AKENTEN APPIAH-MENKA UNIVERSITY OF SKILLS TRAINING
AND ENTREPRENEURIAL DEVELOPMENT

ASSESSING THE IMPACT OF ELECTRIC VEHICLE CHARGING ON LOW VOLTAGE DISTRIBUTION SYSTEM OF TAKORADI

RICHARD ARTHUR

APRIL, 2023

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BY

RICHARD ARTHUR
(200029582)

A thesis submitted to the School of Graduate Studies, Akenten Appiah-Menka University of Skills Training and Entrepreneurial Development in partial fulfillment of the requirements for the award of a Master of Philosophy degree in Power Systems Engineering.

APRIL, 2023

DECLARATION

Candidate's Declaration

I declare that this thesis is the result of my own original work and that no part of it has been presented for another degree at this university or elsewhere.

Candidate's Name …………………………………….

Signature: .... Date: ....

Supervisor's Declaration

I hereby declare that the preparation and presentation of this thesis was supervised in accordance with the guidelines on supervision of thesis laid down by the Akenten Appiah-Menka University of Skills Training and Entrepreneurial Development.

Supervisor's Name: ……………………………………………………………………….

SIGNATURE: .... DATE: ....

ABSTRACT

This research assessed the impact that EV charging has on low voltage (LV) distribution systems at different penetration levels. The existing electric power distribution system of Takoradi, the Western Regional capital city of Ghana was modelled using the power analysis software Electrical Transient and Analysis Program (ETAP 19.0.1). Load flow analysis was then performed on the low voltage distribution system to further assess the total amount of EVs the distribution system can handle. EVs charging impacts on the current LV distribution system were assessed under three different scenarios; current state, minimum and maximum uptakes penetration levels of EVs. Two different EV charger models were employed to represent home charging (HC)-7.4 kW level-2 and fast charging (FC)-50 kW level-3. Voltage variations and transformer loading at twelve substations were meticulously noted in all simulations. The load flow simulation did not show any significant impact on the distribution system at the current state and minimum uptake penetration levels. However, at a maximum penetration level of 1.88% for HC and 1.11% for FC, under voltage conditions were observed at most of the buses with the condition deteriorating to the highest penetration level of 11.63% and 6.87% for HC and FC respectively where the system tend to fail. Domestic/ household loads significantly increased along with the increment of EV penetration levels over the years which contributed to total instability of Takoradi Distribution System (TDS). The impact that EV charging has on low voltage systems are expected to differ from one region to another, based on how many vehicles that are used in a locality, the current power demand, and the layout of the network. In effect, EV loads operating under different charging types have observable impacts on both the load and the voltage variables. The findings of this thesis will assist policy-makers take the appropriate actions needed to manage EV loads.

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DEDICATION

This thesis is dedicated to Mr. John and Mrs. Benedicta Amakye

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

FIGURE PAGE

LIST OF ACRONYMS

AC	Alternating current
BEV	Battery electric vehicles
BMS	Battery management system
BSS	Battery Swap Station
CC	Charging current
CC	Conductive Charging
CO2	Carbon di-oxide
CPF	Continuous power flow
CV	Charging voltage
CYGR	Compounded yearly growth rate
DC	Direct current
DTs	Distribution transformers
ECG	Electricity Company of Ghana
EMI	Electromagnetic induction
EREV	Extended-range electric vehicle
ETAP	Electrical Transient and Analysis Program
EU	European Union
EVs	Electric vehicles
FC	Fast Chargers
FC-PHEV	Fuel cell plug-in hybrid electric vehicles
GHG	Greenhouse gas
HC	Home Chargers
HEV	Hybrid electric vehicles
ICE	Internal combustion engine

ICEVs	Internal combustion engine vehicles
IEC	International Electrotechnical Commission
IPT	Inductive Power Transfer
Li-ion	Lithium-ion
LV	Low voltage
LVD	Load voltage deviation
MV	Medium voltage
NiMH	Nickel-metal-hydride
OEM	Original Equipment Manufacturers
PEV	Plug-in electric vehicles
PHEV	Plug-in hybrid electric vehicle
ZIP model	Polynomial load model
PHC	Population and Housing Census
P-PHEV	Parallel hybrid topology
PQ	Power quality
PURC	Public Utilities Regulatory Commission
S-PHEV	Series hybrid topology
SP-PHEV	Series-parallel configuration
SA	South Africa
SoC	State of charge
TDS	Takoradi Distribution System
USA	United States of America
WPT	Wireless Power Transfer
VDL	Voltage dependent load
VRI	Vehicle to refueling station index

CHAPTER ONE

INTRODUCTION

1.1 Background to the study

In the last few years, electric vehicles (EVs) are considered to be more environmentally friendly thus, recognized as the viable replacement for internal combustion engine (ICE) vehicles to reduce emissions in the transportation industry. In order to combat climate change and urban air pollution, leadership of industrialized nations are taking action to promote the development and marketing of EVs while most of these nations have developed emission regulations (Gomez´ Vilchez, & Jochem, 2020; Glitman, Farnsworth, & Hildermeier, 2019; USEPA, 2019; Akumu, 2019) to regulate emissions produced by light cars.

National and local governments in several nations have begun to assist the use of EVs by giving them preferential status over conventional vehicles through initiatives such as tax breaks, free access to places with little traffic, reduced parking costs, bus lanes, etc. (Ayetor, Quansah & Adjei, 2020). According to (Franz & Nasca, 2021), policymakers are promoting EVs as being more environmentally friendly than cars with ICE. It can be said that an important amount of air pollution is caused by ICE automobiles. (Approximately 16% of the total greenhouse gases (GHG) emitted by humans). This has a negative impact on human health and makes the air quality worse. (Khalid et al., 2019; Burillo et al., 2019).

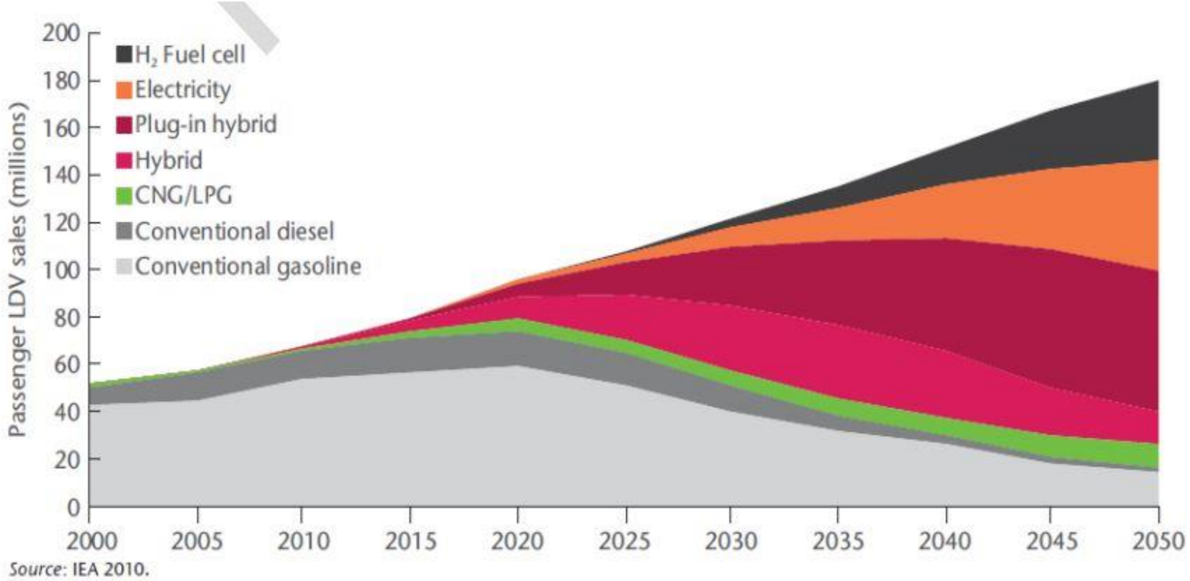
With around 370 different models, the worldwide electric vehicle fleet reached 10 million units in 2020 which only accounts for 1% of the global automobile fleet (Cazzola et al., 2021). China (45%), Europe (24%), and the United States of America -USA (22%) account for the majority of the world's electric vehicles (EVs) (IEA, 2021). 18 of the top 20 Original Equipment Manufacturers (OEM) have indicated their plans to electrify their products by 2030. Within the next 30 years, the European Union (EU) plans to completely phase out ICE automobiles (IEA, 2021). By 2050, about 22 nations have committed to either completely banning ICEV sales or achieving emission free environment. By 2050, both the European Union and the USA hope to achieve zero emissions. The only African country to do that is Cabo Verde, which has promised to build an EV fleet for both public and private transportation by the year 2050, slowly replacing ICEVs. This is due to very few OEMs having immediate plans to put on sale or build EVs in Africa. Volkswagen and other OEMs have committed to selling only EVs in Europe by 2035 but have decided to delay new EV sales in Africa through 2050 (Cars, 2021). Nevertheless, given that Europe and the USA account for the majority of used car imports into Africa, some of the used EVs will probably arrive in Africa earlier than anticipated (Ayetor et al., 2021; Baskin, 2020).

Currently, EVs being imported to Africa nations is restricted by the absence of rules, incentives, and subsidies as well as access to dependable electricity. It is expected that South Africa (SA), which has the most automobiles on the continent, will lead the EV race. Although, just 5000 EVs were utilised in SA at the start of 2020. (eNaTIS, 2020; Gaylor et al., 2020). Shockingly, Mauritius is leading in Africa with about 17,000 EVs as at 2021 (NLTA, 2021). Ghana received over 5,400 Plug-in Electric Vehicles (PEV) between 2017 and 2020. Most of the PEVs were plug-in hybrid electric vehicles (PHEV), a hundred of such EVs, however, were battery electric vehicles (BEV) (ITC, 2020).

The European Commission announced the “20/20” in 2020 climate and bundle of energy in 2008 with the intention to increase the development of renewable fuel sources and decrease carbonic acid emissions (European Commission, 2008). The effects of climate change, rising gasoline costs, the anticipated shortage of oil, and upgrading of battery technology have persuaded a number of automobile manufacturers worldwide (International Energy Agency, 2011) in purchasing brand-new battery-powered car types known as EVs. With Canada’s climate change action plan, a smooth switch to low CO2 technologies might be accomplished without difficulty

(Arias-Londoño, Montoya & Grisales-Noreña, 2020). The plan provides programmes and offering rewards to encourage domestic and businesses to aid in the transformation. One significant element restricting the demand for EVs is the scarcity of EV charging infrastructure. In light of this, Canada has the plan to set a free nightly EV charging for four years for domestic clients since 2017 (Palomino & Parvania, 2018).

Again, it planned to make investments to make charging stations more accessible. The results of studies suggest that availability of EVs in the developing countries can effectively meet 90% of the population's daily driving requirements (Moon et al., 2018; Sexauer, McBee & Bloch, 2012). Possibly, the demand for EV charging load requirement could increase due to the anticipated growth in the deployment of EVs. By 2050, the global target set forth in the Energy Technology Perspectives 2010 BLUE Map is to decrease poisonous emissions caused by energy use by 50%. (Crozier, Morstyn & McCulloch, 2020). To meet the BLUE Map's goal, BEV and PHEV technologies must advance quickly and be used by a large number of light-duty vehicles. By 2030, it is anticipated that 9 million EVs would be sold, compared to 25 million PHEVs. According to the BLUE Map scenario, it is anticipated that by 2050, each vehicle type will sell 50 million units yearly. Figure 1-1 depicts the breakdown of the light-duty car sales annually by technology.



Source: IEA 2010.

Figure 1-1: Yearly light-duty car sales by technology in BLUE Map scenario

Governments all around the world have already set goals for EV adoption in light of recent worries about climate change and the depletion of hydrocarbon deposit. Deployment of EVs have significantly expanded in recent years due to numerous government incentives and current technology advancements. A large portion of the power system loads will be used to compensate for EV charging as the energy consumed for mobility depletes the power system. Taking into account the features of an EV load, the power system's voltage and oscillation stability may benefit. The absence of a charging infrastructure is a serious obstacle to the widespread use of EVs. As a result, governments and EV investors that are interested can take action to develop a charging infrastructure.

The existing charging methods, however, have not given grid issues enough consideration. Though necessary given that many current power systems are operating on the edge of instability, the impact of EV charging on the stability of the power grid of an electrical supply is not completely taken into account. A significant problem is the lack of suitable load models to represent EV load in stability investigations is a major drawback which needs to be addressed.

The impact of EV on low voltage distribution system includes voltage instability, increased peak demand and various power quality issues that has to be addressed (Tiano et al., 2018). When BEV and PHEV are integrated with utility grid, they are treated as a load in a power system. EVs create transformer losses, which raise the temperature and shorten the transformer's lifespan because battery charging is nonlinear (Alame, Azzouz & Kar, 2020). If EVs are widely used, the impact the additional electric demand could have on the system is either positively or negatively (Obeidat et al., 2021; Khalid et al., 2021; Figenbaum, 2017, Soares et al., 2013). In reality, if there are no restrictions on EV charging, the surge in demand during peak electricity hours may complicate the functioning of the power system and lead to the underutilization of power produced by renewable sources. (Hong, Wilson & Xie, 2014; Richardson et al., 2013). As a result, unrestricted charging may necessitate investing in more generating and transmission capacity, wearing down distribution components more quickly, and creating issues with power quality. (Obeidat et al., 2021; Nour et al., 2018; Clement-Nyns, Haesen & Driesen, 2010). If EV charging is aided by more sophisticated charging schemes, both the value provided for the electric energy industry as well as the environmental value might improve (Figenbaum, 2017; Soares et al., 2013; Richardson, Flynn, & Keane, 2012; Lopes, Soares, & Almeida, 2011).

Since under voltage conditions in power system cause disturbance in the system thus, in a situation when there is a heavy load it becomes difficult to deliver the reactive power (VAR) over long distances hence, there is the tendency of generating reactive power close to the load. This is because voltage differences cause reactive power (VARs) to flow, yet power system voltages are only around ±5% of the nominal, therefore the flow of reactive power (VARs) over long distances is not very significant due to this minor voltage difference. Wherefore, the voltage level drops if that reactive power (VARs) is not present at the load centre; certain electronics, like motors, can experience excessive wear and tear from operating at low voltages because they will run too hot (Bilal, Arbab & Zubair, 2019).

1.2 Statement of problem

Despite the environmental friendliness of EVs which vehicular manufacturers globally have adopted and are gradually shifting from ICE vehicles (conventional vehicles) to electric vehicles to decrease the high-rise nonrenewable energy impot and greenhouse emissions from the transportation industry; yet present further obstacle for power providing companies to overcome the rising demand for EVs. (Khalid et al., 2021; Lhendup et al., 2020; Khuntia et al., 2016). Nonlinear loads, like EV chargers, can cause disturbance in distribution circuits, which could harm system components. High penetration of EVs on distribution systems can have numerous negative impacts such as voltage variations or deviations, transformer loading, harmonic distortion, direct current (DC) offset, phase imbalance, etc. if not mitigated. This thesis focuses on power quality challenges introduced by EV charging stations. Consequently, the need has arisen to assess the impact that voltage variation and transformer loading introduces on LV distribution system of Takoradi-Ghana as a result of EV charging.

1.3 Purpose of the study

Considering the urgency with which fossil fuel supplies are running out and the drive that results from this, EVs have the potential to become the most essential mode of transportation on the planet. Nonetheless, with the growing demand for EVs is likely to pose power quality issues or power system constraints such as voltage variation and transformer loading in the distribution feeders which is of great concern to power utilities across the globe. Therefore, there is a need to find out the performance and the capacity of the LV distribution system of Takoradi due to integration of additional EV loads. The research gives an evaluation of how EV charging affects the power distribution infrastructure of Takoradi-Ghana at different penetration levels considering voltage variations and transformer loading.

1.4. General objective

The general objective of this research is to perform a load flow analysis on the low voltage distribution system of Takoradi-Ghana and further assess the total amount of EVs the distribution system can handle.

1.4.1 Specific objectives

This research is focused to accomplish the precise set objectives;

1. Develop a model of an existing low voltage distribution system of Takoradi (station OB), using Electrical Transient and Analysis Program (ETAP).
2. Assess the impact of EV charging on transformer loading and voltage variations at different EV penetration levels.

3. Investigate to what extent the existing low voltage distribution system can accommodate the integration of EVs taking into account the growth of household loads without any upgrades to the current distribution system.

1.5 Significance of the study

EVs significantly contribute to the gradual transition to a low greenhouse gas (GHG) environment. EVs have the overall impact of giving people a choice. Gasoline-powered vehicles will most likely never go ‘out of style’ due to their heritage and history. It is predicted that consumption of energy will rise as the population grows by which urbanization increases and financial system will raise too. Simply said, the purpose of electric vehicles is to help people save money, protect the environment, and prevent the early depletion of fossil fuel resources.

Assessing the impact of anticipated growth in EV charging is paramount. Therefore, maintaining a secure operation, dependability, and high performance of power system elements depends heavily on EV charging. The EV exhibits unpredictable dynamic behaviour in addition to having an energy demand similar to that of a typical household.

Furthermore, it is impossible to predict in advance where, when, or for how long an EV will be connected for charging or how much real and reactive power it will use. As a result, it is prudent to find out the likely impacts of EV penetration on power systems. Recognizing the dangers posed by the growing integration of EVs on the grid to guide governments, EV investors, power distribution companies and other stake holders to take the appropriate actions needed to manage EV loads. In addition, policymakers might take precautions to avoid major technological and economic difficulties. (Khalid et al., 2021; Zhixiong & Zhensheng, 2021; Ayetor et al., 2020; Jreige, Abou-Zeid & Kaysi, 2021; Yan & Kezunovic, 2012). And also develop standards and regulations to guide and govern the growing EV sector in Ghana.

1.6 Scope of the study

The research provides an assessment of transformer loading and voltage variations on the LV distribution infrastructure of Takoradi (station OB) due to additional load of EVs at different penetration levels.

1.7 Organisation of the study

The research is organized as follows: Introduction to chapter one contains the background to the research, problem statement, significance of the study, purpose of the study, research objectives, scope and organization of the study. Chapter two deals with the related literature. The review involves empirical studies and the concept review of the problem under study. A summary of the research methodology is presented in Chapter three. The presentation and data analysis, the results and discussion of the study are presented in Chapter four. Chapter five summarizes the research findings and provides conclusion from the findings including recommendations and suggestions for future studies.

CHAPTER TWO

LITERATURE REVIEW

This chapter discusses the background information and current research that were necessary for this research. The chapter contains EV technology and market scope, EV charging infrastructure, powertrain configurations and topologies, adopted standards for EVs in Africa, Ghana’s readiness for EV, low voltage distribution grid of Ghana, EV charging demand and user behaviour and the impact of EVs on LV distribution system.

2.1 EV history and trend

There is a change underway that will bring in the widespread use of EVs within the next decade. (Randall, 2016). To achieve targets for lowering greenhouse gas (GHG) emissions, EVs been viewed as an alternative to ICEVs. The globe appears to have more hope for EVs now. (Obeidat et al., 2021, Rolim et al., 2013). Due to the urgent problem of oil resource depletion, EVs have the ability to become the most essential form of transportation globally during the next 30 to 40 years. (Jreige, Abou-Zeid & Kaysi, 2021; Sorrell et al., 2010). Penetration levels of EVs are anticipated to rise significantly in the ensuing years, with projections indicating that by 2040, about 30% of the world's passenger fleet will be electric. (McKerracher, 2019). EVs offer an intriguing solution to the increasing reliance on fossil fuels because they significantly reduce air pollution.

However, the interaction and deployment of EVs on the existing power system is the key reasons why deployment of EV is still hampered by many challenges, (Zhixiong & Zhensheng, 2021; Held et al., 2019). The secure and dependable function of computers and commercial machinery is impacted by the quality of the energy (Chudy & Mazurek, 2019). BEV and PHEV are the key emerging technologies to decrease fossil fuel emissions (Jreige, Abou-Zeid & Kaysi, 2021; Putrus et al., 2009). The power system network may have severe stability issues because of the dynamic nature of EV charging (Khuntia et al., 2016). The infrastructure functioning parameters will deteriorate due to quick EV charging at the stations with significant charging demands. Energy issues will be faced by distribution companies all over the world due to the heavy request for EV charging loads. (Lhendup et al., 2020; Burillo et al, 2019). For example, in North America, the utility firms had to construct new producing plants to handle the increased demand from EVs. (Hadley, 2006). Currently, ongoing problem associated with the introduction of new EVs is voltage stability because of the increasing penetration level of EVs. (Lhendup et al., 2020; Bhavanam et al., 2015; Dharmakeerthi, Mithulananthan & Saha, 2014). Voltage instability is reportedly more substantial as a result of EV charging, according to several research conducted in the past. Furthermore, peak times for household loads sometimes coincide with voltage dips experienced by residential customers as a result of the high inrush current used by EV charging. (Klayklueng & Dechanupaprittha, 2014).

As EV sales increase, the request and pressure for charging also increases. Consequently, the creation of a charging infrastructure and effective Inductive Power Transfer (IPT) (Alam et al., 2017) has become necessary to meet the requirements of substantial operation of the EVs (Foley, Winning, & Gallachóir, 2010). Since the distribution system's operating parameters would degrade as a result of the high charging loads of fast EV charging stations, the more charging stations puts additional demand on the network. Unregulated charging of EVs have a quite number of negative impacts, including harmonic distortions, violation in voltage profile, and a rise in peak load

Although both ICE and electric motors are included in HEVs and PHEVs, their ways of operation are distinct. Each topology thus; series, parallel, series-parallel, or complex can be used to combine HEV components. Due to the All-Electric Range feature, which enables a significant mode of operation for HEVs, PHEVs are an advancement over HEV technology and a symbol of the seeming prosperity in the automotive industry because of its less fuel usage and emission

(Khalid et al., 2021; Liu, Wen, & Ledwich, 2012). PEVs are similar to HEVs in terms of their drivetrain layout, but they include larger batteries that can be electrically recharged by the power supply (Gray & Morsi, 2015). Since BEVs only use batteries to power the vehicle, they represent a green technology with zero carbon emissions. The adoption of BEVs presents a number of difficulties, mostly caused by their extreme initial expense, short driving range, and lack of charging infrastructure (Crozier, Morstyn, & McCulloch, 2020). Fuel cell automobile and BEV have similarities except it uses fuel cell as its power supply (Unda et. al. 2014; Richardson, Flynn & Keane, 2010). These studies make it clear that as EV penetration rises, distribution network stability problems will also rise. Therefore, there is a need to find out to what extent the exiting low voltage distribution system can accommodate EV penetration without any upgrades to the current distribution system, taking into account the typical development of household loads.

2.2 State-of-the-art of EV technology advancement

2.2.1 Charging techniques for EVs

As briefly discussed below, there are essentially three different types of EV charging techniques:

2.2.1.1 Battery Swap Station (BSS)

This technique assumes that the battery is rented out on a monthly basis to the BSS owners. This technique uses technology for slow charging, which helps to increase battery life (Ahmad et al., 2018). Locally produced Renewable Energy Sources (RES) like solar and wind can be more easily included into the BSS system. Because of this technique, the drivers can stay inside the car while the dead battery is rapidly replaced. Furthermore, the BSS's battery can be used for the V2G effort. (Sinsel, Stephan, and Gschwendtner, 2021)

2.2.1.2 Wireless Power Transfer (WPT)

This technique uses both primary and secondary coils that are dependent on electromagnetic induction (EMI). The primary coil is positioned on the road, and the secondary coil is positioned inside the car. Due to its capability to enable the EV to recharge conveniently and safely, this technology is currently being accepted. The ability to charge while moving cars is another benefit. Sanguesa et al., 2021)

2.2.1.3 Conductive Charging (CC)

Conductive charging is a technique that needs a direct electric connection between the car and the charging input and offers a high level of charging efficiency. These are the various kinds of charging stations that can be utilized with this technology: Chargers at each level: Level 1, Level 2, and Level 3. For a public charging station, Level 2 and Level 3 are used (Jha and Shrestha, 2021).

2.3 PHEV and BEV powertrain configurations and topologies

This section focuses on EV configurations and topologies. A vehicle with at least one electric motor for traction is considered as EV (Villalobos, 2016). Although there is no worldwide definition for a PEV, but U.S department of energy defines PEV as a light vehicle that uses a battery having a minimum capacity of 4 kWh which is rechargeable from a different supply (US Department of Energy). From the definition, several PEV types can be recognised within this category, primarily PHEVs, BEVs, and fuel cell plug-in hybrid electric cars (FC-PHEV). Depending on how the components and modules interact and how the hybrid system is configured, hybrid powertrains can have one of three basic topologies.

The three topologies—parallel, serial, or combination (power-split)—each have unique characteristics in terms of their weight, price, efficiency, and user-friendliness. Certain benefits and drawbacks are presented by each powertrain architecture. A generator is connected to the traditional ICE in a serial hybrid powertrain system, which is utilised in extended range EVs like the Chevrolet Volt.

The electrical device wired in line to feed electricity into a battery system powered by an onboard generator. This design enables the ICE to operate more efficiently and reduces the time it needs to charge the battery system. To move the vehicle forward, a parallel- hybrid powertrain uses ICE and electric motor, increasing both efficiency and torque (Villalobos, 2016; Shafiee et al., 2012). Because this initial configuration type does not require the generator as a propulsion system, the scaling of parallel HEVs is easier than that of series HEVs. (Arias-Londoño, Montoya, & Grisales-Noreña, 2020).

The most promising of all EV kinds, comes in either parallel or series basic designs. Regenerative braking is used in both architectures to increase system efficiency by adding any extra energy produced while braking to the battery charge (Palomino & Parvania, 2018). The power-split topology is a hybrid design approach used in EVs like the Toyota Prius that combines serial and parallel hybrid architectures. The concept allows for continuously shifting transmission ratios and ideal engine operating conditions by using two electric machines to support the ICE. The series-parallel topology's complex size is caused by the need for several propulsion systems (Sexauer, McBee, & Bloch, 2012). From 2003 to 2012, parallel HEV powertrain architecture dominated the global car market. The power-split type is the second most prevalent architecture introduced during those years, frequently found in Asian vehicles like Toyota (Alame, Azzouz, & Kar, 2020).

BEVs use a variety of distinct powertrain architectures made up of varied quantities and arrangements of the systems and components. Compared to the central motor, the axle motor is more frequently integrated. Alternately, electric machines can be incorporated within the wheel-hub and doing so will reduce driving comfort and dynamics. The Infiniti Emerg-E, which has two motors inside the wheel-hub, and other large luxury automobiles and high-performance prototype automobiles typically use this topology (Rutherford &Yousefzadeh, 2011).

2.3.1 Series-hybrid powertrain

The series hybrid architecture (S-PHEV) has solely electric propulsion, which can be powered by either the ICE using an electric generator or the onboard batteries. Super-capacitors are an alternative energy storage option to batteries. Because there is no requirement for a multiple-speed gearbox or gear box with traction electric, the vehicle is lighter and more straightforward (Villalobos, 2016) as depicted in Figure 2-1.

