



MODELLING THE IMPACT OF UNCOORDINATED PLUG-IN ELECTRIC VEHICLES' CHARGING PATTERNS ON THE LOW VOLTAGE DISTRIBUTION NETWORK

by

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DECLARATION

I, Tebogo Mongale, hereby declare that this research project, which has been submitted to the Central University of Technology Free State, for the degree of Master of Engineering in Electrical Engineering, is my own independent work and complies with the Code of Academic Integrity, as well as other relevant policies, procedures, rules and regulations of the Central University of Technology, Free State.

This project has not been submitted before by any person in fulfilment (or partial fulfilment) of the requirements for the attainment of any qualification.

.....

T. Mongale

Date: March 2024

DEDICATION

To my beloved parents, Ogopoleng Cornelious Mongale and Dinah Mmantshaupe Mongale, who have nurtured and encouraged my passion for learning since my earliest days and continue to do so to this day, I express my heartfelt gratitude. Your unwavering support and guidance have been my constant companions throughout my academic and personal journey. I am immensely proud of you both and will forever cherish the love and sacrifices you have made for me.

ACKNOWLEDGMENTS

I thank Almighty God for being with me throughout this project and affording me the courage and wisdom to complete this research.

To my supervisors, Professor Kanzumba Kusakana and Professor Patric Manditereza, thank you for the support and guidance you afforded me throughout the research process. Your continuous support, encouragement and motivation have been invaluable to me. You have made CUT the greatest institution of learning, thank you! “If I have seen further, it is by standing upon the shoulders of giants.”

A key outcome of my study was to contribute to ongoing PEV integration discussions in South Africa. I am grateful to the South African Bureau of Standards (SABS) for the opportunity to engage in this area through my essay, **"Standardization and Certification: Accelerating Electromobility Adoption in South Africa,"** which won first prize in their competition. This allowed me to represent South Africa at the IEC Young Professionals Program workshop in Edinburgh, where I gained valuable insights into the future development of EV charging infrastructure and emerging standards.

To DigSilent PowerFactory, for providing me with a Thesis License Software to simulate my studies.

To the City of Cape Town, for providing me technical support of the LVDN.

Finally, To the Central University of Technology (CUT), my heartfelt gratitude for its financial assistance, the skills and academic support.

ABSTRACT

South Africa's existing infrastructure predates the widespread adoption of Plug-in Electric Vehicles (PEVs). Given the current energy crisis, the introduction of PEVs' charging activities into residential Low Voltage Distribution Networks (LVDNs) is anticipated to have an adverse impact on various LVDN system parameters, such as the potential for overloading transformers and lines, as well as the possibility of exceeding the voltage's safe operational limits. This study models the impact of PEV charging activities on South Africa's LVDNs. Key factors to the study are the Voltage Unbalance Factor (VUF) and the Voltage Profile. Three scenarios are presented as case studies and simulated on DigSilent Power Factory, the simulations are conducted through a Quasi Dynamic Simulation(QDS) Load Flow Calculation. Case Study 1 and Case Study 2 assess PEV charging activities on the most and least loaded phases of the provided unbalanced network, including upstream and downstream charging at 50% and 100% charging rates, respectively. Results show that integration on heavily loaded phases could potentially destabilise the network, while charging on a least loaded phase reduces the unbalance factor. Case Study 3 adopts a stochastic approach to integrating PEVs into the network, providing a more realistic and dynamic overview of its potential impact. The LVDN and load profiles utilised in this study are derived from real-life data obtained from the City of Cape Town (CoCT).

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ACRONYMS AND ABBREVIATIONS

AC	Alternating Current
API	Application Programming Interface
BEMS	Battery Energy Management System
BESS	Battery Electric Storage Systems
BEV	Battery Energy Vehicle
CH ₄	Methane
CoCT	City of Cape Town
CO ₂	Carbon Dioxide
CUT	Central University of Technology
DC	Direct Current
DFFT	Department of Fishing, Forestry and Trade
DSM	Demand Side Management
DTIC	Department of Trade and Competition
DNO	Distribution Network Operator
EAF	Energy Available Factor
EV	Electric Vehicle
G2V	Grid to Vehicle
GHG	Green House Gases
GIS	Global Information Sterlite
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
IDM	Integrated Demand Management
IEC	International Electrotechnical Commission
IEEE	International Electrical and Electronic Engineering

LC	Low Carbon
LEV	Light Electric Vehicle
LVD	Low Voltage Distribution
LVDN	Low Voltage Distribution Network
MV	Medium Voltage
NO	Nitrogen Oxide
NR	Newton Raphson
NRS	National Regulation Standards
OEM	Original Equipment Manufacture
PDF	Probability Distribution Function
PEV	Plug-in Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
PQ	Power Quality
PV	Photovoltaic
QDS	Quasi Dynamic Simulation
SA	South Africa
SABS	South African Bureau of Standards
SANS	South African National Standards
SOC	State Of Charge
VBA	Visual Basic Applications
VRE	Variable Renewable Energy
VUF	Voltage Unbalance Factor
V2G	Vehicle to Grid
ZEV	Zero Electric Vehicle

Chapter 1 : INTRODUCTION

1.1. BACKGROUND

The transition from Internal Combustion Engine (ICE) to PEV plays a significant role in addressing the global challenges posed by greenhouse gas emissions and climate change. For instance, in South Africa road transport alone accounts for 91.2% of transport emissions from the combustion of ICE vehicles [1]. ICE vehicles depend on fossil fuels, such as petroleum, to convert chemical energy into mechanical energy, resulting in the emission of Carbon Dioxide (CO₂) alongside other emissions [2]. CO₂, a significant greenhouse gas, plays a crucial role in trapping heat within Earth's atmosphere, consequently intensifying global warming [3], thus posing a substantial environmental concern. Traditionally, ICE vehicles in South Africa have been the main vehicle used by residential citizens as their primary mode of transport. However, the transition towards PEVs as a viable multifaceted solution has emerged as a consequence of increased environmental awareness, technological advancements, the pressing need to mitigate air pollution and greenhouse gas emissions, and the ratification of the Kyoto Protocol and the Paris Agreement by the Department of Forestry, Fisheries, and Environment (DFFE), South Africa's primary custodian for overseeing Environmental Affairs. This prompted the Department of Trade, Industry, and Competition (DTIC) to lay the groundwork by publishing the Green Paper, which sets the stage for South Africa's journey toward a greener automotive future, focusing on transitioning from the ICE era to electro-mobility solutions and technologies. Subsequently, in December 2023 the publication of the White Paper followed, serving as a comprehensive policy document outlining the government's detailed strategy and specific proposals regarding the shift towards Electric Vehicles (EVs) in South Africa.

While policies strive to facilitate a smooth transition, a significant challenge arises from the country's capacity to deliver sustainable, high-quality energy, resulting in frequent occurrences of loadshedding to prevent a collapse of the entire power system [4]. Power grids are typically

designed to achieve a high load factor, indicating efficient utilisation of electrical resources. However, Eskom, South Africa's primary power producer, has faced challenges in maintaining a high load factor due to various factors, including the ageing electrical infrastructure and declining average capacity factor, known as the Energy Availability Factor (EAF), of thermal plants. In response, Eskom has implemented the Integrated Demand Management (IDM) programme, which aims to optimise the load profile to increase high load factor (24/7) sales[5].

Despite these efforts, the persistence of the power crisis highlights a closer examination of factors influencing grid stability. Maintaining a constant voltage is crucial for grid stability. When the force on electrons is steady, managing electron flow becomes easier, reducing losses and improving efficiency. This is especially important in areas with fluctuating electricity demands, such as residential loads. Understanding voltage stability is key, especially with the integration of new technologies like PEVs. This highlights the significance for Distribution Network Operators (DNOs) to comprehend the impact of voltage when integrating PEVs into the network. Therefore, proactive planning and coordination are critical to ensure the seamless integration of PEVs into the network while upholding voltage stability. This study aims to evaluate the extent to which PEV integration may disrupt voltage values and subsequently affect the Voltage Unbalance Factor (VUF).

1.2. PROBLEM STATEMENT

The South African electrical grid was not originally designed to accommodate the charging demands of PEVs, prioritising a high load factor to reduce costs. However, with the increasing adoption of EVs, the stochastic integration of a large number of EVs charging simultaneously poses significant challenges. This uncontrolled or unlimited charging behaviour can lead to undesirable peaks in the utility grid, resulting in various issues such as increased power consumption, overloading of distribution transformers and lines, and high current in neutral due to phase unbalance and voltage fluctuations.

Current studies relating to the impact of electric vehicles in South Africa predominantly focus on the feasibility and the environmental and economic aspects of EV integration. Consequently, knowledge and experience regarding the interaction and compatibility between charging patterns and the grid are limited, specifically within South Africa's low-voltage distribution network. The growing number of electric vehicles may exacerbate issues on the low-voltage grid, including transformer and feeder overloads, heightened peaks in electricity consumption, and stability concerns within the network.

Two primary concerns arise from the integration of electric vehicles:

I. System Voltage Stability:

Given ongoing load shedding and demand reduction efforts, South Africa's power grid operates with limited flexibility. In this context, the uncoordinated charging or discharging of PEVs introduces abrupt load fluctuations that can destabilize system voltage and frequency. This is particularly critical in residential low-voltage networks, where phase loading is often uneven. Concentrated charging on a single phase can worsen phase imbalances, elevate neutral currents, and degrade power quality ultimately placing added stress on already vulnerable infrastructure.

II. Power System Stability:

The integration of large-scale EV charging activities with stochastic charging patterns may significantly reduce the transient stability limit and compromise overall system power stability.

1.3. AIMS AND OBJECTIVES OF THE STUDY

The AIM of this study is to investigate the impacts of stochastic single-phase PEV charging, based on time, rating and location of charging at residential households on the Voltage profile and VUF.

- To identify and select a proper low-voltage distribution network with PEV charging stations, and to assess related parameters such as Voltage.
- To develop a model of the selected low-voltage network with the main components, such as transforms, feeders and loads, using DigSilent.
- To simulate different scenarios of uncoordinated PEV charging based on time, rating and location, and assess the impact on parameters, such as grid Frequency and Voltage Unbalance.
- To recommend a suitable charging pattern that may minimise the issues based on the simulation results. These recommendations are based on energy efficiency and demand response methods.

1.4. RESEARCH METHODOLOGY

The following methods were applied for this research:

Literature Review: An extensive global literature review was conducted to explore the impact of stochastic PEV charging on distribution networks. The review focused on key technical aspects, particularly the effects on voltage levels across the network. Critical elements such as the rate of PEV charging, and the location and tapping level within the distribution network, were examined to assess their influence on network performance. The review included an analysis of South Africa's electrical infrastructure to evaluate its readiness for the integration of electric vehicles.

Data collection: To support the analysis, data such as load and voltage profiles were requested from the City of Cape Town's municipality. This data was crucial for customising and formulating a mathematical model to simulate stochastic PEV charging patterns.

The following parameters were considered from the literature to establish a charging load profile:

- PEV charging power
- Energy required

- Charging duration
- Start charging time

The following factors were considered for the LVDN:

- Transformer ratings
- Charging location within the distribution grid
- Voltage profile
- Load profile

The primary aim of collecting this data was to assess the extent of voltage drops at distribution transformers, ensuring that these remain within tolerable limits.

Simulation Model using DigSilent PowerFactory: A simulation model was developed using DigSilent PowerFactory, focusing on a four-wire three-phase distribution network. The model aimed to evaluate voltage deviations and the VUF. A modified local utility network, specifically an 11kV network, was used as the base case study. The data collected was used to initialise the system parameters, with particular reference to the selected Low Voltage Distribution Network.

The simulation included load and power flow analyses to assess the impact on individual residential customers, voltage profiles at residential transformers (for both 380V three-phase and 230V single-phase systems), and overall system operations of the existing network. The scenarios included both pre-integration conditions and varying levels of PEV charging, from half to full loading on random phases, until voltage levels fell below the required limits. The same approach was applied to evaluate the network's power system stability.

The simulation model was applied based on a four-wire three-phase distribution network for Voltage deviations and Unbalance Factors. This network will be a modified local utility

network (11kV network), which will be used as a base-case study network. The collected data will be used to initialise the parameters of the system, with reference to the selected Low Voltage Distribution Network. The simulation studies include a load/power flow analysis to assess the corresponding impacts from individual residential customers, voltage profiles at residential transformers (for the 380V three-phase and 230 single-phase system) and the system operations of the existing network (Base Network) before the integration of PEVs, and for half- to full-load charging of PEVs at random phases of the network, until the Voltage drops below the required limit. The same process will be followed for the network's power system stability.

Recommendations: Information obtained from the simulation results will be used to advise both users and utility companies on the potential impacts of uncoordinated PEV charging.

1.5. CONTRIBUTION TO KNOWLEDGE

Scientific outcomes:

- A power system model that can replicate the behaviour of an actual South African Low Voltage distribution grid, which may be used to study the impact of PEVs charging activities.
- Baseline for South Africa to measure PEV impact.
- Identified modelling gaps and proposing directions for future studies.

Social impact:

- The research will bring the recommendations to utilities and independent Electric Vehicle users faced with Impact of Stochastic integration of PEV's charging activities to the LV Distribution grid of South Africa.

1.6. HYPOTHESIS

Uncoordinated PEVs charging patterns have a significant impact on the Low Voltage Distribution Network, resulting in increased voltage fluctuations beyond tolerable limits.

1.7. DELIMITATION OF THE STUDY

As a result of the magnitude of this project, a prototype will not be built. Simulation results may be presented, analysed, and discussed, using actual data from the selected existing case study.

1.8. PUBLICATIONS DURING THE STUDY

Conference paper:

- Mongale, Tebogo, Kanzumba Kusakana, and Patric Manditereza. "Modelling the Impact of Uncoordinated Plug-In Electric Vehicles' Charging Patterns on the Low Voltage Distribution Network." In 2024 7th International Conference on Electronics and Electrical Engineering Technology (EET), pp. 21-28. IEEE, 2024.[92]

1.9. THESIS LAYOUT

This thesis is divided into five chapters, with the main research results presented in Chapters 4.

Chapter 1 introduces the study by outlining the research context, objectives, methodology, and scope.

Chapter 2 reviews the integration of PEVs into South Africa's LVDN. It focuses on the impact of PEVs on network parameters like voltage profiles and VUFs. The chapter distinguishes between Zero Emission Vehicles (ZEVs) and Plug-in Hybrid Electric Vehicles (PHEVs), highlighting PEVs' role in reducing greenhouse gas emissions. Economic implications, power quality concerns, and coordinated charging strategies are also discussed. Finally, it explores managing PEV charging uncertainties using stochastic methods and summarising relevant studies on VUF, voltage stability, and smart charging strategies.

Chapter 3 presents the modelling of the proposed Low Voltage Distribution Network and its system components, comprising an external source, step-down transformer, Bus Bars, Circuit Breakers, distribution cables, residential loads, and Plug-in Electric Vehicles. The mathematical model and the system components are then implemented in DigSilent PowerFactory for simulation.

Chapter 4 presents the simulation results, based on the integration of Plug-in Electric Vehicles with a modelled Low Voltage Distribution Network using DigSilent PowerFactory. The simulations are carried out to study the behaviour of the proposed Low Voltage Distribution Network's Voltage characteristics with various integration scenarios of integrating PEVs, focusing on the rate, location and time of charge.

Chapter 5 presents the conclusions of the findings and provides recommendations for future research in the field of Low Voltage Distribution Network integration with Plug-in Electric Vehicles.

Chapter 2 : LITERATURE REVIEW

2.1. INTRODUCTION

To understand the impact of PEVs on LVDNs, it is essential to examine the evolution of the transportation industry and how the shift from ICE vehicles to PEVs intersects with LVDN infrastructure. This chapter begins by exploring the progression from ICE vehicles to PEVs, the adoption strategies for PEV integration, and the resulting effects on LVDNs. It concludes with recommended integration methods specific to South Africa, and suggests areas for future research to support sustainable PEV adoption within the country's LVDN.

2.2. Evolution of Internal Combustion Engine to Plug-in Electric Vehicles

2.2.1. Internal Combustion Engine (ICE)

ICE vehicles are the conventional mode of transport globally. As suggested by the name 'ICE', these vehicles rely primarily on the burning of fossil fuels for propulsion. This process combines air and fuel, then compresses them using a piston, and ignites the mixture to cause an explosion, as shown in Figure 2.1. The explosion forces the piston down, thereby creating a power stroke that rotates the crankshaft, which initiates the cycle for the other pistons,

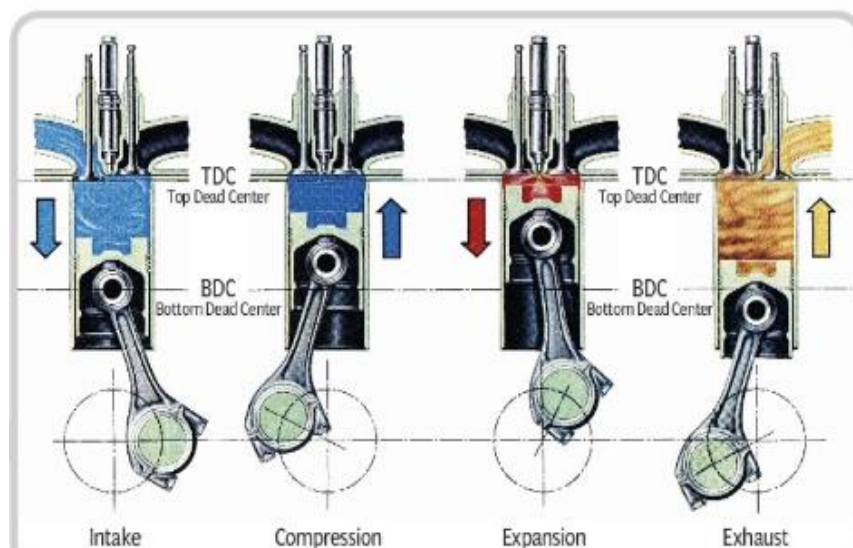


Figure 2.1: Combustion Engine Process [6]

resulting in a continuous rotation of the crankshaft that is eventually linked to the vehicle's wheels.

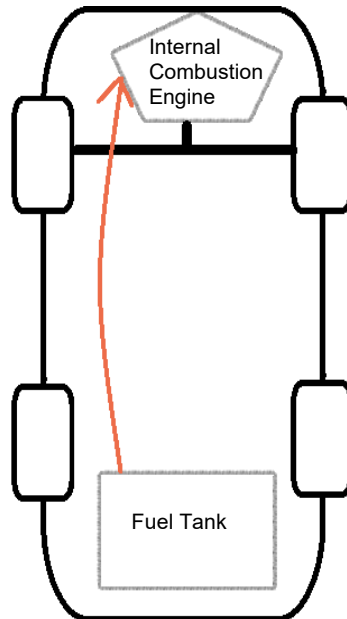


Figure 2.2: Internal Combustion Engine Vehicle

Figure 2.2 shows an image of a typical ICE vehicle, which consists of a Combustion Engine. When an ICE vehicle is ignited, the fuel system injects gasoline or diesel into the engine and the air intake system pulls in air from outside. In a gasoline engine, a spark plug ignites the fuel-air mixture, causing a controlled explosion, while in a diesel engine, the mixture ignites from the high pressure and heat created by the piston [6]. This explosion pushes the pistons down, turning the crankshaft and converting the fuel's energy into mechanical power that moves the car. This process produces several byproducts, including CO₂, carbon monoxide (CO), nitrogen oxides (NO_x), and unburned hydrocarbons. The exhaust valve then opens, allowing the piston to push these byproducts out of the combustion chamber. These exhaust gases travel through the engine's exhaust system and are eventually released into the atmosphere through the vehicle's tailpipe.

2.2.2. Types of Electric Vehicles

An EV is a type of vehicle designed to use electrical power for propulsion. Unlike traditional vehicles powered by ICEs that burn fossil fuels to generate motion, EVs operate using electricity stored in batteries. This electrical energy is then used to supply an electric motor to convert electrical energy to mechanical energy. When applying the brakes the opposite occurs. The motor now works as a generator to convert the vehicle's kinetic energy into electrical energy to be stored in batteries[7].

Authors [8-10], collectively emphasise that PEVs rely on external electrical sockets for recharging, thus supporting the core concept of PEV functionality.

Lombardi et al. discuss the integration of PEVs into modern power systems, highlighting their battery storage systems, which allow them to both consume from and supply energy to the grid via vehicle-to-grid (V2G) technology[8].

Similarly, Martínez addresses the challenges and infrastructure demands of widespread EV adoption. It introduces a dynamic framework for understanding evolving EV charging profiles, focusing on the growing need for accessible charging infrastructure to meet future charging demands [9].

Savari et al. expand on the technological aspects of EV charging, including infrastructure and customer experience. It emphasises the increasing attention EVs have received due to their ability to reduce fossil fuel consumption and emissions, driven by the advancement of charging technology and infrastructure. The discussion of charging station selection and power transfer technologies highlights the practical side of recharging PEVs via external sockets [10].

An illustration of the fundamental operational principle of a general electric vehicle is seen in Figure 2.3. When the ignition is turned on, the operation of an electric vehicle begins with the activation of the battery pack, initiated by the vehicle's control system during the power-up sequence. Once the battery pack is active, the direct current (DC) stored in the battery is

converted to alternating current (AC) by the inverter. This AC is then supplied to the electric motor, which converts the electrical energy into mechanical energy. This mechanical energy is transmitted through the reduction drive to the wheels, propelling the vehicle forward. During braking, the electric motor operates in reverse, capturing and reusing energy that would otherwise be lost. As the wheels turn the motor in this regenerative braking process, electricity is generated, slowing down the vehicle and recharging the batteries.

