 ]);
        set(tx,'string',myTextMessage);


end
%-----------------------------------------------------------------
```