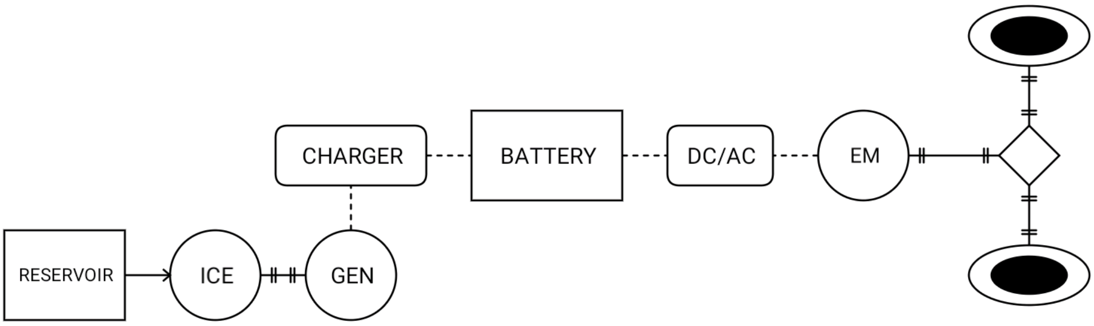


Figure 2-1: Series-hybrid power train configuration (Villalobos, 2016)

A significant disadvantage of this architecture, though, is the sheer volume of energy transformations required. In other words, the ICE's mechanical power must be turned first into electric power, and then back into mechanical power. The efficiency suffers accordingly, especially at high speeds (Alame, Azzouz, & Kar, 2020 and Villalobos, 2016).

2.3.2 Parallel-hybrid powertrain

The most typical and affordable hybrid architecture is the parallel-hybrid topology (P-PHEV). (Palomino & Parvania, 2018; Villalobos, 2016). The mechanical transmission of parallel-hybrid is more complicated compared to the one in series-hybrid version, but the electric generator is eliminated. The electric motor only functions if the battery is not discharged, so the ICE must be built to give the greatest request for sustainable energy. This makes the ICE in the parallel-hybrid architecture huge compared to the series hybrid architecture; however, the electric motor and batteries are portable. This architecture is therefore better suitable for high speeds. However, due to its diminished battery capacity and electric motor power makes it ineffective at slow speeds (Villalobos, 2016). Figure 2-2 shows parallel hybrid power train topology, where both engines have the ability to create a traction.

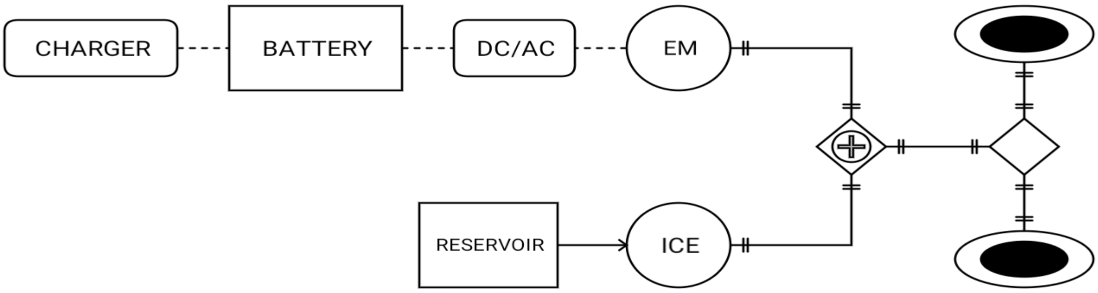


Figure 2-2: Parallel hybrid power train topology (Villalobos, 2016)

An alternate parallel-hybrid uses an ICE to power one axle while an electric engine powers the other. The mechanical system is streamlined in this manner, and four-wheel traction is made possible. When the driver brakes or the battery runs out in this design, the electric engine can also function as regenerative braking, charging the battery (Arias-Londoño, Montoya, & Grisales-Noreña, 2020; Villalobos, 2016).

2.3.3 Series-parallel hybrid topology

In a series-parallel design (SP-PHEV), the ICE can provide both electrical power and mechanical torque. With the help of a power-split component, the SP-PHEV can transmit ICE torque to either the wheels or the generator. Figure 2-3 shows series-parallel hybrid power train topology.

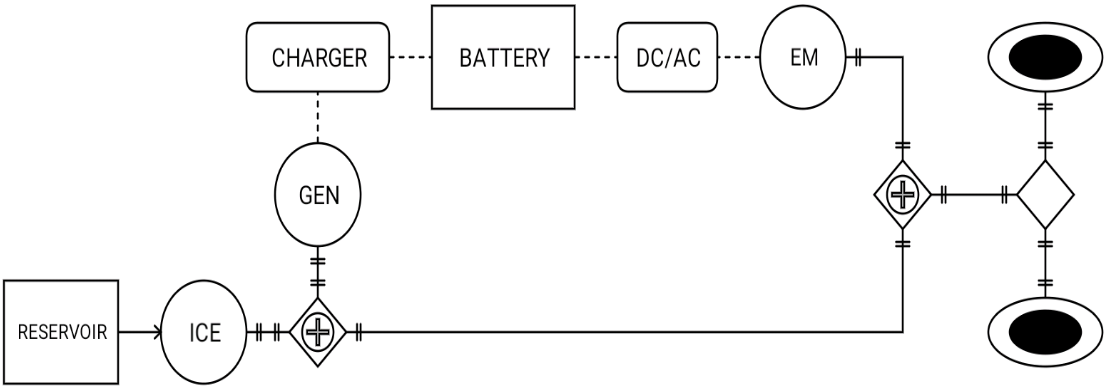


Figure 2-3: A series-parallel hybrid powertrain architecture (Villalobos,2016)

To maximise performance and efficiency, a control system chooses the ideal compromise between the two-traction equipment (Khalid et al., 2021; Alame, Azzouz, & Kar, 2020; Gomez ´Vilchez & Jochem, 2020; Villalobos, 2016). The mechanical complexity of the system necessitates the use of a generator, as in the series hybrid design. Due to that, the price is somewhat more expensive than with series and parallel train designs. (Villalobos, 2016).

2.3.4 Battery electric vehicle

The only sources of power for battery powered EVs are batteries and ultracapacitors. Electricity from the grid is used to recharge these batteries. Additionally, brakes that regenerate energy may be utilised to recharge the batteries as the car slows down. (Villalobos, 2016). Figure 2-4 shows the battery electric vehicle (BEV) basic architecture.

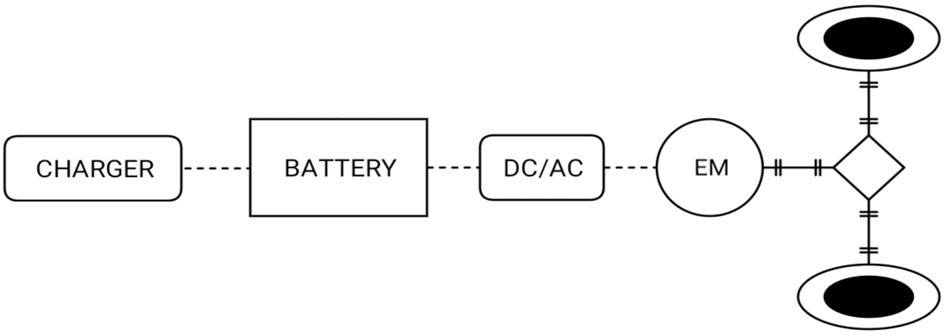


Figure 2-4: BEV basic architecture (Villalobos, 2016)

According Figure 2-4 the topology of BEVs and the main components include: Electric battery, that powers every BEV loads. Battery management system (BMS), which keeps track of and regulates the total condition of the battery to prevent premature battery deterioration and safety concerns. An electric charger that, in accordance with BMS draws energy from the electrical grid to charge the batteries. A motor drive or inverter that converts direct current to alternating current. The vehicle's electric traction motor is powered by the chargers and an electric motor, which provides the vehicle with the mechanical torque it needs.

2.4 Configuration of EV charger

The EV charger divides the power used to charge EVs into an AC side and a DC side. It is possible to display the individual charging capacities of the two sides when combining different types of batteries with EV chargers. The battery charging power can be used to represent the DC load model boundary, whereas the single EV load model is the AC side load model. Figure 2-5 shows EV charger setup for one phase load modelling.

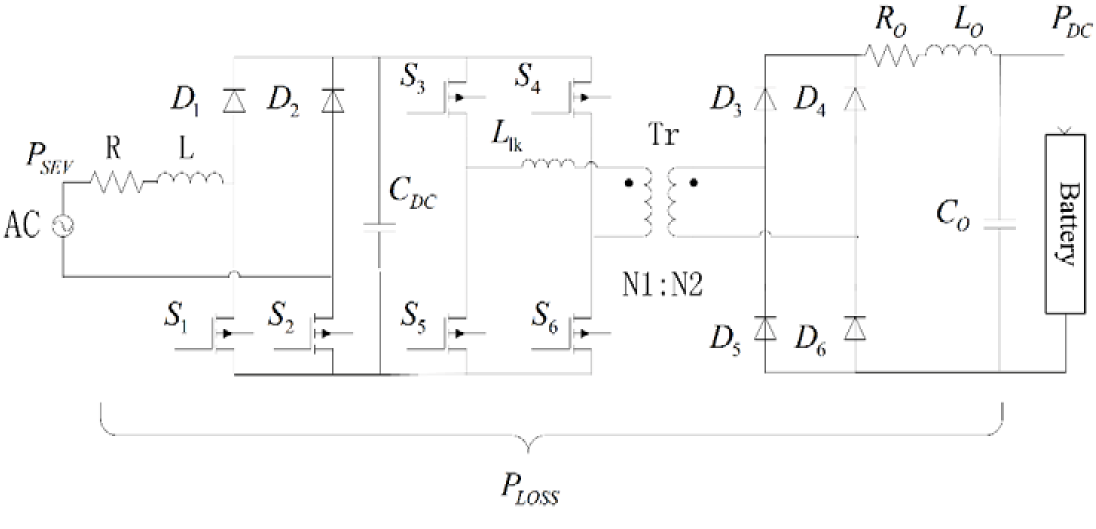


Figure 2-5**:** Single-phase EV charger configuration (Fan, Wang &Yan, 2018)

Modeling EV load with different types of chargers is possible. Experiments are used to validate the dynamic characteristics of the lithium-ion battery model, and they exhibit high accuracy (Fan, Wang &Yan, 2018; Tremblay & Dessaint, 2009). Simple battery datasheets from manufacturers can be used to get the dynamic battery model parameters (Fan, Wang &Yan, 2018; Tremblay &

Dessaint, 2009). The constant voltage charging procedure is used to start the battery's charge before switching to the constant current charging operation., in the range of 20% to 90% SoC. (Fan, Wang &Yan, 2018: Qian et al., 2011).

2.5 Global standards for EV chargers

A group of specialists develops the worldwide standards, which are thereafter generally embraced. Different global standards have been created and published in order to successfully deploy EV chargers. Table 2-1 and Table 2-2 discuss the various EV charging standards that are mentioned in literature (IEEE Standard 1547, 2018, NFPA 70, 2011, and CHAdeMO Protocol Development, 2018).

Table 2-1 Global standards for EV chargers (Khalid et al., 2021)

National Fire Protection Association (NFPA)	**Underwriters Laboratories (UL) Inc**	**International Organization for Standardization**	**International Electromechanical Commission (IEC)**	**Japan Electric Vehicle Association**
•NFPA 70: Safety management •NEC 625/626: Charging systems for EVs. •NFPA 70E: For safety. •NFPA 70B: Maintenance of electrical equipment.	•UL 2231: Safety Purposes. •UL 2594/2251, 2201: EVSE	•ISO 6469-1:2009: Used for on-board rechargeable energy storage systems. • ISO/CD 6469-3.3: Safety specifications	• IEC-1000-3-6: Issues of power quality. • IEC TC 69: Regarding infrastructure of charging and safety requirements. •IEC TC 64: Electrical installation, electric shock protection. • IEC TC 21: Regarding battery management.	•JEVS C601: EVs charging plugs. •JEVS D701: Batteries. • JEVS G101-109: Fast Charging.

Table 2-2 Continuation of global standards for EV chargers (Khalid et al., 2021)

Society for Automobile Engineers (SAE)	**Institute of Electrical and Electronics Engineers (IEEE)**	**Isolation and Technical Safety Standards**
•J1772: EV conductive connector/ charging approach. •J2894: Issues of power quality •J2836/2847/2931: Communication purposes. •J1773: Inductive coupled charging. •J2293: The specification for EVs can be found for energy transfer systems.	•IEEE 2030.1.1: Fast DC charging for EVs. •IEEE P2690: Charging network management, Vehicle authorisation. •IEEE P1809: Electric transportation guide. •IEEE 1547: Interconnecting electric system with distributed resources/Tie Grid. •IEEE 1901: Provides data rate when vehicles are charged overnight. •IEEE P2030: Interoperability of smart grid. •IEEE 519-2014: Power quality standards	•SAE J-2929: Standard relates to the propulsion battery system's safety. • SAE J-2910: This standard covers tests for hybrid electric trucks and the electrical safety buses. •SAE J-2344: Lays out guidelines for EV safety. • SAE J-2464: The safety guidelines for rechargeable energy storage systems (RESS) •ISO 6469-1:2009 (IEC): Standard relates to electrically powered vehicles, on-board RESS, inside and outside personal protection. • ISO 6469-2:2009 (IEC): Safe EV operation and protection against internal failures •ISO 6469-2:2001 (IEC): Protections against electrical hazards •IEC TC 69/64: Infrastructure for EV safety, electrical installation, electric shock protection. •NFPA 70/70 E: Guidelines for workplace safety, charging system security, branch circuit protection. • UL 2202: The protection of the charging system is covered by standards. • UL 2231: This standard deals with the protection of the supply circuits. • UL 225a: It offers safety guidelines for couplers, plugs, and outlets. • DIN V VDE 0510-11: Outlines safety guidelines for installing batteries and using backup batteries.

These global standards have been carefully designed to address the safety, dependability, and interoperability concerns of the EV sector (Falvo et al., 2014; Khalid et al., 2021). These standards are used by a number of different industries, including as EV manufacturers, ESS manufacturers, EV charger safety equipment manufacturers, utility companies, EV charger manufacturers, code authorities, researchers, academics, and insurance firms.

2.6 Deployment of EVs in Africa

In the upcoming years, huge investments will be made in the electricity sector by numerous African nations to improve environmental sustainability whereas increasing access to energy (Ayamolowo et al., 2022; Du et al., 2021; Qudrat-Ullah & Nevo, 2021; Maji et al., 2019; Mutombo & Numbi, 2019). Additionally, due to urbanization and the rate of anticipated population increase, proprietorship of automobile is anticipated to increase rapidly across the continent., As a result, African nations can pursue a low-cost and sustainable energy strategy by utilizing the current state of the world's EV uptake, whiles avoiding becoming ensnared in carbon-intensive energy infrastructures (Hill et al., 2018).

With 72 million vehicles now in use, emissions from the transport sector in Africa are expanding at a pace of 7% annually. (Ayetor et al., 2021). The 2.5 million registered automobiles in Ghana provided 44% of the country's 2016 carbon emissions (EPA, 2018). EVs have been seen as the optimum way to cut emissions in the transportation industry. Most African nations view pure electric vehicles as the technology that will allow them to finally transition to zero emissions and reduce their carbon footprint (Ayetor, Quansah & Adjei, 2020). This will assist in achieving some environmental sustainability goals. Since 2009, countries like Mauritius have waived a 50% excise duty on EV and PHEVs as a first step in the process (Barry and Damar-LadkooEconomics, 2016). Thus, between 2009 and 2019, the number of new and used PHEVs rose from 43 to 11,841 vehicles (Akumu, 2019). Pure EV registration rose from 2 to 132 between 2011 and 2019. (Prithipaul, 2018).

Before purchase, prospective EV owners will be concerned about the availability of charging stations and the related prices (Palomino and Parvania, 2018). It is unquestionably the best reason to get EV (Gnann et al., 2018). More than 85 percent of EV charging takes place in the house. whereas users would rather want to charge their devices overnight at home, they will opt to do so during the day at a quick universal facility (Moon et al., 2018). The maximum fuel sulphur concentration for Euro types 1, 2, 3, 4, and 5 is, respectively, 2000 ppm, 500 ppm, 350 ppm, 50 ppm, and 10 ppm. When compared to Ghanaian requirements, Euro One emissions regulations guarantee a 16% percent reduction in PM emissions compared to the standards of Ghana. In comparison to GS 1219:2018, Euro 2, 4, and 5 guarantee 67, 90, and 99 percent reduced PM emissions, respectively. The high expense of refined low Sulphuric acid gasoline and processors' incapacity to convert gasoline to low-sulphur fuel are the main causes of fuels with a high sulphur concentration in Africa (Ayetor, Quansah & Adjei, 2020). For instance, although local refineries exist in Ghana, Nigeria, Angola, South Africa, Zambia, Cote d'Ivoire, Niger, and Senegal, none of them can operate because of unavailable technology. Satirically, oil is purchased from these nations by the rest of Africa. Sulfur typically makes up 0.5 percent of crude oil. To convert fuel into low-sulfur fuel, a refinery technology process called hydro-desulphurization is required. African refineries lack this capability (Abdoun, 2018). To achieve low-sulfur fuels in Africa, such facilities must be upgraded with financial assistance.

2.7 Ghana's readiness for EVs

Automobile electrification has become a crucial part of automakers' global propulsion strategy to reduce fuel consumption, combat greenhouse gas emissions that cause climate change, and boost energy security by utilising a variety of energy sources (Rahman, Khan, & Amini, 2020). GHG emanations from Ghana in 2016 were 42.15 mega tones CO2 equivalent (MtCO2e). According to, (A & Ghana's Fourth Nation, 2019), this is an increase of 7.1 percent above emissions in 2012 (39.35 MtCO2e). Energy is Ghana's second-largest contributor to emissions. This shows a rise of 7.1% above emissions in 2012 (39.35 MtCO2e) (A and Ghana's Fourth Nation, 2019). Energy is Ghana's second-largest contributor to emissions. The third-place contributor, forestry and land use, accounts for 36% of all national emissions (15.02 MtCO2e) (FOLU). 66 percent of the total net emissions are carbon dioxide emissions (EPA, 2019).

The Ghanaian government declared in its 2018 budget for 2019 that it has implemented tax-free options for fully electric automobiles (Kwofi, 2021). Energy Commission, Ghana's electricity regulating body, launched the "Drive Electric Initiative" in 2019 as part of a campaign to promote EV usage in the transport industry of Ghana. (Energy commission, 2019). Hydro, thermal, and sustainable power sources are used in Ghana to generate power. Thermal, hydroelectric, and renewable power plant percentage shares in 2017 were 59.9, 39.9, and 0.2 percent, respectively (Energy Commission, 2019). Table 2-3 depicts Ghana’s energy generation and supply mix.

Table 2-3 Ghana’s energy generation and supply mix for 2017 (Energy Commission, 2018; Ayetor et al., 2020).

Generation Plants	**Installed Capacity (MW)**	**Average Capacity Available (MW)**	**Total Generation (GWh)**	**Percentage Share %**
Hydro Power Plants	1580	825	5616	39.9
Thermal Power Plants	2796	1316	8425.5	59.9
Renewables	22.5	11.5	28	0.2
Total (including embedded generation)	4,398.5	2,198	14,069	100

Table 2-3 demonstrates that the total generation and installed capacity for the grid were both 4398.5 MW and 14,069 GWh, respectively (Energy Commission, 2018). This is equivalent to a 1120 GWh monthly grid supply on average. The overall amount of energy supplied increased to 1564.11 GWh in April 2019. Though, a surplus of 98.59 GWh was left after 1465.52 GWh were used up in the same month (Ayetor et al., 2020). Before any type of EV enters the African market, there are a number of issues that must be resolved (Kwofi, 2021; Ayetor et. al., 2020). Ghana does not, however, have any electric car regulations and standards. It is recommended to use the International Electrotechnical Commission (IEC) EV standards for infrastructure and charging (Ayetor. Quansah & Adjei, 2020).

In order to develop standards and regulations to direct and oversee Ghana's expanding EV sector, the Electricity Company of Ghana (ECG) has requested cooperation from the Ghana Standards Authority, the Energy Commission, the Public Utilities Regulatory Commission (PURC), and other pertinent bodies and institutions to put together standards and regulations to govern deployment of EV (Ghanaweb Business News, 2020). Currently, ECG has set up two EV charging stations at the Accra locations of Stanbic Heights and the A&C Mall in East Legon, and plans to install ultra-fast EV charging hardware at their partner filling stations along the major highways to support EV drivers when they travel between towns and other regions in Ghana. This hardware would charge electric vehicles in between 15 and 30 minutes (Ghanaweb Business News, 2020).

In terms of payment methods for EV charging systems, ECG suggests adopting hardware for EV charge-up that will strictly be cashless and use bank credit and debit card. Once ECG's connectivity with select financial service partners is complete, it will also be possible to use an authorised mobile pay App (Ghanaweb Business News, 2020). According to (Ayetor, Quansah & Adjei, 2020), hybrid electric vehicles like the Toyota Prius have a reduced total price of ownership per mile than the well-known Toyota Corolla. A reasonable cut of up to 30% can be anticipated.

2.8 Review of EV charging

The main parts of EVs are their battery packs. The decision of users to embrace plug-in and hybrid EV technologies rather than ICEs is influenced by a variety of criteria, including battery cost, lifetime, driving range, charging time, and location. The most important and costly component of HEVs and all EVs is the energy storage system (Khalid et al., 2021; Conti, 2016; Masoum et al., 2010). Interest in EVs is constrained by the complexity of battery charging system design and the scarcity of charging outlets. Also, the rising use of battery chargers may have negative effects on the electric utility industry. In order to satisfy customer demands, many battery types are used in cars, including those with greater drive range and lower total costs.

The main battery families used in EVs are lithium-ion (Li-ion) and nickel-metal-hydride (NiMH) batteries (Sabarimuthuet et al., 2020; Pillai & Bak-Jensen, 2010). The Li-ion and NiMH properties are affected by the type of vehicle in which they are incorporated, despite each family has separate chemical and electrical properties. Li-ion batteries outperform NiMH batteries in terms of density of power and specific energy. Several EVs, notably the Chevy Volt 2013 and Nissan Leaf 2011, employ Li-ion batteries, while Toyota Prius 2010 HEVs use NiMH batteries (Sabarimuthuet al., 2020; Dubey & Santoso, 2015).

EV battery chargers can be classified as on-board or off-board and can be distinguished by unidirectional or bidirectional power flow. On-board chargers restrict excessive power usage because of their weight, size, and cost considerations (Khalid et al., 2021; Yan & Kezunovic, 2012). One crucial aspect of power electronics technology to further advancing EV development is minimising the size and weight of power-electronic converters installed into vehicles. (Rahman, Khan, & Amini, 2020). Either conductive or inductive is available in on-board chargers. Unidirectional power flow in charging systems eliminates the need for complicated hardware and connectivity specifications. (Hilshey et al., 2012). Contrarily, bidirectional chargers provide grid energy infusion (Liu, Wen, & Ledwich, 2012).

There are three power levels that EV charging systems can offer: Level I, slow charging; Level II, semi-fast charging; and Level III, DC rapid charging. Domestic users only need to connect a Level I charger to a typical 120-V/15-A single-phase grounded outlet to charge their EVs overnight in their garage. Infrastructures are not required for Level I charging because the system can be installed inside the vehicle. Institutions both public and private typically employ Level II charging, which calls for a 208 V or 240 V plug.

As semi-fast charging devices provide sufficient power and are simple to implement into the majority of facilities and has generated interest in the literature from scholars and developers (Gray & Morsi, 2015). Tesla cars come with Level II on-board charging systems that only need an outlet. In Canada, level II charging is most frequently employed and advised by automakers

(Crozier, Morstyn, & McCulloch, 2020). Despite the substantially shorter charging time of less than an hour offered by Level III chargers, this power level necessitates costly charging infrastructure (Khalid et al., 2019; Jang, 2018; Zhang et al., 2018; Gao et al., 2016; Hou et al., 2016; Zhang and Mi, 2016, Zheng et al. 2013). High-power chargers shorten charging times but could also raise peak loads, overloading local distribution transformers (DTs) leading to a rise in transformer losses, temperature, and lifetime reduction (Nour et al., 2018).

2.9 EV charging infrastructure in Ghana

There are three different forms of infrastructure. Private home charging, public charging, and semi-public charging (staff charging area/stations in a working environment) (Zhang et al., 2018; Bhavanam et al., 2015). A national infrastructure is required even if the majority of EVs had to be charged in the house (Denton, 2016). Vehicle to refueling station index (VRI) for conventional automobiles is 1.38. Although, a VRI of 6.8 for 100 km of EV scope is advised for EVs. Majority of cars in Ghana do not go more than 100 miles daily; however, a nationwide infrastructure for charging will increase EV consumer interest and public trust (Ayetor. Quansah & Adjei, 2020). For the majority of EV owners, most popular type of charging will be in the house. For this reason, qualified electricians will need to construct household charge points to make room for specialised circuits that will guarantee the demand for EV charging (A and Your Driving Costs., 2018). Domestic charging is expected to take place overnight because the typical full charging time on single-phase for the majority of EVs is close to 8 hours. A completely charged EV will need to be recharged again halfway (62 miles) during a 118-mile trip from Accra to Kumasi, which will take at least 20 minutes. Such a trip will require two breaks with charging times of at least 20 minutes each, one at the start and one in the middle, to be completed (Ayetor. Quansah & Adjei, 2020).

Since large voltages and currents are involved, there must be some established policies followed if any nation is to permit EV charging facility. There must be standard connections, sockets, and installation techniques in place. At the moment, Ghana has no such requirements for EVs (Ayetor. Quansah & Adjei, 2020). IEC is the top organisation in the world which has brough together 100 specialist and 162 nations for creating and publishing global standards for every type of electrical, electronic, and associated technologies. The standard system for charging EVs is IEC 61851–1:2017. As shown in Table 2-4, it reviewed and revised safe charging modes for EVs.

Table 2-4 Modes and requirements for charging EVs (IEC 61851–1:2017–01)

Mode	**Mode Description**	**Maximum Current**	**Maximum Voltage**
Mode 1	The charging apparatus is hitherto built inside the car. uses a plug and socket from a third party to charge. has no safety safeguards and cannot communicate with the source of the charge.	16A	1: 250 V AC, 1- phase 2: 480 V AC, 3-phase
Mode 2	An electrical wire or wall socket sensor ensures safety. Connecting to a regular AC supply socket allows for charging. Communication is established prior to charging to ensure that the vehicle's criteria are met.	32 A	1: 250 V AC, 1-phase 2: 480 V AC, 3-phase
Mode 3	Charging only takes place at an AC charging station that is secured and protected (overcurrent and shutdown protection). When using 43.5 kW of charging power, charging can be finished in under one hour.	1: 32 A 2: 70 A 3: 63 A 4: 250 A	1: 250 V AC, 1-phase 2: 250 V AC, 1-phase 3: 480 V AC, 3-phase 4: 480 V AC, 3-phase
Mode 4	Use only DC charging stations with advanced communication and security (overcurrent and shutdown). One can charge using up to 170 kW of power.	AA: 200 A BB: 250 A EE: 200 A FF: 200 A	AA: 600 V DC BB: 600 V DC EE: 600 V DC FF: 1000 V DC

The differences in the charging types are determined by the type of energy supply, utmost charging power and the EV’s mode of communication employed. Home/domestic charging is referred to in modes 1 and 2 methods of charging. Some countries do not permit charging in mode 1 due to the absence of safety features. The majority of nations that have embraced EVs advocate mode 2.