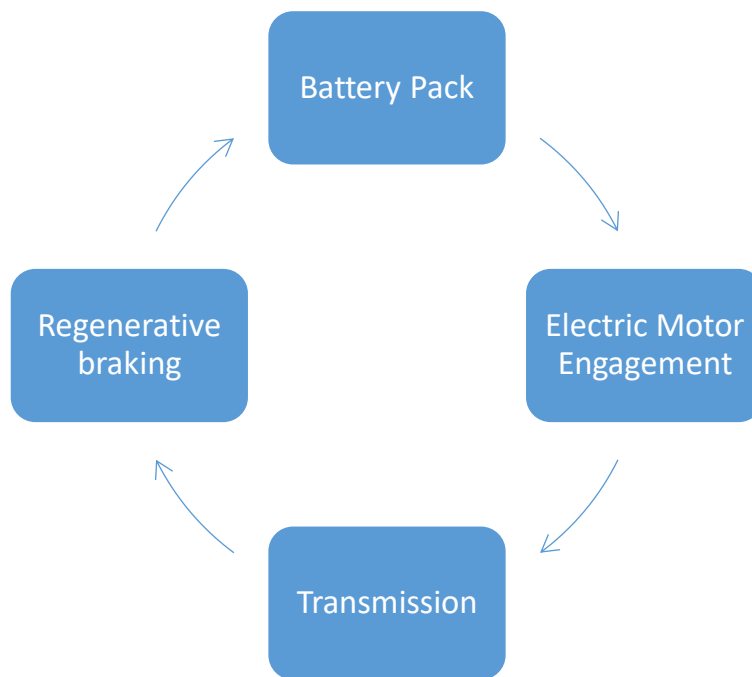


Figure 2.3: Electric Vehicle Powertrain

2.2.3. Hybrid Electric Vehicles (HEVs):

HEVs use a combination of an ICE and an electric motor to power the vehicle, depending on various propelling configurations (Series or Parallel). HEVs rely on the mechanical energy from the engine during propulsion and the vehicle's wheels during braking to charge its onboard batteries. The stored energy can later power the electric motor, helping to propel the vehicle and improve efficiency, reducing emissions from ICE vehicles. Holmén and

Sentoff illustrate how the stored energy in HEVs used to power the electric motor, contributes to improved efficiency and reduced emissions [11].

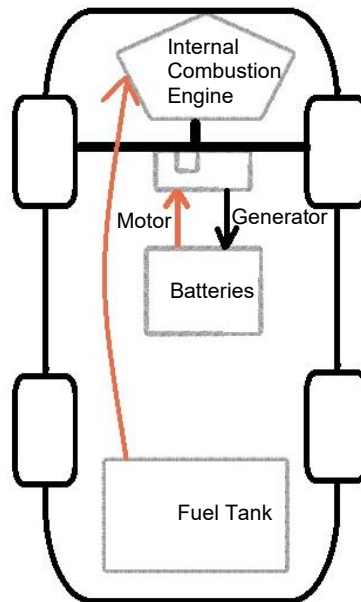


Figure 2.4: Hybrid Electric Vehicle

2.2.4. Plug-in Electric Vehicles (PEVs):

A PEV is a type of electric vehicle that can be recharged by plugging it into an external source of electricity. It includes both Battery Electric Vehicles (BEVs) that run solely on electric power, and PHEVs that combine electric and ICE power. Despite variation in the charging rate, which is subject to the manufacturer's specifications, a 3.3kW charging rate has been mostly used as a baseline[12].

Binetti et al. conducted a study on large-scale penetration of EVs charging at 3.3kW in residential areas. The results showed signs of grid instability through increased peak loads, voltage drops, and system losses. Coordinated charging strategies, such as the S-RTG algorithm, were proposed to mitigate these effects by optimising charging times based on EV owner preferences, reducing voltage unbalance and improving overall grid performance[13]

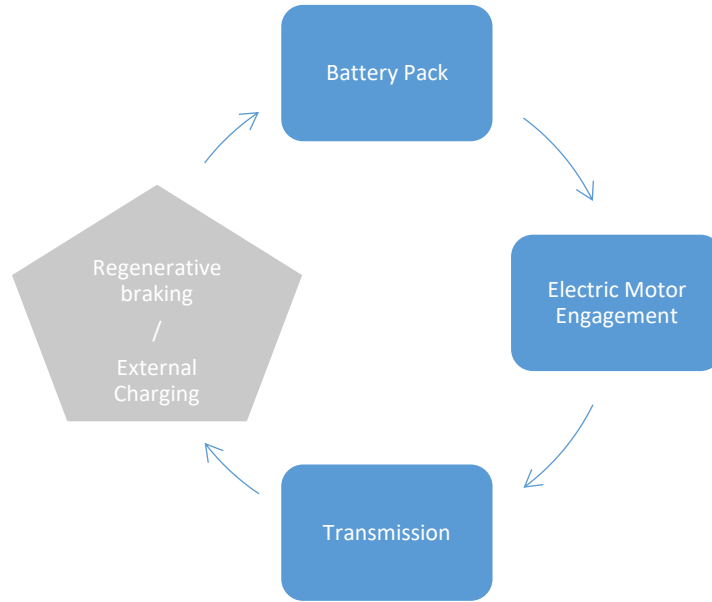


Figure 2.5: Plug-in Electric Vehicle Powertrain

Table 2.1 below showcases the vehicle sales of Hybrid Electric Vehicles in South Africa. It highlights the widespread adoption of HEVs across various brands and models, with a total of 4 924 units sold:

Table 2.1: Hybrid Electric Vehicles Sales [85]

HYBRID ELECTRIC VEHICLES	Vehicle Sales
TOYOTA Prius	1 166
LEXUS RX	602
TOYOTA Auris	448
HONDA JAZZ	393
TOYOTA Yaris	390
HONDA CR-Z	333
LEXUS CT	321
MERCEDES S-Class	225
LEXUS GS	177

HONDA Insight	165
LEXUS ES	118
MERCEDES E-Class	104
LEXUS UX	82
PORSCHE Cayenne	79
BMW 3 Series	76
INFINITI 050	68
BMW 5-Series	57
LEXUS NX	54
PORSCHE	25
LEXUS LS	17
LEXUS 15	10
BMW 7-Series	8
CITROEN DSS	6
Grand Total	4 924

2.2.5. Plug-in Hybrid Electric Vehicles (PHEVs):

Similar to an HEV, a PHEV is technically a type of HEV. It also combines an ICE with an electric motor to enhance efficiency and performance. The key difference between a PHEV and a traditional HEV is that a PHEV's batteries can be charged from an external electrical source, such as a wall socket or charging station. This allows PHEVs to operate solely on electric power for a certain range, reducing fuel consumption and emissions compared to conventional HEVs, which rely primarily on regenerative braking and the ICE to charge their batteries.

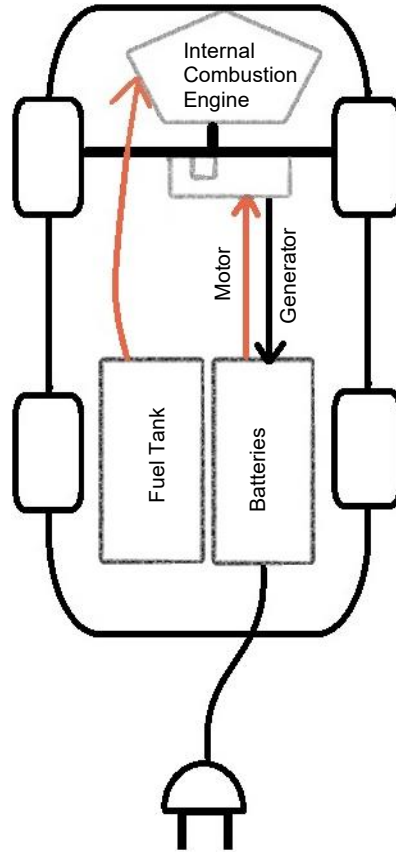


Figure 2.6: Plug-in Hybrid Electric Vehicles

Figure 2.6 shows a typical PHEV. It can be charged using a Type 2 connector and supports a maximum AC charging rate of 3.7 kW, allowing it to be conveniently charged at home or at public charging stations. However, it does not support DC fast charging. With a 3.7 kW charger, the battery takes approximately five hours to fully charge from empty. Once fully charged, the XC90 Recharge can travel up to ± 80 km on electric power alone, making it an ideal choice for daily commutes and short trips. For longer journeys, it offers the flexibility to switch to petrol.

Table 2.2 below highlights the sales of Plug-in Hybrid Electric Vehicles (PHEVs) in South Africa, showing a total of 574 units sold across various models:

Table 2.2: Plug-In Hybrid Electric Vehicles Sales [85]

PLUG-IN HYBRID ELECTRIC VEHICLES (PHEV)	Sum of Vehicle Sales
BMW i3	295
VOLVO XC90	175
BMW X5	31
MERCEDES C-Class	29
LR Range Rover Sport	16
MERCEDES GLE	12
BMW 7-Series	5
LA Range Rover	5
MERCEDES S-Class	4
BMW 3 Series	2
Grand Total	574

2.2.6. Battery Electric Vehicles (BEVs):

BEVs are fully electric vehicles that rely exclusively on electricity stored in high-capacity batteries to power an electric motor for propulsion. BEVs produce zero emissions during operation, as they do not have an internal combustion engine and thus do not burn fossil fuels. The environmental impact of BEVs depends on the source of the electricity used for charging; ideally, using renewable energy sources minimises their carbon footprint. BEVs must be charged using external power sources, including Level 1 (standard household outlets), Level 2 (240V outlets typically found in homes and public charging stations), or DC fast charging (high-speed charging at dedicated stations). Charging times and ranges vary, with ranges typically spanning from ± 160 to more than 640 km per charge, depending on the model and battery capacity. The advantages of BEVs include zero tailpipe emissions, lower operating and maintenance costs, and various government incentives.

However, they face challenges such as limited range compared to gasoline vehicles, longer refuelling times, and reliance on an expanding charging infrastructure.

Table 2.1 below presents an overview of BEV sales in South Africa as of December 2019. It highlights the sum of vehicle sales for three key models: BMW i3, Nissan Leaf, and Jaguar I-PACE, indicating the growing but still limited adoption of BEVs in the country.



Figure 2.8: Tesla Model X

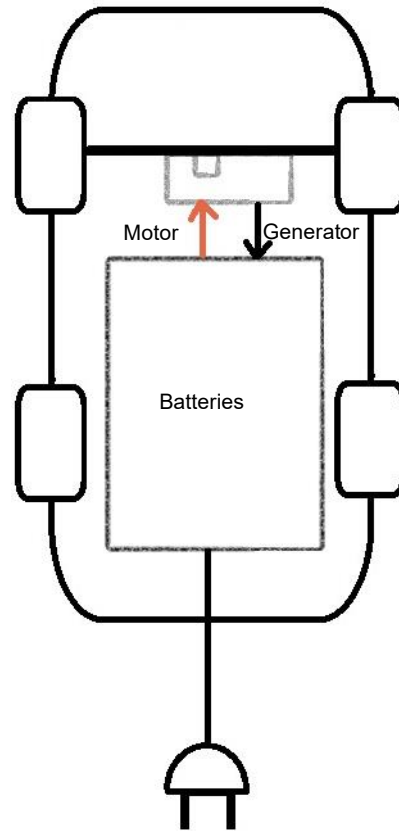


Figure 2.9: Battery Electric Vehicles

Table 2.3: Battery Electric Vehicles Sales [85]

BATTERY ELECTRIC VEHICLES (BEV) (Dec 2019)	Sum of Vehicle Sales
BMW 13	405
NISSAN LEAF	94
JAGUAR I-PACE	46

2.3. SOUTH AFRICA'S ELECTRICAL INFRASTRUCTURE

South Africa's current electrical infrastructure is facing severe pressure from the load side, causing Eskom, South Africa's main power producer, to resort to loadshedding. Various studies have been conducted to evaluate mitigative actions.

Nowakowska and Tubis explored the energy system in South Africa, focusing on the issue of loadshedding and its implications for necessary changes to existing solutions. Eskom supplies over 95% of the country's energy and has instituted a programme of loadshedding, defined as intentional power shutdowns that affect the entire nation [14].

Ayamolowo et al. conducted a study that examined the evolution of South Africa's power system from the pre-apartheid to the post-apartheid era, addressing reforms aimed at meeting a rising energy demand. It highlighted the potential of the country's renewable energy resources and reviewed government initiatives to create a renewable energy dominated grid. Key performance metrics were evaluated, and challenges in the energy system were identified, alongside a proposed model for achieving a predominantly renewable energy grid [15].

2.4. ENVIRONMENTAL BENEFITS OF PLUG-IN ELECTRIC VEHICLES

PEVs offer significant environmental benefits compared to ICE vehicles. The primary advantage is the reduction in greenhouse gas emissions, as PEVs produce zero tailpipe emissions when operating in electric mode. This contributes to improved air quality and helps mitigate climate change by reducing the overall carbon footprint of the transportation sector.

Human activities, such as burning fossil fuels for energy, transportation, and industrial processes, release greenhouse gases (GHGs) into the atmosphere. These gases, including CO₂, methane (CH₄), and nitrous oxide (N₂O), trap heat and contribute to the warming of Earth's

surface. The accumulation of GHGs leads to significant environmental impacts, such as more frequent heatwaves, altered rainfall patterns, and disruptions to agriculture and water resources. This environmental phenomenon, driven by human activities and energy consumption, is referred to as greenhouse gas emissions. In South Africa [16] and other parts of the world [17] where the electricity grid is predominantly coal-reliant, studies indicate that while PEVs have the potential to reduce CO₂ emissions compared to petrol vehicles, the benefits may be offset by higher emissions of other pollutants like NO_x and SO_x.

The link between PEV and carbon emission is a concept known as carbon intensity. Carbon intensity refers to the amount of CO₂ emissions produced per unit of energy or electricity generated, typically measured in grams of CO₂ emitted per kilowatt-hour (g CO₂/kWh) of electricity. This metric is used to assess the environmental impact of energy production. A related concept is the carbon intensity of Gross Domestic Product (GDP) [18], which measures CO₂ emissions per unit of economic output, typically expressed as kilograms of CO₂ per dollar/rand of GDP (kgCO₂/\$GDP). It aims to evaluate how efficiently an economy uses energy and produces goods and services relative to its carbon emissions.

While Plug-in Electric Vehicles (PEVs) are often lauded for their potential to reduce greenhouse gas (GHG) emissions during operation, a more comprehensive evaluation requires a life cycle approach. This includes emissions and environmental impacts from:

- Raw material extraction (especially lithium, cobalt, and nickel for batteries),
- Battery manufacturing and vehicle assembly,
- Electricity generation mix used during charging,
- End-of-life disposal and recycling processes.

Recent life cycle studies suggest that PEVs typically surpass internal combustion engine vehicles (ICEVs) in environmental performance within 2 to 5 years of use, depending on factors like vehicle size, battery capacity, and the carbon intensity of the local grid. In regions

transitioning to low-carbon electricity—such as through increased reliance on renewables—this payback period tends to be shorter.

To enhance the environmental benefit of PEVs, strategies such as battery recycling, ethical sourcing of raw materials, and grid decarbonization are critical. Therefore, while PEVs present a viable pathway for decarbonizing the transport sector, their full sustainability potential is best realized in conjunction with systemic changes in energy and material flows.

Table 2.4 aims to summarise various studies that examine the challenges and opportunities related to PEV adoption in South Africa. It highlights key findings regarding environmental impacts, economic barriers, infrastructure needs, and the importance of integrating renewable energy sources. The table provides insights into how these factors influence the sustainability and feasibility of transitioning to electric mobility in the region.

Table 2.4: Additional Literature on the Environmental Impact of PEVS

S/N	Author	Study	Key Take Away
	a	b	c
[19]	Mokhele	The study discusses concerns about the environmental impact of traditional gas-powered vehicles. It highlights the need for alternative propulsion systems like electric motors. The study found that high costs are the main barrier to PEV adoption in Gauteng province, with respondents supporting government subsidies and improved charging infrastructure.	<ol style="list-style-type: none"> 1. PEVs are expensive to purchase. 2. Government financial incentives are favoured. 3. Need for charging infrastructure. 4. Collaborative effort needed: A supportive environment from all stakeholders is crucial for PEV adoption.

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- [20] Singh et al. Public transport impacts society and the environment. EVs are seen to cut greenhouse gas emissions, but this depends on the source of electricity. In South Africa, with its current reliance on fossil fuels, EVs might not be more eco-friendly than gas-powered cars. This study found that using 100 electric taxis in Johannesburg will only reduce emissions significantly if renewable energy is used at charging stations.
1. Electric Vehicles & Emissions: PEVs may not reduce emissions much with the current power mix.
 2. Increased renewable energy for charging could make EVs more sustainable.
 4. Policy Suggestion: Future planning should include EVs in energy forecasts for better sustainability.
-
- [21] Pillay et al. This study developed the E-StratBEV model to estimate the impact of replacing ICEVs with BEVs. It finds that with the current coal-heavy electricity generation, BEVs offer minimal environmental benefits, though incorporating renewable energy at charging stations could improve their sustainability. Economic factors, such as high vehicle purchases relative to income, also affect BEV adoption and affordability in provinces like Gauteng, Western Cape, and KwaZulu-Natal.
1. BEVs may not reduce emissions significantly in the short term due to reliance on coal-powered electricity.
 2. Using renewable energy at charging stations could improve BEVs' environmental benefits.
 3. Economic factors and credit availability impact BEV adoption and should be considered in energy planning.
-
- [22] Buresh The study investigated the potential impact of PEVs on South Africa's power grid and environmental goals. It finds that while EVs could offer significant benefits, their effectiveness is limited by the reliance on coal-powered electricity. The study reveals that
1. Grid Capacity: The current grid needs upgrades to support PEVs integration.
 2. RES should be considered for grid capacity enhancement.
-

without intervention, the grid cannot support large-scale EV charging. However, incorporating solar-powered charging stations and implementing smart charging strategies can enhance grid capacity, reduce costs, and boost revenue for employers, emphasising the importance of integrating renewable energy and advanced charging solutions for sustainable EV adoption.

3. Smart charging strategies can manage demand and increase revenue.

[23] Buresh et al. This study evaluates how electrifying vehicles in South Africa could strain the coal-reliant power grid and worsen emissions. It suggests that installing solar panels at workplaces for EV charging could reduce the grid burden, make EVs more eco-friendly than petrol cars, and provide financial benefits for both car owners and service providers.

1. Charging EVs from South Africa's grid could overload it and worsen emissions.
2. Solar charging at work makes EVs cleaner than petrol cars.
3. Solar charging is financially beneficial for both vehicle owners and service providers.

[24] Mokhele and Mphethe The study assessed the impact of EVs on carbon emissions in Gauteng, South Africa. It found that with 20% EV adoption, emissions could be reduced by 30% to 35% in a mitigation scenario, but might increase by 1% to 41% under other scenarios. The study emphasises the need for faster EV adoption to effectively cut emissions.

1. Emissions may rise by 1 to 5% without changes.
2. EVs could reduce CO₂ emissions.
3. The need for accelerated EV adoption to meaningfully reduce emissions.

[25] Ateba	<p>The study highlights the global shift towards EVs to reduce greenhouse gas emissions, noting that China's rapid adoption has strained its grid and increased carbon emissions due to coal-based electricity. It advises South Africa, which plans for 50% EVs by 2050, to adopt a more gradual approach. Key recommendations include reevaluating deployment models, ensuring grid stability, and considering market and technology trends. The study stresses learning from China's experience to inform South Africa's EV policies.</p>	<ol style="list-style-type: none"> 1. China's Strain: Rapid EV adoption has strained China's grid and increased emissions. 2. A slower PEV adoption approach is recommended for SA. 3. High EV adoption could cause low-voltage and grid issues.
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The literature review reveals that while PEVs are widely regarded as a solution to reduce greenhouse gas emissions from conventional vehicles, their effectiveness in South Africa is contingent upon several critical factors. High purchase costs, inadequate charging infrastructure, and heavy reliance on coal-based electricity pose significant challenges to widespread PEV adoption.

2.5. ECONOMIC IMPLICATIONS OF PEV INTEGRATION

The aggregated challenges of PEV integration include overloading, which could lead to significant economic losses, especially in developing and underdeveloped countries. Deb et al. indicate that improper placement of EV charging stations, particularly fast-charging stations, leads to overloading, causing voltage instability, reduced reserve margins, and power losses, which negatively affect the reliability and efficiency of the power system. These technical issues translate into significant economic losses, particularly for utilities that face penalties for system performance degradation. In developing and underdeveloped countries, where power

infrastructure is often less resilient, the economic strain of addressing these challenges is more pronounced, reinforcing the need for careful planning to prevent overloading and mitigate financial losses [26].

Overloading increases power demand and causes voltage fluctuations due to increased current flow in the neutral line. South Africa (SA) is currently witnessing a gradual but steady integration of PEVs into its transportation system. However, SA's electrical infrastructure has not been designed to cater for the charging of PEVs. Bokopane et al. support the statement by highlighting the challenges South Africa faces in its electrical infrastructure concerning the integration of EVs. They contend that while factors such as energy security, accessible charging options, and policies influence EV adoption, South Africa's current electrical grid is not fully prepared for the high demand caused by widespread EV penetration. This inadequacy of the infrastructure, especially in terms of handling increased power demand, leads to overloading and voltage fluctuations, particularly as the system has not been originally designed to support the charging needs of PEVs. The study's assessment of the country's readiness aligns with the concerns that overloading will exacerbate existing issues, such as voltage instability, due to the increasing load on an already strained electricity network [27].