There are three main classifications for EV chargers. These categories are Level I, Level II, Level III. Level I chargers in Table 2-5 have a reduced power and voltage limit and require more time to charge than chargers at higher levels. This, however, is easier to install and most suited for charging in the house. Majority of level III chargers are assumed to be networked as illustrated in Table 3. Tables 2-5 shows the characteristics of EV charging infrastructure.

Table 2-5 Characteristics of EV charging infrastructure (ICCT, 2019)

Charging infrastructure level	**Voltage range**	**Power range**	**Charging miles per hour for EV**	**Location of charging**
Level I	120V AC	1.2–1.4kW AC	5–6 km	Home
Level II	208V–240V AC	3–19kW AC	16 –32 km	Home, workplace and public
Level III	400–1000V DC	50kW or more	241–1600 km	Public and intercity

Level I charging is solely for residential/household (home) charging whereas Home, workplace/office, and public charging can all be done at Level II. In comparison of Level II to Level I charging, Level II provides a higher charge rate in miles per hour. A quicker charging and higher speed are offered by Level III charging, which is primarily DC. Table 2-6, depicts the equipment and installation costs for each charger should they be put in place in Ghana.

Table 2-6 Cost of projected EV charger in Ghana together with device and installation (source: Ayetor et al., 2020)

Charging Level	**Hardware charger**	**cost per unit ($)**	**Installation cost for 6 or more chargers per site**	**($)**	**Total cost of infrastructure**
Level I	Not networked	826	labour	400	**5672.76**
			Materials	300	
			Permit	20	
			Total	**720**	
Level II	Not networked	1,299	labour	1,200	**10,169.78**
			Materials	1,100	
			Permit	75	**25,584.83**
	Networked	3,868	**Total**	**2.375**	
Level III	Networked 50 kW	39,335	labour	7,000	**26,3112.3**
			Materials	20,000	
	Networked 150 kW	103,875	Permit	100	
			Total	**27,100**	**650,350.00**

The price of the hardware comprises the purchase price, shipping costs, taxes, and profits. The term "installment fee" is a reference to the price of the labour, licence, and supplies needed for installation. According to Table 2-6, the average cost of a home charger in Ghana is $826. To purchase and install six (6) level I chargers per site in Ghana will cost $5672. Installing level II and level III (50 kW) chargers will cost at least 10,169 and 26,3112 USD for public and workplace installations, respectively. The cost of a typical home charger for an EV in Ghana is 826 dollars, according to (Ayetor, Quansah & Adjei, 2020). but the cost to build ten (10) charging stations is $260,000.

2.10 Low voltage distribution grid of Ghana

The final component of the power system network, the electric power distribution network system, is responsible for delivering electricity to consumers via service conductors after it has been transmitted from the generating station via the National Grid. Figure 2-5 shows the grid architecture for electricity distribution in Ghana.

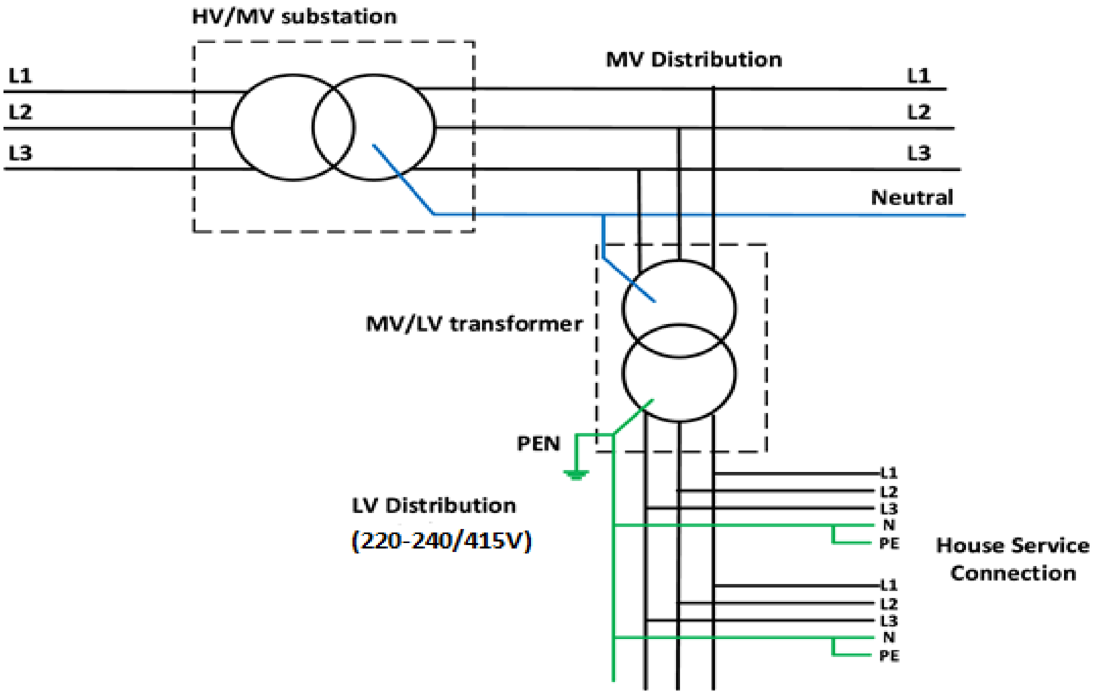


Figure 2-6: Grid architecture for electricity distribution in Ghana (ECG)

Ghana's electricity distribution networks use three-phase transformers that range in power from 11 to 2000 kVA. The three-phase characteristics of the distribution system connect the domestic service. The grid normally offers a three-phase supply with a separate neutral and earth at the residential service connection. A step-down transformer creates the primary distribution line voltage at the distribution substation by reducing the transmission line voltage (161kV) or sub transmission line voltage (33/11kV). The average Ghanaian distribution circuit is depicted by the voltage level in Figure 2-6. Line-to-line voltage is 415 volts, and line-to-neutral voltage is between 220 and 240 volts (Energy commission, 2020).

2.11 Consumer desire for EV charging and habits

The availability of EV charging should be taken into consideration while coordinating EV load over the course of a day, a month, or an entire year. Delivering power system services from EVs depends critically on the consumer habits of EV users and their preparedness to incorporate EV into the grid. (Cazzola et al., 2021). According to the study report by (Christensen, 2011), two data sets—the AKTA data from 350 automobiles in 2002–2003 and the National Travel Survey data—are used to analyse the EV consumer habits of individual households in Denmark. In the analysis, an EV with a standard range of 150 km and a 24-kWh battery capacity are both used. It has been noted that charging at residential locations is often accomplished with a connection to the single-phase grid and takes roughly 7-8 hours to complete; nevertheless,

Three-phase charging using 16 A or 32 A can be used to implement charging in public spaces, such as retail malls, sizable parking lots, etc. The data revealed an intriguing finding: on weekdays, roughly 26% of vehicles are not in use throughout the day, whereas on weekends, about 36% are not used. Both instances involve parking the cars at home (Christensen, 2011). When every EV is connected to the grid, a sizable amount of EV capacity is made accessible for coordination (Christensen, 2011; Clement-Nyns, Haesen & Driesen, 2010). Finally, it is discovered that night pricing by private owners is extremely feasible and that it has a significant potential for the supply of supplementary services overnight (Christensen, 2011). The work by (Bessa et al., 2012) examined the value of EV load forecasting in connection to the day-to-day driving requirements of EV users and the available flexible charging.

There are several connection schemes for charging EVs but the most popular are the USA, China and EU connection schemes. Since Europe uses 400/230V for LV network which is similar to that of Ghana thus, similar EV connection scheme. Therefore, the EU connection schemes is employed in this thesis because the EU circuit is similar to that of Ghana. Figure 2-7 shows the EV connection schemes in Europe.

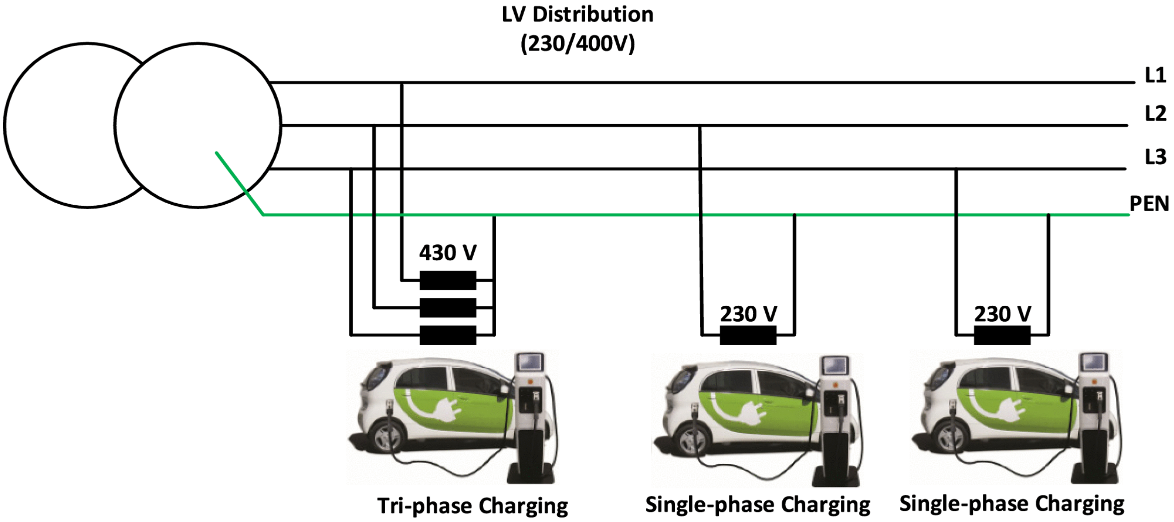


Figure 2-7: EV connection schemes in Europe (Dubey & Santoso, 2015)

This primary distribution line, often known as feeders, supplies energy to a number of distribution transformers, which further reduces the voltages for the secondary distribution lines, that provides: 415V for 3-phase supply, 240V for 1-phase supply, and neutral (Dubey & Santoso, 2015). For single-phase EV charging, one of the phase wires (L1, L2, or L3) and the neutral cable are used to connect the EV load. The single-phase charging system is only capable of 4.6 kVA, 20A at 240V of the maximal power (Dubey & Santoso, 2015).

2.12 Empirical review

Several literatures have addressed EV charging impacts on low voltage distribution systems in terms of several parameters (Franz`o, and Nasca, 2021; Gomez ´ Vilchez and, Jochem, 2020; Rahman et al., 2020; Held and Junge, 2017). According to the studies by (Rahman, Khan and Amini, 2020; Vega-Fuentes and Denai, 2019), high uptake of EVs is likely to pose power quality problems such as deviations in voltage magnitude, transformer loading, transient voltages and currents, DC offset, frequency variations, voltage drop and line loss, harmonics and phase imbalance etc. in the distribution feeders of low voltage network. The study according to (Rutherford and Yousefzadeh, 2011), described how the demand for EVs has accelerated transformer ageing. According to the study's findings regarding voltage variation, the major distribution system would not encounter any voltage violations, however secondary buses are more likely to have voltage variation that is outside of the permitted range. The study by (Held et al., 2019) investigated the impact of EVs on the distribution network for twelve (12) low voltage grids in Germany by considering only level 2 charger with 8kW charging power. The proposed study presented that integration of EVs together with domestic loads resulted in critical network situations depending on various parameters. Thus, thermal and voltage-related network overloads were highly dependent on market penetration and grid topology. According to (Hadley, 2006), a study in North America indicated that, the power utility firms had to construct new producing plants to handle the increased demand from EVs.

Currently, ongoing problem associated with the introduction of new EVs is voltage stability because of the increasing penetration level of EVs. (Lhendup et al., 2020; Bhavanam et al., 2015; Dharmakeerthi, Mithulananthan & Saha, 2014). Voltage instability is reportedly more substantial as a result of EV charging, according to several research conducted in the past. A study was carried out by (Vimitha and Kumar, 2016) on unregulated Plug- In EV charging impact on LV distribution grid and the results have found out that uncoordinated charging of PHEVs decreases the efficiency of the distribution grid. In (Luo et al., 2013), unregulated charging and tariff-based charging were the two charging methods examined in the study. The results proved that uncontrolled charging causes imbalance voltages to rise above 2%. Tariff-based charging method is mandated that EV users consider low-cost charging during the daytime valley hours. The high incursion of EVs leads to traffic congestion on the network, voltage dips, and power losses as its primary effects. According to studies concerning low voltage network-infrastructure of European

Union, voltage deviations at the feeder end were frequent with regulated charging (Nour et al., 2018). The findings have shown that indirect regulated charging allows a greater number of PEVs to be charged from the distribution network without the need for infrastructure upgrades, whereas uncontrolled charging necessitates such upgrades.

Furthermore, peak times for household loads sometimes coincide with voltage dips experienced by residential customers as a result of the high inrush current used by EV charging. (Klayklueng & Dechanupaprittha, 2014). The studies according to (Ul-Haq et al., 2015), examined how voltage unbalance is created by bad charging procedures. Whereas the study by (Weiller, 2011), has shown that the usage of power at public charging locations goes up between 24 and 29% per day compared to charging in the house. The study according to EVs impacts on the Canadian LV network, quick-charging technology has a far greater impact than the slow charging technology (Akhavan-Rezai et al., 2012; Clement-Nyns, Haesen & Driesen, 2010).

Also, research relating to the effects of EV penetration on the Chinese low voltage network has found that, uncontrolled charging contributes to voltage instability and phase imbalance at varied EV penetration levels. Again, in (Ramadan, Ali and Farkas, 2018), the Hungarian low voltage grid was modelled and investigated the impact of transformer loading, feeders loading, voltage deviation and system total losses under two charging scenarios; thus, uncoordinated charging and delayed charging at different penetration levels of PEVs at a constant charging power of 3.3kW (level 1 charger) but level 2 and 3 chargers were not considered. The results have shown that at 60% penetration level with uncoordinated charging, both the distribution transformer and feeders thermal loading experienced violation. However, with the delayed charging, all the grid components function at their normal rating at all penetration levels and no system upgrade was required. Also, (Muthukumar and Vimitha, 2016) investigated the impact of harmonics distortion on LV distribution system as a result of PEV charging using quadratic and dynamic strategies and the results have shown that coordinated charging minimizes power losses and maximizes the power factor of the main grid.

Related research implemented a fast-charging method to extend charging times and provide continuous power to the system. (Akbari, Brenna & Longo, 2018; Wang & Infield, 2018; Guo et al., 2017; Li, Bai, & Tan, 2012). The impact of EVs on voltage stability was addressed by (Abdel-Akher et al., 2017) and outcome have shown that voltage variation and transformer loading are the key factors that affect the stability of power systems networks. Linear increase in system losses caused by high deployment of EVs was studied by (Taylor et al., 2009), the results indicated that heavy integration of EVs causes increase in system losses. Also, a study on distribution system of Patan feeder, Pulchowk in Nepal by (Jha and Shrestha, 2021) investigated the impact of EVs on LV distribution system at different scenarios of load periods before and after EV penetration; without considering different charging levels, different power factor and estimation of future demand. The findings have shown that as the deployment of EVs increased, voltage variation and line loss increased at peak demand period while total harmonic deviation increased at off peak period.

Based on this, a study was performed in Glasgow, UK by (Tian, Tzelepis and Papadopoulos, 2021) to investigate the impact that EV loads (slow and fast charging methods) dynamic behaviour has on power system. The study examined how well common static and dynamic load models used in power system studies could capture the static and dynamic behaviour of EV chargers. The outcome of the study has shown that with both charging methods static model behaviour is almost a constant power. The static behaviour can be expressed well by standard static load models. Another study conducted by (Obeidat et., al, 2021) in Aqaba-Jordan, which considered level 1 and level 2 (7.2 kW) charging approaches to examine the effects of EVs on residential distribution system to evaluate a real distribution system’s load and voltage drop.

Again, a study conducted by (Ahmed, Salehfar and Selvaraj, 2021) evaluated the performance of distribution grids due to the effects of Level 1, Level 2, and DC rapid charging of EVs on distribution feeders by varying the extent of EV penetration levels. The findings of the study have found that the distribution grid exhibits voltage distortion and deviation. The results have shown that the addition of EV charging loads have significant impact on LV distribution systems which create a severe risk to feeder limits and voltage drop.

The research carried out in Bhutan by (Lhendup et al., 2020) conducted load flow analysis using DIgSILENT to examine the impact of EV charging on LV network stability considering only level 2 charging approach and the load flow results have found that at a low penetration level of 0.28% representing 587EVs of 7.4kW both under voltage condition and transformer loading violations can be triggered and at 37.68% penetration level, distribution system is likely to breakdown due to severe voltage drops. Also, a study in Brunel, UK by (Bhavanam et al., 2015) conducted a load flow analysis using ETAP to investigate the potential of a 11kV networked site to accommodate EV charging infrastructure, however future load demand was not addressed. The study considered three different charging approaches (slow, fast and rapid) and discovered that at 17%: 323 EVs can undergo either slow or fast charging while 34 EVs can undergo rapid charging; high deployment of fast and rapid charging can affect grid operation due to voltage variations and transformer loading. Again, a study conducted in Australia investigated the impacts of EV charging on distribution transformers and the results have found that large scale integration of EVs into existing grid systems creates accelerated aging challenges for distribution transformers. Again, a study in Indonesia on distribution network in Jakarta by (Kurniawan et al., 2021) suggested that high EV penetration levels can experience transformer overloading and voltage instability challenges. The findings have shown that voltage stability and distribution transformer loading levels can be maintained within grid code and utility limits, even under the worst-case scenario.

Several studies have shown how EV charging loads have negative effect on various distribution system variables, such as voltage variation (Zhang et al., 2016; Ul-Haq et al., 2015; De Hoog et al., 2015; Bhavanam et al., 2015; Dharmakeerthi et al., 2014; and Geske et al., 2011) and peak load (Burillo et al., 2019; Fakeha, Manisa, & Rahman, 2017; Hüls, & Anne, 2016; Di Silvestre et al., 2013; Fan et al., 2013; McCarthy, & Wolfs, 2010 and Putrus et al., 2009). Therefore, in (Fan, Wang and Yan, 2018), proposed a numerical EV load model suitable for long-term large scale power system numerical simulation to analysed the impact of EV loads on power system voltage stability that considered only level 1 charging approach. The findings have shown that power system numerical simulations are important assistant measures for power system planning, operation and control.

In recent times many researchers have considered load forecasting as an essential method for planning power networks, managing load demands, power supply and the future state of the power system (Jenkins and Kockar, 2022; Zhixiong and Zhensheng, 2021; Zheng et al, 2020; He et al., 2017). Many researchers have used various techniques to project short-term, mid-term and long-term load forecasting (Lhendup et al., 2020; Zheng et al, 2020; Burillo et al., 2019; 2016; Korolko et al., 2016; Zhao and Guo, 2016; Poghosyan et al., 2015). In the past two decades, load forecasting studies have been on short-term (Zhixiong and Zhensheng, 2021; Khuntia et al., 2016). Few studies have analysed mid-term and long-term load forecasting. Lhendup et al., 2020 used both short-term and long-term to project future load but considered only 7.4 kW level-2 charger in the analysis. However, this study employs both short-term and long-term load forecasting technique and considers level 2 and level 3 chargers.

Among the several challenges that high penetration of EVs pose on LV distribution systems, many studies have sought to address the negative impacts of EVs on LV distribution systems. Though transformers are considered essential components of electric power network, the cost of replacing them is very expensive. With the introduction of additional load of EVs, the distribution system should be able to accommodate both the additional EV load and the existing load without damaging the transformers and endangering the stability of the distribution system. Therefore, it is important that all power distribution companies assess the capacity of the existing distribution system to meet the growing demand for EVs. In light of this, all studies on the stability of the distribution system mentioned above found the load flow analysis appropriate to address such challenges. Consequently, considering the power that EVs draw from the grid, it is important to investigate the volumes of EVs integrated together with existing load that can be lumped on LV distribution system of Takoradi (station 0B). To address the aforementioned challenge, this thesis proposes a load flow analysis to assess the impact that level 2 and 3 charging approaches (fast and rapid) of EV have on LV distribution system of Takoradi (station OB) with the focus on voltage variations and transformer loading.

2.13 Summary of the review

The review helped in looking out for gaps in other related studies that hold some level of significance to this research. The identification of the gaps brought to light the research topic of this thesis as "assessing the impact of EV charging on LV distribution system of Ghana". EV charging on the LV distribution systems may result in issues with the grid itself and transformers may get overloaded and experience large voltage drops at the end of the feeders as a result of the additional load brought on by EV charging. Most of the methodologies proposed in the literature aided to adopt a load flow analysis in this thesis. The Load flow analysis which offers insights on power system performance is one of the crucial techniques for addressing these problems. Thus, this thesis employs load flow analysis technique to find out the capacity of LV distribution systems performance with the introduction of EVs at different penetration levels and investigate to what extent the LV distribution system can accommodate EV penetration along with the growth of household loads in Takoradi since EV deployment is a new wave coming to Africa and by extension Ghana. It was deduced from the review that; several studies have been done on the impact assessment of EV charging on power quality with concentration on harmonic distortions and losses but very few studies have been done on voltage variations and transformer loading which are also major factors that affect power system network.

Massive integration of EV loads on distribution system creates frequent power quality (PQ) issues because of the nonlinear nature of EV chargers (Ramadan, Ali & Farkas, 2018). A huge number of EV chargers signify a sizable additional load demand that must be met. Therefore, to effectively incorporate EVs into distribution networks, it is important to develop new charging techniques, infrastructures, and tactics. (Vega-Fuentes & Denai, 2019; Nour, 2018; Bhavanam et al., 2015). Increasing EV penetration on the LV distribution systems is likely to cause stability issues on the network. Therefore, this has necessitated a study to determine the impact of transformer loading and voltage variation as a result of the maximum degree of EV deployment together with the typical development of household loads that the existing LV network in Takoradi can handle without any upgrades to the current network. Due to this, the research seeks to find out the stability of LV distribution system in Takoradi to ascertain whether or not the system can withstand the strike of incursion of EV charging. This thesis contributes to knowledge of how future EV load and domestic will enhance the effectiveness of load flow analysis.

CHAPTER THREE

MATERIALS AND METHODS

This chapter discusses the chosen methodology, the data sources and materials employed to achieve the aim of the thesis and to obtain the desired results and conclusions. To achieve the objectives of this research, the low voltage distribution (LV) system of Takoradi was modelled in Electrical Transient Analysis Program (ETAP). Simulation analysis was performed at different EV penetration levels to find out the strike of increasing load incursion on the low voltage systems for comparison of the current typical load and additional EV load for three different scenarios.

3.1 Research design

The capacity of the LV network performance of Takoradi due to the additional EV loads was investigated using the flow chart in Figure 3-1to achieve the objectives of this research.

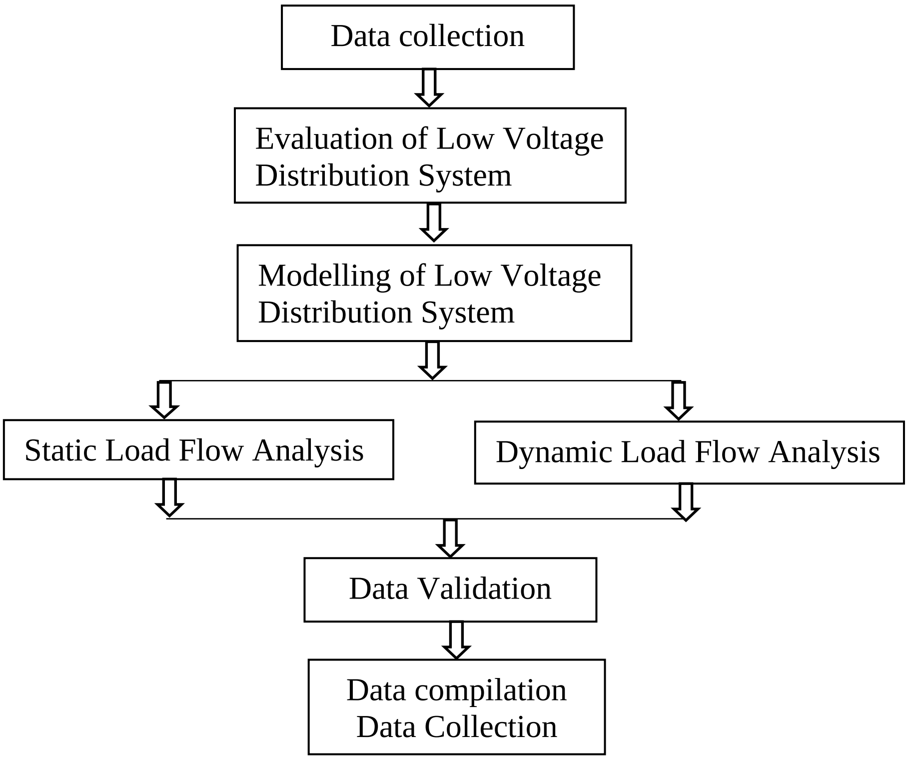


Figure 3-1: Methodology flow chart

Using the real data collected from the Electricity Company of Ghana (ECG), Takoradi branch, a model of the current Takoradi low voltage system together with EV loads were created in the ETAP 19.0.1 simulation software. The current LV power distribution system built was then evaluated. The LV distribution modelled was run and the simulation findings were validated with the measured value. Data compilation and analysis was undertaken afterwards.

3.1.1 Modelling of the investigated distribution system

The model of Takoradi Distribution System (TDS) was developed in EPAT 19.0.1 simulation software. Following the placement of substations on the distribution system, a one-line diagram was first created, and then the entire LV distribution system was designed and validated as presented in Figure 3-2.

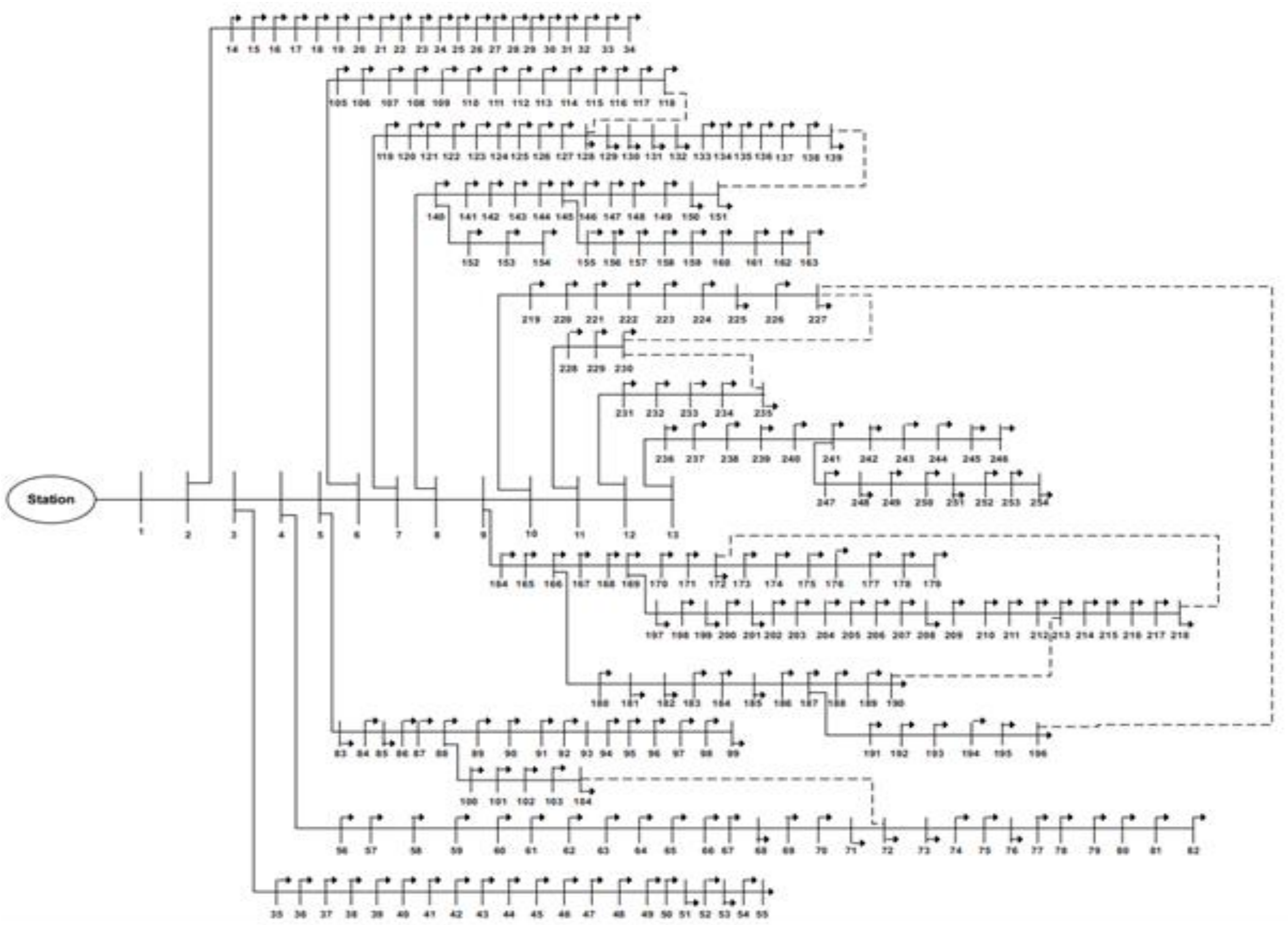


Figure 3-2: A line diagram of LV distribution system in Takoradi

The parameters of the transformers were entered manually in the transformer window. The entire Takoradi city is supplied by twelve 11kV feeders emanating from two 10MVA, 33/11kV substations. The TDS is a radial LV distribution system of 415/240V which has 237 transformers of which 106 of them are dedicated to companies and the remaining 131 are for domestic loads. The TDS has 254 busbars, 251 branches and 511 lines. The average yearly peak load of the Takoradi network used in this study is from the year 2014 to 2021. The average load for the year 2021 was used as the base for the model. Snapshot of the TDS simulated model in ETAP is presented in Appendix I and the bus voltage levels and transformer loading levels are shown in Appendix II.

3.2 Required data

3.2.1 Real branch data

The branch data was entered into the branch editor window which includes: Branch Z, R, X, or X/R values and units, tolerance, and temperature, if relevant; transmission line, length, and unit; transformer rated kV and kVA/MVA, tap, and LTC settings and finally the impedance base kV and base kVA/MVA

3.2.2 Static and EV loads data

The load flow data required for static load includes: rated kV, kVA/MVA, and power factor and percentage (%) loading while the EV load data required includes: kW and voltage rating for chargers; Ampere-hour (Ah) and voltage rating for batteries.

3.3 ETAP application software

Several simulation setup software can perform load flow analysis and real time simulation. Some of this software include; MATLAB Simulink, PSAT, DIgSILENT, PSCAD, MOO-NF, MOO-WF, CYME power engineering software among others. Electrical Transient and Analysis

Program (ETAP) software is a powerful tool which can be used to execute load flow analysis on power system modeled in a single line diagram. Inside the ETAP simulation, there are different simulators like Unbalanced Load Flow, ANSI Short Circuit, Optimal Load Flow. Transient Stability, Motor Starting, Harmonic Load Flow, Star Protection Coordination, Reliability Assessment, Time Domain Load Flow, Switching Optimization, Switching Sequence Management and Arc Flash can also be performed using ETAP.

ETAP 19.0.1 was chosen to perform load flow analysis due to its uncontrollably usage in real life systems. The main factors in adopting ETAP 19.0.1 to model the low voltage distribution system are its good graphical user interface and the clear-cut output reports produced by the outcome of the analyzer. The decision-making process was made more effective by features such as alarms, warning reports, autonomous device condition monitoring for power systems, and colour codes in identifying the busbar loading levels, followed by the outcome displayed on screen together with the model. In this research, load flow analysis was primarily performed and run to find real and reactive power flows, voltage variations and transformer loading to determine the stability of the system.

3.3.1 Steady state simulation

The Adaptive Newton-Raphson, Newton Raphson, and Fast-Decoupled load flow calculation methods are among the three (3) available in the ETAP 19.0.1 version. Although they both offer unique convergent features, sometimes one is more beneficial for achieving the greatest results or outcomes. Thus, better efficiency, reduced computational time and an approximation of the power system network’s good results. Any of these load flow methods can be selected based on the system configuration, generation, loading situation, and the initial bus voltages. For this research the ETAP 19.0.1 software was set to adaptive Newton-Raphson.

3.4 Load modelling

Static and dynamic load models are the two major categories of load models, which accurately describe how real and reactive power react to specific power system situations. In the static load model, load features are expressed as algebraic function at some point in time. Because there is no dynamic data in the static load, a power system dynamic model is required to investigate the behavior of the power system under small and major disruptions. In-depth analyses on EV charging strategies for static and dynamic loads is shown below.

3.4.1 Models for static load

In most cases, the models for static load are utilised to determine how loads behave in steady state. Due to the static load model's lack of consideration for dynamic actions, power system loads, such as EVs, could be modelled as static loads. This captures both the active and reactive power sensitivity. In this study, two conventional static load models thus, a polynomial load model (ZIP model) and an exponential load model were employed. Although they use distinct mathematical operations, both models depict the connection between the supply of voltage and the use of electricity. Equations 3.1 and 3.2, present the real and reactive power equations discussed in the ZIP (Kontis et al., 2015).

$$P = P_0 = p_1{}^{\overline{V}^2} + p_2{}^{\overline{V}} + p_3 \text{ ……………………… Equation 3.1}$$

$$Q = Q_0 = q_1{}^{\overline{V}^2} + q_2{}^{\overline{V}} + q_3 \text{ ……………………… Equation 3.2}$$

Where $P_0, Q_0, and\ V_0,$ show the real power, reactive power and voltage at each time the supply voltage equals 1 p.u or 100%. For Equations 3.1 and 3.2, $p_{1-}\, p_3\ and\ q_{1-}\, q_3$ are the model’s framework when approaching to 1 or 100%, the load will behave either continuous power, constant current, or constant resistance. The voltage supplied per unit is represented by the independent parameter $\overline{V}$ in Equation 3.3. If the nominal voltage V_0, matches real voltage supplied, then $\overline{V}$ will equal to 1 or 100%.

$$\overline{V} = \frac{V}{V_0} \text{ ……………………… Equation 3.3}$$

The exponential model provides a description of how real and reactive power relate to voltage (Korunovi'c et al., 2018; Kontis et al., 2015; and Bokhari, Alkan, & Dogan, 2013) primarily using the voltage parameters α and β, as indicated in Equations 3.4 and 3.5.

$$P = P_0(\overline{V})^{\propto} \text{……………………… Equation 3.4}$$

$$Q = Q_0(\overline{V})^{\beta} \text{ ………………………Equation 3.5}$$

The connection between the real and reactive power in relation to voltage is described by the exponential model. In contrast to the ZIP model, the exchange of real and reactive power in relation to voltage supply is described by a single parameter. When the parameters α and β are approaching 2, the load may be thought of as having a steady-state impedance. When the parameters α and β are approaching 1, the load may be thought of as having continuous current flowing through it. In the end, the real and reactive power exchange remains constant in relation to the voltage when parameters α and β are approaching 0. Accordingly, the load acts like a steady or constant power source.

As previously stated, the two standard load model of a completed EV charger models for methods A and B (where A is a typical AC/DC charger that charges significantly more slowly and B is a standard DC fast charger, all of which are presented in details). The main common load model formation allows for the acquisition of static values and subsequent characterization of the static characteristic of a standard EV charger using the exponential model (Korunovi'c et al., 2018; Kontis et al., 2015; Bokhari, Alkan, & Dogan, 2013) contains only two parameters. Curve fitting was employed to use simulation-based data to approximatively determine the load parameters of the target expressions. After running a variety of simulations and obtaining the outcomes (active power and voltage), approximating the load variables (i.e., p_1, p_2, p_3 in ZIP model) was proposed. The least-squares method was selected as the way of obtaining the parameters (Kontis et al., 2015). The target equation and the response information are needed for such a strategy (i.e., simulation results extracted). Using least-squares essentially reduces the total of the squared residuals or offsets positions along a curve:

$$s = \sum_{i=1}^{n}(y_i - \hat{y}_i)^2 \text{ …………………….. Equation 3.6}$$

where s is the estimated total of square errors, y_i is the actual response and $\hat{y}_i$is the value of the fitted response. The parameter with the lowest error estimate s is selected based on the curve fitting results.

3.4.2 Models for dynamic load

The model for the dynamic load is a continuation of the models for static load which can be employed to record and portray quicker situations, such as disruptions. It needs to be remembered that, the dynamic load model utilised in this study is referred to in literature as the exponential recovery model. Compared to the exponential static load model described in the part before, is different. According (Tian et al., 2021), the values at constant prior to and following a disruption can be represented by the parameters $(\frac{V}{V_0})^{as}, (\frac{V}{V_0})^{at}$ (which derive from the exponential parameters of the static load model). According to (Tian et al., 2021), the exponential recovery load model, illustrated in Equations 3.7 and 3.8, show the common dynamic load models utilised in power system non-static research.

$$T_p \frac{dP_r}{dt} + P_r = P_s(V) - P_t(V) = P_0(\frac{V}{V_0})^{as} - P_0(\frac{V}{V_0})^{at} \text{ ………….. Equation 3.7}$$

$$P_1 = P_r + P_0(\frac{V}{V_0})^{at} \text{ …………………………………………… Equation 3.8}$$

P_1in Equation 3.8 is the total amount of energy used and P_r is the energy recovery component (which is described into details). Equation 3.9 can be employed to express the dynamic load model's total response. A static component of the expression in Equation 3.9 defines it. (ie., $P_0(\frac{V}{V_0})^{at}$ and $P_0(\frac{V}{V_0})^{as}$) and a dynamic part $(1 - e^{-t/T_p})$. This is simply a first order system. (Kontis et al. (2015).

$$P_1(t) = \left[(P_0(\frac{V}{V_0})^{as} - P_0\left(\frac{V}{V_0})^{at}\right)\left(1 - e^{-t/T_p}\right) + P_0\left(\frac{V}{V_0})^{at}\right)\right] \propto \text{……… Equation 3.9}$$

This is where it should be mentioned that the static component $P_0(\frac{V}{V_0})^{as}$ was derived from the outcomes of Equation 3.3. The use of thorough EV charging models enabled the execution of a variety of dynamic simulations. The dynamic portion of the expressions in Equation 3.9 is represented by the parameters P_r and T_p. The dynamic response can be represented by Equation 3.9 using the dynamic and static components of the specified dynamic load model.

3.4.3 EV loads' components and modelling approach

Most EVs charging load is made up of the battery, charger, and the regulating components. The load is significantly impacted by the battery's charging characteristics. The battery and grid are connected by the EV charger. The control modules of EV chargers are made to correspond to industry standards and are also developed to meet a range of requirements. Despite their various architectures, energy levels, and mechanisms, the EV charger primarily influences the charging load and efficiency significantly from the perspective of load modelling. To establish an EV load single model, the features of the battery and the charger's impact can be combined. Aggregate EV loads are made up of numerous single EV loads, each of which has both charging period and power level. By adding EVs' capacity for charging with various State of Charging (SoC) levels simultaneously, loads of aggregate EVs may be estimated using the single EV load model.

3.4.4 Modelling of DC side load

The charging procedure of the DC side power is expressed as

$$P_{DC} = I_{C\,X}\,V_C \text{ ……………………………….. Equation 3.10}$$

Where I_C and V_C represent the voltage terminal of the battery and charging current, respectively. Current drawn when charging and the quantity of SoC cause the lithium-ion battery's terminal voltage to fluctuate throughout this time. As the charging period lengthens during the constant voltage charging phase, the charging current declines. The SoC fulfils Equation 3.11 during the constant current charging phase, where S_{intial} is the starting SoC, I_{CC} represents charging current, C represents battery's rating capability (Ah), and *t* is the charging period (h).

$$S = S_{initial} + \frac{I_{CC}}{C} \times t \text{ ………………….. Equation 3.11}$$

Using simulation or real-world data, the following numerical fit may be made for the interaction of the charging current (I_{CC}), battery voltage and SoC during the constant current charging time.

$$V_C = f_1(s) = \sum_{i=0}^{4} a_i S^i \text{ …….………… Equation 3.12}$$

Where a_i is the coefficient, f_1 is the differential equation. The relationship can be accurately represented by the fourth order polynomial. Equations 3.11, 3.12, and 3.13 can be used to create the following DC side load model during the constant current charging time:

$$P_{DC} = I_{CC} \times f_1(S) = f_2(S_{initial}, I_{CC}, t) \text{ ……………… Equation 3.13}$$

f_1 and f_2 represent the differential equations. According to Equation 3.13, the starting SoC and charging current may be employed to establish the time-changing DC side charging capacity for a specific EV battery model's during the constant current period. After the constant current period has ended, the constant voltage (CV) charging period starts. While the constant current (CC) drops with time, the battery voltage at the conclusion of the CC charging cycle is employed as CV charging voltage and maintained throughout. The following can be used to specify when the

CV charge period starts:

$$t_{seg} = C\,\frac{S_{seg} - S_{initial}}{I_{CC}} \text{ ………………. Equation 3.14}$$

Where, S_{seg} is the SoC level at t_{seg}, t_{seg} is the period since the initial charging intervals change position. The current battery voltage is indicated as

$$V_{Cseg} = f_1(S_{seg}) \text{ …………...……. Equation 3.15}$$

The connection with the charging current and the charging period during the CV phase may be expressed as follows;

$$I_C = f_3(t, I_{CC}) = I_{CC}\sum_{i=0}^{4} b_i(t - t_{seg})^i \text{ ………………. Equation 3.16}$$

In this case, b_i is the constant coefficient. Equation 3.16 employs a polynomial of the fourth order. Equations 3.10, 3.14, 3.15, and 3.16 can be used to create the following DC boundary load model during the CV charging duration:

$$P_{DC} = I_C \times V_{CSeg} = f_4\left(S_{initial}, S_{Seg}, I_{CC}, t\right) \text{ ………………. Equation 3.17}$$

According to Equations 3.4 and 3.8, the EV load model on DC side is

$$P_{DC} = \begin{cases} f_2(S_{initial}, I_{CC}, t) & 0 < t < t_{seg} \\ f_4\left(S_{initial}, S_{Seg}, I_{CC}, t\right) & t_{seg} < t < t_{seg} + t_{CV} \end{cases} \text{ ……………. Equation 3.18}$$

Where t_{CV} represent CV charging duration, that may be found by consulting the specifications for batteries either from the manufacturer or actual billing history. When the charge times change, the starting SoC and SoC level (or battery voltage) changes as well, and the CC charging current all affect the DC side charging power.

3.4.5 Modelling of AC side load

Using the effectiveness of charging and power factor, the EV charger connects both DC and AC sides load models. The power factor can be maintained using the 1-phase EV charger. The changes in energy frequency and battery voltage have no effect on how efficiently batteries are charged. However, during AC side charging. voltage and charging current on the DC side also changes and charging efficiency is clearly affected. The simulation results add more support to the aforementioned conclusions. The CV is maintained constant over the CC time, and the grid voltage has the biggest impact on the charging efficiency. A quadratic equation may be used to depict the connection between charging effectiveness and grid voltage using Equation 3.19 following the 1st-step fitting of the simulated data.

$$\eta_C = f_5(\ U_{AC}) = c_2 U_A^2 + c_1 U_{AC} + c_0 \text{ ……………… Equation 3.19}$$

Where η_C and U_{AC} represent effectiveness of charging and grid's AC voltage respectively, in which the EV charger is plugged in; $c_{0\,,} c_1, c_2$ are the undetermined constant coefficients. Including the charging current and unknown steady-state coefficient modifies Equation 3.19 to produce Equation 3.20.

$$\eta_C = f_6(\ U_{AC}, I_C, t) = c_2^1 U_A^2 + c_1^1 U_{AC} + c_0^1 + d[f_3(t, I_{CC}) - I_{CC} \text{ …….. Equation 3.20}$$

Where c_0^1, c_1^1, c_2^1 represent voltage coefficients, I_{CC} represents charging current and d is the unknown steady-state coefficient to depict the impact of CC on the efficiency.

Putting together Equations 3.18. 3.19 and 3.20, will arrive at Equation 3.21 which represent a single EV load model that considers the characteristic of the battery and EV charger impact. This can be obtained as:

$$P_{SVE} = \begin{cases} \frac{f_2(S_{initial}, I_{CC}, t)}{f_6(\ U_{AC}, I_C, t)} & 0 < t < t_{seg} \\ \frac{f_4(S_{initial}, S_{Seg}, I_{CC}, t)}{f_6(\ U_{AC}, I_C, t)} & t_{seg} < t < t_{seg} + t_{CV} \end{cases} \text{ ………………. Equation 3.21}$$

Where P_{SVE} is the amount of power that a single EV charging draws from the grid. It is important to known the power that a single EV absorbs from the grid to facilitate the quantity of EVs to integrate onto the network.

3.4.6 Model for the initial SoC distribution

The driving behaviours, battery life, and range anxiety of the customers all have a big impact on the initial SoC distribution. It is plausible to assume that the first SoC distribution will be a cutoff of the standard distribution with no chance of happening when EVs are widely used, for any starting SoC that is adverse. This is because of big-number law and central limit theorem (Fan, Wang and Yan, 2018). In Equations 3.22 and 3.23, $S_{initial,\ i}$ represent resulting charging starting SoC, N represents total amount of acquired starting SoC. $S_{initial,}$ and $\hat{\sigma}^2$ represent both the sample's mean and variance values, whereas the starting SoC's true distribution being represented by $N(\mu, \hat{\sigma}^2)$.

$$\overline{S}_{initial} = \frac{1}{N}\sum_{i=1}^{N}(S_{initial,\ i}) \text{ ………………………..….. Equation 3.22}$$

$$\hat{\sigma}^2 = \frac{1}{N}\sum_{i=1}^{N}(S_{initial,\ i} - \overline{S}_{initial})^2 \text{ ……………….. Equation 3.23}$$

Taking into consideration the EV battery consumption limit and the charging behaviour when the statistical data on EV charging is insufficient. The average day-to-day driving distance may be used to assess the mean value of the initial SoC distribution. and the variance accurately projected depends upon the actual regulation of the usual distribution. One or more teams may be formed from all of the EVs. depending on a specific SoC period once the distribution of the first SoC has been identified (ie., 0.05 or lower). The likelihood of every team interval depending on the distribution determines the percentage of a size for every team, Equation 3.21 is used by the EVs in the same team to calculate the charging power. By multiplying the single EV load by the number of teams, it is possible to calculate the charging load for each group.

3.4.7 Newton-Raphson load flow with EV load

Newton-Raphson iterative method has several advantages over the Fast Decoupled, and accelerated Gauss Seidel iterative methods because it takes fewer iterations regardless of the size of the system, (Muzzammel et al., 2019; Gonzalez-Longat and Rueda, 2015). Voltage-dependent load (VDL) characteristics were discovered by the EV load. As a result, the Newton-Raphson load flow algorithm needs to be modified in order to accommodate EV load. Equations 3.24 and 3.5 illustrate the necessary adjustments to the algorithm's real and reactive load flow equations. (Kongjeen and Bhumkittipich, 2016; Dharamakeerthi and Mithulananthan, 2015).

$$P_{Gi} - P_{Di}(v) = v_i \sum_{k=1}^{N_B-1} v_j \left[G_{ij} cos\delta_{ij} + B_{ij} sin\delta_{ij}\right] \text{ ……… Equation 3.24}$$

$$Q_{Gi} - Q_{Di}(v) = v_i \sum_{k=1}^{N_{PQ}} v_j \left[G_{ij} sin\delta_{ij} + B_{ij} cos\delta_{ij}\right] \text{ ……..…. Equation 3.25}$$

Where δ_{ij} is the bus voltage angle between buses i and j. The entire number of buses and the total of load buses are represented as N_B and N_{PQ}, respectively. The introduction of real and reactive power at bus i are represented by P_{Gi} and Q_{Gi}, respectively. The real and reactive power consumption of the load at bus i are given by P_{Di} and Q_{Di}, respectively. G_{ij} and B_{ij} describe the conductance and susceptibility of feeder ij. As a result, it is very necessary to modify the diagonal components of J_2 and J_2 of the normal load flow Jacobian. Equations 3.24 and 3.25, which are differential equations, are modified to fit the sparse matrix of the Newton-Raphson load flow algorithm.

3.4.8 Continuous power flow (CPF) method

With the purpose of analysing the effects of various loading margins on the size of EVs in low voltage electric power distribution systems, the traditional power system model was solved using the CPF approach. Here are some nonlinear differential algebraic equations (Fan, Wang, Yan, 2018; Milano, 2005).

$$x = f(x, y, p) \text{ ……………….. Equation 3.26}$$

$$0 = g(x, y, p) \text{ ………………… Equation 3.27}$$

Where x represents state variable $x \in \mathbb{R}''$; y is the algebraic variable $y = \mathbb{R}'''$; p is the set of independent variables $p \in \mathbb{R}^{\ell}$; f are the differential equations $f\colon \mathbb{R}'' \times \mathbb{R}''' \times \mathbb{R}^{\ell} \mapsto \mathbb{R}''$

and g are the algebraic equations $g: \mathbb{R}''' \times \mathbb{R}''' \times \mathbb{R}^{\ell} \mapsto \mathbb{R}'''$ A prediction step and a corrector step make up the CPF approach. Reconstructing the load flow equation with the addition of the load parameter λ, real and reactive power can be tailored for the problem-solving process using Equations 3.24, 3.25, 3.26 and 3.27, respectively (Kongjeen and Bhumkittipich, 2016; Koasungnean et al., 2015; Milano, 2005).

$$0 = f(x, y, \lambda) \text{ …………………. Equation 3.28}$$

$$0 = g(x, y, \lambda) \text{ …………………. Equation 3.29}$$

Where $\lambda \in \mathbb{R}$ represents loading specification, employed to change the base case generator, load and drive powers p_{G0}, p_{L0}, and p_{D0} respectively;

$$P_G = (\lambda + \gamma k_G) P_{G0} \text{ ……………….. Equation 3.30}$$

$$[P_G, Q_L] = \lambda [P_{L0}, Q_{L0}] \text{ …………….. Equation 3.31}$$

3.4.9 Load voltage deviation (LVD)

The bus voltage variation caused by an increase in load of the power system was resolved using the LVD. Equation 3.32 can be used to describe the LVD's need to minimize the load voltage bus. (Kongjeen and Bhumkittipich, 2016; Koasungnean et al., 2015).

$$LVD = \sum_k^n \left(\frac{V_k^{ref} - V_k}{V_k^{ref}} \right)^2 \text{ ……………. Equation 3.32}$$

Where V_{ref} and V_k are voltage reference and load voltage bus, respectively. Their critical settings are normally set at 1 p.u. or 100% depending whether per unit or percentage is used.

3.5 Estimation of domestic/household load

The domestic/household load growth of any growing locality is inevitable (Lhendup et al., 2021; Khuntia et al., 2016). A typical load increase in Takoradi municipality was estimated according to the data set from ECG, Takoradi branch from 2014 to 2021 as displayed in Table 3-1.

Table 3-1: Yearly average peak load of Takoradi from 2014-2021

Real data from ECG. Takoradi branch								
Year	2014	2015	2016	2017	2018	2019	2020	2021
Average peak load (MW)	16.92	16.98	17.94	18.24	19.54	21.12	23.22	25.31

The data in Table 3-1 shows a yearly increase in load which indicates a 5.92% load growth over the years. The load in the year 2021 is seen as the highest of all the loads and has been used as the base load for other load projection per the scenario. This served as an annual load augmentation in the simulation. Table 3-2 gives a breakdown of the load in 2021 according to the load on each feeder.

Table 3-2: Yearly average peak load on each feeder

S/N	**Feeder**	**Yearly load (MW)**
1	B01	2.72
2	B09	2.34
3	B67	1.20
4	B11	1.82
5	B41	2.05
6	B32	1.67
7	B21	3.86
8	B81	2.04
9	B51	2.11
10	B71	1.75
11	B52	1.82
12	B87	1.93
Total		**25.31**

Table 3-2 indicates the total load on each feeder in the year 2021. The load demand per each feeder in the year 2021 aided the projection for the domestic load up to the year 2050. The projected domestic/household that will be available in the year 2025, 2030, 2040 and 2050 was the focus of this study. Equation 3.33 was used in Excel Spread Sheet to extrapolate for the CYGR and the outcome is displayed in Table 3-3 which shows the projected yearly rise in domestic load by 2050.