However, for residential networks, the current load modelling techniques applied in the South African National Standards (SANS), a reference document governing design standards, do not consider PEVs as a general household load [28], as existing design models predate the adoption of PEVs. Furthermore, SA is currently battling power challenges and often manages various loadshedding stages to avoid a total collapse of the country's power supply [29].

2.6. POWER QUALITY AND NETWORK STABILITY

The parallel developments of increasing PEV integration and SA's continued power quality challenges necessitate studying the impact of PEVs on the LVDN. Studies have been conducted in this area. Anti' et al. [30] examined the impact of integrating low carbon (LC) technologies, including PEVs, on the VUF in a low-voltage LVDN. They showed that

penetration of single-phase loads and distributed generators, like PVs and EVs, can increase voltage unbalance, potentially harming power quality (PQ). The results indicate that while these technologies can elevate VUF, proper management allows PQ values to remain within the standards set by EN 50160 and IEC 61000-3-13. These are similar to the South African version SANS 61000-3-2, which outlines the voltage characteristics and acceptable limits for power quality parameters in public distribution networks.

2.6.1. Voltage Profile Characteristics

As part of the voltage profile characteristics, Niels et al. [31] documented a non-compliant VUF in relation to the EN50160 standards. The author quantified the impact of single-phase on-board charging strategies for PEVs within a heavily loaded, unbalanced Flemish three-phase low-voltage residential grid. It modelled two strategies – voltage droop charging and PEV-based peak shaving – without requiring communication with the distribution grid. It analysed grid voltages against the probabilistic and deterministic limits of the EN 50160 standard at a 100% PEV penetration rate. The findings indicated that voltage droop charging effectively eliminated critical voltages below 0.85 pu and reduced voltage unbalance, with minimal effect on overall charging time. In contrast, EV-based peak shaving ensured full compliance with EN 50160, thereby avoiding the need for infrastructure upgrades, while electrically driven distances remained unaffected by the charging strategies.

From a hosting capacity perspective, Leemput et al. conducted a subsequent study that observed an inversely proportional relationship between the charging rate and hosting capacity. They found that, while fast charging had a minimal impact on the grid, the slow charging strategies, particularly residential off-peak charging, resulted in the lowest hosting capacity due to load synchronisation effects. This highlights the importance of incentivising grid-friendly charging practices, as adopting these strategies significantly enhances the EV hosting capacity compared to the effects of fast charging [32].

While Deb et al. show that placing fast-charging stations at stronger bus bars can be managed effectively, while placement at weaker bus bars can lead to voltage instability [26]. Koundinya et al. establish a load profile for EV Charging Stations and examine their impact on the static voltage profile of the distribution system. By calculating the Voltage Stability Index (VSI) and Voltage Stability Factor (VSF), they provide a detailed analysis of how EV loads can alter the voltage profile and stability of both upstream and downstream bus bars. The results emphasise the need to assess the strength of these bus bars to ensure stable operations when integrating EV charging loads. Both studies indicate that understanding the strength of bus bars is crucial for maintaining system stability [33].

2.6.2. Coordinated Charging Strategies

Coordinated charging strategies refer to systematic approaches designed to optimise the charging processes of PEVs within electrical distribution networks. These strategies aim to mitigate the negative impacts of uncoordinated charging, such as voltage fluctuations and increased grid stress, by aligning charging schedules and rates with grid conditions and demand patterns. Although this study did not focus on coordinating charging per se, it discussed the characteristics of coordinated charging within the context of uncoordinated charging activities. By modelling the impact of stochastic PEV charging behaviours, the study highlighted how these characteristics influenced the overall performance of the low-voltage distribution network. Understanding these dynamics was important for analysing how varying user behaviours, charging times, and power demands affected power quality and system reliability, ultimately supporting the integration of renewable energy sources.

A key takeaway from Kikhavaniet al. is that an algorithm effectively coordinated the PEV charging and discharging processes of Grid to Vehicle (G2V) and V2G, leading to significant improvements in power quality, voltage profiles, and current balance within unbalanced low-voltage distribution systems. By optimising phase assignments and managing the integration of PEVs, the algorithm reduced grid stress and enhanced overall system stability [34].

In a probabilistic analysis study utilising the Monte Carlo approach, Angelim examined the impact of PEVs on voltage quality within distribution systems. The research employed real statistical data to model user behaviour, revealing a tendency for voltage degradation as the penetration level of electric vehicles increased. This approach emphasised the importance of understanding variability in load behaviours, and provided insights into the system's performance that would not have been captured through deterministic methods. The findings highlighted significant issues such as voltage unbalance (VU) and undervoltage (UV) occurrences, thereby enhancing the overall understanding of network reliability under varying conditions [35].

2.6.3. Electric Vehicle-to-Grid- and Grid-to-Electric Vehicle Technology

When considering loadshedding, multiple studies view PEVs as part of a solution rather than a contributing factor [36]. The study suggested that, despite the significant and somewhat unpredictable load that PEVs represent during battery charging, they can also function as a critical renewable source for the grid that acts as a substantial reserve. This capability allows PEVs to supply auxiliary services to the grid, which can help manage fluctuations in energy supply and demand. Thus, when considering loadshedding, the study aligns with others that view PEVs not merely as additional loads that could strain the grid, but as integral components of a solution that enhances overall grid stability and efficiency.

Liu et al. authored subsequent studies. The former illustrated the potential of PEVs as integral components in addressing under-frequency loadshedding challenges. By proposing adaptive strategies that enabled EVs to participate in under-frequency loadshedding, the research underscored how EVs could act as distributed energy storage resources to enhance frequency stability and reduce power outages. The hierarchical framework developed for coordinating communication between the control centre, PEV charging stations, and PEV terminals ensured that PEVs could effectively respond to loadshedding events. The study emphasised coordinated strategies that leveraged EVs' capabilities to mitigate the adverse

effects of load shedding, thereby filling a critical gap in understanding how network parameters were affected when PEVs were integrated into systems facing loadshedding scenarios [37].

The latter marked a significant advancement by being the first to propose adaptive under-frequency loadshedding electric vehicle strategies, enabling the active participation of PEVs in under-frequency loadshedding. It developed a hierarchical framework that facilitated the dispatch of instructions from the control centre to EVs, based on real-time information exchange among the control centre, EV Charging Stations, and EV terminals. This framework ensured system frequency stability while significantly reducing the need for load removal during under-frequency loadshedding events [38].

2.7. ADDRESSING UNCERTAINTIES IN PEV CHARGING

The biggest challenge with uncertainties is to model their impact accurately and effectively. This often involves complex statistical methods and assumptions, which can be difficult to validate and may not always capture the true nature of the uncertainties involved. Uncertainties associated with PEV charging, such as when to charge, for how long, who is charging, and where on the network charging occurs, have led authors to explore the inter-operability of multiple software applications to address these uncertainties.

In [39], a stochastic modelling and simulation technique is proposed to analyse the impact of PEV charging demands on distribution networks. It distinguishes itself from previous deterministic approaches by utilising actual measurements and survey data to derive feeder daily load models, EV charging start times, and battery state of charge. By incorporating stochastic parameters through methods like roulette wheel selection, the research has generated distribution operation security risk information, including potential over-current and under-voltage scenarios, derived from three-phase distribution load flow studies. The study defines voltage and congestion impact indicators and compares deterministic and stochastic analytical approaches to demonstrate the essential information needed for distribution network reinforcement planning. Numerical results illustrated the effectiveness of

the proposed stochastic models in reflecting system losses and security impacts of EV integration. These findings underscore the uncertainties associated with PEV charging, including the timing, duration, participant, and location of charging events. Consequently, the study indicates that authors have increasingly explored the inter-operability of multiple software applications to address these uncertainties effectively, marking a shift toward more dynamic and adaptable solutions in managing EV integration within distribution systems. Furthermore, uncertainties associated with PEV charging, such as when to charge, for how long, who is charging, and where on the network charging occurs, have led authors to explore the inter-operability of multiple software applications to address these uncertainties.

Ghadimi has leveraged DigSilent PowerFactory in conjunction with a Python script for stochastic analysis to address uncertainties related to PEV charging, such as when and where charging occurs. PHEVs are designed for home or corporate charging, and PowerFactory's Application Programming Interface (API) was used to call an external Python file, automating various tasks and processes [40].

One widely adopted approach for stochastic integration in DigSilent PowerFactory (a widely used power system software) involves using a Probabilistic Analysis method [41-44]. This method facilitates energy analysis by representing uncertainties as distribution functions and utilises the Monte Carlo method to generate a load-flow report.

2.8. ADDITIONAL LITERATURE REVIEW

A further general literature review conducted is reflected below in Table 2.5, which discusses studies that integrate PEVs into the distribution systems.

Table 2.5: Additional Literature Review

Author	PEV Charging Impact on the Grid			
	Title	Methods used	Results	Recommendation
	a	b	c	d
[45] Tomislav et al. (2021)	A Comprehensive Analysis of the Voltage Unbalance Factor in PV and EV Rich Non-Synthetic Low Voltage Distribution Networks	Conducted a quantitative descriptive study using a web-based survey in Gauteng Province. Sampling Likert-scale questions on EV technology. Data analysed using percentages and chi-square tests for demographic differences.	High EV prices are the main barrier to adoption in Gauteng. Strong support exists for government incentives like subsidies, tax rebates, and improved charging infrastructure. Majority prefers EVs with increased driving range. Charging stations at fuel stations and workplaces are crucial for adoption. Responses vary significantly by gender, education, region, and car type.	Introduce EV purchase incentives, expand charging infrastructure, increase EV model variety, raise awareness, and implement dedicated lanes and toll exemptions for EVs.
[46] Jabalameli et al. (2019)	Stochastic Assessment of Plug-in Electric Vehicles Charging in LV Distribution Network on Voltage Unbalance	Developed a model examining PEV penetration, charging rate, and location using a Monte Carlo simulation over a 24-hour period for Australia.	Uncoordinated PEV charging leads to substantial voltage unbalance and transformer overloading. Coordinated charging reduces these issues by shifting charging to off-peak hours. Voltage unbalance is more significant at the feeder's end than at the beginning. The phase	Continue implementing smart charging strategies to manage PEV charging activities. Place PEVs on lower load phases to reduce voltage imbalance. Consider the location and rate of PEV charging in planning and managing LV distribution networks.

			connection of PEVs (high load phase vs. low load phase) greatly influences voltage unbalance.	
[47] Razmara et al. (2016)	Bilevel optimization framework for smart building-to-grid systems	Developed mathematical models of commercial buildings and the distribution grid to optimize operations. Applied a bilevel solution approach for interaction between building energy management system and DSO control centres. Introduced a building to grid index to assess optimal building-grid operations while maximizing load factor and minimizing energy costs.	The framework integrates building and grid operations, balancing energy cost reduction and improving grid load factors. The building-to-grid index reduces costs and improves load factors with bilevel optimization.	Continue using bilevel optimization for coordination between building energy management and the grid, with further research on infrastructure, forecasting, scalability, and communication.
[48] He et al. (2012)	Optimal scheduling for charging and discharging of electric vehicles	Mathematically formulates Global Scheduling Optimization and Local Scheduling Optimization as convex optimization problems, and are solved using interior point methods	Global scheduling minimizes costs but is impractical, while local scheduling is nearly as effective and more practical. Both reduce costs and flatten load profiles, with battery lifetime impact considered.	Adopt the scalable locally optimal scheduling scheme for dynamic EV arrivals, enhance forecasting accuracy for improved efficiency, and integrate factors like battery degradation and user preferences in future work.

<p>[49] Shaukat et al. (2018)</p>	<p>A survey on electric vehicle transportation within smart grid system</p>	<p>Review existing research on transportation electrification technologies, focusing on Vehicle-to-Grid technology, energy storage in EVs, and charging infrastructure. It addresses the challenges and benefits of energy storage technologies in EVs, including technical performance and economic implications.</p>	<p>EVs offer significant environmental and economic benefits, including reduced emissions and lower transportation costs.</p>	<p>Develop smart charging and V2G technology for optimal EV integration. Advance energy storage research to improve performance and reduce costs. Establish regulations and standards for smooth EV integration into the SG.</p>
<p>[50] Fachrizal et al. (2021)</p>	<p>Combined PV EV hosting capacity assessment for a residential LV distribution grid with smart EV charging and PV curtailment</p>	<p>Integrated different energy management system scenarios using a Stochastic time series for the energy profiles used.</p>	<p>Combining smart EV charging and PV curtailment+ offers the best overall performance.</p>	<p>Explore integrating battery energy storage systems and other demand-side management strategies for enhanced grid stability and efficiency. Apply the proposed framework to other combined technologies, such as wind–EV or PV–heat pump systems, to assess hosting capacities.</p>
<p>[51] Hariri et al. (2021)</p>	<p>Investigation of impacts of plug-in hybrid electric vehicles' stochastic characteristics</p>	<p>Developed an analytical model for smart grids with PHEVs' stochastic behaviour. Validated using Monte Carlo simulation. Sensitivity analysis on</p>	<p>The analytical model determines the optimal number of PHEV states, balancing speed and accuracy.</p>	<p>Use Analytical models for quick reliability assessments in high PHEV scenarios. Explore its sensitivity to car owner</p>

	modelling on smart grid reliability under different charging scenarios	parameters (distance, departure, arrival times). Applied to Kashan, Iran electric network.		behaviour and stochastic factors.
[52] Nafisi (2021)	Investigation on distribution transformer loss-of-life due to plug-in hybrid electric vehicles charging	Evaluation of PHEV penetration impacts on transformer life using Monte Carlo simulation to model load and owner behaviour uncertainties. Application to a real-life residential distribution system. Analysis of charging periods and penetration levels. Transformer aging modelled with thermal models and IEEE standards for oil-immersed transformers.	Evening charging raises transformer Loss of Life rates significantly. Nighttime charging has minimal impact, while daytime charging causes moderate increases.	Implement smart charging strategies to mitigate adverse effects on distribution transformers. Prioritize nighttime charging to extend transformer life and reduce network stress.
[53] Molina et al. (2020)	Light electric vehicle (LEV) charging strategy for low impact on the grid	LEV recharging scheduled during demand valleys, avoiding peak hours. Strategies: home, public buildings, electrical stations. Applied to Spain with varying LEV penetration and fleet growth scenarios.	The methodology demonstrates potential to flatten the demand curve, LEV penetration showing reduced peak impact. Proper scheduling suggests increased demand can be managed within existing grid capabilities.	Implement policies for recharging points and off-peak incentives. Support infrastructure with tariffs and subsidies.

[54] Leemput et al. (2012)	A Case Study of Coordinated Electric Vehicle Charging for Peak Shaving on a Low Voltage Grid	Introduces an online bid coordination strategy to the conventional smart charging, to coordinate electric vehicle charging for peak shaving. Coordinated and Uncoordinated Load Flow calculations were compared to assess nodal voltage and unbalance factor deviations.	Results displayed standard Smart charging improvements, With minimal communication and predictive knowledge. Coordinated charging reduced peak power demand, managed peak shaving and voltage deviations.	The study recommends considering optimized EV charging process, due to close correlation Coordinated charging the efficient use of the distribution network.
[55] Hartvigsson et al. (2022)	A large-scale high-resolution geographic analysis of impacts of electric vehicle charging on low-voltage grids	Develops a synthetic LVDN model using high-resolution GIS data, combining household and EV charging profiles through cost-optimization charging strategies. Measures voltage levels, transformer and line loading to identify non-compliance.	EV charging risks are highest in cities, lower in urban areas, and lowest in rural areas. Direct charging causes more violations than price-optimized strategies, which are more effective in urban areas	Future studies to focus on analyse household electricity usage and driving behaviour, assess tariff systems' impact on violations, optimize simulation models, and evaluate more low-voltage grids.
[56] Schachler et al. (2021)	A large-scale high-resolution geographic analysis of impacts of electric	Simulated future scenario and analysed uncoordinated and market-oriented charging impacts on grid overloading, voltage issues, and curtailment.	Market-oriented charging reduces peak loads but increases night and noon charging peaks, causing urban grid issues. It reduces PV curtailment slightly but increases	Allow network operators to curtail EV charging demand to manage grid issues. Optimize charging by considering renewable energy sources.

	vehicle charging on low-voltage grids		load-driven problems. Uncoordinated charging causes evening grid issues, with no optimization for renewable integration.	Explore measures to reduce high charging simultaneities and assess economic trade-offs of charging strategies.
[57] Habib et al. (2014)	Impact analysis of vehicle-to-grid technology and charging strategies of electric vehicles on distribution networks: A review	The authors reviewed the benefits and challenges of V2G technology and various EV charging strategies, including coordinated, uncoordinated, delayed, off-peak charging, and intelligent scheduling.	V2G enhances grid stability and renewable integration but faces challenges like battery wear and infrastructure demands. Coordinated charging reduces strain, while uncoordinated charging increases it.	V2G implementation needs smart grid integration, coordinated charging, and supportive policies and standards for smooth integration.
[58] Akil et al. (2021)	Impact of Electric Vehicle Charging Profiles in Data-Driven Framework on Distribution Network.	Develops a SOC-based coordinated charging method for EVs, compares it with uncoordinated charging, and integrates PV and BES systems to reduce peak loads.	SOC-based coordinated charging lowers grid power consumption, line loading, transformer loading, and power losses, especially with PV and BES integration.	SOC-based coordinated charging for better energy efficiency and smoother EV integration. Future research to optimize grid infrastructure using real-time SOC data.
[59] Muratori (2018)	Impact of uncoordinated plug-in electric vehicle	Integrates residential and transportation energy needs, simulating different PEV	PEV charging has minimally impacts demand but alters patterns. Clustering increases peak	Research should focus on consumer behaviour, smart

	charging on residential power demand.	market shares and charging power levels.	demand, requiring infrastructure upgrades, and higher in-home charging worsens effects.	charging, and non-residential charging to assess grid impacts.
[60] Guerrero et al. (2022)	Power System Impacts of Electric Vehicle Charging Strategies	Uses a production cost model with multiple planning horizons to analyse the effects of EV charging on system costs, dispatch, reserves, and variable renewable energy curtailment.	Uncoordinated charging increases costs and peak loads. Coordinated charging reduces costs, curtails variable renewable energy, and improves system efficiency.	Strongly recommends on coordinated EV charging to reduce costs and improve variable renewable energy integration.
[61] Tirunagari et al. (2022)	Reaping the Benefits of Smart Electric Vehicle Charging and Vehicle-to-Grid Technologies: Regulatory, Policy and Technical Aspects.	Reviews existing research on unmanaged EV charging and smart charging/V2G benefits, using simulations to show the adverse effects of uncoordinated charging and the benefits of smart charging.	Unmanaged charging increases peak load, power losses, and voltage issues. Smart charging alleviates these, providing economic, social, and environmental benefits. V2G improves grid performance and supports renewable energy.	Developing regulations for smart charging, updating policies to support EV growth, providing financial incentives, standardizing protocols, and supporting research and development through pilot projects.
[62] Clement-Nyins et al. (2009)	The Impact of Charging Plug-In Hybrid Electric Vehicles on a Residential Distribution Grid	Uses load flow analysis with the backward-forward sweep method, optimization techniques to minimize losses and optimize charging, and analyses scenarios with uncoordinated and coordinated	Uncoordinated charging causes power losses and voltage deviations. Coordinated charging improves efficiency. Stochastic programming shows minimal efficiency loss from forecasting errors.	The study recommends smart metering for coordinated charging, grid reinforcement for unmanaged loads, and further research on voltage control and grid balancing.

		charging at different PHEV penetration levels and charging periods.		
[63] Clement-Nyns and Driesen (2011)	The impact of vehicle-to-grid on the distribution grid	Uses simulations on the IEEE 34 node test feeder to assess PHEV impacts, exploring uncoordinated and coordinated charging, PHEV penetration, and DG integration.	Uncoordinated charging causes grid issues: coordinated charging improves stability. V2G supports the grid, and PHEVs balance renewable energy, reducing reinforcement needs.	Implementation of coordinated charging, integrating V2G technology, using smart meters with real-time pricing, and further research on V2G economics and battery technology.
[64] Ahmed et al. (2021)	Impact of Electric Vehicle Charging on the Performance of Distribution Grid	Uses OPAL-RT's real-time simulator and evaluates the impact of L1, L2, and DC fast charging on voltage deviation, peak demand, and harmonic distortion in a residential grid.	A correlation between EV charging (L2 and DC fast chargers) and increased voltage deviations and harmonic distortions, worsened by higher EV penetration. DC fast chargers require voltage compensation and harmonic filters, while uncontrolled charging causes grid instability, mitigated by inductive filters.	implement harmonic filters and voltage compensation to mitigate EV charging impact. Future studies focus on optimal charging station placement and coordinate strategies.
[65] Crozier et al. (2020)	The opportunity for smart charging to mitigate the impact of electric vehicles	Models uncontrolled EV charging using a conditional probability method, incorporating convex	Uncontrolled EV charging increases peak demand and requires significant infrastructure upgrades. While the transmission	Smart charging strategies should balance transmission and distribution needs, consider spatial EV adoption,

	on transmission and distribution systems	optimization for smart charging, Monte Carlo simulations for stochastic charging patterns, and analysis of Britain power system's spatial variations in vehicle use, electricity demand, and network structure.	network can handle domestic EV charging, it fails under certain conditions. Smart charging reduces distribution network interventions but raises peak demand at the transmission level.	and use coordinated algorithms to optimize load without conflicts.
[66] Masoum et al. (2014)	Fuzzy Approach for Online Coordination of Plug-In Electric Vehicle Charging in Smart Grid	Online fuzzy coordination algorithm integrates fuzzy reasoning with maximum sensitivity selection optimization, addressing random plug-ins, energy prices, and charging preferences. Simulated with varying PEV penetration and wind generation.	The algorithm improves over uncoordinated and maximum sensitivity selection-coordinated methods, reducing energy costs and grid losses. It enhances voltage profiles, lowers peak demand, boosts system reliability at high PEV penetration, and leverages wind distributed generation output during peak periods for cost and stability benefits.	Adopt Algorithms for real-time PEV charging coordination in smart grids. Explore near-global optimization techniques, like genetic algorithms and particle swarm optimization, to enhance solution quality. Integrate renewable energy sources, such as wind and solar, to boost grid efficiency and sustainability.
[67] Chadha et al. (2022)	A review on Smart Charging impacts of Electric Vehicles on Grid	Comprehensive literature review analysing EV charging impacts on grid performance, addressing peak demand, voltage instability, and reliability. Examined charging	High charging loads, especially at fast-charging stations, increase peak demand and cause voltage instability. Demand Side Management and smart charging strategies, along with TOU	Conduct further research on the integration of distributed energy resources and advanced grid management techniques to accommodate the growing number of EVs. Enhance

		methods for BEVs, HEVs, PHEVs, and FCEVs and their grid implications.	pricing, can help smooth the load curve and reduce peak demand.	charging infrastructure and promote the adoption of renewable energy sources to support sustainable EV growth.
[68] Zhou et al. (2017)	Research on Impacts of the Electric Vehicles Charging and Discharging on Power Grid	Simulation modelling and theoretical analysis assess the impacts of EV integration on power quality, distribution planning, and economic operation. The study also explores vehicle-to-grid technology, enabling EVs to act as both consumers and suppliers of electricity.	Large-scale EV charging can cause significant issues such as harmonic pollution, voltage drops, and three-phase imbalances, which degrade power quality and affect network stability and efficiency. Economic impacts include increased net losses and reduced lifespan of distribution transformers and cables due to high load and harmonic currents.	Further development of coordinated charging control methods to manage the timing and distribution of EV charging loads, reducing peak demand and enhancing grid stability. Continued exploration of harmonic control measures and the integration of V2G technology to improve grid reliability and lower operational costs.
[69] Sohail et al. (2022)	Effects of uncoordinated electric vehicle charging on a distribution network	An IEEE 13-bus 11 kV residential distribution system was used to analyse substation and transformer performance under varying EV penetration levels. Dynamic load flow analysis was conducted with MATLAB and Open DSS, using a polynomial-based ZIP load model for EVs.	Uncoordinated EV charging significantly stresses the distribution network, causing poor power quality, low voltage levels, increased power loss, and overloading of feeders, cables, and transformers. Residential transformers and distribution lines experienced severe under-voltage and over-current issues,	Implementing coordinated EV charging strategies to mitigate adverse effects. Upgrading distribution infrastructure and adopting smart grid technologies to manage increased load effectively. Promoting off-peak charging and integrating renewable energy sources to alleviate

			especially during peak hours, leading to higher system losses and faster infrastructure aging.	stress on the distribution network.
[70] Rawat et al. (2019)	Impact assessment of electric vehicle charging/discharging strategies on the operation management of grid accessible and remote microgrids	Analysed four EV charging/discharging strategies. Used a 2m point estimate method to address uncertainties in load demand, solar/wind energy, and grid prices. Conducted sensitivity analysis on battery parameters' impact on remote microgrid economics.	Demonstrated that controlled EV charging can significantly enhance the operation of microgrids; concluded that smart management of charging/discharging can reduce operational costs.	Micro-grid operators account for uncertainties in renewable energy sources and load demands. Recommended increasing battery capacity and optimizing initial SOC to enhance microgrid performance.
[71] Ninković et al. (2020)	Coordination of electric vehicles charging in the distribution system	Used GAMS with the CONOPT solver to analyse uncoordinated, dual-tariff, and coordinated charging scenarios, chosen for its fast convergence and accuracy.	Showed that the proposed coordinated charging solution significantly improves voltage profiles and reduces grid impact compared to uncoordinated and dual tariff charging scenarios; concluded that coordinated charging minimizes voltage drops and power losses, delivering the best voltage profile throughout the day.	Emphasising the need for a Smart Grid and better communication in the distribution system; suggesting further research on V2G and renewable energy integration for optimised charging patterns.

<p>[72] Solanke et al. (2020)</p>	<p>A review of strategic charging–discharging control of grid-connected electric vehicles</p>	<p>Comprehensive literature review analysing charging–discharging strategies and their grid impacts, including uncontrolled, controlled, intelligent, bi-directional, and multistage hierarchical methods. Examined technical challenges such as overloading, power quality issues, and power loss.</p>	<p>Uncontrolled charging causes grid instability, but the multistage hierarchical approach, using genetic algorithms and AI-based controls, effectively manages load capacity, improves power quality, and reduces electricity costs, optimizing grid performance and EV integration.</p>	<p>Further research into interdisciplinary computational models for improved EV aggregator coordination; exploration of the commercial potential of aggregators and optimisation of V2G systems to address grid challenges; implementation of smart charging infrastructure and policies to support widespread EV adoption and integration into the power grid.</p>
<p>[73] Diaz-Londono et al. (2024)</p>	<p>Comparison and Analysis of Algorithms for Coordinated EV Charging to Reduce Power Grid Impact</p>	<p>Proposed two Model Predictive Control -based smart charging strategies: one minimizes costs by charging during low-price periods, and the other prevents transformer overloads by maximizing flexibility. Compared with uncoordinated and coordinated strategies using real-world datasets in three scenarios: single station, average parking lot, and worst-case occupancy.</p>	<p>The flexibility maximization strategy reduces transformer overloads. The economic Model Predictive Control strategy is cost-effective but may increase peak power if grid constraints are ignored. Grid-aware strategies prevent overloads by coordinating EV charging with grid limits.</p>	<p>Coordinated charging pools to ensure reliable EV operations; implementation of smart charging strategies considering grid constraints for seamless integration; future studies on integrating renewable energy sources with charging strategies and evaluating long-term impacts on grid stability.</p>

[74] Habib et al. (2018)	Assessment of electric vehicles concerning impacts, charging infrastructure with unidirectional and bidirectional chargers, and power flow comparisons	Reviewed existing literature and technical studies, analysing different charging power levels and topologies, including on-board and off-board systems. Compared unidirectional and bidirectional chargers in terms of hardware, cost, power flow, and grid impacts.	Unidirectional charging is simpler but limited. Bidirectional charging supports V2G, aiding grid stability, though costly. EVs can cause grid issues, but controlled charging mitigates this. Economic benefits depend on battery and infrastructure improvements.	Enhance charging infrastructure with a focus on standardisation and smart grid integration; implement policies and incentives to promote EV adoption and support V2G technology development; continue research on battery life, cost reduction, and efficient charging systems; increase public awareness of EV benefits and sustainable transportation solutions.
[75] Deilami et al. (2011)	Real-Time Coordination of Plug-In Electric Vehicle Charging in Smart Grids to Minimize Power Losses and Improve Voltage Profile	Simulated the real-time smart load management algorithm on a modified IEEE 23 kV system with PEVs, considering penetration levels and charging time zones.	Uncoordinated PEV charging increases peak demand, voltage fluctuations, and power losses. The algorithm reduces these issues, optimizing charging schedules in real-time, maintaining voltage, reducing losses, and minimising energy generation costs.	Implement real-time smart load management in smart grids for reliability and efficiency; use real-time coordination to manage PEVs and maintain grid stability; develop communication infrastructure for real-time PEV charging control.
	A critical review of the effect of light duty electric vehicle	Conducted an extensive literature review on EV charging issues and solutions,	Uncoordinated EV charging causes grid issues. Coordinated schemes reduce problems. Strong	Optimise EV station placement, integrate renewable energy, implement smart

<p>[76] Tasnim et al. (2023)</p>	<p>charging on the power grid</p>	<p>evaluating charging schemes, infrastructure configurations, smart charging, and optimal location selection. Assessed impacts on power system planning, grid economy, and the environment.</p>	<p>infrastructure and careful grid planning are needed. EVs cut emissions, but costs and electricity prices affect economic impact. Renewables and coordinated charging improve viability.</p>	<p>charging, and adopt V2G technology for grid support.</p>
<p>[77] Ibrahim and Gaber (2024)</p>	<p>Electric Vehicles: From Charging Infrastructure to Impacts on Utility Grid</p>	<p>Comprehensive review of unmanaged EV charging effects on power quality, including voltage violations, asset overloading, and harmonic distortion, along with exploration of mitigation strategies.</p>	<p>Uncoordinated charging causes grid instability, voltage fluctuations, and higher operational costs. The paper discusses the impact of various EV technologies (BEVs, HEVs, PHEVs, and FCEVs) on the grid.</p>	<p>Adopt smart charging and V2G technologies for bidirectional power transfer; establish effective infrastructure and regulatory frameworks; implement coordinated charging strategies and dynamic pricing models to mitigate grid impacts.</p>
<p>[78] Gonzalez et al. (2019)</p>	<p>Impact of non-systematic electric vehicle charging behaviour on a distribution substation</p>	<p>Used a multi-agent EV model in Python to simulate the impact of non-systematic EV charging on base load at the HV/MV substation level. Considered two case studies in France, using real travel and grid data, focusing on uncoordinated charging strategies.</p>	<p>Non-systematic plug-in behaviour reduces weekday peak load but increases weekend peaks. It limits flexibility for smart charging and V2G, requiring more energy per session. Larger battery sizes reduce weekly sessions but may need higher charging power.</p>	<p>Analyse driving and charging behaviour for EV impact assessment; consider regional characteristics and implement smart charging for load management; study the effects of EV characteristics, charging infrastructure, tariffs, and user preferences on grid integration.</p>

[79] Deilami and Muyeen (2020)	An Insight into Practical Solutions for Electric Vehicle Charging in Smart Grid	Reviewed EV battery infrastructure and charging strategies, focusing on uncontrolled charging impacts. Tested maximum sensitivity selection and genetic algorithm optimization on modified IEEE 23 kV and low voltage residential networks, with a comparative analysis to validate effectiveness.	Uncontrolled EV charging causes power quality issues, voltage instability, and increased peak demand. Controlled charging strategies, especially maximum sensitivity selection and genetic algorithm, improve grid performance, with MSS offering faster computation and better customer satisfaction. Controlled charging mitigates the impacts of high EV penetration.	Adopt controlled EV charging, implement smart charging tech and V2G systems, optimize renewable energy integration for improved grid efficiency.
[80] Nour et al. (2020)	Review of Positive and Negative Impacts of Electric Vehicles Charging on Electric Power Systems	Literature review on EV charging impacts, covering peak demand, voltage instability, unbalance, harmonics, overloading, and power losses. Explores controlled charging benefits like frequency regulation and power quality improvement.	Uncontrolled EV charging can increase peak demand, voltage deviations, phase unbalance, and power losses; controlled charging strategies mitigate these impacts and improve power quality while supporting renewable energy integration.	Study the economic feasibility of EV charging/discharging methods, coordinate between transmission and distribution operators, and plan public charging infrastructure; research EV integration with renewables and develop smart charging strategies.
[81] Wang et al. (2018)	Coordinated Electric Vehicle Charging with Reactive Power Support to Distribution Grids	Developed two frameworks for managing active and reactive power dispatch of distributed EVs: one using an optimal power flow model and the	Coordinated charging lowers costs and accommodates more EVs at non-unity power factor. Case studies show improved grid performance and cost reduction.	Include reactive power in EV charge scheduling, enable EVs to provide voltage support without impacting battery life, and prioritize advanced

		other focusing on optimal EV charging with reactive power support.		charging infrastructure for EV participation in reactive power markets.
[82] Aoun et al. (2024)	Dynamic Charging Optimization Algorithm for Electric Vehicles to Mitigate Grid Power Peaks	Development of Proof of Need charging algorithm prioritizing EVs based on SoC, vehicle count, charger capacity, and user preferences; tested to compare uncoordinated and coordinated charging demand.	The algorithm reduces peak charging demand, adjusts schedules in real-time, prevents overloads, and improves grid stability and user satisfaction.	Implement charging algorithm at local substations and for managing EV fleets, integrate with V2G and V2V strategies; policymakers to support dynamic management systems for grid reliability with rising EV adoption.
[83] Mahmud et al. (2023)	Global challenges of electric vehicle charging systems and its future prospects: A review	Reviewed literature and data on the impact of EV charging on power systems, including load distortion, voltage deviation, frequency imbalance, harmonic injection, overloading, power loss, and grid instability. Explored smart charging benefits.	Smart charging cuts peak power demand and optimizes system performance and supports future technologies.	Adopt smart charging strategies to manage growing EV demand; implement government policies and incentives for smart charging infrastructure; integrate renewable energy sources with EV charging to promote sustainability and reduce fossil fuel dependency.
[84] Li and Jenn (2024)	Impact of electric vehicle charging demand on power	Used a travel demand model, EV adoption model, and empirical EV charging data to project uncontrolled EV	Residential areas will need twice the upgrades, highlighting the potential to ease grid stress by shifting home charging.	Upgrade feeders prone to overloading; implement demand response and promote workplace/public charging to

	distribution grid congestion	charging profiles at high granularity and large scale.		reduce peak load; enact regulations to address infrastructure strain; focus future work on heavy-duty EVs and demand-side developments.
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2.8.1. Correlation Analysis on Uncoordinated Charging Impact

The correlation analysis across multiple studies highlights the common challenges posed by uncoordinated EV charging on distribution grids, particularly regarding voltage instability, peak demand, and grid congestion. The following findings are noted:

General findings from the studies:

a) Voltage issues:

- Multiple studies (Leemput et al., Hartvigsson et al., Schachler et al., Guerrero et al., Clement-Nyns et al.) consistently report that uncoordinated charging results in voltage drops, deviations, and imbalances, which compromise grid stability. Ahmed et al. (2021) and Sohail et al. (2022) further emphasise that these issues are compounded by harmonic distortions and voltage deviations, especially with high levels of EV penetration.

b) Peak demand:

- Studies such as those by Guerrero et al. (2022), Akil et al. (2021), and Leemput et al. (2012) highlight that uncoordinated charging increases peak demand, which results in overloading of grid components like transformers, feeders, and cables. Such increased peak demands intensify the need for infrastructure upgrades to prevent failures and inefficiencies.

c) Power losses and efficiency:

- Research by Clement-Nyns and Driesen (2011) and Zhou et al. (2017) indicates that uncoordinated charging leads to increased power losses, particularly during peak periods. As EVs become more prevalent, grid efficiency declines, with significant economic implications for grid operators (Crozier et al., 2020; Guerrero et al., 2022).

d) Economic and infrastructure impacts:

- The integration of uncoordinated charging strains grid infrastructure, resulting in faster ageing and increased operational costs. Sohail et al. (2022) and Rawat et al. (2019) discuss the economic inefficiency of relying on existing infrastructure without reinforcements, underlining the necessity for substantial investments in grid modernisation.

Identified gaps:

a) Limited focus on stochastic and dynamic charging:

- Most studies assume static load profiles or simplified assumptions. There is a lack of dynamic real-time simulations considering stochastic, location-specific, and time-varying charging behaviours. More detailed, real-time approaches are needed to capture the grid's dynamic response to fluctuating demand.
- However, in the case of South Africa, there is no baseline study to benchmark future PEV impact studies, which is what this study aims to achieve.

b) Underexplored regional variability:

- While urban grid impacts are widely discussed (e.g., Hartvigsson et al., 2022), there is limited exploration of regional differences, especially between urban and rural areas. Further studies are needed to investigate the impact of regional variability and EV adoption rates on uncoordinated charging.

c) Absence of policy or regulatory impact analysis:

- While smart charging (Tirunagari et al., 2022) is suggested as a solution, there is a gap in research on policy frameworks that would support the integration of EVs in an uncoordinated charging environment. Regulations on charging

tariffs, incentives, and grid investment need more attention to ensure sustainable integration.

d) V2G and renewable energy integration:

- Although some studies (Zhou et al., 2017; Ninković et al., 2020) mention Vehicle-to-Grid (V2G) and renewable energy integration, the full potential of V2G systems in mitigating uncoordinated charging impacts remains underexplored. Further research should focus on optimal charging strategies that incorporate V2G and renewable energy to ease grid stress.

e) Grid adaptation and smart grid technologies:

- There is limited research on how smart grid technologies like real-time monitoring and demand response can help alleviate uncoordinated charging problems. More studies are needed to explore how smart metering and advanced grid management systems can optimise grid operations and integrate renewable energy sources effectively.

f) Long-term infrastructure impact:

- Few studies focus on the long-term degradation of grid infrastructure due to uncoordinated charging, especially wear and tear on transformers and cables. Addressing this gap is critical for understanding the economic and resilience implications of long-term uncoordinated charging.

2.9. CONCLUSION

In summary, the integration of PEVs into the electrical grid presents both opportunities and challenges. While PEVs offer significant environmental benefits by reducing greenhouse gas emissions, their widespread adoption poses challenges to existing electrical infrastructure.

Smart charging solutions, economic implications, power quality, and network stability are critical factors that have to be addressed to ensure successful integration of PEVs. South Africa's current power challenges and gradual PEV integration highlight the need to understand and mitigate the impact of PEVs on the LVDN.

While extensive research has examined voltage instability, peak demand, and grid congestion caused by uncoordinated EV charging, focus on stochastic and dynamic charging behaviours is still limited. Most studies rely on static load profiles or simplified assumptions, neglecting the complexity of location-specific and time-varying charging patterns. Furthermore, real-time dynamic simulations that capture the grid's response to fluctuating demand are notably absent. In the South African context, there is no baseline study to benchmark the impact of Plug-in Electric Vehicles on the Low Voltage Distribution Network. This study seeks to fill that gap by providing foundational insights and methodologies for future PEV impact assessments.

Chapter 3 : MODELLING

3.1. INTRODUCTION

This chapter presents the modelling of the base low-voltage distribution network system components used in the study. The network design layout consists of an External Grid, Transformer, Bus Bar, Distribution Lines, and Residential load, as well as PEVs charging. Hence, the mathematical models for all network parameters are shown respectively. The mathematical model for the system's component may be applied in DigSilent PowerFactory.

3.2. LVND COMPONENTS

The studied LVND displayed in Figure 3.1 is a simplified portion of a real-life existing model provided by the City of Cape Town (CoCT) in the Western Cape province of South Africa. The model is used for studying the VUF and Voltage Profile and is subjected to real-time loadshedding conditions. The LVND is a four-wire, three-phase system, comprising an external source supplying 800kVA to a 11kV/0.4kV distribution transformer. This transformer further provides power to 115 households, of which 73 are represented as a single external load. Additionally, 42 households form our sample size. They are supplied by seven distribution kiosks, denoted in the software as general domestic loads and BUS BARS, respectively. The measured data presented in Figure 3.2 reveals an unbalanced power consumption in the network.

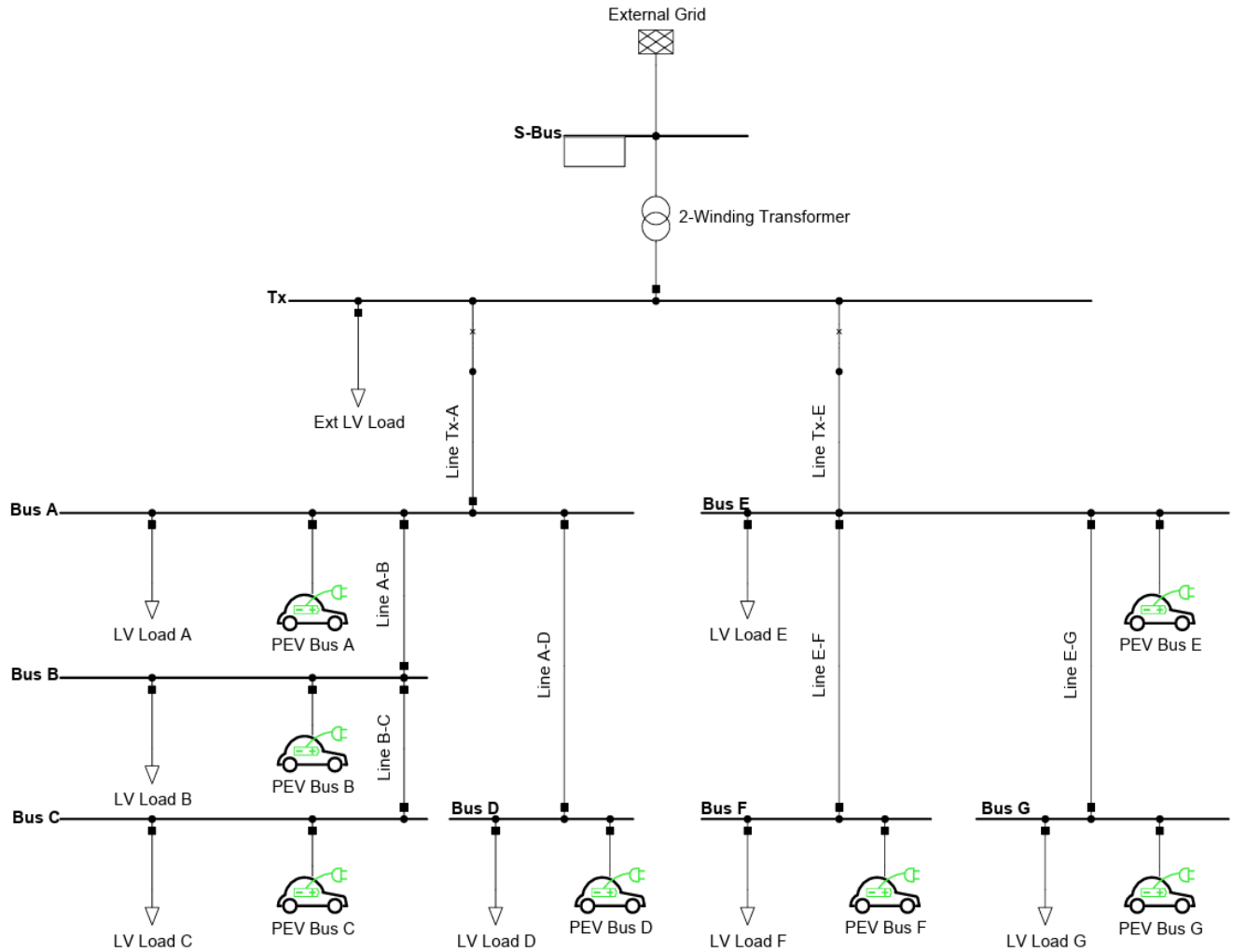


Figure 3.1: A portion of Muizenberg's LV DN in Cape Town, South Africa.