Table 3-3: Actual and predicted compounded yearly growth rate of domestic load of Takoradi (2014-2050)

Year	**Average peak Load (MW)**	**Number of years**	**Growth rate (%)**	**Remarks**
2014	16.92	0	0	None
2015	16.98	1	0.35461	Actual growth
2016	17.94	2	2.970078	Actual growth
2017	18.24	3	2.535635	Actual growth
2018	19.54	4	3.664737	Actual growth
2019	21.12	5	4.534275	Actual growth
2020	23.22	6	5.416917	Actual growth
2021	25.31	7	5.921602	Actual growth
2022	25.30714	8	5.161154	Predicted growth
2023	26.50679	9	5.114313	Predicted growth
2024	27.70643	10	5.055312	Predicted growth
2025	28.90607	11	4.989152	Predicted growth
2026	30.10571	12	4.918977	Predicted growth
2027	31.30536	13	4.846818	Predicted growth
2028	32.505	14	4.74008	Predicted growth
2029	33.70464	15	4.701433	Predicted growth
2030	34.90429	16	4.629681	Predicted growth
2031	36.10393	17	4.559141	Predicted growth
2032	37.30357	18	4.490066	Predicted growth
2033	38.50321	19	4.422614	Predicted growth
2034	39.70286	20	4.356876	Predicted growth
2035	40.9025	21	4.292899	Predicted growth
2036	42.10214	22	4.230694	Predicted growth
2037	43.30179	23	4.170252	Predicted growth
2038	44.50143	24	4.111547	Predicted growth
2039	45.70107	25	4.054542	Predicted growth
2040	46.90071	26	3.999192	Predicted growth
2041	48.10036	27	3.945449	Predicted growth
2042	49.3	28	3.893261	Predicted growth
2043	50.49964	29	3.842574	Predicted growth
2044	51.69929	30	3.793336	Predicted growth
2045	52.89893	31	3.745494	Predicted growth
2046	54.09857	32	3.698994	Predicted growth
2047	55.29821	33	3.653787	Predicted growth
2048	56.49786	34	3.609823	Predicted growth
2049	57.6975	35	3.567053	Predicted growth
2050	58.89714	36	3.525432	Predicted growth

The projected load growth was used to calculate the expected loads at the substations in order to ascertain the power demands for both the minimum uptake and maximum uptake scenarios and the results are shown in Appendix II. According to Table 3-3, the difference in domestic load demand between 2015 and 2025 is 11.93 MW representing 4.64% growth rate; which is approximately the same as the average domestic load demand in every decade (10 years) say 2030 and 2040; and 2040 and 2050 is 12MW. The domestic demand in Takoradi is likely to increase by 12MW in every ten (10) years.

It is important to note that, the actual demand may be higher than the projection in this thesis. This is because the projections are based on the historical demand in Takoradi which may not reflect the actual domestic demand. This estimation will help when planning reinforcement and expansion of the network with the addition of EV load. The results acquired was used to plot the CYGR of domestic load of Takoradi as shown in Figure 3-3.

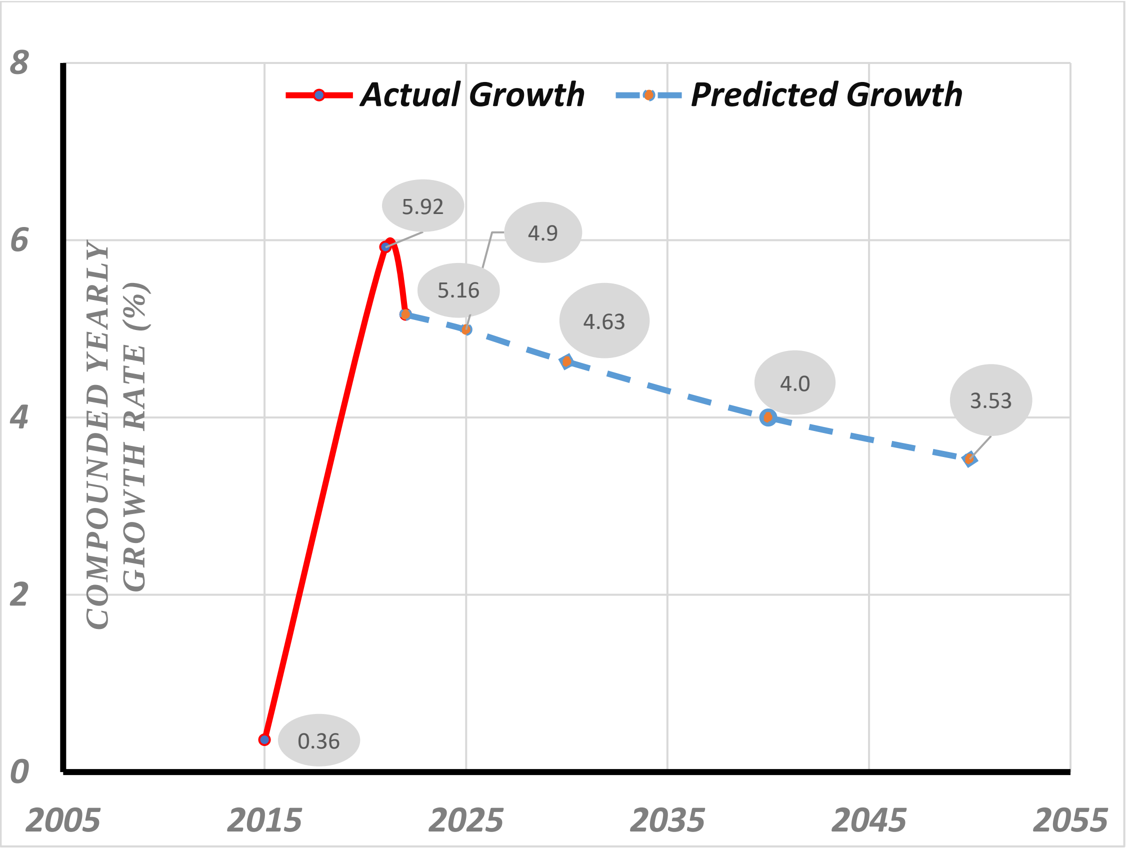


Figure 3-3: CYGR of domestic load of Takoradi (plotted based on ECG Takoradi data)

The compounded yearly growth rate (CYGR) load increase for residential load is shown in Figure 3-3 and is projected to decrease from 5.92% to 4.99% by 2025. It is anticipated to decrease even more by 2050, reaching 3.53%. The data on the network from 2014 to 2021 was extrapolated in excel spread sheet using Equation 3.33 to ascertain the growth rate of domestic load up to 2050. These growth levels as presented in Table 3-3 were calculated and used together with the EV growth levels for minimum and maximum uptake level scenarios in the simulation.

$b = x(1 + i)^n$ ……………..…. Equation 3.33 (Lhendup et al., 2020)

Where x represents initial average peak value which is kept at fixed, i represents growth rate, n is the number of years, and b is growth value.

3.5.1 Estimation of EVs at different penetration level

In this research, three scenarios were considered to project the totality of EVs; namely the current state, the minimum uptake, and the maximum uptake. The current state is made up of EV strength as of 2021; and for the minimum and maximum uptake scenarios, a compounded yearly increase rate of 10% and 20% respectively is employed according to *(*SAARC Energy Centre, 2019). Getting historical data on pure EVs in Takoradi was quite difficult, therefore, this research considered 20 EVs for HCs and 12 EVs for FCs for the current state scenario to help estimate for the total number of EVs for HCs and FCs for the minimum and maximum uptake scenarios.

According to (Ayetor, Quansah & Adjei, 2020; Burillo et al., 2019), more automobiles are anticipated to be on the road in the upcoming years, therefore it can be concluded that EV penetration will also be higher in the coming years. In estimating for the number of EVs that will be available by 2050, Equation 3.33 was used for both the minimum and maximum uptakes (Jenkins & Kockar, 2022; Zhixiong & Zhensheng, 2021; Khuntia et al., 2016) The additional load of EVs integrated in the system at different penetration levels is presented in Table 3-4.

Table 3-4: Projected number of electric vehicles (2021-2050)

Scenario	**Year**	**Total HC**	**Penetration level**	**Total FC**	**Penetration level**
Current state	2021	20	0.058%	12	0.035%
Minimum uptake	2025	29	0.084%	18	0.052%
	2030	47	0.14%	29	0.084%
	200	122	0.35%	75	0.22%
	2050	317	0.92%	195	0.56%
Maximum uptake	2025	42	0.12%	25	0.072%
	2030	105	0.30%	62	0.18%
	2040	650	1.88%	384	1.11%
	2050	4025	11.63%	2378	6.87%

Report according to the Ghana Statistical Service in the Population and Housing Census (GSS PHC, 2021), suggest that the yearly average population growth rate of Ghana stands at 2.16% currently which is anticipated to grow from the current state of 2.16% to 4.3% by 2050. Also, the Western Region population is predicted to increase from the current level of 2.0% to 4.1% by 2050 (GSS PHC, 2021). Considering the expanding population, it is however predicted that the total fleet of cars would increase by 2050.

As a result, the level of EV penetration can be estimated as the ratio of EVs to the overall estimated vehicle fleets (Lhendup et al., 2020; Hong, Wilson & Xie, 2014). The estimated vehicle fleets by 2050 is projected to be 34614. By 2025 a penetration level of 0.084% will be attained for the minimum uptake and by 2050 a higher penetration level of 11.63% will be obtained for the maximum uptake level for HC. Similarly, by 2025 a penetration level of 0.052% will be achieved for the minimum uptake and by 2050 a higher penetration level of 6.87%. Equation 3.34 was used to calculate the various penetration levels for the three scenarios.

NB: For minimum uptake $b = x(1+0.1)^n$ and for the maximum uptake $b = x(1+0.2)^n$ (Lhendup et al., 2020).

$Penetration\ level = \frac{EVs}{Total\ vehicle\ fleet} \times 100\%$ ……………………………… Equation 3.34.

Current level was calculated for HC using the total EV at 2021

$$\frac{20}{34614} \times 100\% = 0.058\%$$

Penetration level for the minimum uptake was calculated using the total EV at 2025:

$$\frac{29}{34614} \times 100\% = 0.084\%$$

Penetration level for the maximum uptake was calculated using the total EV at 2050:

$$\frac{4025}{34614} \times 100\% = 11.63\%$$

To facilitate the calculation for subsequent penetration levels, the same procedure was followed through to obtain the penetration levels for both minimum and maximum uptake levels for HC and FC and the results provided in Table 3-4 above.

3.6 Assessment of EV charging on low voltage distribution system

Synchronisation of EV load throughout a day, a month, or a year should take into account the EVs' charging capacity. Electric grid penetration of EVs is uncertain due to unpredictability in charging and discharging patterns. When an EV enters the low voltage distribution system, it could lead to numerous quality power issues as shown in Figure 3-4.

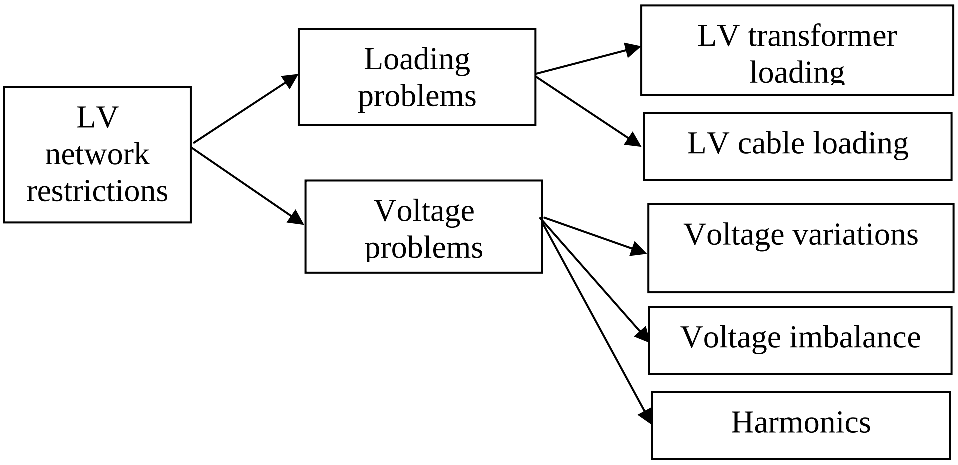


Figure 3-4: Classification of network restrictions

Accurately estimating the impacts that EV charging has on LV distribution system is challenging due to this uncertainty and different driving styles. The low voltage distribution grid is affected in different ways by increased electrical loads brought on by EVs being charged inefficiently. Considering the numerous challenges that EV charging poses on low voltage distribution grid, this research considers voltage magnitude or variations and transformer loading as the two prime conditions worth investigating.

3.6.1 Voltage variations impacted by EV load

Evaluating EVs load impacts on LV distribution system voltage began by analysing the behaviour of EV load in a voltage failure situation. Then the numeric simulation was carried out to assess the impact of EV load on voltage variations for current state, minimum uptake and maximum uptake scenarios. The voltage levels at the selected buses when EVs were not integrated were validated with the real data.

3.6.2 Impact of EV load on transformer loading

EV charging impact on LV distribution system was evaluated according to the limitation of rated capacity of the transformer. Since the transformers were the main limitation to charge the loads, the transformers were loaded according to the typical load and the EV load for the three scenarios thus current state, the minimum uptake, and the maximum uptake. The penetration level of EV charging may be constrained by the base load and the transformer power capacity, but the ambient temperature also has a significant impact. Table 3-5 shows the average real and reactive flow from 2021 to 2050 before EV deployment.

Table 3-5: Real and reactive load flows from 2021 to 2050 before EV penetration

S/N	**Feeder**	**Substation**	**2021 MW**	**2021 MVar**	**2025 MW**	**2025 MVar**	**2030 MW**	**2030 MVar**	**2040 MW**	**2040 MVar**	**2050 MW**	**2050 MVar**
1	B01	Airport Ridge 2	0.2059	0.0696	0.2156	0.0702	0.2250	0.0734	0.2334	0.0762	0.2411	0.0789
2	B09	Kwesimintsim	0.3306	0.1102	0.3461	0.1157	0.3610	0.1211	0.3744	0.1259	0.3866	0.1303
3	B67	West Tanokrom	0.2579	0.0869	0.2699	0.0888	0.2817	0.0928	0.2922	0.0965	0.3081	0.0998
4	B11	SSNIT Flat	0.1463	0.0478	0.1531	0.0501	0.1598	0.0524	0.1657	0.0544	0.1711	0.0563
5	B41	Roundabout	0.4857	0.1612	0.5085	0.1693	0.5305	0.1772	0.5504	0.1843	0.5685	0.1908
6	B32	WCL	0.3449	0.1131	0.3609	0.1186	0.3767	0.1241	0.3907	0.1290	0.4036	0.1335
7	B21	GP Sawmill	0.4189	0.1380	0.4385	0.1448	0.4574	0.1514	0.4745	0.1574	0.4900	0.1629
8	B81	Raybow	0.3085	0.1024	0.3229	0.1075	0.3369	0.1125	0.3494	0.1170	0.3607	0.1210
9	B51	BOG	0.2368	0.0778	0.2477	0.0816	0.2583	0.0853	0.2677	0.0886	0.2764	0.0916
10	B71	Ghacem 2	2.4993	0.8559	2.6132	0.8989	2.7232	0.9407	2.8220	0.9785	2.9120	1.0122
11	B52	Star Hotel	0.2254	0.0758	0.2359	0.0771	0.2461	0.0806	0.2552	0.0837	0.2635	0.0866
12	B87	Airforce Quarters	0.2741	0.0907	0.2869	0.0952	0.2994	0.0996	0.3106	0.1036	0.3208	0.1072
		Total	**5.7343**	**1.7682**	**5.9992**	**2.0178**	**6.2560**	**2.1110**	**6.4862**	**2.1947**	**6.6961**	**2.2711**

The information presented in Table 3-5 shows the real and reactive power elements consumed in the low voltage distribution system before EV penetration. Both the real and reactive power components show a marginal yearly increase from the year 2021 to 2050. The real power flow ranged between 5.7343MW to 6.6961MW while the reactive power flow ranged between 1.7682MVar to 2.2711MVar. The difference in power flow between in the year 2021 and 2050 is 0.9618MW for the real power and 0.5029Mvar for the reactive power component.

3.6.3 EV load forecast

Two EV charger models were considered to represent a slow charger (7.4 kW level-2) and fast charger (50 kW DC) (Tian et al., 2021; Muratori, 2018; Watson et al, 2015). The energy consumption by the EVs come from the numerous Home Chargers (HC) and Fast Chargers (FC) that will be put at various sites and their current levels kept at 32A and 63A accordingly.

$$\text{Energy demand of EVs} = Rated\ power\ of\ the\ charger \times the\ total\ number\ of\ chargers \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{ Equation 3.35}$$

Table 3-6 presents the estimated energy demand of EVs (HC-7.4kW and FC-50kW) for different penetration levels.

Table 3-6 Estimated energy demand of EVs for different penetration levels

Scenario	**Year**	**Total FC**	**Total HC**	**Load (MW)**		**Total load (MW) (FC + HC)**
				FC	**HC**	
Current state	2021	12	20	0.60	0.15	0.75
Minimum uptake	2025	18	29	0.90	0.22	1.12
	2030	29	47	1.45	0.35	1.80
	2040	75	122	3.75	0.90	4.65
	2050	195	317	9.75	2.35	12.1
Maximum uptake	2025	25	42	1.25	0.31	1.56
	2030	62	105	3.10	0.78	3.88
	2040	384	650	23.25	4.81	19.86
	2050	2378	4025	118.9	29.79	148.7

The estimated probable energy demand for EVs in 2021 is 0.75 MW. By 2050, the energy needed will be roughly 12.1 MW for the minimum uptake level and 148.7 MW for the maximum uptake level. Equation 3.35 was adopted for the computation of the probabilistic energy demand by EVs and the results shown in Table 3-6 indicating the overall EVs energy demand at different penetration levels for both HC and FC infrastructure from 2021 to 2050 and Figure 3-5 shows the load forecast for domestic and EV loads curve from 2021-2050.

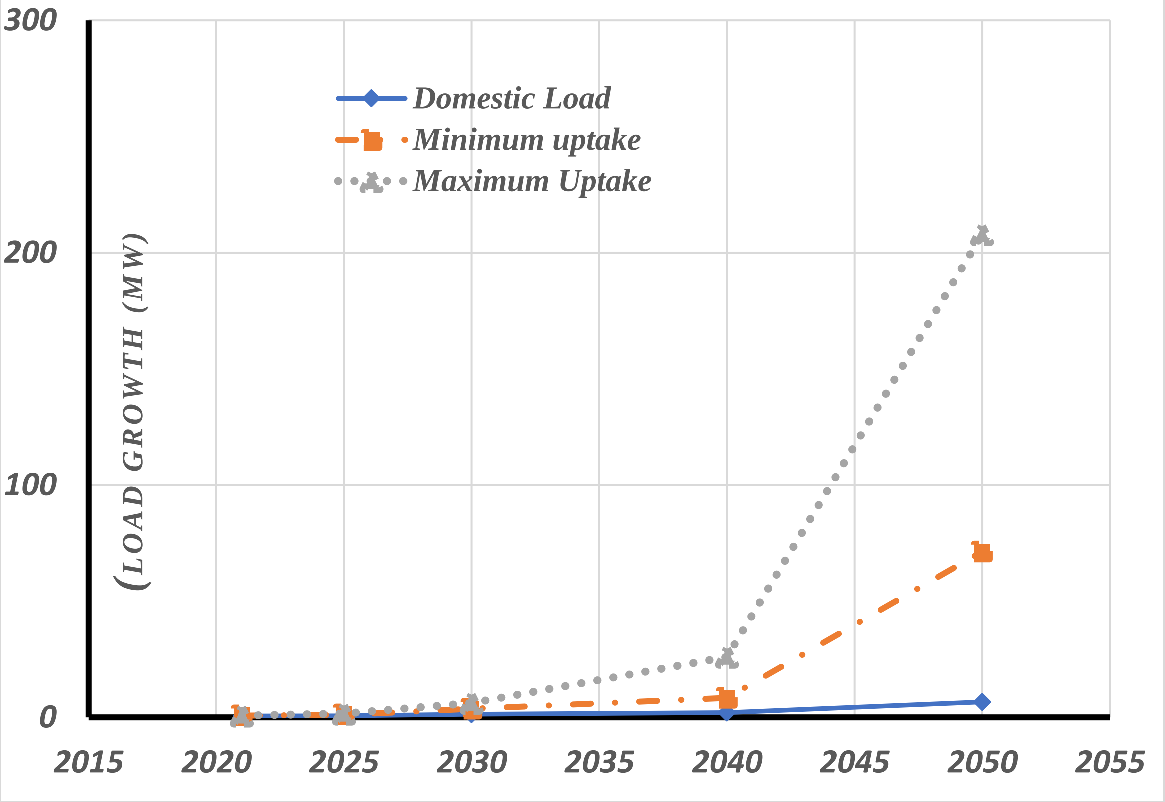


Figure 3-5: Load forecast for domestic and EV loads (2021-2050)

The overall load projection for EV together with the growth of typical household load is depicted in Figure 3-5. The domestic load showed a slight change in load demand from the year 2021 to 2040 until it began to rise up to the year 2050. Thus, domestic load presented almost a linear graph. With the deployment of EV load for both minimum and maximum uptakes an appreciable rise in load was observed from 2030 and beyond. The cumulative energy demand attained for a minimum uptake level is rounded to be 72MW and 208MW for maximum uptake level by 2050. The demand may increase depending on EV deployment and the actual domestic demand.

3.6.4 Explanation of study scenarios

The study scenarios were selected based on the available literature to compare the results of the proposed load flow analysis with existing studies. Many studies have considered level 1 and level 2 chargers separately in their analysis and others both. Few studies have analysed the impacts of all the three levels of chargers. Limited works have combined level 2 and level 3 in their studies. For this study, level 2 and level 3 chargers were employed and three scenarios were established to achieve the set objectives. The various scenarios were simulated for the analysis of the solution. Tables 3-3, 3-4 and 3-6 show the scenarios and the parameters considered for the various situations. **The current state scenario** involves the domestic load as at 2021, 20 (7.4 kW level-2) and 12 (50 kW level-3). For both **the minimum and maximum uptake scenario**, projections for future load demands were done for four (4) target years; thus 2025, 2030, 2040 and 2050. The various scenarios played on position and quantity of load. The various quantity of EV loads integrated to the network for both the minimum and maximum uptake scenarios during the deployment of both HC and FC infrastructures have been presented in Table 3-6 above.

3.6.5 Positions of transformers and loads EVs on the system

The diagram of the modelled Takoradi Distribution System (TDS) showing the positions of various transformers and loads is display in Figure 3-6.

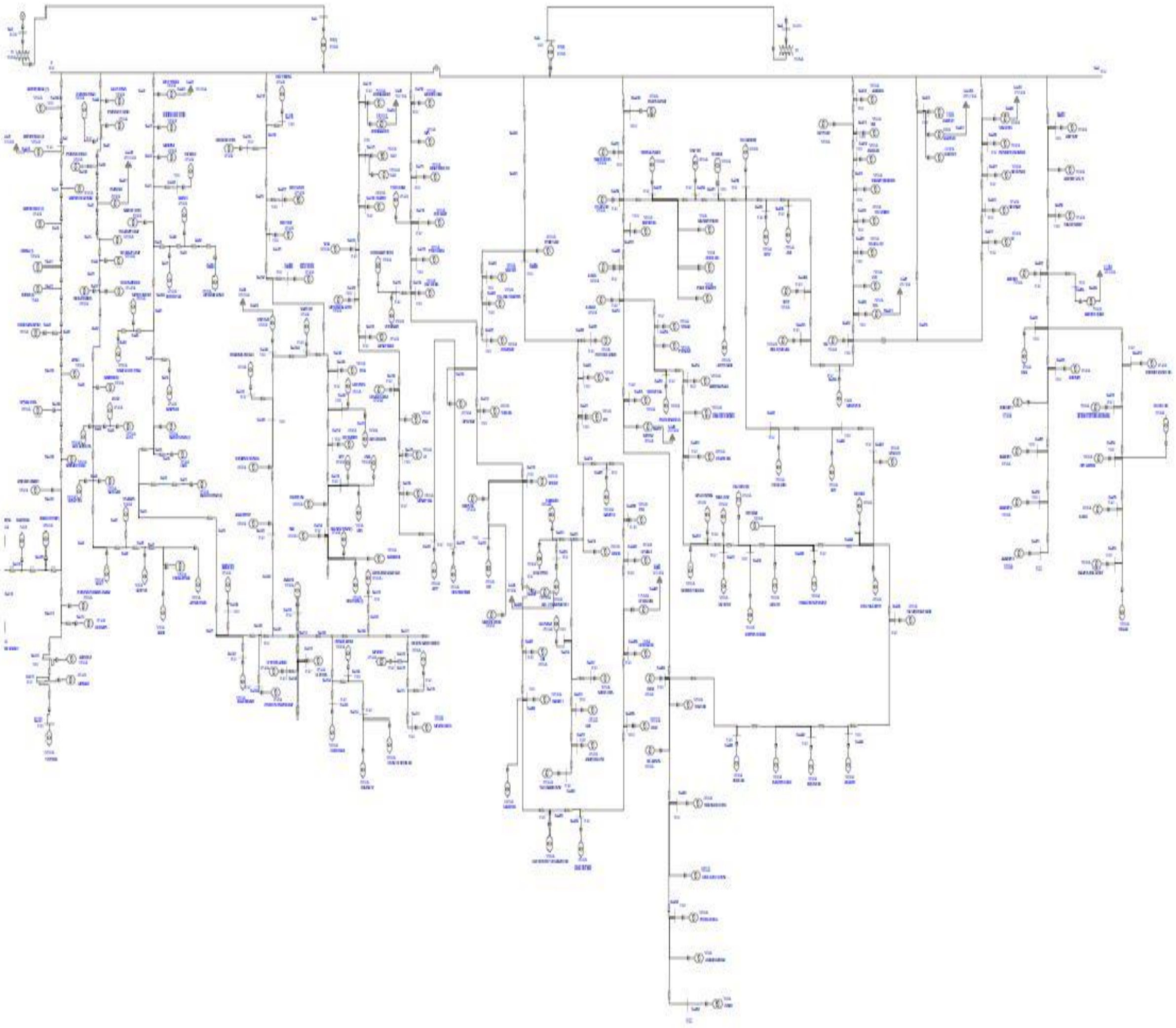


Figure 3-6: Snapshot of modelled TDS showing load positions

Twelve (12) transformers with one from each feeder were carefully selected from the network for the load flow analysis. An overall load of 468, including both the existing load and EV load on the low voltage lines were combined and placed on the transformers. The EV load for the year under review was added to the existing load on the transformer and the model's load editor window was updated with the new values, and the distribution system's behaviour was then simulated. Initially, both charging load for HC and FC were separately added to 2021 existing load and then load flow analysis was run separately. For more simulations on the distribution system, estimated EV loads and projected existing loads for the same year were added and then load flow analysis were performed. Table 3-7 illustrates the details of the selected substations together with distribution of 12 FCs and 20 HCs that were initially simulated.