The LV DN assumptions are as follows:

- Bus Bar A to G can only feed six households each, with two houses per phase.
- Each household can only house one PEV at a time, for cases where integration is 100% or less.
- The loadshedding conditions are simulated from real-life household profiles; therefore, the PEV profiles are set to be off during loadshedding.

3.2.1. External grid

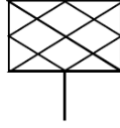


Figure 3.2: External grid.

The external grid component is used to represent the network beyond the boundaries of the studied system, encompassing the larger transmission network to which the local system is connected. In this study, it is configured to "Slack Bus" as its bus type. In this form it assumes the role of balancing the power in the system, ensuring the balance of active and reactive power by adjusting generation to match total power demand, including system losses as shown in:

$$P_{in} = P_{load} + P_{losses} \quad (3.1)$$

where:

- P_{in} : Injected power
- P_{Load} : Power consumed by Household or PEV
- P_{Losses} : Power loss in the Network.

Designating the external grid's bus as the Slack Bus provides a stable voltage reference for the network, facilitating precise analysis and ensuring system stability.

3.2.2. Plug-in Electric Vehicle (PEV)

A PEV converts stored electric power from batteries into mechanical energy for propulsion through external charging. Figure 3.3 shows an icon representing the integrated PEV.

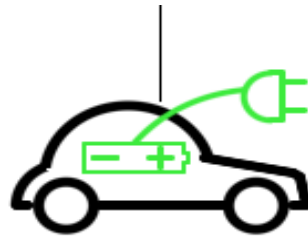


Figure 3.3: Plug-in Electric Vehicle (PEV)

The Nissan Leaf PEV, which is one of the earliest PEVs to achieve widespread adoption globally, serves as the reference PEV in this study. The characteristics of the Nissan Leaf are provided in Table 3.1. The charging rate for the Nissan Leaf is set at a constant 3.3 kW with an assumed unity power factor [85-86]. This constant charging rate facilitates the evaluation of the dynamic network profile under the specified 3.3 kW charging impact. Although recent PEV models support higher charging rates, the 3.3 kW rate is employed as a baseline for analysis. Any increase in the charging rate or reduction in the power factor is expected to adversely affect the network.

Table 3.1 PEV characteristics

S/N	Characteristics	Details
	A	B
1.	PEV Model	Nissan Leaf
2.	Charing Rate	3.3kW
3.	Charging mode	Constant
4.	Power Factor	Unity

The charging profile is displayed in Figure 3.4 below, which includes loadshedding downtime.

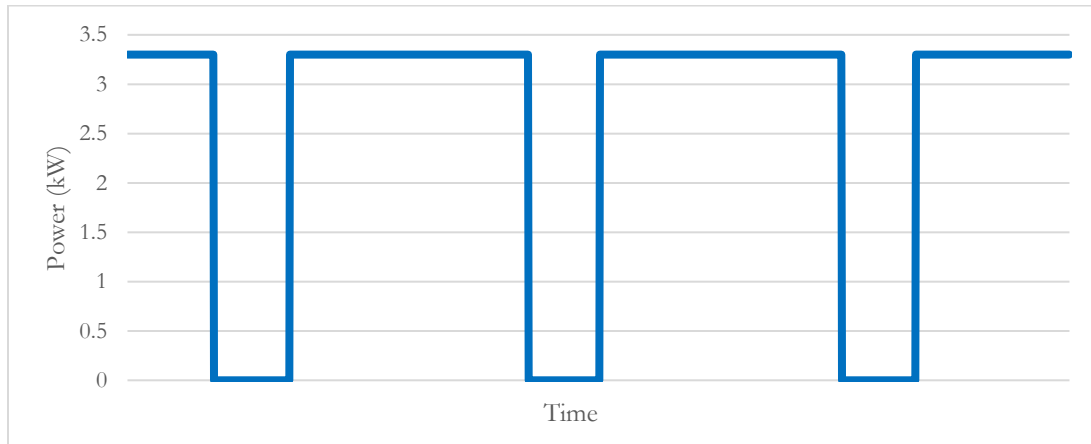


Figure 3.4: PEV charging profile

3.2.3. Household Loads



Figure 3.5: Low-voltage load.

Each domestic low-voltage load is characterised by a three-phase electrical setup where each phase is connected to a neutral point to supply a household. This distribution technology is represented as 3PH PH-E. The nominal voltage supply for the line-line voltage is $\pm 400\text{V}$ at 50Hz, and the phase-earth introduces the phase voltage of $\pm 230\text{V}$ at 50Hz, as per equation ((3.2):

$$V_{phase} = \frac{V_{line}}{\sqrt{3}} \quad (3.2)$$

The power demand profile of the household load was collected from the local distribution transformer and distributed among households according to their proportional consumption as per the provided load profiles.

3.2.4. Distribution Lines

Distribution lines are essential components of the LVDN and are responsible for effective distribution of electrical power. These lines possess inherent impedance characteristics that play a key role in influencing the active and reactive power equations in load flow calculations. The impedance (Z) of distribution lines is an important determinant of voltage drops and power losses within the network. Specifically, higher resistance (R) results in increased active power losses, while higher reactance (X) affects reactive power flows and voltage stability by inducing a voltage drop that is out of phase with the current.

The impedance Z_{ij} of a distribution line between buses i and j is expressed as:

$$Z_{ij} = R_{ij} + jX_{ij} \quad (3.3)$$

where:

- R_{ij} is the resistance of the line.
- X_{ij} is the reactance of the line.

The admittance Y_{ij} is the inverse of the impedance and can be written as:

$$Y_{ij} = \frac{1}{Z_{ij}} = \frac{1}{R_{ij}} + j \frac{1}{X_{ij}} = G_{ij} + jB_{ij} \quad (3.4)$$

where:

- G_{ij} is the conductance of the line.
- B_{ij} is the susceptance of the line.

The complex power flowing in a distribution line is given as:

$$S_i = P_i + jQ_i = V_i I_i^* \quad (3.5)$$

$$S_i = (V_i \angle \theta_i) \times \left(\frac{V_j \angle -\theta_j}{Z_{ij}} \right) \quad (3.6)$$

$$S_i = V_i \angle \theta_i \times \left(\frac{1}{Z_{ij}} \right) \times (V_j \angle -\theta_j) \quad (3.7)$$

$$S_i = V_i \times V_j \times \left(\frac{1}{R_{ij} + jX_{ij}} \right) \times (\angle \theta_i \times \angle -\theta_j) \quad (3.8)$$

$$S_i = |V_i| \times |V_j| \times (G_{ij} + jB_{ij}) \times (\angle \theta_i - \theta_j) \quad (3.9)$$

Decomposing this into real and imaginary parts using Euler's formula:

$$e^{j(\theta_i - \theta_j)} = \cos(\theta_i - \theta_j) + j \sin(\theta_i - \theta_j) \quad (3.10)$$

$$P_i = |V_i| \times |V_j| (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) \quad (3.11)$$

$$Q_i = |V_i| \times |V_j| (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) \quad (3.12)$$

Therefore, considering that multiple Bus Bars can be connected to bus i, equation ((3.11) and ((3.12) can then be rewritten to represent the general active and reactive power equation as equation (3.13) and (3.14):

$$P_i = V_i \sum_{j=1}^n V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) \quad (3.13)$$

$$Q_i = V_i \sum_{j=1}^n V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) \quad (3.14)$$

where:

- S_i is the apparent power injection at bus i .
- P_i is the active power injection at bus i .
- Q_i is the reactive power injection at bus i .
- V_i and V_j are the voltage magnitudes at buses i and j .
- G_{ij} is the conductance between buses i and j .
- B_{ij} is the susceptance between buses i and j .
- θ_{ij} is the voltage angle difference between buses i and j .
- N is the total number of buses in the system.

Therefore, P_{in} from equation (3.1) can then be represented as equation (3.5), which is the sum of equation (3.13) and (3.14) given as equation (3.15):

$$S_i = V_i \sum_{j=1}^n V_j [(G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) + (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij})] \quad (3.15)$$

The physical length of the distribution line and its configuration influence the overall impedance. Longer cables typically have higher impedance, affecting both active and reactive power distribution. The cable characteristics used are shown in

Table 3.2 below:

Table 3.2: Cable characteristics

S/N	Cable Characteristics		
	Name	Type	Length
	A	B	C
[19]	Line Tx-A	NAYSEY 3x120rm/16 6/11kV	45 m
[20]	Line Tx-E	NAYSEY 3x120rm/16 6/11kV	258 m
[21]	Line A-B	NAYSEY 3x120rm/16 6/11kV	29 m
[22]	Line A-D	NAYSEY 3x70rm/16 6/11kV	107 m
[23]	Line B-C	NAYSEY 3x70rm/16 6/11kV	58 m
[24]	Line E-F	NAYSEY 3x70rm/16 6/11kV	70 m
[25]	Line E-G	NAYSEY 3x70rm/16 6/11kV	60 m

Where "NAYSEY 3x120 rm/16 6/11 kV" specifies a cable with the following characteristics:

- NAYSEY: Cable type designation.
- 3x120: Three conductors with a cross-sectional area of 120 square millimetres each.
- rm: Round, multi-stranded conductors.
- /16: Cross-sectional area of the neutral conductor, 16 square millimetres.
- 6/11 kV: Voltage rating of the cable, 6/11 kilovolts

3.2.5. Bus Bar

A Bus Bar typically serves as a common junction point where multiple electrical circuits connect in a system. The purpose of this Bus Bar is to distribute injected power into the network. The status of the network is measured at each Bus Bar. From equation (3.1), the input power p_{in} is expressed as the total power consumed (P_{Load}) at each Bus Bar is given by equation (3.16) and the injected power:

$$P_{Load}(t, l) = P_{HH}(t, l) + P_{PEV}(t, l) \quad (3.16)$$

Where:

P_{Load} : represents the power required by loads connected directly to a Bus Bar,

- t : is the time.
- l : is the location of the Bus Bar on the network.
- P_{HH} : represents the power demand of all households.
- P_{PEV} : represents the power demand of all PEVs connected to a Bus Bar, respectively.

3.3. STOCHASTIC MODELLING FOR PEV INTEGRATION

The battery charging rate of the PEV is modelled as a sizable load independent of the uncertainties associated with driver behaviour leading to the charge [87]. The integration level is determined by the number of PEVs charging, relative to the number of households [88], as described in equation (3.17).

$$PEV_{Int-level}(\%) = \frac{\Sigma PEV_{charging}}{\Sigma House Holds} \quad (3.17)$$

Where:

- $PEV_{Int-level}(\%)$: PEV integration level given in %.
- $\Sigma PEV_{charging}$: Number of PEVs charging.
- $\Sigma House Holds$: Total number of households sampled.

The percentages 100%, 75%, 50%, and 25% correspond to 42, 32, 21, and 11 PEVs charging per household, respectively. Notably, PEV charging interruptions exclusively occur during designated loadshedding hours. The integration impact throughout the day was assessed by employing a systematic approach as per the flow chart shown in Figure 3.6.

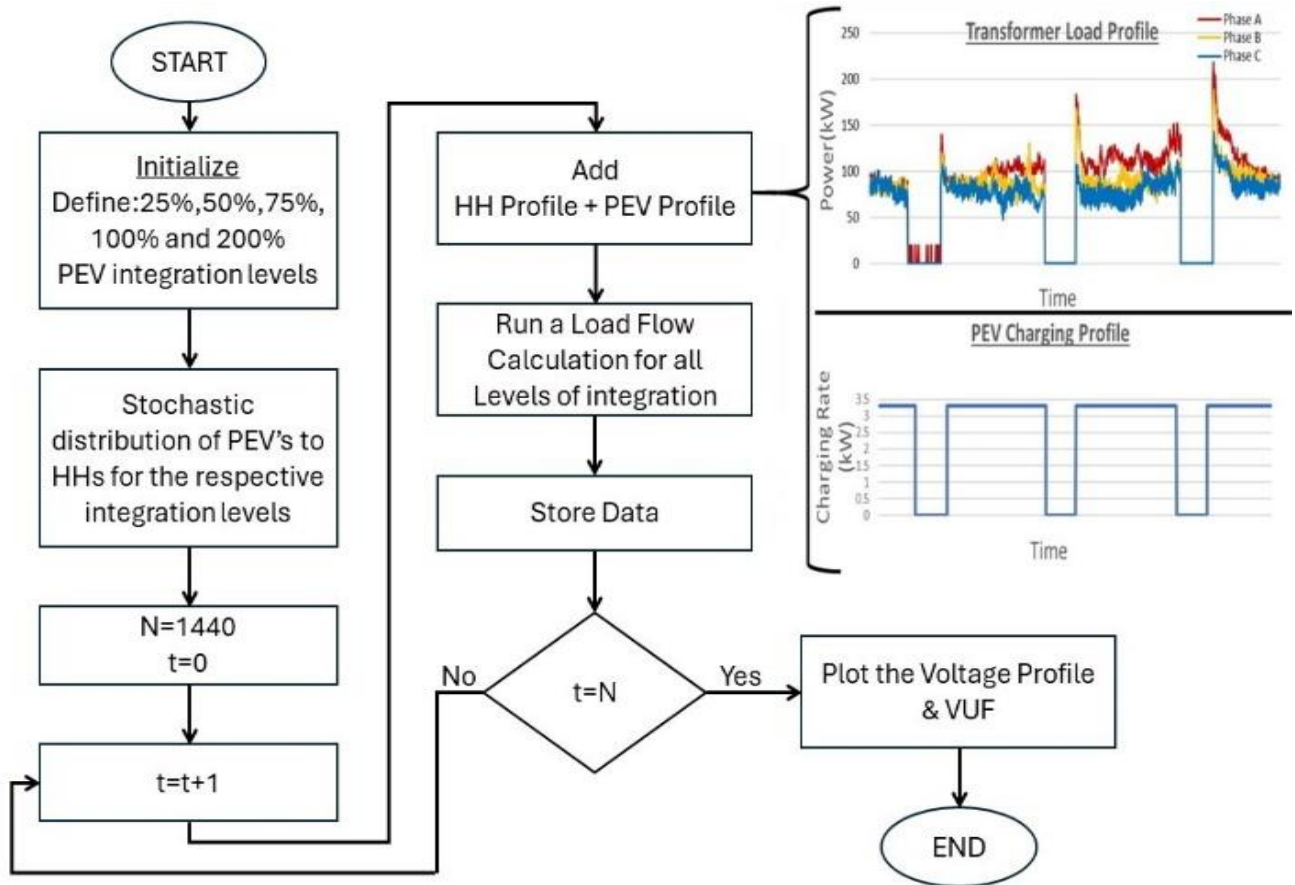


Figure 3.6: Framework for the Stochastic Approach

The variation in the load demand provides various realistic load profiles against which to measure the network's performance. This is further integrated with discrete PEV percentage integration levels for a dynamic daily profile. The Excel VBA code was employed to randomly distribute PEVs to households.

3.3.1. Excel VBA code

The Excel VBA code facilitates the random representation of PEV charging across different phases by following a structured methodology. Initially, it extracts unique numeric values from a specified cell range, which are then converted into specific letters. This conversion step categorises the numeric values, allowing for a more intuitive representation of the data. The letters are then randomly shuffled and placed into various cells within an Excel worksheet.

In the thesis, the random integration of PEV charging into the LVDN was represented using the following steps:

a) Bus Bar distribution:

Houses were assigned to Bus Bars, with each Bus Bar used no more than six times. In Excel, this was achieved by generating and counting random numbers to ensure a balanced distribution. The Bus Bars were labelled A to G, corresponding to numbers 1 to 7, respectively.

b) Count and allocation:

Excel was used to count how frequently each Bus Bar number appeared. For example, if the number 3 appeared four times, it indicated that four PEVs were assigned to Bus Bar C (since C corresponds to 3). The Bus Bars A to G were mapped to the numbers 1 to 7, respectively, based on these counts.

c) Phase allocation:

PEVs were then assigned to specific phases within each Bus Bar. Using Excel's random number generation, numbers between 1 and 3 were generated, with each number representing a phase (1 = Phase A, 2 = Phase B, and 3 = Phase C). Each number was assigned to a phase ensuring that each phase was utilised no more than twice for each Bus Bar.

This approach allowed for a detailed and randomised representation of PEV charging distribution across the network.

3.3.2. Interpretation of the Integration Phase Distribution Table

25% Integration Phase Distribution:

- A total of 11 PEVs are randomly distributed across Bus Bars A to G.
- Bus Bar A: Two PEVs in Phase A and one in Phase B.
- Bus Bar C: Three PEVs in total; two in Phase C and one in Phase A.
- Bus Bars B and E: No PEVs charging.

50% Integration Phase Distribution:

- A total of 21 PEVs are randomly allocated across Bus Bars A to G.
- Bus Bar A: One PEV on Phase A and Phase B, and two PEVs on Phase C.
- Bus Bar B: One PEV on Phase A.
- Bus Bar C: One PEV on Phase A and two PEVs on Phase B.
- Bus Bar D: One PEV on Phase B.
- Bus Bar E: Two PEVs on Phase A, and one PEV each on Phases B and C.
- Bus Bar F: One PEV on Phase A and two PEVs on Phase C.
- Bus Bar G: Two PEVs on Phases A and B, and one PEV on Phase C.

75% Integration Phase Distribution:

- A total of 32 PEVs are randomly allocated across Bus Bars A to G.
- Bus Bar A: Two PEVs on Phases A and C, and one PEV on Phase B.
- Bus Bar B: Two PEVs on Phase B, and one PEV each on Phases A and C.
- Bus Bar C: Two PEVs on Phases A and C, and one PEV on Phase B.

- Bus Bar D: Two PEVs on Phases A, B, and C.
- Bus Bar E: One PEV on Phases A, B, and C.
- Bus Bar F: Two PEVs on Phases A, B, and C.
- Bus Bar G: One PEV on Phases A, B, and C.

100% Integration Phase Distribution:

- A total of 42 PEVs are randomly distributed across Bus Bars A to G, ensuring that each phase on every Bus Bar is occupied.

Table 3.3: PEV Distribution

25% Integration Phase Distribution						
Bus A	Bus B	Bus C	Bus D	Bus E	Bus F	Bus G
A	-	C	B	-	C	C
B	-	C	-	-	-	A
-	-	A	-	-	-	B
-	-	-	-	-	-	B
50% Integration Phase Distribution						
Bus A	Bus B	Bus C	Bus D	Bus E	Bus F	Bus G
C	A	A	B	C	C	A
C	-	B	-	A	C	A
A	-	B	-	A	A	B
B	-	-	-	B	-	B

-	-	-	-	-	-	C
75% Integration Phase Distribution						
Bus A	Bus B	Bus C	Bus D	Bus E	Bus F	Bus G
A	A	A	A	C	A	B
B	B	C	A	B	A	A
C	C	B	B	A	B	C
C	B	A	B	-	B	-
A	-	C	C	-	C	-
-	-	-	C	-	C	-
100% Integration Phase Distribution						
Bus A	Bus B	Bus C	Bus D	Bus E	Bus F	Bus G
A	A	A	A	A	A	A
A	A	A	A	A	A	A
B	B	B	B	B	B	B
B	B	B	B	B	B	B
C	C	C	C	C	C	C
C	C	C	C	C	C	C

3.4. THREE-PHASE LOAD FLOW APPROACH

Load flow calculations are important for analysing the steady-state conditions of a power system. It provides an update on the status of the power system's operating parameters at a point in time. In this study, a total of 1 440 load-flow calculations are performed over a period

of 24 hours, in steps of one-minute intervals, and further used for VUF and voltage deviation analysis. This provides sufficient data to accurately represent the voltage deviations from the base profile, as the data is modelled per minute. SANS[89] recommends a tolerance timescale of 10 minutes to declare Undervoltage for conditions where the voltage has dropped below the $\pm 10\%$ nominal voltage of 230V at 50Hz. The load flow is simulated on DigSilent PowerFactory using the Quasi Dynamic Simulation (QDS) approach, which makes use of the Newton-Rapson (NR) iterative method. This can be equated to capturing a snapshot of the network's status every minute, as the load demand fluctuates over a 24-hour period, simulated for various integration levels.

3.3.1. Power mismatch

For each bus i in the power system, the real power mismatch ΔP_i and reactive power mismatch ΔQ_i are defined as:

$$\Delta P_i = P_i^{Specified} - P_i^{Calculated} \quad (3.18)$$

$$\Delta Q_i = Q_i^{Specified} - Q_i^{Calculated} \quad (3.19)$$

where

- $P_i^{Specified}$: refers to the real power value that is expected or required at bus i due to the power demanded by loads connected to bus i .
- $P_i^{Calculated}$: The calculated power from equation (3.13).
- $Q_i^{Specified}$: refers to the reactive power value that is expected or required at bus i due to the power demanded by loads connected to bus i .
- $Q_i^{Calculated}$: The calculated power from equation (3.14).

These mismatches quantify the deviation between specified (or measured) power injections and those calculated using an equation based on the current system state of the network. For the initial calculation, the state variables (voltage magnitude and phase angle) are initially set to $V=1$ p.u and $\theta=0^\circ$.

Voltage magnitude and phase angle are important state variables, defining the electrical conditions at different nodes. In the Newton-Raphson method, these variables are updated iteratively to refine the estimation of voltage magnitudes and angles across the entire power system.

3.3.2. Newton-Raphson Method

The Quasi Dynamic Simulation (QDS) makes use of the Newton-Raphson method given in equation (3.20) as its iterative approach. This method begins by linearising power flow equations (3.13) and (3.14) around an initial estimate of the system state, setting voltage magnitudes and angles at all buses to 1 p.u. and 0° , respectively. Subsequently, the power mismatch between specified and calculated values is evaluated.

$$x_n = x_{n-1} - \frac{f(x_{n-1})}{f'(x_{n-1})} \quad (3.20)$$

where:

- x_n : Represents the state variables, which is the (n)th estimate of the voltage magnitudes and angles across all buses in the power system. It is an updated guess obtained in each iteration of the Newton-Raphson method.

- x_{n-1} : Represents the previous estimate, (n-1)th, which is an estimate of the voltage magnitudes and angles obtained in the previous iteration. It serves as the starting point for refining our estimate in the current iteration.
- $f(x_{n-1})$: represents the vector of power mismatches ΔP and ΔQ at the (n-1)th estimate of voltage magnitudes and angles. These mismatches quantify the deviation between the calculated and specified (or measured) power injections and are evaluated using the current state variables.
- $f'(x_{n-1})$: is the derivative of the vector of power mismatches “ $f(x_{n-1})$ ” which is represented in the form of a Jacobian matrix (J). The Jacobian matrix consists of partial derivatives of the power mismatches in respect of the voltage magnitudes and angles. It quantifies how each element of the power mismatch vector changes with small perturbations in x_{n-1} .

3.3.3. The Jacobian matrix

The Jacobian matrix, denoted as J, is a matrix of all first-order partial derivatives of a vector-valued function. It contains partial derivatives of $F(x)$ with respect to x , where x represents the state variables (voltage magnitudes and angles).

The Jacobian matrix J is typically structured as shown in equation (3.21):

$$J = \begin{bmatrix} \frac{\partial \Delta P_i}{\partial \theta_j} & \frac{\partial \Delta P_i}{\partial V_j} \\ \frac{\partial \Delta Q_i}{\partial \theta_j} & \frac{\partial \Delta Q_i}{\partial V_j} \end{bmatrix} \quad (3.21)$$

$$J = \begin{bmatrix} \frac{\partial \Delta P_1}{\partial \theta_1} & \frac{\partial \Delta P_1}{\partial |V_1|} & \dots & \frac{\partial \Delta P_1}{\partial \theta_n} & \frac{\partial \Delta P_1}{\partial |V_n|} \\ \frac{\partial \Delta Q_1}{\partial \theta_1} & \frac{\partial \Delta Q_1}{\partial |V_1|} & \dots & \frac{\partial \Delta Q_1}{\partial \theta_n} & \frac{\partial \Delta Q_1}{\partial |V_n|} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \frac{\partial \Delta P_n}{\partial \theta_1} & \frac{\partial \Delta P_n}{\partial |V_1|} & \dots & \frac{\partial \Delta P_n}{\partial \theta_n} & \frac{\partial \Delta P_n}{\partial |V_n|} \\ \frac{\partial \Delta Q_n}{\partial \theta_1} & \frac{\partial \Delta Q_n}{\partial |V_1|} & \dots & \frac{\partial \Delta Q_n}{\partial \theta_n} & \frac{\partial \Delta Q_n}{\partial |V_n|} \end{bmatrix} \quad (3.22)$$

Where :

- $\frac{\partial \Delta P_i}{\partial \theta_j}$: Represents the sensitivity of the real power mismatch at bus i in respect of a small change in the phase angle at bus j.
- $\frac{\partial \Delta P_i}{\partial V_j}$: Represents the sensitivity of the real power mismatch at bus i in respect of a small change in the voltage magnitude at bus j.
- $\frac{\partial \Delta Q_i}{\partial \theta_j}$: Represents the sensitivity of the reactive power mismatch at bus i in respect of a small change in the phase angle at bus j.
- $\frac{\partial \Delta Q_i}{\partial V_j}$: Represents the sensitivity of the reactive power mismatch at bus i in respect of a small change in the voltage magnitude at bus j.
- n : Represents the number of buses in the power system.

Once the J computation is complete, the state variables are updated to find the corrections to the current guesses. The software repeats the process of recalculating mismatches, constructing the Jacobian matrix, solving for corrections, and updating state variables until the mismatches are within an acceptable tolerance.

3.5. VOLTAGE UNBALANCE FACTOR

The International Electrotechnical Commission's (IEC's) definition for calculating the VUF is the ratio of the Negative Phase Voltage to Positive Phase Voltage as seen in equation (3.23) [90]. It is the same as South Africa's NRS 048-2:2003[90] standards.

$$\%VUF = \frac{V(-)}{V(+)} \times 100\% \quad (3.23)$$

where:

$$V(-) = \frac{V_{ac} + \alpha^2 V_{ba} + \alpha V_{cb}}{3} \quad (3.24)$$

$$V(+)= \frac{V_{ab} + \alpha^2 V_{bc} + \alpha V_{ca}}{3} \quad (3.25)$$

$V(-)$ = Negative Phase Sequence Voltage.

$V(+)$ = Positive Phase Sequence Voltage.

α = Angular Shift

The Nominal Voltage characteristics for power quality is outlined in [90], as follows:

- Nominal Voltage: 230V with a deviation limit of $\pm 10\%$ and a tolerance limit for the Voltage Unbalance Factor (VUF) of 2% for LVDNs.
- Grid Frequency: 50Hz.

3.6. CONCLUSION

This chapter covered essential aspects of modelling the integration of Plug-in Electric Vehicles into the Low Voltage Distribution Network (LVDN). We began with an overview of LVDN components, focusing on transformers, feeders, and loads, which form the backbone of electricity distribution.

A key contribution of this chapter was the introduction of Stochastic Modelling for PEV Integration using Excel VBA code. This approach allows us to simulate various charging scenarios based on stochastic parameters such as time, rating, and location, providing valuable insights into their effect on grid performance and reliability.

We also explored the Three-Phase Load Flow approach, detailing the application of the Newton-Raphson method and the Jacobian matrix for solving non-linear power flow equations efficiently. This robust numerical technique ensures accurate and iterative solutions.

Additionally, we investigated the VUF to assess voltage symmetry across phases, which is crucial for maintaining network stability and equipment longevity.

Overall, this chapter lays a strong foundation for analysing and optimising PEV integration strategies in LVDNs. By employing advanced modelling techniques and computational tools like Excel VBA and DigSilent PowerFactory, we are prepared to identify solutions that enhance grid resilience, energy efficiency, and the effective integration of sustainable transportation technologies.

Chapter 4 : SIMULATION RESULTS

4.1. INTRODUCTION

This chapter presents the simulation results for PEV integration into South Africa's LVDN system model, developed in Chapter 3, using DigSilent PowerFactory software. The simulations are carried out with the aim of studying the behaviour of the proposed LVDN against the adaptation of PEV charging activities at various integration levels and network configurations, such as charging on a heavily loaded and least loaded phase, as well as upper and downstream charging. The parameters of the network, LV Households and PEV, are used as loads to the developed model and the main power supply from the external grid to a step-down transformer, and subsequently distributed into the LVDN circuitry. This network is modelled in respect of a portion of the City of Cape Town's LVDN and is used as case studies for simulation purposes.

4.2. SIMULATION RESULTS

Generally, in South Africa, electricity is supplied to households through an LVDN transformer. This transformer steps down the voltage from Medium Voltage (MV) levels of 33kV or 11kV to the standard ± 0.4 kV line voltage. This voltage is then distributed to various Bus Bars along with a neutral line. From the Bus Bars, a single live line running parallel to a neutral line supplies the households with a nominal phase voltage of ± 230 V at 50Hz as per the standards. This LVDN topology is used as the base case study for simulation purposes.

4.2.1. Simulation results Case A- Base Case

Figure 4.1 displays a three-phase unbalanced power demand profile of the nine buses LV residential feeder without any PEVs, indicated in red, yellow, and blue. The power demand profile represents the residential loads, measured from the secondary side of the distribution transformer. Due to loadshedding the peak demand is divided into two time periods: from

17:32 to 18:08 pm, and again from 20:39 to 21:06 pm, peaking at approximately 150 kW. Additionally, there is a loadshedding surge between 20:06 and 20:39, reaching its peak at 217.77kW.

In an LVDN the VUF is measured at the bus bars along a feeder, which best paints a picture of the phase distribution. However, measuring closer to the supply source would produce a lower unbalanced factor as it is the average of its subsequent distribution points. To obtain a clearer reflection of the unbalance in the network under this study, we measure the VUF at all buses along the feeder down to the last bus. Figure 4.2 is an illustration of the VUF for the respective bus bars. The graph indicates that the network is still healthy in terms of its VUF parameter, with the peak spike VUF value of 1.8%, which is the result of the surge due to the return in power from loadshedding.

The total voltage drop witnessed in the network pre-PEV integration displays voltage levels that are within tolerable limits. Figure 4.3 is the Base Voltage profile pre-PEV Integration. The profile shows that the average voltage drop is between $\pm 3\%$ and $\pm 5\%$ voltage drops, thus suggesting that the current-voltage profile is healthy, despite the inrush caused by loadshedding.

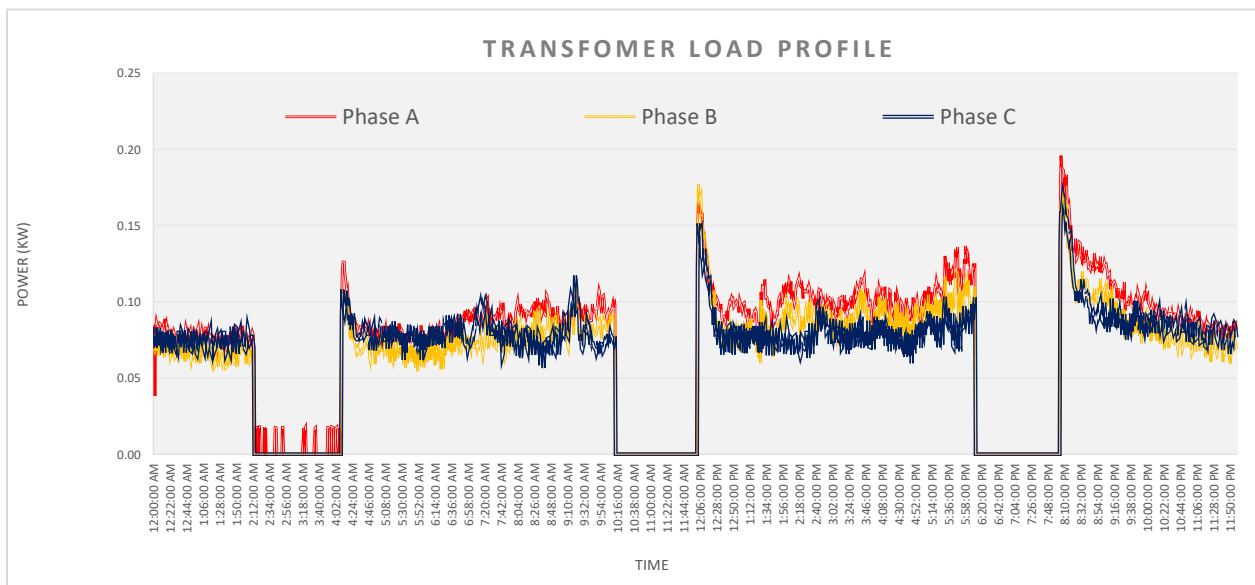


Figure 4.1: Distribution transformer loading base profile

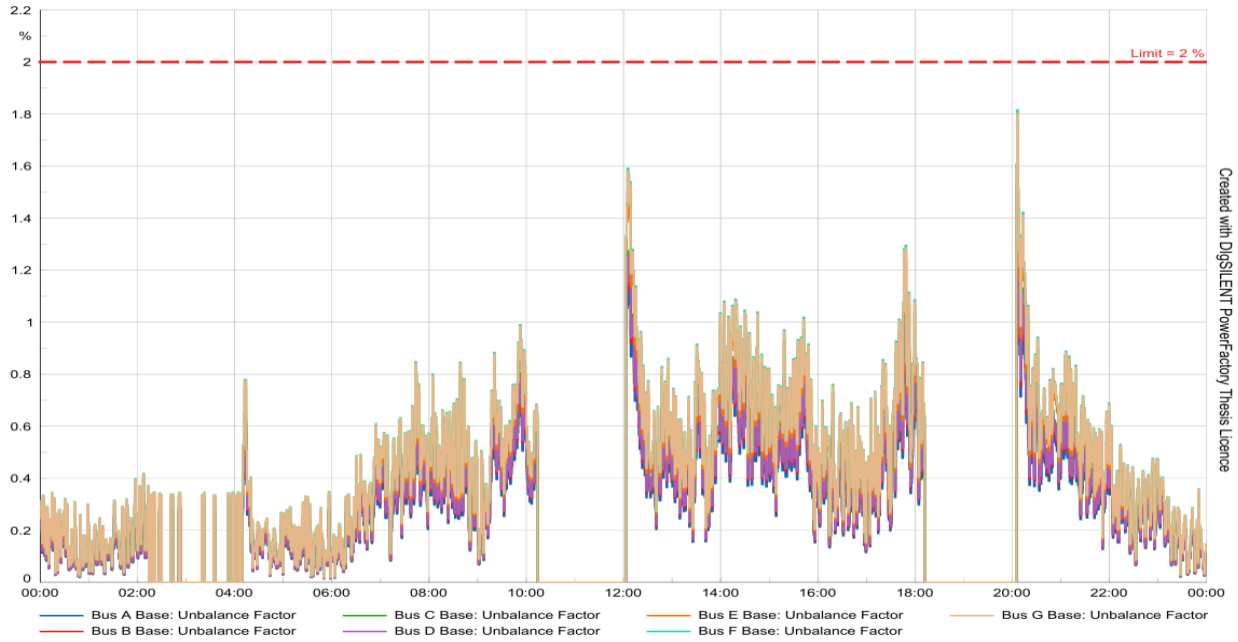


Figure 4.2: Base VUF



Figure 4.3: Base voltage drop

4.2.2. Simulation results Case B- Impacts of Phase and Number of PEVs on Voltage and VUF

A major challenge with integrating PEVs into an already unbalanced LVDN is the risk of either increasing or decreasing the VUF in the system. However, this integration could also have the advantage of stabilising the VUF. It is expected that integration on a heavily loaded phase (Phase A in this study) could potentially result in an increase in the VUF. On a lightly loaded phase (Phase B) it could lead to a reduction in the network's VUF[12;17;20]. However, this depends on the time of charge. Charging outside of peak hours results in less loaded phases having a slightly increased VUF. Under this case study, PEVs are connected to only one phase of the network, which is charged with a 230V/3.3kWh home charger on the daily load profile.

Figures 4.4 and 4.5 illustrate the average VUF when PEVs are connected to Phase A and Phase B, respectively. It can be observed that when PEVs are connected to the low-load phase

(Phase B), the VUF remains within the acceptable limit of 2%. Additionally, this configuration displays a more constant aggregate VUF, ranging between 0.2% and 0.4%, with slightly improved VUF values compared to the Base Network. These improvements are particularly noticeable around 08:37 am and 20:43 pm.

Conversely, the connection of PEVs to a heavily loaded phase results in an increase in VUF deviation. The rate of charge and the position of charge on the network are critical factors influencing both the VUF and the voltage profile. When PEVs are connected to the heavily loaded Phase A, the position of charge (whether upstream or downstream of a feeder network) and the rate of charge significantly affect the network's voltage dynamics. This is evident in two primary key pointers. Firstly, an increase in load results in an increased VUF profile, keeping the pattern constant, which means that the ratio of the Negative Phase Voltage to the Positive Phase Voltage has increased as explained in Chapter 3. Secondly, increasing the load on a heavily loaded phase of the farthest bus bar causes serious concerns on the network. This demonstrates the importance of planning in PEV integration to mitigate adverse impacts on the LVDN.

Downstream charging and increased rate of charge demonstrate increased VUF, as well as voltage drop along the feeder. Furthermore, the increased charging rate (6.6kWh) at the beginning of the feeder has a lesser impact relative to 3.3kWh charging rate at the far end of the feeder. This can be seen on the red circles in Figure 4.6, which indicate VUF exceeding tolerable limits as compared to Figure 4.7, where the VUF is within parameters. It is also observed that load-shedding conditions induce high spikes in the profiles, more so during the peak hours (18:37 pm). Here we see spikes drop to the maximum tolerable limit of 0.9pu, suggesting that any further increase in the charging rate or network beyond this point would be a concern. On the other hand, Figure 4.7 demonstrates how the least loaded Phase (Phase B) improves the overall VUF. However, during off-peak hours, increased charging rates downstream relatively show small increased VUF gaps between the 3.3kWh and the base values. During peak hours, the VUF is improved with no visible gaps between the base values and the 3.3kWh charging rate. This means that PEV charging on the least loaded phase

improves the overall VUF. The cause of this behaviour can be defined by using equation (3.23) which shows that the VUF is inversely proportional to the positive phase sequence voltage; hence an increase in load on the heavier loaded phase increases the voltage drop on the positive phase sequence, which increases the VUF. Adding a load on a least loaded phase reduces the voltage difference between the heavily and least loaded phases, which constitutes an improved VUF.

The influence of PEV integration with loadshedding is evident in Figure 4.6. Upon power restoration at 12:00 and 20:00, the increased loading causes the VUF to spike, surpassing the safe operating limits of 2%. In contrast, on the least loaded phases, as depicted in Figure 4.7, the VUF profile remains within limits.