Table 3-7: Details of the selected substations and distribution of HCs and FCs for base model study

S/N	**Feeder**	**Substation**	**Bus**	**Rating (KVA)**	**Percentage Impedance (%Z)**	**X/R Ratio**	**HC**	**FC**
1	B01	Airport Ridge 2	15	500	4	1.5	1	1
2	B09	Kwesimintsim	39	800	5	3.5	2	1
3	B67	West Tanokrom	56	500	4	1.5	1	1
4	B11	SSNIT Flat	100	315	4	1.5	1	1
5	B41	Roundabout	106	1250	5	3.5	2	1
6	B32	WCL	130	1500	6.25	6	2	1
7	B21	GP Sawmill	148	1250	5	3.5	2	1
8	B81	Raybow	171	800	5	3.5	2	1
9	B51	BOG	227	750	5	3.5	1	1
10	B71	Ghacem 2	229	8000	8.35	13	3	1
11	B52	Star Hotel	231	500	4	1.5	1	1
12	B87	Airforce Quarters	240	750	5	3.5	2	1
		Total					**20**	**12**

Based on the initial model simulation, it was assumed that each of the 12 feeders, had one 50kW FC installed which is fed through a 11/0.415kV 3-phase system transformer. Electricity linked to HC comes from the LV supply cables of 0.415V/240V of the household/domestic providing system because the majority of domestic supply is single-phase. All HC load real power and power factor were taken to be 7.4kW and 95% respectively. Likewise, FC loads were taken to be 50kW and the power factor set to unity or 100%. A number of loads were combined into one and lumped on the transformers and then load flow analysis was performed to ascertain the effect of EV load on the LV system of Takoradi. When EV penetration on the system is heavy, voltage variations and transformer loading can be considered as the main parameters that hinder the distribution system's performance.

CHAPTER FOUR

RESULTS AND DISCUSSION

This chapter presents the outcomes of various approaches and validation information for the three various simulation scenarios: current state, minimum uptake and maximum uptake. The real and reactive load flow components, the voltage variations and transformer loading were calculated using ETAP 19.0.1 simulation software. Load flow analysis was then performed on LV distribution system of Takoradi, Ghana with a rise in EV incursion at different penetration levels and evaluated EVs charging impacts on LV system. Throughout the research period, several assumptions and simplifications were made to facilitate a working model and generation of results.

4.1. Load flow analysis

As the basic step of impact analysis of EV charging, load flow analysis was performed on LV distribution system accompanied by a rise in EV penetration. The primary goal of the load flow was to find out whether the low voltage distribution system can withstand EV incursion at different penetration level without updating or improving the existing distribution system together with the normal growth of existing loads on the transformers. Load flow analysis was performed to observe the behaviour of the existing LV distribution system conditions and afterwards the varied real and reactive power, and voltage variations is brought on by the adoption of EVs.

4.1.1 Validation of the model

In this section, the Takoradi peak load demand model results and bus voltage levels developed in this thesis was tested with real data from 2016 to 2021. The details of the comparison are presented in Table 4-1. The first part of the Table 4-1 compares the simulated results of average peak load with the real data while the second part compares the simulated bus voltages with the real data.

Table 4-1 Validation of load demand and voltage model

Real data verses simulated data (average peak load)						
Year	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Real (MW)	17.94	18.24	19.54	21.12	23.33	25.31
Simulated (MW)	18.37	18.61	19.95	21.74	24.09	25.93
Error (%)	4.3	3.7	4.1	6.2	7.6	6.2
Real data verses simulated data (average voltage level)						
Real (V)	387	398	410	407	411	409
Simulated (V)	388	403	414	416	414	407
Error (%)	1	5	3	9	3	-2

Load flow analysis was carried out and validation of data was undertaken to test the system to ascertain whether the steady state operating constraints are violated or not and to compare the real data with the simulated results. For the first part of Table 4-1, the margin of error is observed within the range 3.7% and 7.6% in the year 2017 and 2020 respectively. These error margin falls within the accepted limit of ±5% (standard EN 50160). With the second part of Table 4-1, the error margin ranged between -2% to 9% in the year 2021 and 2019 respectively. The error margin is within the standard range of +10% /-6% of power quality standard (EN 50160).

4.1.2 Power flows for current state scenario

The results for real and reactive power flows for the current state scenario during the integration of HC and FC infrastructure at different penetration level together with the domestic load is shown in Table 4-2.

Table 4-2 Real and reactive power flows for current state scenario (2021)

S/N	**Feeder**	**Substation**	**Bus**	**HC MW**	**HC MVar**	**FC MW**	**FC MVar**
1	B01	Airport Ridge 2	15	0.2126	0.0691	0.2606	0.0046
2	B09	Kwesimintsim	39	0.3436	0.1149	0.3911	0.0095
3	B67	West Tanokrom	56	0.2646	0.0869	0.3148	0.0067
4	B11	SSNIT Flat	100	0.1530	0.0501	0.1992	0.0043
5	B41	Roundabout	106	0.4990	0.1659	0.5519	0.0119
6	B32	WCL	130	0.3583	0.1177	0.4055	0.0069
7	B21	GP Sawmill	148	0.4322	0.1426	0.4823	0.0091
8	B81	Raybow	171	0.3219	0.1071	0.3689	0.0083
9	B51	BOG	227	0.2433	0.0801	0.2941	0.0057
10	B71	Ghacem 2	229	2.5164	0.8624	2.6679	0.0763
11	B52	Star Hotel	231	0.2320	0.0758	0.2812	0.0054
12	B87	Airforce Quarters	240	0.2876	0.0954	0.3225	0.0719
		Total		**5.8645**	**1.9680**	**6.5400**	**0.2204**

The power consumed by both HC and FC at different penetration level and at different power demand. When the results of HC and FC in this current state scenario (2021) was compared to the real and reactive results before EV penetration (Table 3-4), the results showed some level of similarity with very slight difference which had no effect or negative effect on the network. This suggested that, in the current state scenario, the system can contain or withstand both HC and FC infrastructure.

4.1.3 Real and reactive flows for HC and FC infrastructure–minimum uptake scenario

In this section, the real and reactive power flow results for minimum uptake level scenario during the deployment of both HC and FC infrastructure at different penetration levels along with domestic load is presented and detailed analysis is provided below.

4.1.3.1 Power flows for minimum uptake scenario during HC integration

The real and reactive power flows result for minimum uptake scenario from 2025-2050 during the deployment of HC infrastructure at different penetration levels together with domestic load is shown in Table 4-3.

Table 4-3 Real and reactive power flows for HC – minimum uptake scenario (2025 – 2050)

S/N	**Feeder**	**Substation**	**Bus**	**2025 MW**	**2025 MVar**	**2030 MW**	**2030 MW**	**2040 MW**	**2040 MVar**	**2050 MW**	**2050 MVar**
1	B01	Airport Ridge 2	15	0.2289	0.0747	0.2448	0.0801	0.2723	0.0896	0.3817	0.1284
2	B09	Kwesimintsim	39	0.3591	0.1204	0.3936	0.1329	0.4390	0.1496	0.5306	0.1842
3	B67	West Tanokrom	56	0.2764	0.0910	0.2946	0.0973	0.3308	0.1100	0.4155	0.1405
4	B11	SSNIT Flat	100	0.1598	0.0524	0.1729	0.0569	0.1983	0.0658	0.2669	0.0904
5	B41	Roundabout	106	0.5283	0.1764	0.5569	0.1866	0.6081	0.2051	0.7785	0.2684
6	B32	WCL	130	0.3878	0.1280	0.4166	0.1380	0.4627	0.1543	0.6287	0.2149
7	B21	GP Sawmill	148	0.4582	0.1517	0.4900	0.1629	0.5452	0.1826	0.6785	0.2313
8	B81	Raybow	171	0.3428	0.1146	0.3697	0.1243	0.4271	0.1452	0.5184	0.1796
9	B51	BOG	227	0.2608	0.0861	0.3102	0.1036	0.3323	0.1115	0.4278	0.1466
10	B71	Ghacem 2	229	2.6419	0.9098	2.7747	0.9605	2.9642	1.0339	3.1791	1.1192
11	B52	Star Hotel	231	0.2423	0.0793	0.2589	0.0850	0.2935	0.0970	0.3701	0.1242
12	B87	Airforce Quarters	240	0.3002	0.0999	0.3191	0.1066	0.3826	0.1295	0.4675	0.1613
		Total		**6.1865**	**2.0843**	**6.5820**	**2.2347**	**7.1814**	**2.3158**	**8.6433**	**2.9890**

Table 4-3 illustrates the real and reactive power consumed by HC infrastructure at different penetration level and at different power demand for minimum uptake scenario. The results show a gradually slight increase in both the real and reactive components of power in all the transformers from 2025 to 2050. From Table 4-3, it is seen that substation GHACEM 2 on feeder B71 recorded the highest real power and reactive while SSNIT Flat recorded the lowest from 2025 to 2050. Because the penetration of EV load was not much all the substations did not see any disturbances in the system, thus, the system accommodated HC infrastructure.

4.1.3.2 Power flows during FC integration–minimum uptake scenario

In this section, the results for real and reactive power flows for minimum uptake scenario from 2025-2050 during the integration of FC infrastructure at different penetration levels along with domestic load is presented in Table 4-4.

Table 4-4 Real and reactive power flows for FC – minimum uptake scenario (2025 – 2050)

S/N	**Feeder**	**Substation**	**Bus**	**2025 MW**	**2025 MVar**	**2030 MW**	**2030 MW**	**2040 MW**	**2040 MVar**	**2050 MW**	**2050 MVar**
1	B01	Airport Ridge 2	15	0.2707	0.0050	0.2802	0.0053	0.3811	0.0099	0.6052	0.0257
2	B09	Kwesimintsim	39	0.4074	0.0102	0.4705	0.0136	0.6222	0.0241	1.1964	0.0925
3	B67	West Tanokrom	56	0.3274	0.0072	0.3394	0.0078	0.4424	0.0133	0.6241	0.0272
4	B11	SSNIT Flat	100	0.2063	0.0046	0.2130	0.0049	0.2648	0.0076	0.4001	0.0179
5	B41	Roundabout	106	0.5760	0.0130	0.6954	0.0192	0.9021	0.0321	1.4973	0.0909
6	B32	WCL	130	0.4710	0.0093	0.5348	0.0121	0.8766	0.0328	1.4117	0.0884
7	B21	GP Sawmill	148	0.5029	0.0099	0.6180	0.1505	0.9119	0.0332	1.2632	0.0658
8	B81	Raybow	171	0.3841	0.0091	0.3945	0.0096	0.6447	0.0259	1.0015	0.0643
9	B51	BOG	227	0.3055	0.0062	0.3638	0.0088	0.4642	0.0144	0.8185	0.0464
10	B71	Ghacem	229	2.9339	0.0936	3.2382	0.1132	3.8756	0.1643	5.2042	0.3089
11	B52	Star Hotel	231	0.2921	0.0058	0.3024	0.0062	0.3931	0.0106	0.5803	0.0238
12	B87	Airforce Quarters	240	0.3460	0.0078	0.4070	0.0108	0.5110	0.0172	1.0086	0.0693
		Total		**7.0233**	**0.1815**	**7.8572**	**0.3619**	**10.290**	**0.3855**	**15.611**	**0.8552**

Similarly, Table 4-4 shows the real and reactive power consumed by FC infrastructure at different penetration level and at different power demand for minimum uptake scenario. According to Table 4-4, a notable observation is that the real power increased significantly while the reactive power increased marginally from the year 2025 to 2050. The real power ranged between 7.0233MW to 15.611MW while the reactive fell within 0.1851MVar and 0.8552MVar Compared the results to when HC infrastructure was integrated, it was observed that no major increase in real power flows per se but the reactive power flows were drastically reduced. No malfunction in lines and transformers was seen. This means when EV deployment is less, the power demand is also seen to be less. Thus, for the minimum uptake level scenario the system was able to accommodate FC infrastructure and no considerable power loss was observed.

4.1.4 Real and reactive flows for HC and FC infrastructure–maximum uptake scenario

In this section, the real and reactive power flow results for maximum uptake level scenario during the deployment of both HC and FC infrastructure at different penetration levels along with domestic load are presented with detailed analysis below.

4.1.4.1 Power flows during HC deployment–maximum uptake scenario

The real and reactive power flows result for maximum uptake scenario from 2025-2050 during the integration of HC infrastructure at different penetration levels together with domestic load is presented in Table 4-5.

Table 4-5 Real and reactive power flows for HC – maximum uptake scenario (2025 – 2050)

S/N	Feeder	Substation	Bus	2025 MW	2025 MVar	2030 MW	2030 MW	2040 MW	2040 MVar	2050 MW	2050 MVar
1	B01	Airport Ridge 2	15	0.2358	0.0771	0.2643	0.0869	0.4818	0.1653	1.1282	0.4549
2	B09	Kwesimintsim	39	0.3660	0.1229	0.4193	0.1423	0.6796	0.2433	1.8702	0.9038
3	B67	West Tanokrom	56	0.2834	0.0934	0.3140	0.1041	0.4765	0.1632	1.1713	0.4740
4	B11	SSNIT Flat	100	0.1606	0.0569	0.1859	0.0615	0.3208	0.1106	0.6342	0.2483
5	B41	Roundabout	106	0.5353	0.1764	0.5890	0.1982	0.9542	0.3368	2.4048	1.0674
6	B32	WCL	130	0.3948	0.1304	0.4290	0.1424	0.8596	0.3040	2.5684	1.2424
7	B21	GP Sawmill	148	0.4651	0.1541	0.5224	0.1744	0.9035	0.3175	2.4082	1.0935
8	B81	Raybow	171	0.3497	0.1170	0.4087	0.1384	0.6875	0.2466	1.4697	0.6488
9	B51	BOG	227	0.2676	0.0885	0.3102	0.1036	0.3323	0.1115	1.1511	0.4863
10	B71	Ghacem 2	229	2.6560	0.9151	2.2876	0.9848	3.3451	1.1873	6.8680	2.9495
11	B52	Star Hotel	231	0.2491	0.0816	0.2782	0.0917	0.4692	0.1607	1.0196	0.4031
12	B87	Airforce Quarters	240	0.3071	0.1023	0.3654	0.1233	0.6832	0.2468	1.3297	0.5769
		Total		**6.2705**	**2.1157**	**6.2940**	**2.3516**	**10.193**	**3.5936**	**24.023**	**10.549**

Table 4-5 shows the results for real and reactive power consumed by HC infrastructure at different penetration level and at different power demand. The value for the real power in 2025 and 2030 is approximately the same but increased almost twice in 2040 and approximately four (4) times in 2050. There was a slight difference in reactive power flow in the years 2025 and 2030. However, the reactive power in the year 2050 is approximately three (3) times more than that of 2040. This suggest that as deployment of EVs increases power losses also increases. However, with the deployment of HC no substation showed any considerable amount of power losses.

4.1.4.2 Power flows for maximum uptake scenario during FC integration

The real and reactive power flow results for maximum uptake scenario from 2025-2050 during the integration of HC infrastructure along with domestic load is presented in Table 4-6.

Table 4-6 Real and reactive power flows for FC – maximum uptake scenario (2025 – 2050)

S/N	**Feeder**	**Substation**	**Bus**	**2025 MW**	**2025 MVar**	**2030 MW**	**2030 MW**	**2040 MW**	**2040 MVar**	**2050 MW**	**2050 MVar**
1	B01	Airport Ridge 2	15	0.2740	0.0050	0.3732	0.0095	0.9424	0.0657	1.1383	0.1862
2	B09	Kwesimintsim	39	0.4547	0.0127	0.6095	0.0230	1.4188	0.1375	2.5756	0.0925
3	B67	West Tanokrom	56	0.3271	0.0072	0.4323	0.0127	0.9257	0.0625	1.6799	0.5056
4	B11	SSNIT Flat	100	0.2061	0.0046	0.3479	0.0083	0.4208	0.0205	0.5262	0.2483
5	B41	Roundabout	106	0.6722	0.0177	0.8834	0.0307	2.2621	0.2187	3.9364	1.4381
6	B32	WCL	130	0.5184	0.0113	0.7750	0.0254	2.4699	0.2902	3.8726	1.8906
7	B21	GP Sawmill	148	0.5981	0.0141	0.7561	0.2271	2.3150	0.2383	3.2421	1.1260
8	B81	Raybow	171	0.4371	0.0115	0.5864	0.0213	1.6040	0.1751	2.1846	0.7717
9	B51	BOG	227	0.3051	0.0062	0.4561	0.0139	1.0141	0.0757	1.5878	0.4916
10	B71	Ghacem 2	229	2.9780	0.0954	3.4540	0.1297	6.9152	0.5812	13.124	6.9685
11	B52	Star Hotel	231	0.2918	0.0058	0.3024	0.0062	0.9147	0.0624	1.5653	0.4112
12	B87	Airforce Quarters	240	0.3939	0.0101	0.5004	0.0165	1.2498	0.1117	2.4018	0.9458
		Total		**7.4475**	**0.2014**	**9.4722**	**0.5243**	**22.453**	**2.0395**	**37.835**	**14.889**

Table 4-6 depicts the results for real and reactive power consumed by FC infrastructure at different penetration level and at different power demand. With this scenario, the total real and reactive power components from 2025 to 2040 noticed a significant change but did not raise any alarm of line malfunction except in the year 2050. The total real power in the year 2050 is approximately twice compared to the real power in 2040 and a little over five (5.08) times more than the real power in 2021. Similarly, the reactive power in the year 2050 will be seven and half times $\left(7\frac{1}{2}\right)$ more compared to the reactive power in the year 2040 and approximately seventy-four (74) times more compared with the reactive power in the year 2021. This means that high deployment of EVs causes load demand to rise and also produces high losses. Therefore, a contingency plan is needed for buck-up (Lhendup et al., 2020; Bhavanam et al., 2015, 2015; Dubey and Santoso, 2015).

4.1.5 Discussions

The real and reactive power consumed by both HC and FC infrastructure at different penetration level was assessed under different power demand. The outcome of the findings presents that during the current state scenario (2021) a total of 20 EVs (HC-7.4kW) and 12EVs (FC-50kW) loads representing 0.058% and 0.035% penetration levels respectively, together with the domestic/household load did not cause any problem to the distribution system.

Again, with the minimum uptake scenario, the total load for both HC and FC infrastructures from the year 2025-2050 was 515 EVs (HC-7.4KW) and 317 EVs (FC-50KW) representing a power demand of 3.811MW and 15.85MW; thus, a penetration level of 1.5% and 0.92% respectively, along with the residential loads was accommodated by the network without any considerable number of losses. The results for the minimum uptake level scenario suggest that, the distribution system had the ability to accommodate both HC and FC development along with the residential load growth.

Furthermore, for maximum uptake scenario, a total penetration load for both HC and FC infrastructures from 2025-2050 was 4822 EVs (HC-7.4kW) and 2849 EVs (HC-7.4kW) representing a power demand of 35.68MW caused an approximately 40.97% load increase during the integration of HC infrastructure; and a demand of 142.45MW during FC deployment which is a little over five and half $(5\frac{1}{2})$ times more than the power demand for the present infrastructure.

The real and reactive components in the year 2025 to 2040 did not produce much losses compared to the real and reactive component in the year 2050. Since EV loads are inductive loads, the current wave lags the voltage wave, therefore, higher volumes of EV penetration produced extreme losses which caused line malfunction thus, has a negative impact on the distribution system. This suggest that power factor improvement is needed on the distribution network.

4.2 EV charging impact on TDS (voltage variations)

The LV system is a conventional distribution system that serves to connect the supply points for individual customers to the MV network. Despite the distribution system components loading, voltage drop is one key factor in LV distribution systems. The standard (EN 50160) specifies the requirements for power quality, and in the same manner, the voltage differences at the various buses should comply with those standards. Once the quantity of EVs increased, a lot of power was needed to charge the EV batteries. Due to the extra voltage losses in the secondary service voltages caused by higher load demand, the service voltage quality is impacted. (Dubey and Santoso, 2015, Bhavanam et al., 2015). Therefore, it is important to always keep the voltage within the permitted or statutory limits. Table 4-7 shows the voltage levels at the selected buses without EV penetration from 2025 to 2050.

Table 4-7 Voltage levels at the buses before EV penetration from 2021 to 2050

S/N	**Feeder**	**Substation**	**Bus**	**2021 (%)**	**2025 (%)**	**2030 (%)**	**2040 (%)**	**2050 (%)**
1	B01	Airport Ridge 2	15	98.15	98.05	97.95	97.86	97.78
2	B09	Kwesimintsim	39	97.99	97.88	97.78	97.68	97.60
3	B67	West Tanokrom	56	98.25	98.17	98.11	97.99	97.92
4	B11	SSNIT Flat	100	98.23	98.15	98.05	97.96	97.89
5	B41	Roundabout	106	98.21	98.12	98.02	97.94	97.89
6	B32	WCL	130	97.92	97.81	97.70	97.60	97.51
7	B21	GP Sawmill	148	97.89	97.78	97.67	97.57	97.48
8	B81	Raybow	171	97.84	97.72	97.61	97.51	97.42
9	B51	BOG	227	97.40	97.26	97.13	97.01	96.90
10	B71	Ghacem 2	229	97.15	97.00	96.86	97.73	96.61
11	B52	Star Hotel	231	97.86	97.75	97.64	97.54	97.45
12	B87	Airforce Quarters	240	98.12	98.02	97.92	97.83	97.75
		Average		**97.92**	**97.81**	**97.70**	**97.69**	**97.51**

From Table 4-7, it is clearly seen that even when EV loads were not added, there was a slight voltage dip from 2021 through to 2050. However, the average voltage levels at the buses for these years under review ranged between 97.51% and 97.92% which fell within the standard voltage limit (power quality standard EN 50160). In the year 2021, all the buses recorded the highest voltage levels compared to all the other years which suggest that less load has no significant impact on the bus voltages.

4.2.1 Voltage variations for current state scenario at different penetration level

In the current state scenario, for both HC and FC, voltage violations were not seen when the penetration level for HC and FC were just 20 EVs (7.4kW) and 12 EVs (HC-50kW) respectively.

EV charging loads were comparatively less than the entire load in 2021, indicating that the EV charging load had a little impact on the grid. The secondary service voltage of the 11/0.415kV transformer was kept in the standard range of +10% /-6% to be in adherence to power quality standard EN 50160. Figure 4-1 illustrates the percentage (%) operating voltage at the substations at different penetration level during the current state scenario.

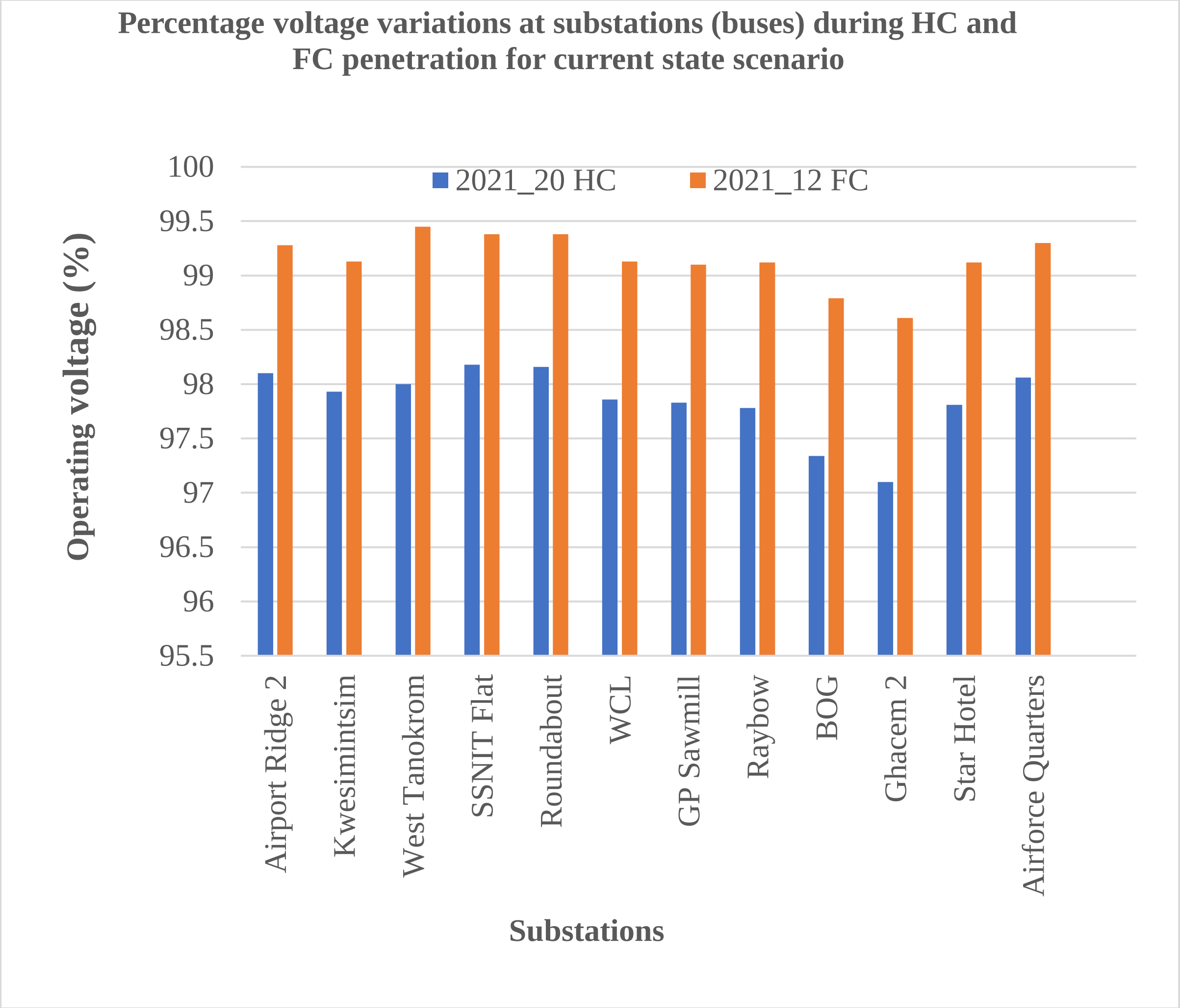


Figure 4-1: Voltage variations at the substations during the current state scenario

For voltage identification of the buses in ETAP, the critical voltage restrictions are set at 95% for under voltage conditions and 105% for over voltage conditions in ETAP 19.0.1 project settings. The load flow simulation showed that all the bus operating voltages were found to be over the critical voltage limits of 95% but did not exceed the critical voltage limits of 105% for over voltage conditions. The operating voltages during HC and FC deployment ranged between 97.1% to 98.18% and 99.1% to 99.45% respectively.

4.2.2 Voltage variations during HC and FC deployment (minimum uptake scenario)

In this section, the voltage variation results at the substation buses for minimum uptake level scenario during the deployment of both HC and FC infrastructure at different penetration levels are presented in bar charts with detailed analysis provided below.

4.2.2.1 Voltage variations for minimum uptake scenario during HC penetration

In the year 2025, when EV penetration level rose to 0.084% representing 29 EVs of HC infrastructure, all the buses operating voltages were observed within 97.18% to 98.14% which is above the critical operating voltage for under voltage conditions but lower than the critical operating voltage set for over voltage conditions. This means that no under voltage nor over voltage conditions were seen. Figure 4-2 shows percentage (%) operating voltage at substations at different penetration level for HCs during the minimum uptake scenario.

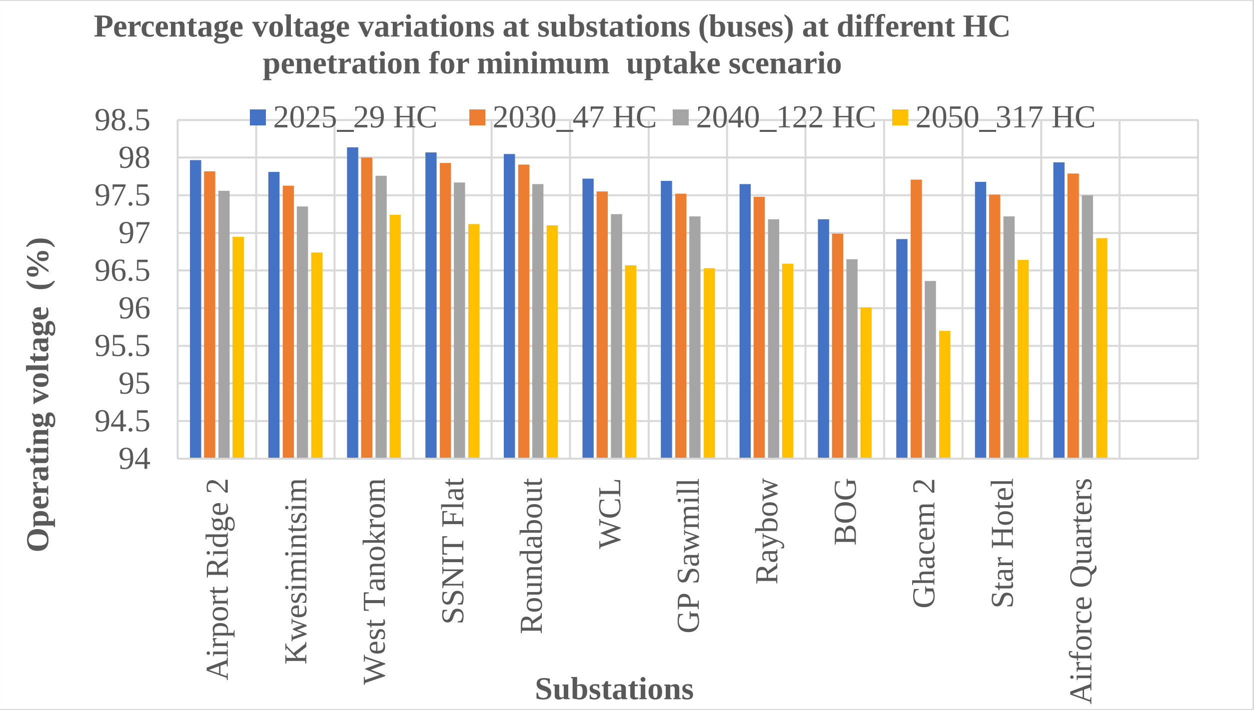


Figure 4-2: Voltage variations at buses during HC penetration for minimum uptake scenario

According to the results, when EV penetration level reached 0.35% and 0.92% corresponding to 122 EVs and 317 EVs respectively; all the bus operating voltages were seen between 97.18% to 97.76 in the year 2040 and 95.7% to 97.24% in the year 2050. No under voltage nor over voltage situations were observed. The research conducted by (Lhendup et al., 2020; Muratori 2018; Held and Junge, 2017; Dubey and Santoso, 2015 and Bhavanam et al., 2015) identified neither under voltage nor over voltage conditions when 100 EVs of 7.4kW chargers were integrated in low voltage distribution system which confirms the results of this research that even when 317 EVs of 7.4kW chargers were integrated the voltages fell within the accepted range (power quality standard EN 50160).

4.2.2.2 Voltage variations for minimum uptake scenario during FC integration

The results during FC integration are shown in Figure 4-3 which illustrates the percentage (%) operating voltage at substations at different penetration level during the deployment of FC infrastructure for the minimum uptake level scenario.

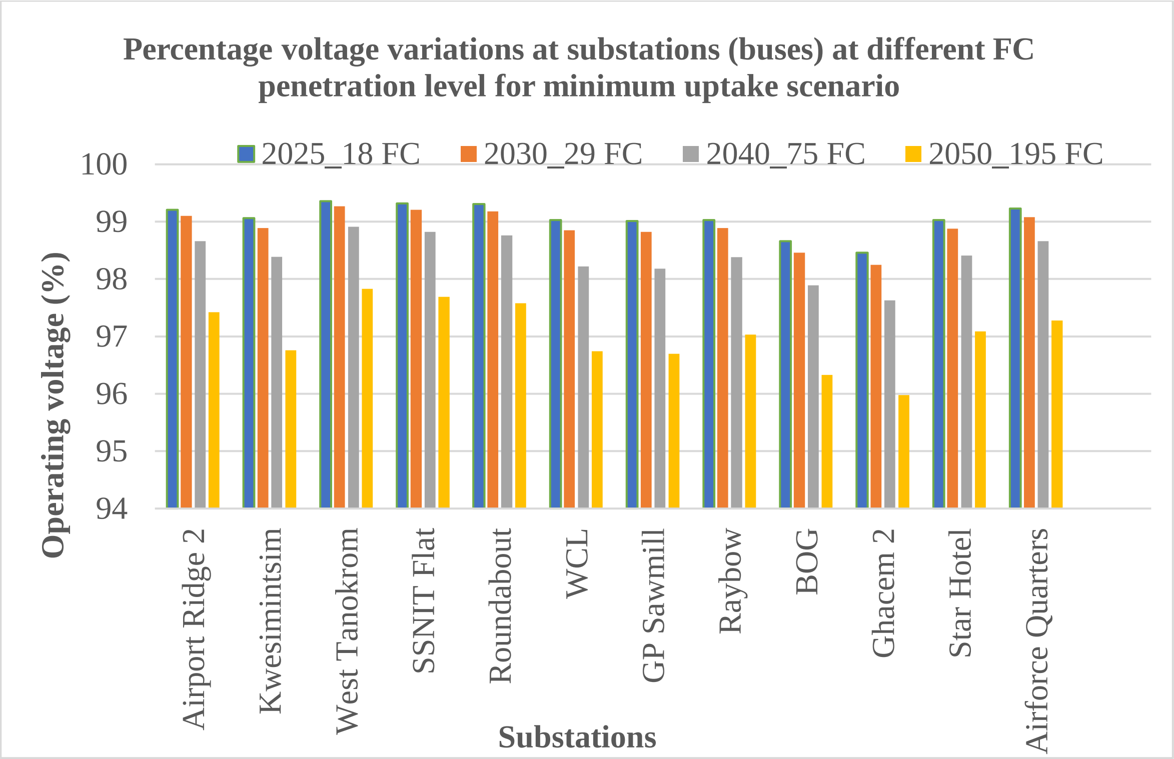


Figure 4-3: Voltage variations at the buses during FC penetration for minimum uptake scenario

Similarly, when FC infrastructure were added no voltage variations were observed. The bus operating voltages were between 98.46% to 99.38% for 2025 and 95.98% to 97.83% for 2050 which is within the statutory limits. West Tanokrom and Ghacem 2 substations recorded the highest and the lowest voltage levels in all those years. Per the results it means that no voltage variations were observed during FC integration at different penetration levels for the minimum uptake scenario.

4.2.3 Voltage variations during HC and FC integration (maximum uptake scenario)

In this section, the voltage variation results at the buses for maximum uptake level scenario during the deployment of both HC and FC infrastructure at different penetration levels are presented in bar charts with detailed analysis provided below.

4.2.3.1 Voltage variations for maximum uptake scenario during HC penetration

With the maximum uptake scenario, under voltage nor over voltage conditions were not seen until EV penetration level hit 1.88% corresponding to 650 EVs (HC-7.4Kw). The results show that, the bus operating voltages ranged between 95.18% and 96.55% expect Ghacem 2 substation which was connected to bus 229 registered 94.86% indicating under voltage situation. The results during HC penetration are shown in Figure 4-4 which illustrates percentage (%) operating voltage at the substations at different penetration level for HCs during the maximum uptake scenario.

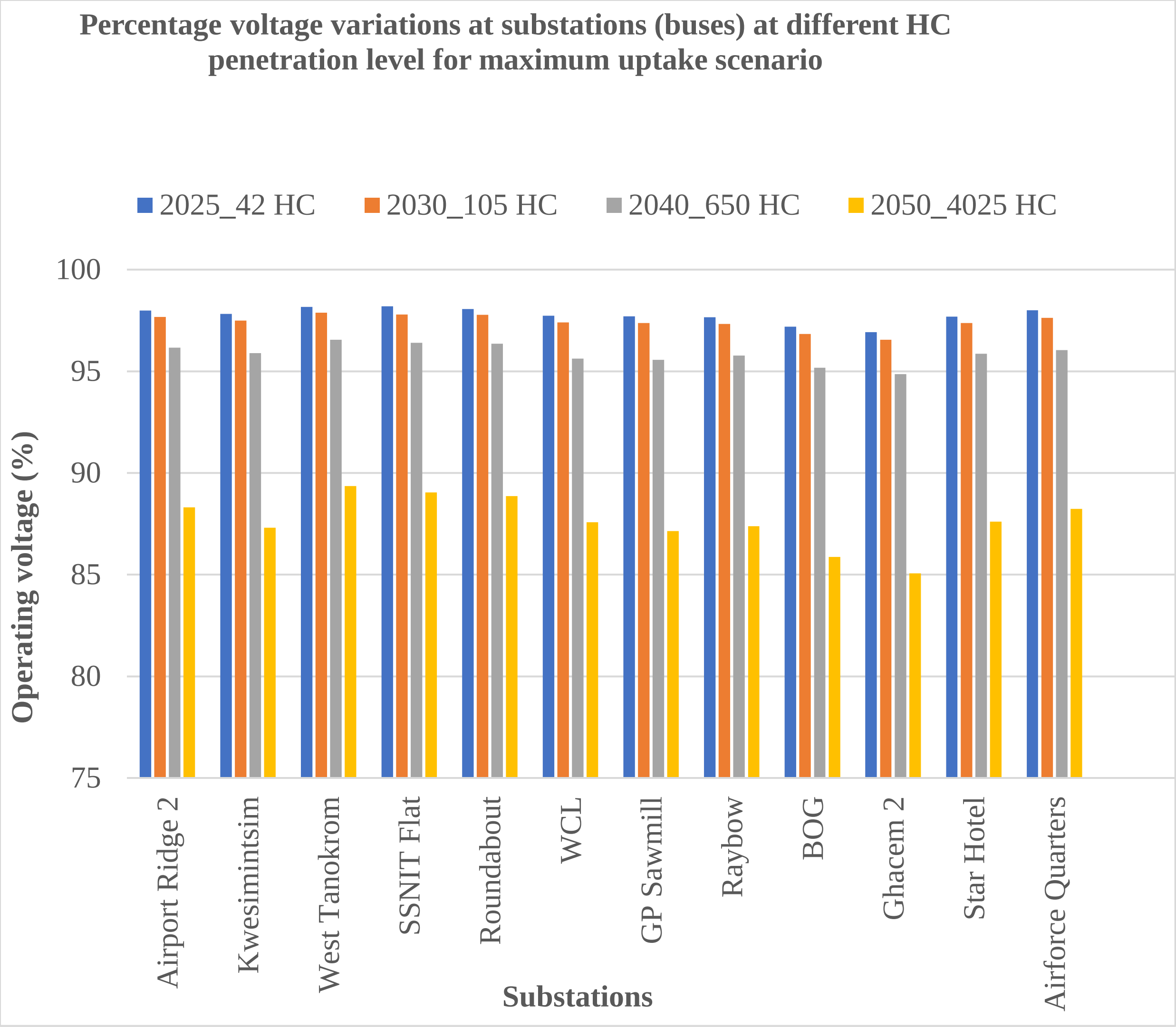


Figure 4-4: Voltage variations at buses during HC penetration for maximum uptake scenario

All voltages at the substations in the year 2050 at penetration level 11.63% corresponding to 4025 EVs (HC-7.4Kw) showed under voltage conditions at all the buses and the system tends to malfunction when EV load was increased. The HC equipment performed poorly due to voltage drops. This confirms the results in literature that higher penetration of EVs caused voltage variations or voltage drops. Furthermore, the studies by (Obeidat et al., 2021; Lhendup et al., 2020; and Bhavanam et al., 2015) confirms that when a higher quantity of EVs of 7.4 kW are deployed in low voltage distribution system, under voltage conditions occurred in the feeders which confirms the results of this research.

4.2.3.2 Voltage variations for maximum uptake scenario during FC integration

Similarly, for integration of FC infrastructure, voltage violations did not occur in the years 2025 and 2030. However, when the penetration level reached 1.11% corresponding to 384 EVs (FC-50kW) created under voltage condition at seven (7) buses namely bus 39, 130, 148, 171, 227, 229 and 231 which were connected to substations Kwesimintsim, WCL, GP Sawmill, Raybow, BOG, Ghacem 2 and Star Hotel respectively. For 2050, as EVs increased and therefore 6.87% of EV penetration which corresponds to 2378 EVs of 50kW were considered and the results revealed that all the buses were operating under voltage condition. The operating voltages fell between 57.42% and 70.01%, hence poor performance of equipment due to severe voltage drops. Figure 4-5 depicts percentage (%) operating voltage at the substations at different penetration level for FC during the maximum uptake scenario.

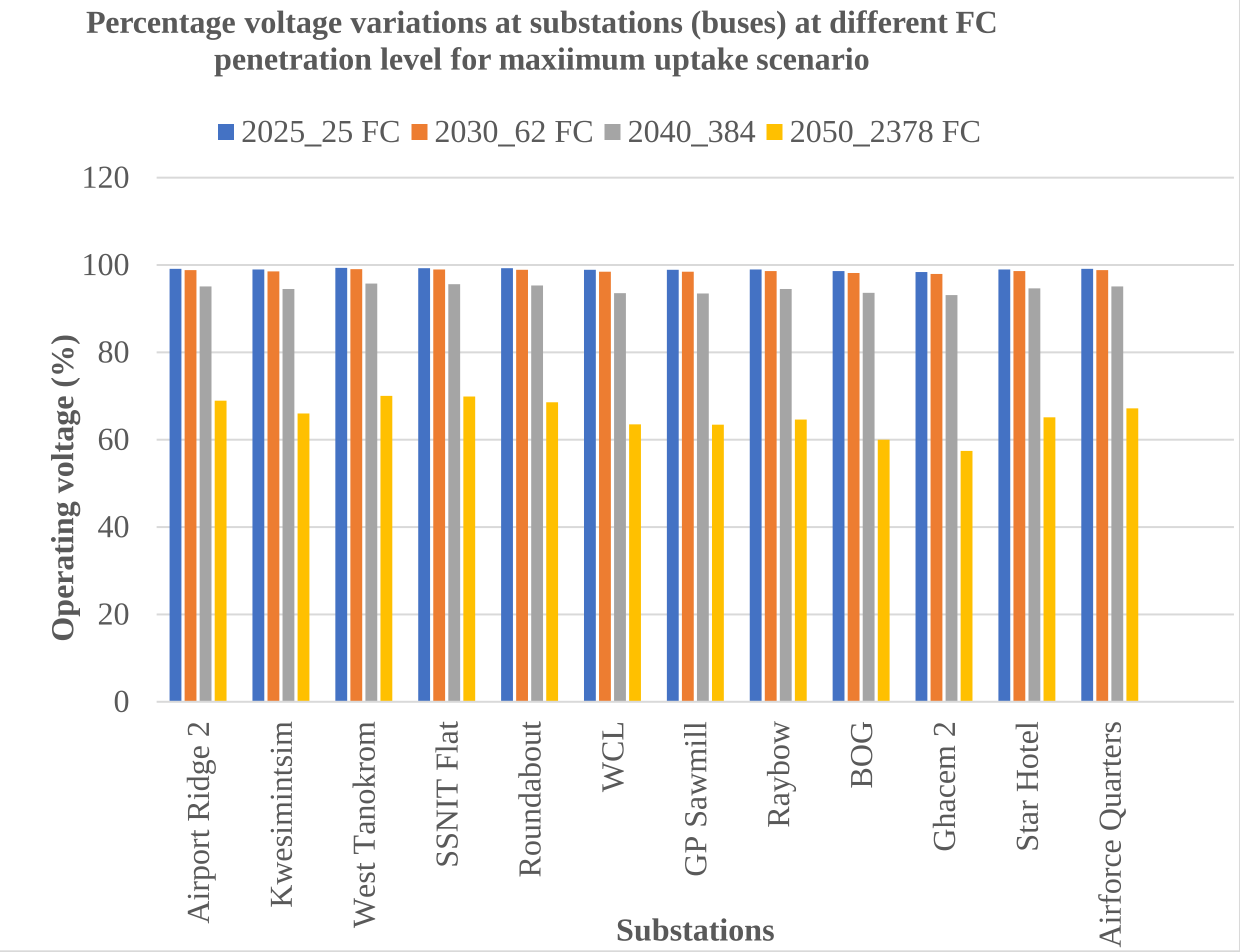


Figure 4-5: Voltage variations at buses during FC penetration for maximum uptake scenario

FC infrastructure created under voltage conditions at all the buses thus, a drop in voltage levels in the feeders. Literature has it that, high increase in EV penetration can cause system disintegration due to severe voltage violations at all the substations which confirms the outcomes of this thesis. A reinforcement of the system (voltage regulation) can be considered as immediate solution because higher EV penetration caused problems to the distribution system. The results obtained in this research is similar to the results achieved in the studies conducted by (Obeidat et al., 2021; Lhendup et al., 2020; Muratori 2018 and Bhavanam et al., 2015) that concluded that heavy deployment of FC can cause severe voltage drops.

4.2.4 Discussions

Since low voltage and high voltage conditions create problems in power quality issues in power systems, it is key and safe to always keep the voltage within the accepted power quality standard for voltage (EN 50160). During the current state scenario, integration of both HC and FC infrastructure did not register any voltage violations.

Following the deployment of HC and FC infrastructure during the minimum uptake scenario, the highest EV penetration of 317 EVs (HC-7.4 kW) and 195 EVs (FC-50 kW) in the year 2050 did not show any voltage variation conditions, thus the system was able to contain EV penetration.

During the maximum uptake scenario, when 650 EVs of (HC-7.4 k W) were deployed, only bus 275 showed under voltage condition. Also, integration of 4025 EV of (HC-7.4kW) showed all the buses operating undervoltage. Again, with the integration of 384 EVs of (FC-50kW) majority of the buses registered voltage drops conditions (undervoltage). Finally, with the deployment of 2378 EVs of (FC-50kW) all the bus operating voltages showed severe under voltage conditions. In conclusion, it is seen that in a distribution system, power losses on the buses lead to significant voltage variations. Therefore, high deployment of EVs can cause massive voltage variations that consequently affect the performance of LV distribution system. Voltage correction technique is suggested.

4.3 Impact of EV load on transformer loading

The simulation findings showed that as EV penetration on LV distribution system increased, transformer loading also increased. A higher number of EV penetration causes overloading and increasing overloading can cause the damaging of the transformers. Therefore, daily loading or peak loads must be kept below 100% of the maximum loading to keep the transformer operating safely. This must be understood to guarantee that grid elements like the distribution transformer, wires, and cables function within the permitted or statutory limit. Table 4-8 presents the state of transformer loading levels at all the selected substations before EV penetration from 2021 to 2050.

Table 4-8**:** Percentage loading levels at the substations before EV penetration from 2021 to 2050

S/N	**Feeder**	**Substation**	**Bus**	**2021 (%)**	**2025 (%)**	**2030 (%)**	**2040 (%)**	**2050 (%)**
1	B01	Airport Ridge 2	15	43.5	45.3	47.3	49.1	50.7
2	B09	Kwesimintsim	39	43.8	45.6	47.6	49.4	51.0
3	B67	West Tanokrom	56	54.3	56.8	59.3	61.6	63.6
4	B11	SSNIT Flat	100	48.9	51.1	53.4	55.4	57.2
5	B41	Roundabout	106	40.9	42.9	44.7	46.4	48.0
6	B32	WCL	130	24.2	25.3	26.4	27.4	28.3
7	B21	GP Sawmill	148	35.3	36.9	38.5	40.0	41.3
8	B81	Raybow	171	40.6	42.5	44.4	46.1	47.6
9	B51	BOG	227	33.2	34.8	36.3	37.6	38.8
10	B71	Ghacem 2	229	33.0	34.5	36.0	37.3	38.5
11	B52	Star Hotel	231	47.4	49.6	51.8	53.7	55.5
12	B87	Airforce Quarters	240	38.5	40.3	42.1	43.7	45.1
		Average		**40.3**	**42.1**	**44.0**	**45.6**	**47.1**

The information presented in Table 4-8 shows that none of the substations was overloaded before EV penetration. In 2021, the percentage loading levels at the substations before EV penetration ranged between 38.5% and 53.4% and increased gradually in 2025, 2030, 2040 and 2050, where the maximum percentage loading was seen in the year 2050 ranging between 45.1% to 63.6%. The average loading at the transformers in the year 2025 to 2050 were observed to be less than

50% of their rated capacity.

4.3.1 Transformer loading impact for the current state scenario

The section presents the results for the percentage transformer loading during the integration of both HC and FC infrastructure for the current state scenario at different EV penetration level. This is illustrated in Figure 4-6 which shows transformer loading impact at all substations.

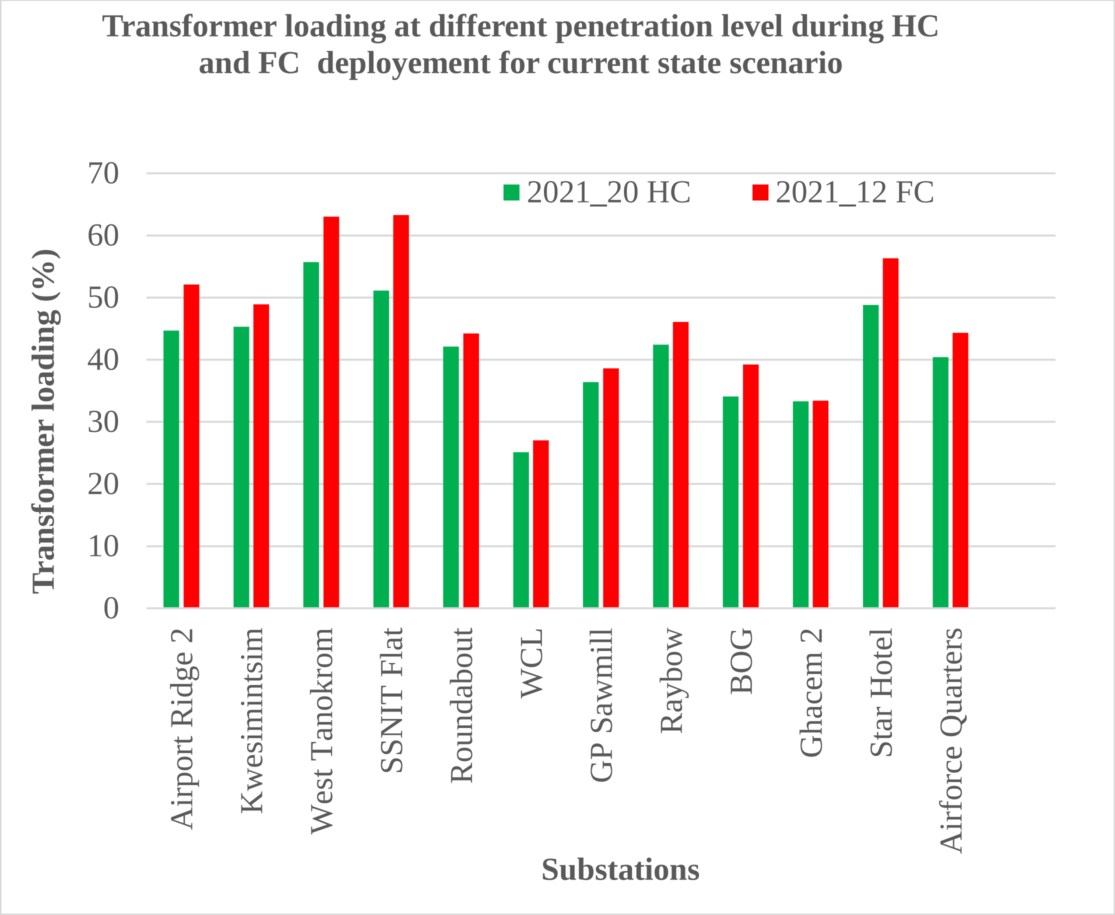


Figure 4-6: Transformer loading impact during HC and FC integration – current state scenario

On performing the load flow analysis, the results at the current state scenario showed that all the 12 substations accommodated both HC and FC infrastructure without any issue. The percentage loading ranged between 25.1% and 55.7% during the integration of HC infrastructure while 27% and 63.3% during FC infrastructure. West Tanokrom and WCL substations recorded the highest and the lowest voltage levels respectively.

4.3.2 Transformer loading impact for minimum uptake level scenario

In this section, the results for transformer loading levels for minimum uptake level scenario during the deployment of both HC and FC infrastructure at different penetration levels are presented in bar charts and detailed analysis is provided below.

4.3.2.1 Transformer loading for minimum uptake scenario during HC penetration

For HC in the minimum uptake scenario, the results revealed that when the penetration level reached 0.92% corresponding to 317 EVs, the HC infrastructure was accommodated through all the 12 substations as shown in Figure 4-7 which illustrates the percentage transformer loading impact at all substations during HC for minimum uptake scenario at different EV penetration levels.