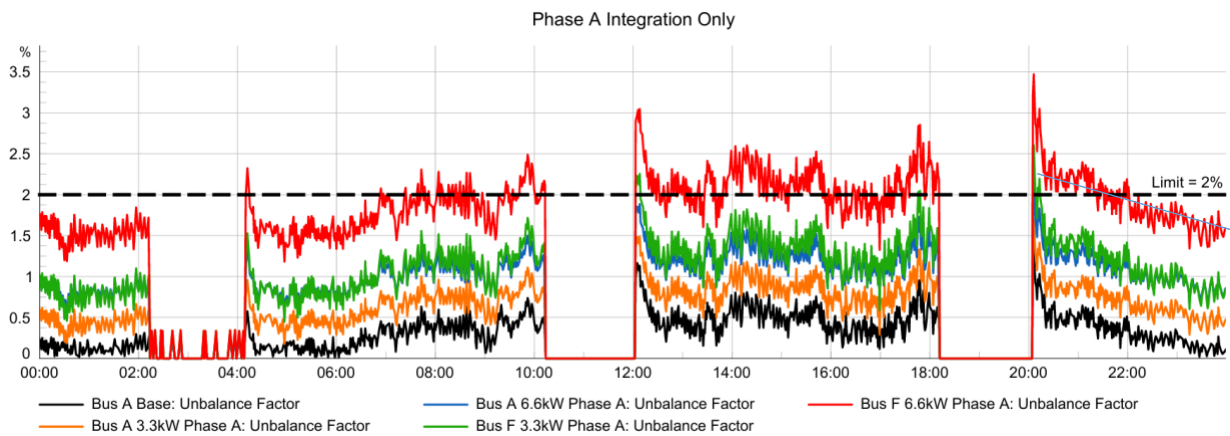


Figure 4.4: Integration on Phase A only

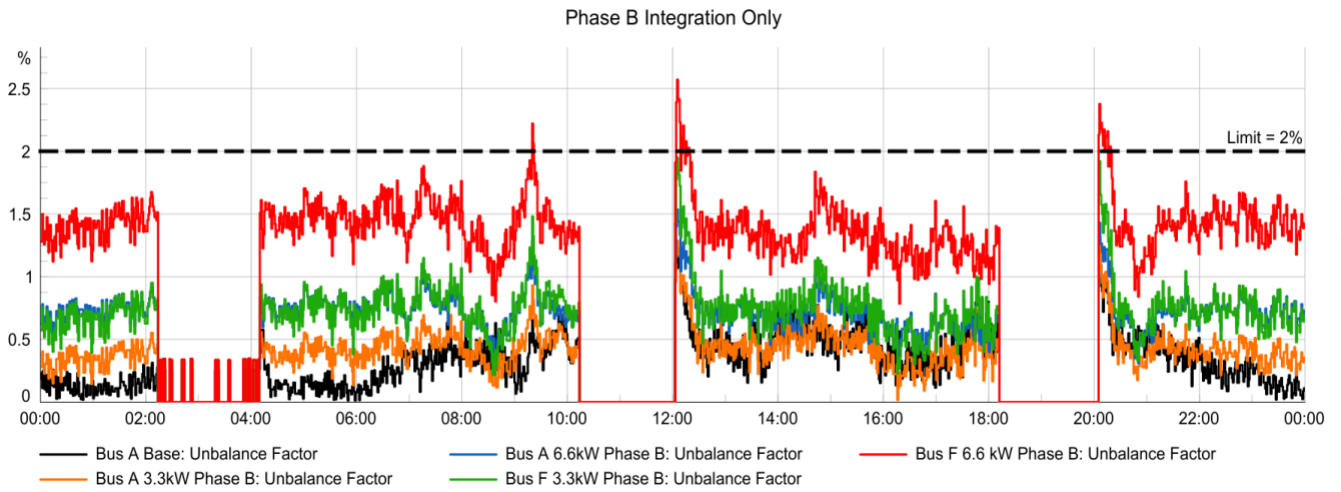


Figure 4.5: Integration on Phase B only

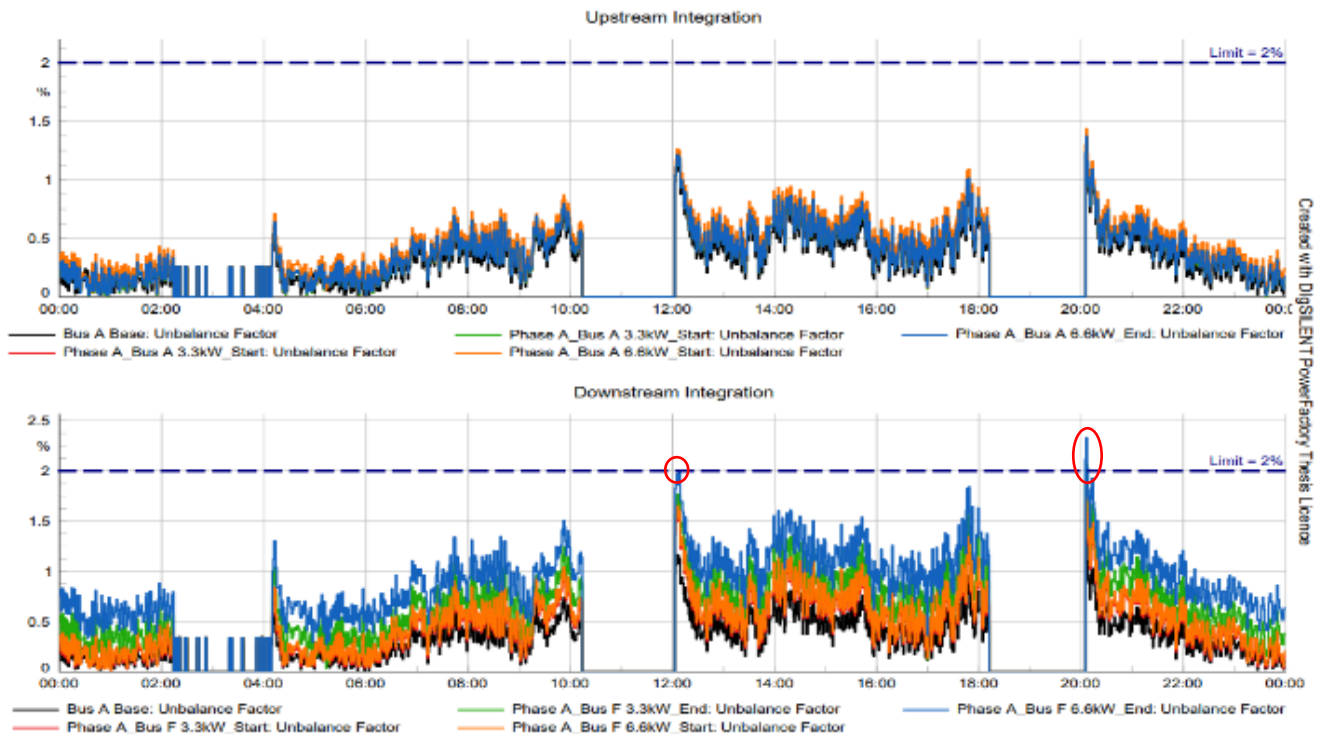


Figure 4.6: Phase A (heavily loaded phase)

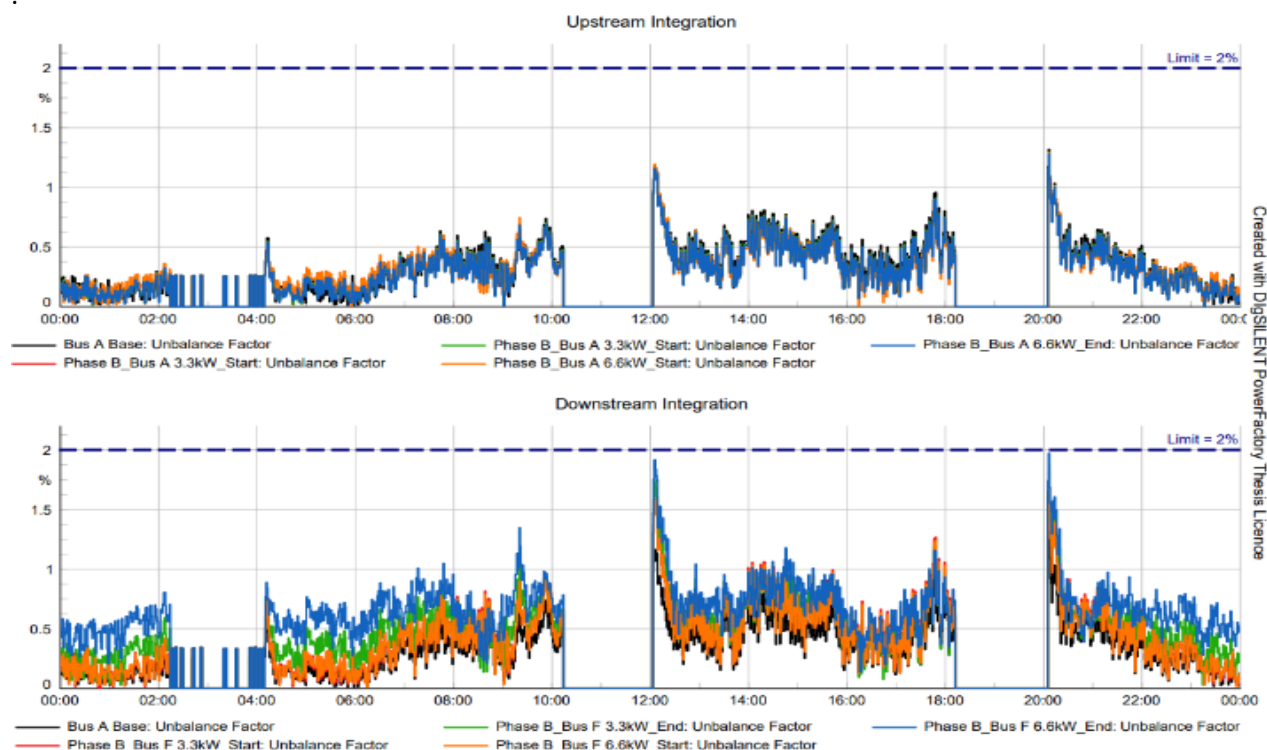


Figure 4.7: Phase B (least loaded phase)

4.2.3. Simulation results Case C- Random Integration

The PEV integration level is defined as the total number of PEV plugged into the LVDN, which is considered from 25%, 50%, 75%, and 100%, and a further 200% for a sensitivity analysis in this study. The simulation is run for all levels of PEV integration independently. As per Figure 3.6, the simulation is executed multiple times for varying load demands, as already explained in Chapter 3.

Loading			
Integration	Transformer	Line Loading	
		Tx-AD	Tx-EG
%	%	%	%
0	119.99	96.14	74.17

Table 4.2 shows the highest voltage drop values at pre-

25	124.02	109.42	80.91
50	131.49	116.45	111.30
75	135.50	144.69	135.50
100	139.94	151.81	118.69

loadshedding and post-loadshedding conditions along the feeder as PEV integration increases. The voltage drop is proportional to the integration of PEVs, and the voltage drops pre-loadshedding are within the SA Standards for tolerable voltage drop limits[90]. This suggests that the network is capable of accommodating 100% integration prior to loadshedding; however, upon the return of power, loadshedding results in a spike that drops the pre-loadshedding voltage values further by $\pm 2.5\%$. Furthermore, as expected, bus bars F and G appear to be experiencing the highest voltage drop due to their location being furthest from the supply bus. Concerning voltage drops are seen from 50% PEV integration on bus G and a further 1.13% voltage drop on bus F above the $\pm 10\%$ limit, lasting up to ± 10 minutes for 100% PEV integration. However, further challenges are experienced upstream.

Table 4.2 shows the loading impact as PEV integration increases. The distribution transformer is already

Loading			
Integration	Transformer	Line Loading	
		Tx-AD	Tx-EG
%	%	%	%
0	119.99	96.14	74.17
25	124.02	109.42	80.91
50	131.49	116.45	111.30
75	135.50	144.69	135.50
100	139.94	151.81	118.69

experiencing overloading as a result of the loadshedding surge under the base case, which translates to increased loading with increased PEV integration. Lines experiencing the heaviest

loading are the two parallel lines furthest upstream, with Line Tx-AD supplying a larger load relative to Line Tx-EG, hence Tx-AD experiences the most overloading.

Table 4.1: Voltage Drop

Voltage Drop			
Integration	Pre-loadshedding	Post-loadshedding	Bus Bar
%	%	%	
0	5.98	8.48	F
25	6.72	9.24	G
50	7.52	10.09	G
75	7.81	10.43	F
100	8.45	11.13	F

Figure 4.8 depicts the base profile pre-PEV integration, and Figure 4.9 illustrates the impact at 100% PEV integration. The profiles show that the average voltage drop ranges from $\pm 3\%$ to $\pm 5\%$, and from $\pm 4\%$ to $\pm 8\%$ for 0% and 100% off-peak average voltage drops, thus suggesting that the current voltage profiles can cater for up to 100% integration for off-peak hours. However, a further analysis is conducted where the PEV is increased to 200% integration, which implies that all households have two vehicles each, all charging at the same time. The results are shown in Figure 4.10, which reflect an increased voltage drop to a point where the farthest downstream Bus Bar voltage operates at the threshold margins and on

various intervals during off-peak hours; thus, the profile flags under-voltage conditions. This is due to increased current consumption in the network.



Figure 4.8: Voltage Profile for 0% PEV Integration

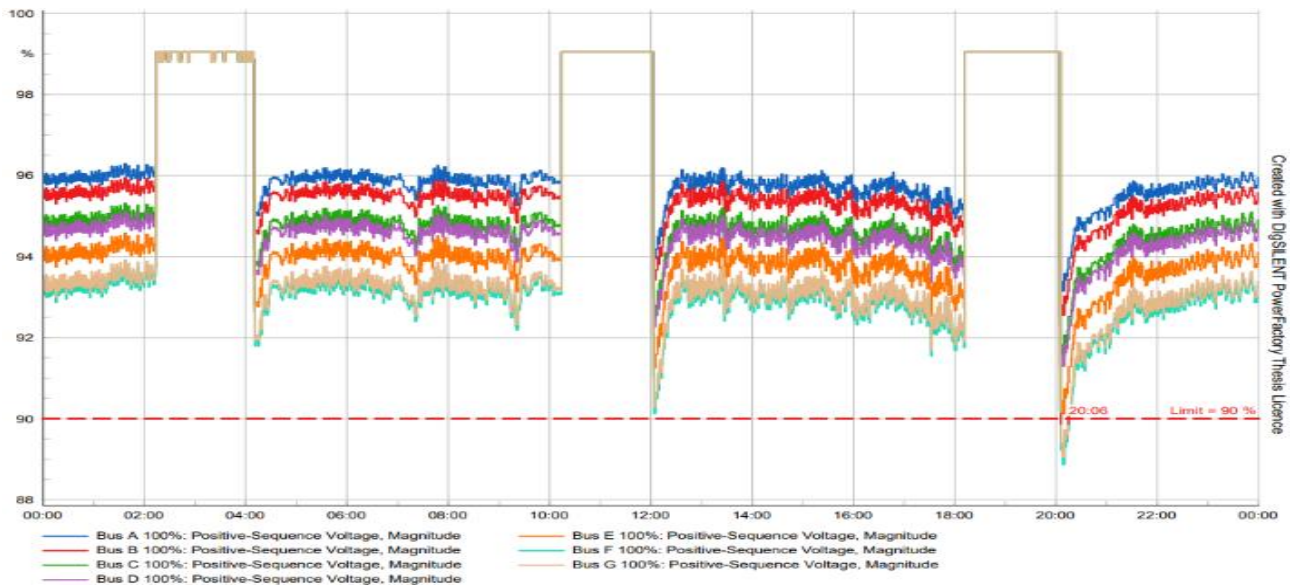


Figure 4.9: Voltage Profile for 100% PEV Integration

Importantly, even at 100% integration the voltage and VUF remain within acceptable limits. However, according to [14], South Africa intends to double its EV penetration by 2037; therefore, a sensitivity analysis study is performed to establish at what degree of integration would any of the phases operate outside the recommended standards during off-peak hours, since peak hours are cleared up by loadshedding.

Table 4.2: Loading impact as PEV integration increases

Loading			
Integration	Transformer	Line Loading	
		Tx-AD	Tx-EG
%	%	%	%
0	119.99	96.14	74.17
25	124.02	109.42	80.91
50	131.49	116.45	111.30
75	135.50	144.69	135.50
100	139.94	151.81	118.69

4.2.4 Sensitivity Analysis at 200% PEV Penetration

An extreme-case scenario is modelled to assess system performance under a 200% PEV penetration rate, equivalent to two PEVs per household. This stress test revealed significant deviations in voltage profiles, particularly at feeder ends, with VUF values exceeding the regulatory 2% limit. The increased load concentration intensified phase imbalance, elevated neutral currents, and contributed to more pronounced voltage dips during simultaneous charging periods. These findings underscore the importance of controlled integration mechanisms, such as phase-aware allocation and coordinated

charging strategies, to preserve voltage quality in high-penetration environments. Results from the 200% integration Figure 4.10 indicate that voltage and VUF issues that could occur in South Africa’s network in the future.

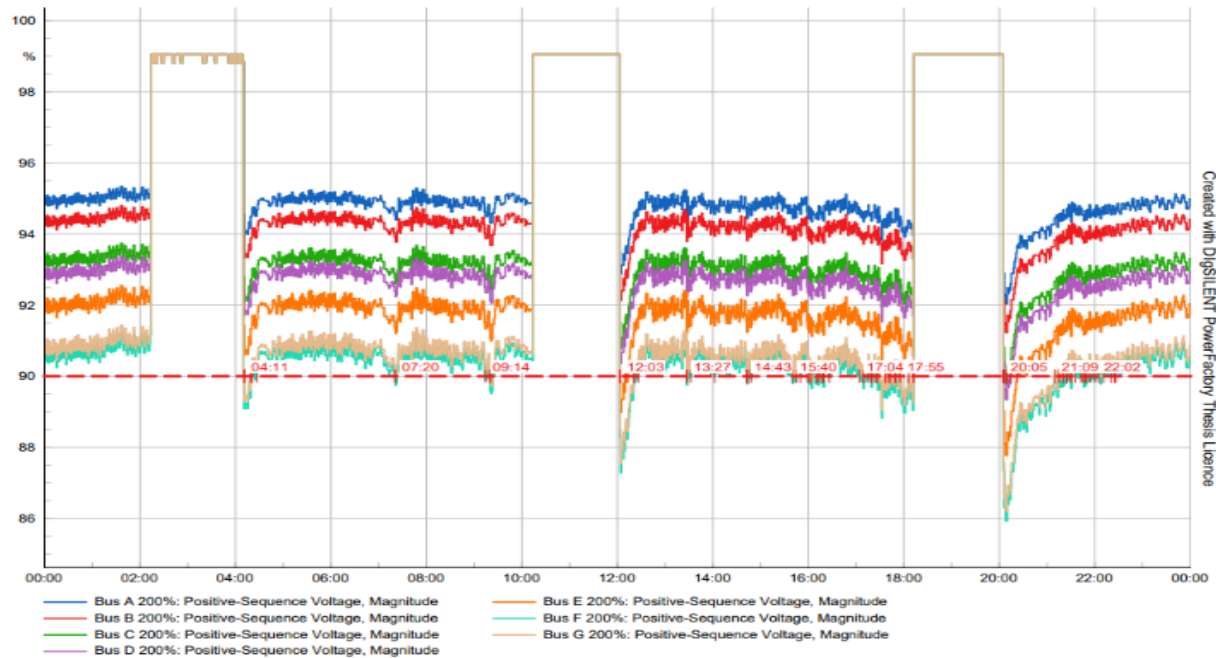


Figure 4.10: Voltage profile for 200% PEV integration

4.3. CONCLUSION

The integration of PEVs into South Africa’s LVDN, as simulated in this study, highlights the potential impacts on voltage profiles and the VUF. The results indicate that the LVDN can accommodate up to 100% PEV integration under normal conditions, with the voltage and VUF remaining within acceptable limits. However, during loadshedding and subsequent power restoration, voltage drops and VUF spikes pose significant challenges, particularly on heavily loaded phases and during high charging rates. Sensitivity analysis for 200% PEV integration further reveals that future increases in EV penetration could lead to voltage and VUF issues. These findings underscore the importance of planning for future LVDNs and optimising PEV charging patterns to mitigate adverse effects on future LVDNs.

Chapter 5 : CONCLUSION AND FUTURE WORK

5.1. CONCLUSION

This chapter outlines the conclusion of the research carried out, based on the analysis and modelling of the uncoordinated impact of Plug-In Electric Vehicles' charging patterns on the low-voltage distribution network (LVDN). The aim of this study was to investigate the impacts on the voltage profile and VUF for stochastic integration of single-phase PEV charging, focusing on time, rating and location of charging at residential households.

Chapter 2 outlines a theoretical overview of the integration of Plug-in Electric Vehicles (PEVs) into the LVDN in South Africa. It explores existing studies on the behaviour and impact of PEV charging, focusing on types of PEVs, their environmental benefits, and economic implications. The chapter addresses power quality and network stability issues, including voltage profile characteristics, coordinated charging strategies, and loadshedding. It also discusses the uncertainties in PEV charging and methodologies to address them, using methods of analysis in DigSilent PowerFactory.

Chapter 3 shows the different steps for the mathematical modelling of the LVDN and its system components, and the calculation framework adopted. The proposed network configuration consisted of the external grid, distribution transformer, bus bars, underground cables, low-voltage residential loads and PEVs. The corresponding simulation model has been developed, using DigSilent PowerFactory.

Chapter 4 performed the simulations based on the PEV integration case study models developed in Chapter 3, using DigSilent PowerFactory. The simulations are carried out with a view to studying the behaviour of the LVDN as PEV charging activities are integrated into the network, primarily focusing on time, rating and location of charging at residential households. The load profile and the LVDN parameters of the three phases to single phase distribution systems used was obtained from the City of Cape Town in South Africa, and was used during simulations. The results of the different case studies have shown that the LVDN

can host PEV up to 100% integration, with challenges being identified with regard to positional charging and time of charge.

5.2. RECOMMENDATIONS

Based on the findings of this study, several practical recommendations are proposed to mitigate the negative impacts of Plug-in Electric Vehicle integration on South Africa's Low Voltage Distribution Network:

- **Time-of-Use Charging Incentives**
Encourage off-peak charging through differential electricity pricing or time-of-use tariffs to reduce demand during peak hours and after load shedding.
- **Smart Charging Infrastructure**
Implement smart charging systems capable of dynamic load management, prioritising balanced phase allocation and coordinating charging times to prevent overloads and reduce VUF deviations.
- **Load Forecasting and Phase Balancing**
Employ real-time load forecasting and enforce phase balancing strategies in residential areas to avoid uneven phase loading and voltage instability.
- **Vehicle-to-Grid (V2G) Integration**
Explore V2G capabilities where PEVs can temporarily discharge power back to the grid during peak demand or recovery from load shedding, providing ancillary support.
- **Public Awareness and Education**
Raise awareness among consumers about optimal charging behaviours and the broader grid impacts of uncoordinated charging, particularly after load restoration events.

- Infrastructure Upgrades
Plan for long-term upgrades to residential feeders, distribution transformers, and control systems to handle increased PEV penetration.

5.3. FUTURE WORK

The study revealed that undertaking research in the following areas is important:

- Further studies on Frequency analysis and coordinated charging strategies' impact on LVDNs for loadshedding conditions.
- Investigating how current load-modelling techniques used in LVDN design standards could consider the integration of PEVs as a general household load.

REFERENCES

- [1] Department of Trade, Industry and Competition. South African EV White Paper. Pretoria: Department of Trade, Industry and Competition, 2023.
- [2] Xie, Jian-bo. "Evaluation of carbon footprint and energy input of internal combustion engine vehicles in China." *Environmental Progress & Sustainable Energy* 42, no. 1 (2023): e14040.
- [3] Mangion, Josh Jacobson, and Michael Bertolacci. "Earth's CO₂ battle: a view from space." (2023).
- [4] Inglesi-Lotz, Roula. "Load shedding in South Africa: Another nail in income inequality?." *South African Journal of Science* 119, no. 9/10 (2023).
- [5] Covary, Theo. "SOUTH AFRICA: ENERGY EFFICIENCY DEMAND SIDE MANAGEMENT EXPERIENCE (2004–2022)." (2023).
- [6] Ferrari, Giancarlo, Angelo Onorati, and Gianluca D'Errico. *Internal combustion engines*. Società Editrice Esculapio, 2022.
- [7] Mi, Chris, and M. Abul Masrur. *Hybrid electric vehicles: principles and applications with practical perspectives*. John Wiley & Sons, 2017.
- [8] Lombardi, P., P. Vasquez, and Z. A. Styczynski. "Plug-in electric vehicles as storage devices within an Autonomous power system. Optimization issue." In *2009 IEEE Bucharest PowerTech*, pp. 1-7. IEEE, 2009.
- [9] Belman Martínez, Aaron. "Evolving Electric Vehicle Charging Profiles: A Crucial Consideration for Energy System Models." PhD diss., 2023.
- [10] Savari, George Fernandez, M. Jagabar Sathik, L. Anantha Raman, Adel El-Shahat, Hany M. Hasaniien, Dhafer Almakhles, Shady HE Abdel Aleem, and Ahmed I. Omar. "Assessment of charging technologies, infrastructure and charging station recommendation schemes of electric vehicles: A review." *Ain Shams Engineering Journal* 14, no. 4 (2023): 101938.

- [11] Holmén, Britt A., and Karen M. Sentoff. "Hybrid-electric passenger car carbon dioxide and fuel consumption benefits based on real-world driving." *Environmental science & technology* 49, no. 16 (2015): 10199-10208.
- [12] Ipakchi, Ali, and Farrokh Albuyeh. "Grid of the future." *IEEE power and energy magazine* 7, no. 2 (2009): 52-62.
- [13] Binetti, Giulio, Ali Davoudi, David Naso, Biagio Turchiano, and Frank L. Lewis. "Scalable real-time electric vehicles charging with discrete charging rates." *IEEE Transactions on Smart Grid* 6, no. 5 (2015): 2211-2220.
- [14] Nowakowska, M., and A. Tubis. "Load shedding and the energy security of Republic of South Africa." *Journal of Polish Safety and Reliability Association* 6, no. 3 (2015): 99-108.
- [15] Ayamolowo, Oladimeji Joseph, P. T. Manditereza, and K. Kusakana. "South Africa power reforms: The Path to a dominant renewable energy-sourced grid." *Energy Reports* 8 (2022): 1208-1215.
- [16] Singh, Ranjay, Abhishek Kumar, Arvind R. Singh, Raj Naidoo, Ramesh C. Bansal, and Praveen Kumar. "Environmental feasibility of incorporation of electric taxis in South Africa." *The Journal of Engineering* 2019, no. 18 (2019): 5078-5084.
- [17] Veza, Ibhama, Muhammad Zacky Asy'ari, M. Idris, Vorathin Epin, IM Rizwanul Fattah, and Martin Spraggon. "Electric vehicle (EV) and driving towards sustainability: Comparison between EV, HEV, PHEV, and ICE vehicles to achieve net zero emissions by 2050 from EV." *Alexandria Engineering Journal* 82 (2023): 459-467.
- [18] Rozenberg, Julie, Steven J. Davis, Ulf Narloch, and Stephane Hallegatte. "Climate constraints on the carbon intensity of economic growth." *Environmental Research Letters* 10, no. 9 (2015): 095006.
- [19] Moeletsi, Mokhele Edmond. "Future policy and technological advancement recommendations for enhanced adoption of electric vehicles in South Africa: A survey and review." *Sustainability* 13, no. 22 (2021): 12535.

- [20] Singh, Ranjay, Abhishek Kumar, Arvind R. Singh, Raj Naidoo, Ramesh C. Bansal, and Praveen Kumar. "Environmental feasibility of incorporation of electric taxis in South Africa." *The Journal of Engineering* 2019, no. 18 (2019): 5078-5084.
- [21] Pillay, N. S., A. C. Brent, and J. K. Musango. "Affordability of battery electric vehicles based on disposable income and the impact on provincial residential electricity requirements in South Africa." *Energy* 171 (2019): 1077-1087.
- [22] Buresh, Kevin. "Impacts of electric vehicle charging in South Africa and photovoltaic carports as a mitigation technique." PhD diss., Stellenbosch: Stellenbosch University, 2021.
- [23] Buresh, K. M., Mark D. Apperley, and M. J. Booysen. "Three shades of green: Perspectives on at-work charging of electric vehicles using photovoltaic carports." *Energy for Sustainable Development* 57 (2020): 132-140.
- [24] Moeletsi, Mokhele Edmond, and Mphethe Isaac Tongwane. "Projected direct carbon dioxide emission reductions as a result of the adoption of electric vehicles in Gauteng province of South Africa." *Atmosphere* 11, no. 6 (2020): 591.
- [25] Ateba, Benedict Belobo. "Electric Vehicle Deployment in China and the Associated Implications on the Electricity Grid and Carbon Footprint: Lessons for South Africa."
- [26] Deb, Sanchari, Kari Tammi, Karuna Kalita, and Pinakeshwar Mahanta. "Impact of electric vehicle charging station load on distribution network." *Energies* 11, no. 1 (2018): 178.
- [27] Bokopane, Lindiwe, Kusakana Kanzumba, and Herman Vermaak. "Is the South African Electrical Infrastructure Ready for Electric Vehicles?" In 2019 Open Innovations (OI), pp. 127-131. IEEE, 2019.
- [28] SANS 507-1:2007, "Electricity distribution guidelines for the provision of electricity distribution networks in residential areas", ISBN 978-0-626-19171-9, Standards South Africa, Pretoria.
- [29] Inglesi-Lotz, Roula. "Load shedding in South Africa: Another nail in income inequality?" *South African Journal of Science* 119, no. 9/10 (2023).

- [30] Antić, Tomislav, Tomislav Capuder, and Martin Bolfek. "A Comprehensive Analysis of the Voltage Unbalance Factor in PV and EV Rich Non-Synthetic Low Voltage Distribution Networks." *Energies* 14, no. 1 (2021): 117.
- [31] Leemput, Niels, Frederik Geth, Juan Van Roy, Annelies Delnooz, Jeroen Büscher, and Johan Driesen. "Impact of electric vehicle on-board single-phase charging strategies on a Flemish residential grid." *IEEE Transactions on Smart Grid* 5, no. 4 (2014): 1815-1822.
- [32] Leemput, Niels, Frederik Geth, Juan Van Roy, Pol Olivella-Rosell, Johan Driesen, and Andreas Sumper. "MV and LV residential grid impact of combined slow and fast charging of electric vehicles." *Energies* 8, no. 3 (2015): 1760-1783.
- [33] Koundinya, Nihith SPVS, S. Vignesh, K. Narayanan, Gulshan Sharma, and Tomonobu Senjyu. "Voltage stability analysis of distribution systems in the presence of electric vehicle charging stations with uncoordinated charging scheme." In *2020 International Conference on Smart Grids and Energy Systems (SGES)*, pp. 303-308. IEEE, 2020.
- [34] Kikhavani, Mohammad Reza, Amin Hajizadeh, and Amir Shahrinia. "Charging coordination and load balancing of plug-in electric vehicles in unbalanced low-voltage distribution systems." *IET Generation, Transmission & Distribution* 14, no. 3 (2020): 389-399.
- [35] Angelim, Jorge H., and Carolina de M. Affonso. "Probabilistic impact assessment of electric vehicles charging on low voltage distribution systems." In *2019 IEEE PES Innovative Smart Grid Technologies Conference-Latin America (ISGT Latin America)*, pp. 1-6. IEEE, 2019.
- [36] De Nigris, M., I. Gianinoni, Samuele Grillo, S. Massucco, and F. Silvestro. "Impact evaluation of plug-in electric vehicles (PEVs) on electric distribution networks." In *Proceedings of 14th International Conference on Harmonics and Quality of Power- ICHQP 2010*, pp. 1-6. IEEE, 2010.
- [37] Liu, Hui, Bin Wang, Ni Wang, Qiuwei Wu, Yude Yang, Hua Wei, and Canbing Li. "Enabling strategies of electric vehicles for under frequency load shedding." *Applied Energy* 228 (2018): 843-851.

- [38] Liu, Hui, Houlin Pan, Ni Wang, Muhammad Zain Yousaf, Hui Hwang Goh, and Saifur Rahman. "Robust under-frequency load shedding with electric vehicles under wind power and commute uncertainties." *IEEE Transactions on Smart Grid* 13, no. 5 (2022): 3676-3687.
- [39] Leou, Rong-Ceng, Chun-Lien Su, and Chan-Nan Lu. "Stochastic analyses of electric vehicle charging impacts on distribution network." *IEEE Transactions on Power Systems* 29, no. 3 (2013): 1055-1063.
- [40] Ghadimi, Noradin. "Electric Vehicle Charging Effects on Low Voltage Grids." (2018).
- [41] Khodakarami, Alireza, Hassan Feshki Farahani, and Jamshid Aghaei. "Stochastic characterization of electricity energy markets including plug-in electric vehicles." *Renewable and Sustainable Energy Reviews* 69 (2017): 112-122.
- [42] Valseira-Naranjo, Eduardo, Andreas Sumper, Roberto Villafafila-Robles, and David Martínez-Vicente. "Probabilistic method to assess the impact of charging of electric vehicles on distribution grids." *Energies* 5, no. 5 (2012): 1503-1531.
- [43] Betancur, Daniel, Luis F. Duarte, Jesús Revollo, Carlos Restrepo, Andrés E. Díez, Idi A. Isaac, Gabriel J. López, and Jorge W. González. "Methodology to evaluate the impact of electric vehicles on electrical networks using Monte Carlo." *Energies* 14, no. 5 (2021): 1300.
- [44] Yu, Yunhe, David Reihls, Saumitra Wagh, Aditya Shekhar, Daniel Stahleder, Gautham Ram Chandra Mouli, Felix Lehfuss, and Pavol Bauer. "Data-driven study of low voltage distribution grid behaviour with increasing electric vehicle penetration." *IEEE Access* 10 (2022): 6053-6070.
- [45] Antić, Tomislav, Tomislav Capuder, and Martin Bolfek. "A Comprehensive Analysis of the Voltage Unbalance Factor in PV and EV Rich Non-Synthetic Low Voltage Distribution Networks." *Energies* 14, no. 1 (2021): 117.
- [46] Jabalameli, Nasim, Arindam Ghosh, Xiangjing Su, and Binayak Banerjee. "Stochastic Assessment of Plug-in Electric Vehicles Charging in LV Distribution Network on

- Voltage Unbalance." In 2019 9th International Conference on Power and Energy Systems (ICPES), pp. 1-6. IEEE, 2019.
- [47] Razmara, Meysam, Guna R. Bharati, Mahdi Shahbakhti, Sumit Paudyal, and Rush D. Robinett. "Bilevel optimization framework for smart building-to-grid systems." *IEEE transactions on Smart Grid* 9, no. 2 (2016): 582-593.
- [48] He, Yifeng, Bala Venkatesh, and Ling Guan. "Optimal scheduling for charging and discharging of electric vehicles." *IEEE transactions on smart grid* 3, no. 3 (2012): 1095-1105.
- [49] Shaukat, N., B. Khan, S. M. Ali, C. A. Mehmood, J. Khan, U. Farid, M. Majid, S. M. Anwar, M. Jawad, and Z. Ullah. "A survey on electric vehicle transportation within smart grid system." *Renewable and Sustainable Energy Reviews* 81 (2018): 1329-1349.
- [50] Fachrizal, Reza, Umar Hanif Ramadhani, Joakim Munkhammar, and Joakim Widén. "Combined PV EV hosting capacity assessment for a residential LV distribution grid with smart EV charging and PV curtailment." *Sustainable Energy, Grids and Networks* 26 (2021): 100445.
- [51] Hariri, Ali-Mohammad, Maryam A. Hejazi, and Hamed Hashemi-Dezaki. "Investigation of impacts of plug-in hybrid electric vehicles' stochastic characteristics modeling on smart grid reliability under different charging scenarios." *Journal of Cleaner Production* 287 (2021): 125500.
- [52] Nafisi, Hamed. "Investigation on distribution transformer loss-of-life due to plug-in hybrid electric vehicles charging." *International Journal of Ambient Energy* 42, no. 7 (2021): 744-750.
- [53] Bastida-Molina, Paula, Elías Hurtado-Pérez, Ángel Pérez-Navarro, and David Alfonso-Solar. "Light electric vehicle charging strategy for low impact on the grid." *Environmental Science and Pollution Research* 28, no. 15 (2021): 18790-18806.
- [54] Leemput, Niels, Frederik Geth, Bert Claessens, Juan Van Roy, Raf Ponnette, and Johan Driesen. "A case study of coordinated electric vehicle charging for peak shaving on a low voltage grid." In 2012 3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe), pp. 1-7. IEEE, 2012.

- [55] Hartvigsson, Elias, Maria Taljegard, Mikael Odenberger, and Peiyuan Chen. "A large-scale high-resolution geographic analysis of impacts of electric vehicle charging on low-voltage grids." *Energy* 261 (2022): 125180.
- [56] Schachler, Birgit, Anya Heider, Tim Röpke, Florian Reinke, and Carsten Bakker. "Assessing the impacts of market-oriented electric vehicle charging on German distribution grids." (2021): 128-136.
- [57] Habib, Salman, Muhammad Kamran, and Umar Rashid. "Impact analysis of vehicle-to-grid technology and charging strategies of electric vehicles on distribution networks—a review." *Journal of Power Sources* 277 (2015): 205-214.
- [58] Akil, Murat, Emrah Dokur, and Ramazan Bayindir. "Impact of electric vehicle charging profiles in data-driven framework on distribution network." In *2021 9th International Conference on Smart Grid (icSmartGrid)*, pp. 220-225. IEEE, 2021.
- [59] Muratori, Matteo. "Impact of uncoordinated plug-in electric vehicle charging on residential power demand." *Nature Energy* 3, no. 3 (2018): 193-201.
- [60] Alvarez Guerrero, Jose David, Thomas L. Acker, and Rafael Castro. "Power system impacts of electric vehicle charging strategies." *Electricity* 3, no. 3 (2022): 297-324.
- [61] Tirunagari, Sridevi, Mingchen Gu, and Lasantha Meegahapola. "Reaping the benefits of smart electric vehicle charging and vehicle-to-grid technologies: Regulatory, policy and technical aspects." *IEEE Access* 10 (2022): 114657-114672
- [62] Clement-Nyns, Kristien, Edwin Haesen, and Johan Driesen. "The impact of charging plug-in hybrid electric vehicles on a residential distribution grid." *IEEE Transactions on power systems* 25, no. 1 (2009): 371-380.
- [63] Clement-Nyns, Kristien, Edwin Haesen, and Johan Driesen. "The impact of vehicle-to-grid on the distribution grid." *Electric Power Systems Research* 81, no. 1 (2011): 185-192.
- [64] Ahmed, Sina Ibne, Hossein Salehfar, and Daisy Flora Selvaraj. "Impact of Electric Vehicle Charging on the Performance of Distribution Grid." In *2021 IEEE 12th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, pp. 1-8. IEEE, 2021.

- [65] Crozier, Constance, Thomas Morstyn, and Malcolm McCulloch. "The opportunity for smart charging to mitigate the impact of electric vehicles on transmission and distribution systems." *Applied Energy* 268 (2020): 114973.
- [66] Masoum, Amir S., Sara Deilami, Ahmed Abu-Siada, and Mohammad AS Masoum. "Fuzzy approach for online coordination of plug-in electric vehicle charging in smart grid." *IEEE Transactions on Sustainable Energy* 6, no. 3 (2014): 1112-1121.
- [67] Chadha, Sonali, Vaibhav Jain, and Hemant Raj Singh. "A review on Smart Charging impacts of Electric Vehicles on Grid." *Materials Today: Proceedings* 63 (2022): 751-755.
- [68] Zhou, Xuesong, Lei Zou, Youjie Ma, and Zhiqiang Gao. "Research on impacts of the electric vehicles charging and discharging on power grid." In *2017 29th Chinese Control And Decision Conference (CCDC)*, pp. 1398-1402. IEEE, 2017.
- [69] Sohail, Abeer, Rashna Khan, Syed Hammad Mukhtar, Aiman Najeeb, and Ahmad Usman. "Effects of uncoordinated electric vehicle charging on a distribution network." In *2022 19th International Bhurban Conference on Applied Sciences and Technology (IBCAST)*, pp. 591-597. IEEE, 2022.
- [70] Rawat, Tanuj, Khaleequr R. Niazi, Nikhil Gupta, and Sachin Sharma. "Impact assessment of electric vehicle charging/discharging strategies on the operation management of grid accessible and remote microgrids." *International Journal of Energy Research* 43, no. 15 (2019): 9034-9048.
- [71] Ninković, Tamara, Martin Čalasan, and Saša Mujović. "Coordination of electric vehicles charging in the distribution system." In *2020 19th International Symposium INFOTEH-JAHORINA (INFOTEH)*, pp. 1-6. IEEE, 2020.
- [72] Solanke, Tirupati Uttamrao, Vigna K. Ramachandaramurthy, Jia Ying Yong, Jagadeesh Pasupuleti, Padmanathan Kasinathan, and Arul Rajagopalan. "A review of strategic charging–discharging control of grid-connected electric vehicles." *Journal of Energy Storage* 28 (2020): 101193.
- [73] Diaz-Londono, Cesar, Paolo Maffezzoni, Luca Daniel, and Giambattista Grusso. "Comparison and Analysis of Algorithms for Coordinated EV Charging to Reduce Power Grid Impact." *IEEE Open Journal of Vehicular Technology* (2024).

- [74] Habib, Salman, Muhammad Mansoor Khan, Farukh Abbas, and Houjun Tang. "Assessment of electric vehicles concerning impacts, charging infrastructure with unidirectional and bidirectional chargers, and power flow comparisons." *International Journal of Energy Research* 42, no. 11 (2018): 3416-3441.
- [75] Deilami, Sara, Amir S. Masoum, Paul S. Moses, and Mohammad AS Masoum. "Real-time coordination of plug-in electric vehicle charging in smart grids to minimize power losses and improve voltage profile." *IEEE Transactions on smart grid* 2, no. 3 (2011): 456-467.
- [76] Tasnim, Moshammed Nishat, Shahrin Akter, Mohammad Shahjalal, Tamanna Shams, Pooya Davari, and Atif Iqbal. "A critical review of the effect of light duty electric vehicle charging on the power grid." *Energy Reports* 10 (2023): 4126-4147.
- [77] Ibrahim, Rania A., and Ibrahim M. Gaber. "Electric Vehicles: From Charging Infrastructure to Impacts on Utility Grid." In *Power, Energy and Electrical Engineering*, pp. 326-337. IOS Press, 2024.
- [78] Venegas, Felipe Gonzalez, Marc Petit, and Yannick Perez. "Impact of non-systematic electric vehicle charging behaviour on a distribution substation." In *2019 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe)*, pp. 1-5. IEEE, 2019.
- [79] Deilami, Sara, and S. M. Muyeen. "An insight into practical solutions for electric vehicle charging in smart grid." *Energies* 13, no. 7 (2020): 1545.
- [80] Nour, Morsy, José Pablo Chaves-Ávila, Gaber Magdy, and Álvaro Sánchez-Miralles. "Review of positive and negative impacts of electric vehicles charging on electric power systems." *Energies* 13, no. 18 (2020): 4675.
- [81] Wang, Jingyuan, Guna R. Bharati, Sumit Paudyal, Oğuzhan Ceylan, Bishnu P. Bhattarai, and Kurt S. Myers. "Coordinated electric vehicle charging with reactive power support to distribution grids." *IEEE Transactions on Industrial Informatics* 15, no. 1 (2018): 54-63.
- [82] Aoun, Alain, Mehdi Adda, Adrian Ilinca, Mazen Ghandour, and Hussein Ibrahim. "Dynamic charging optimization algorithm for electric vehicles to mitigate grid power peaks." *World Electric Vehicle Journal* 15, no. 7 (2024).

- [83] Mahmud, Ishtiak, Mohtarima Begum Medha, and M. Hasanuzzaman. "Global challenges of electric vehicle charging systems and its future prospects: A review." *Research in Transportation Business & Management* 49 (2023): 101011.
- [84] Li, Yanning, and Alan Jenn. "Impact of electric vehicle charging demand on power distribution grid congestion." *Proceedings of the National Academy of Sciences* 121, no. 18 (2024): e2317599121.
- [85] Mohubedu, Simon Mabushi. "Developing a framework to promote the adoption of electric vehicles in South Africa." PhD diss., 2022.
- [86] Jaafar, Abdul Hassan, Aatur Rahman, A. K. M. Mohiuddin, and Mahbubur Rashid. "Modelling of an advanced charging system for electric vehicles." In *IOP Conference Series: Materials Science and Engineering*, vol. 184, no. 1, p. 012023. IOP Publishing, 2017.
- [87] Ramadan, Hassanien, Abdelfatah Ali, and Csaba Farkas. "Assessment of plug-in electric vehicles charging impacts on residential low voltage distribution grid in Hungary." In *2018 6th International Istanbul Smart Grids and Cities Congress and Fair (ICSG)*, pp. 105-109. IEEE, 2018.
- [88] Aslan, Nurullah, Erdal KILIC, and Mustafa Şekkel. "Modeling of Electric Vehicles as a Load Of The Distribution Grid." *International Journal of Automotive Science And Technology* 7, no. 1 (2023): 54-62.
- [89] Nour, Morsy, Abdelfatah Ali, and Csaba Farkas. "Evaluation of electric vehicles charging impacts on a real low voltage grid." *Int. J. Power Eng. Energy* 9, no. 2 (2018): 837-842.
- [90] NRS 048-2: 2007, "Electricity Supply – Quality of Supply. Part 2: Voltage characteristics, compatibility levels, limits and assessment methods," 2007.
- [91] Standard, I. E. C. "61000-4-27: Testing and Measurement Techniques- Unbalance." *Immunity Test*, Aug (2000).
- [92] Mongale, Tebogo, Kanzumba Kusakana, and Patric Manditereza. "Modelling the Impact of Uncoordinated Plug-In Electric Vehicles' Charging Patterns on the Low Voltage



Distribution Network." In 2024 7th International Conference on Electronics and Electrical Engineering Technology (EET), pp. 21-28. IEEE, 2024.