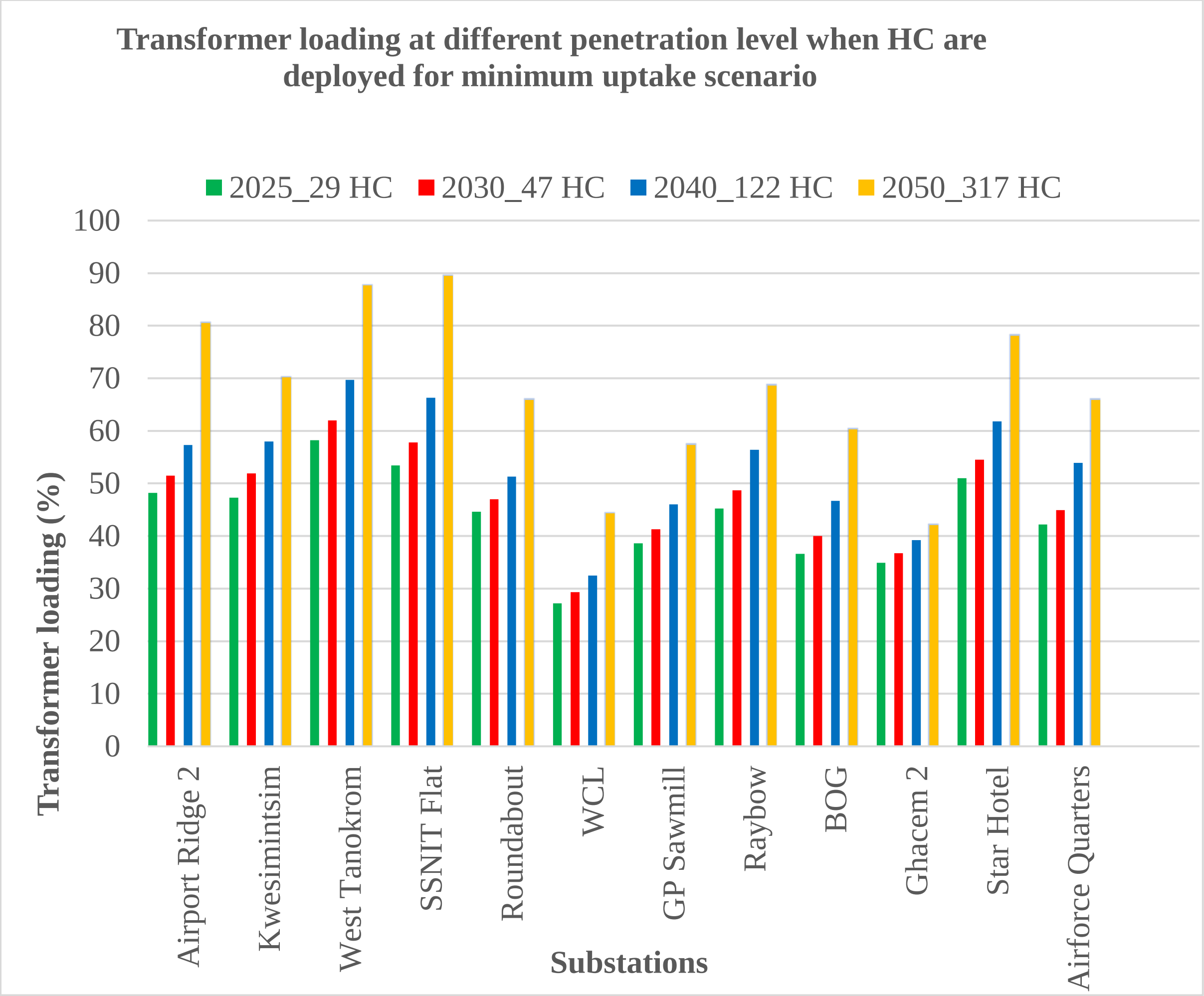


Figure 4-7: Transformer loading impact during HC deployment for minimum uptake scenario

SSNIT Flat substation recorded the highest loading in the year 2050 while West Tanokrom substation recorded the highest loading in the years 2025, 2030 and 2040. On the other hand, Ghacem 2 substation recorded the lowest loading in the year 2050 while WCL substation recorded the lowest loading in the years 2025, 20330 and 2040.

The results observed for the years 2025, 2030, 2040 and 2050 in this minimum uptake scenario shows that no transformer operated under overloaded condition which confirmed the results achieved in the work according to (Lhendup et al., 2020 and Yaminidhar et al., 2015) where DigSilent Power Factory and ETAP were used respectively; concluded that, when a total of say 500EVs and/or 1000EVs of 7.4kW charger load are deployed on LV networks, it possible for the LV distribution networks to accommodate such EVs without creating any instability in the system.

4.3.2.2 Transformer loading for minimum uptake scenario during FC integration

Likewise, at different penetration level of FC, all the transformers are seen to accommodate FC infrastructure in the years 2025, 2030 and 2040 except in the year 2050 where an overload was observed. Kwesimintsim substation recorded the highest loading in the year 2050 while West Tanokrom substation registered the highest loading in the year 2040 and SSNIT Flat substation registered the lowest loading in the years 2030 and 2025. WCL substation registered the lowest loading in the years 2050, 2030 and 2025 whereas lowest loading in the 2040 was observed at Ghacem 2 substation. Figure 4-8 depicts the percentage transformer loading impact during FC integration at the substations at different penetration level for minimum uptake scenario.

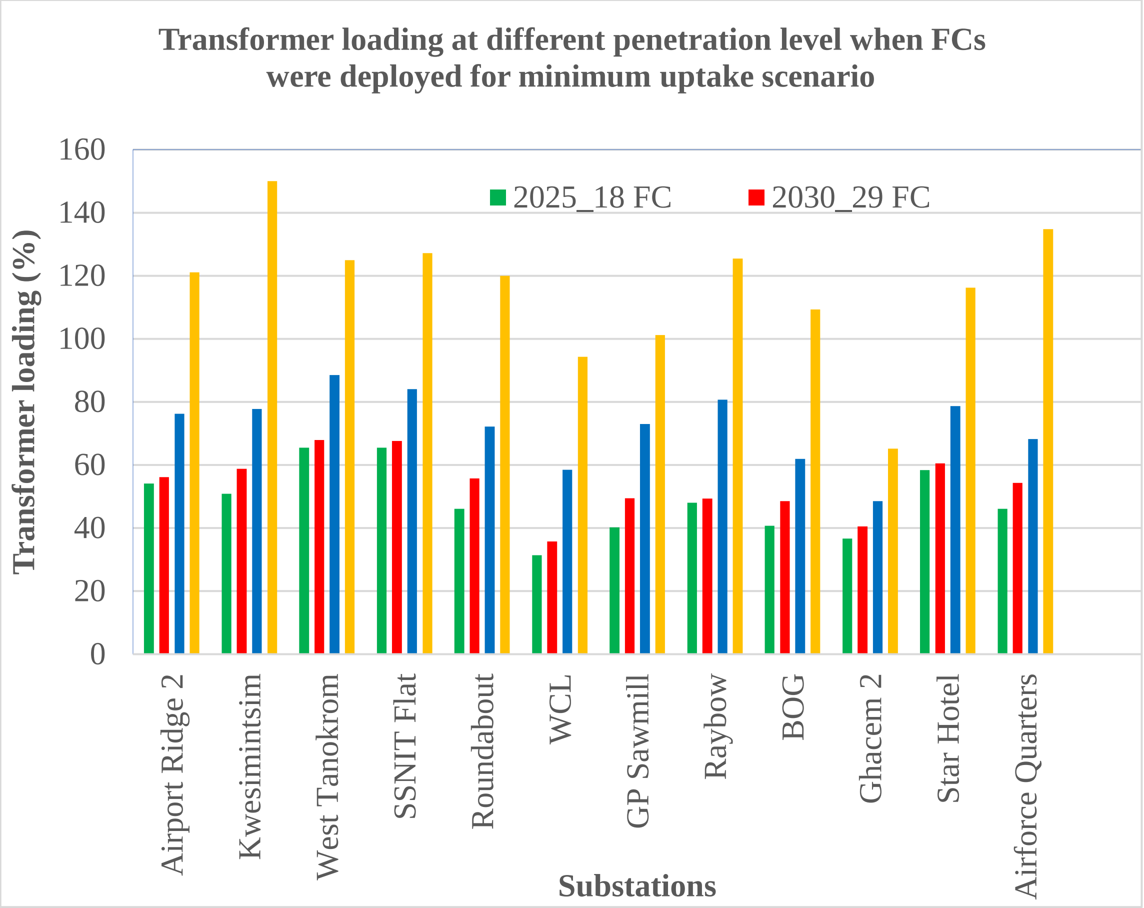


Figure 4-8: Transformer loading impact during FC for minimum uptake scenario

The results showed that ten (10) transformers are found loaded above their rated capabilities which operated between 101.2% to 150% whereas two (2) transformers at WCL and Ghacem 2 accommodated FC infrastructure which operated at 94.3% and 65.2% respectively. A contingency plan is needed if the loading of transformers is beyond 80% to 90%, according to a standard prescription or rule by the power companies (Lhendup et al., 2020; Dubey & Santoso, 2015; Luo et al., 2013;). However, for ECG in Ghana, a backup plan is implemented when the transformer loading is greater than 75% of the nominal voltage.

4.3.3 Transformer loading impact for maximum uptake level scenario

In this section, the transformer loading levels results for maximum uptake level scenario during the deployment of both HC and FC infrastructure at different penetration levels are presented in bar charts with detailed analysis provided below.

4.3.3.1 Transformer loading for HC at different penetrations (maximum uptake)

For HC in the maximum uptake scenario, when the penetration level reached 1.88%, it was observed that all the 12 substations were capable to adopt HC infrastructure from 2025 till 2040 where HC overloaded transformers at Airport Ridge 2, West Tanokrom and SSNIT flat which operated at 101.9%, 100.7% and 107.7% respectively. Figure 4-9 illustrates the percentage transformer loading impact at all substations during HC integration for maximum uptake scenario at different EV penetration levels.

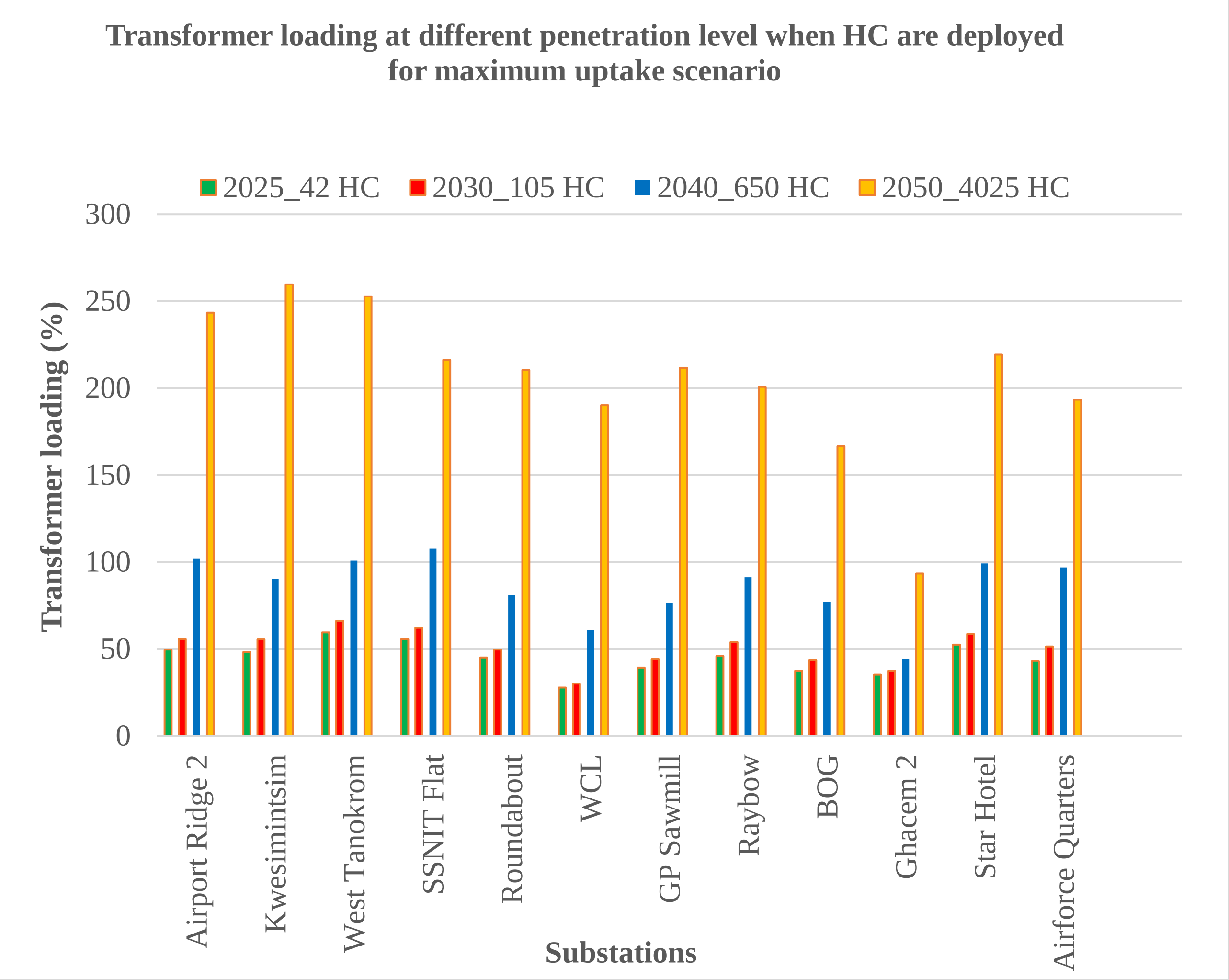


Figure 4-9: Transformer loading impact during HC integration for maximum uptake scenario

According to the results, in the year 2050, when the penetration level got to 11.63%, HC infrastructure overloaded all the transformers which operated within the range 166.6% to 259.6%

except Ghacem 2 substation which operated at 93.4% which did not exceed 100% loading but above the standard loading limit. At this point, the results suggest that the maximum transformer loading by 2050 will be 259.6%. This means that the load on transformers will be approximately five (4.86) times higher by 2050 compared to the loading on the present infrastructure when EVs were not deployed. It is evidently clear from the results that all the feeders had a separate loading curve. The attained results in this research are similar to the findings achieved in the work by (Lhendup et al., 2020 and Bhavanam et al., 2015) concluded that heavy deployment of HC on LV network overloads the transformers.

4.3.3.2 Transformer loading for FC at different penetrations (maximum uptake)

During FCs deployment in this maximum uptake scenario, the results revealed that when the penetration level hit 1.11% all the substations were found loaded above 100% expect Ghacem 2 which operated at 86.7%. Likewise, when the penetration level reached 6.87% all the substations could not withstand FC infrastructure thus, loaded beyond 100%.

The transformer at Kwesimintsim recorded the highest loadings in the years 2050, 2030 and 20025 while the transformer at Raybow registered the highest loading in the year 2040. The lowest loading in the years 2050 and 2025 were observed at the transformers at SSNIT Flat and WCL respectively. In the years 2040 and 2030 the lowest loading was observed at Ghacem 2 substation. Figure 4-10 depicts the percentage transformer loading impact at substations at different EV penetration level for FCs during maximum uptake scenario.

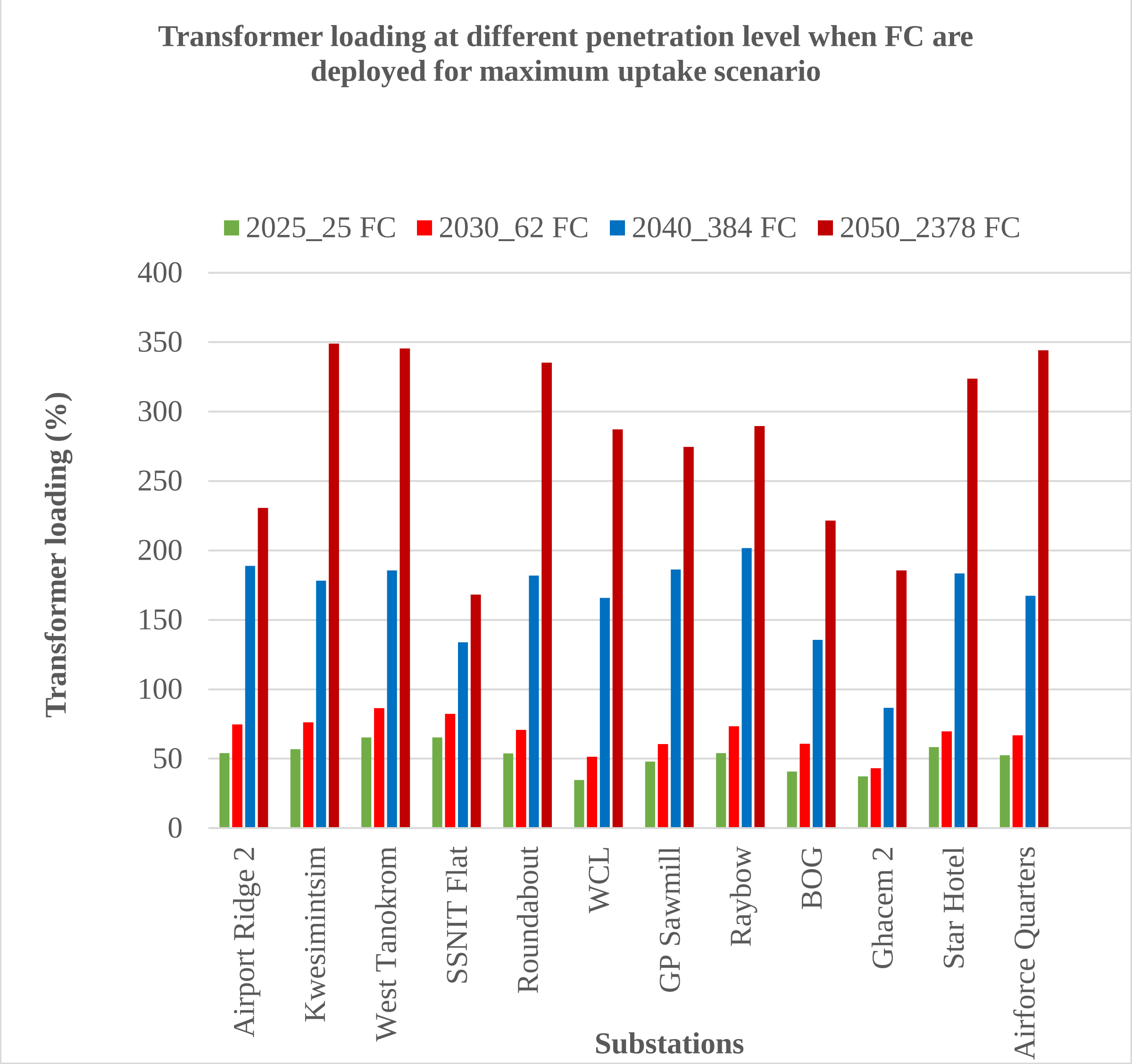


Figure 4-10: Transformer loading impact during FC integration for maximum uptake scenario

Per the results, the maximum loading on transformers by 2030, 2040 and 2050 will be 86.5%, 201.7% and 349% respectively. The results also suggested that beyond 0.18% penetration level, transformer loadings will be a little over one and half ($1\frac{1}{2}$) times in 2030, approximately four times more in 2040 and increase approximately six and half ($6\frac{1}{2}$) times as much as the loading on the current infrastructure is now by 2050. As EV loads increased overload was created in the service transformers and increased system losses. The results revealed that each feeder had a different loading curve. Likewise, the results achieved in this research is similar to the results attained in the work by (Lhendup et al., 2020 and Bhavanam et al., 2015).

4.3.4 Discussions

The system load rises as additional users join the grid, existing users install new appliances, or new users switch out their older equipment for more power-hungry models. During the current state scenario, no transformer was overloaded due to less deployment of both HC and FC infrastructures.

For minimum uptake scenario, it was observed that over 1000 EVs of (HC-7.4Kw) chargers did not overload the transformers based on loading penetration levels at the substations. Similarly, when FC infrastructure was deployed, the loading of the transformers observed from 2025 to 2040 did not show overloading but in the year 2050 almost all the transformers were overladed.

For maximum uptake scenario, all the 12 substations accommodated HC infrastructure from 2025 till 2040 where three transformers at Airport Ridge 2, West Tanokrom and SSNIT flat were seen loaded approximately between 170% and 260%. With the deployment of FC infrastructure, no overloading was observed between until the year 2040 where the maximum loading was approximately 200% and almost 350% maximum loading in the year 2050. Thus, a network upgrade or expansion is suggested.

In conclusion, the addition of new customers and the development of new applications for electricity both contribute to the growth in energy consumption within an electric utility system. Heavy deployment of both HC and FC infrastructure overloaded service transformers which created new load peaks that exceeded the rated capacity of the transformers. This accelerates in the deterioration of distribution system components.

CHAPTER FIVE

SUMMARY OF FINDINGS, CONCLUSION AND RECOMMENDATION

This chapter lays out the concluding summary and conclusion for the research. The aim of this chapter is to summarise the findings of the thesis and provide suggested recommendations and relevant suggestions for further research.

5.1 Summary of findings

The main objective of the study was to perform a load flow analysis on the low voltage distribution system of Takoradi (station OB) and further assess the capacity of the distribution system's performance due to additional load of EVs. To achieve this objective, ETAP 19.0.1 was adopted to model the distribution system and then load flow analysis was undertaken. Also, two different EV charger models were employed to represent home charging (HC)-7.4 kW level-2 and fast charging (FC)- 50 kW level-3. With the growing demand for EVs is likely to pose power system constraints hence, the capacity of TDS's performance was investigated due to the additional load of EVs. The adoption of EVs together with the present state of the distribution system followed by changes in voltage, real and reactive power flows bring change to the distribution system.

The first specific objective of the research was to develop a model of an existing low voltage distribution system of Takoradi. The performance of the distribution system in the year 2021 was used to develop the base system. This base system, which shows the real and reactive power flows, the voltage profile used and transformer loading is the foundation for the development of the existing LV distribution network.

Research specific objective two assessed the impact of EV charging on LV distribution system at different penetration levels. At the beginning of the research, three different scenarios, current state, minimum uptake level, and maximum uptake level were set to facilitate in the impact analysis of EV charging on the existing low voltage distribution system. EV penetration level was estimated for four (4) levels under the minimum and maximum uptake level scenarios and the number of EVs depended on the EV penetration level. Separate assessments were made for the current domestic load and then domestic load with EVs were assessed independently from 2021 through to 2050 as per the projections.

The impact assessment focused on voltage variations (stability). From the load flow analysis, the findings showed that deployment of EV charging infrastructure for HCs and FCs in the current state scenario was possible to accommodate EVs. Also, all the buses operated above the critical voltage limits of 95% for under voltage conditions but did not exceed the critical voltage limits of 105% for over voltage conditions. Similarly, with the minimum uptake scenario, when EV penetration level was at 0.92% (317 EVs of 7.4kW) for HCs and 0.56% (195 EVs of 50kW) for FCs infrastructures no voltage variations were observed. No substation was overloaded when HCs were added, however with the addition of FCs infrastructure, majority of the substations were found loaded above their rated capabilities, thus operated between 101.2% to 150%. Likewise, for the maximum uptake scenario, when EV penetration level for HC infrastructure reached 1.88% (650 EVs of 7.4kW), all the buses operated within the allowed limit except Ghacem 2 which was connected to bus 275 recorded undervoltage condition of 94.86%.

Also, when the penetration level for FC infrastructure reached 1.11% (384 EVs of 50kW), percentage operating voltage of most of the substations fell below the statutory limit. At worst-case scenario during the year 2050 when penetration level for both HC and FC infrastructure got to 11.63% (4025 EVs of 7.4kW) and 6.87% (2378 EVs of 50kW) respectively, a worst-case scenario was seen at most of the buses where the entire system became susceptible to failure due to severe voltage drops. The operating voltage for both HC and FC fell between 57.42% and 89.35% during the maximum uptake scenario.

The third specific objective of the research was to investigate to what extent the exiting low voltage distribution system can accommodate EV penetration without any upgrades to the current distribution system, taking into account the growth of domestic/household loads. Deployment of EV charging infrastructure depended on the transformer loading situation at the three different scenarios of EV penetration levels. The outcomes of the investigation show that, when the penetration level hit 1.88% in the year 2040, HC infrastructure overloaded transformers at Airport Ridge 2, West Tanokrom and SSNIT flat which operated at 101.9%, 100.7% and 107.7% respectively. Likewise, at 11.63% penetration level for HC in the year 2050, all the substations were seen loaded above 100% except Ghacem 2 which was 93.4% loaded but above the standard loading limit which is between 80% and 90%.

FC infrastructure overloaded all the substations above 100% at 1.11% penetration level in 2040 except Ghacem 2 which was loaded at 86.7%. Again, in the year 2050 when FC penetration level reached 6.87%, all the substations could not withstand FC infrastructure thus, all the substations were seen loaded beyond 100%. The results also suggested that beyond 0.18% penetration level for FC, the maximum loading on transformers will be approximately two (2) times higher in 2030, approximately four (4) times higher by 2040 and approximately seven (7) times higher by 2050.

The investigated results discussed in this research indicated that, a significant penetration of EVs created new load peaks that exceeded the rated capacity of the service transformer which resulted in under voltage conditions and transformer loading violations on the LV distribution system of Takoradi

5.2 Conclusion

The impact assessment focused on voltage variations and transformer loading. The peak load values for the base year (2021) were evaluated under two different charging types (home and fast) at all substations were carefully assessed.

The results also provide an assessment of EV deployment at different penetration levels for three different scenarios. The simulation results showed that voltage stability was mostly caused by voltage instability. For the current state scenario, deployment of 20 EVs of HC and 12 EVs of FC did not cause any problem to the distribution system. Similarly, with the minimum uptake scenario, all the substations accommodated 317 EVs for HC and 195 EVs for FC infrastructures without any significant condition. However, as the penetration level increased over the years undervoltage conditions and transformer loading variations were observed for some substations when the penetration level reached 1.88% for HC and 1.11% for FC during the maximum uptake scenario. Likewise, the system tends to fail when the penetration level reached 11.63% for HC and 6.87% for FC due to severe under voltage condition. The load flow analysis indicated that massive deployment of EVs on LV distribution systems is likely to cause under voltage conditions for existing power networks.

In conclusion, the research investigated the extent with which the exiting LV distribution system can accommodate EV penetration together with the growth of residential loads. Transformer loading at twelve substations was meticulously simulated under various scenarios of penetration levels to assess the overall quantity of EVs the distribution network can handle. The results also, showed that another reason that prevents EV penetration is overloaded cables and equipment. As the EV load demand increased, overload was created in the service transformers which increased system losses and each feeder had a different loading curve. Domestic/ household loads significantly increased along with the increment of EV penetration levels over the years which contributed to total instability of TDS. The impact of EV charging on LV distribution systems is anticipated to differ geographically (region by region) depending on the local vehicle usage, current load demand and the network topology.

In effect, the overall load flow results of this research suggest that, EV loads under different charging types have noticeable impacts on both the load and the voltage variables.

5.3 Recommendations

Availability of EV data was a major concern in this research. In Ghana, there is no systematic data collection mechanism. Therefore, the existing distribution system data required for this thesis was obtained from various secondary sources including ECG, DVLA, Energy commission and other national and international publications.

The research recommends that, it is crucial to have an accurate projection of how EVs will be distributed throughout the network when designing a future distribution system and where EVs would be widely used. The first step is to estimate the total quantity of EVs in the system and then calculation of demand is done in accordance with the specific EV penetration level.

To keep a stable distribution system operation, power distribution companies must be cognizant of any potential difficulties associated with EV penetration into distribution system. As a result, performing system assessments and considering corrective action for any disparities are crucial methods at the beginning of EV adoption thus this research can be adopted by distribution power companies as a guide.

Maintaining the standard voltage, significant reinforcing of lines and substations will be needed. Thus, it is important to take voltage-controlling methods into account to address voltage stability issues caused by high EV uptake.

Specific areas with a high concentration of EV, low domestic energy consumption and areas that already have substations with a capacity below the normal dimensions should be looked at when upgrading the network.

The projections in this thesis can be adopted and re-evaluated by following the sales of EVs. It is envisaged that the findings of this research would provide power distribution companies, policy-makers, academics, engineers, and planners a head start on understanding the anticipated impact of utilising EVs and, as a result, enable them to take the appropriate steps to control EV loads.

5.4 Suggestion for further study

Further studies can be undertaken to better understand the potential effects that EV charging may have on the electric utility sector, particularly distribution systems. The results obtained in this research have also uncovered an area that give motivation for further research.

The effect of high penetration of EVs cause undervoltage and overload conditions. Therefore, where and when to charge EVs is particularly important to aid in the stability of the distribution system. The model can be improved by considering optimization of the EV charging.

Low voltage correction (regulation) methods that mitigate EV charging concerns and infrastructural improvement were not addressed in this research. Undertaking such study can bring to light which of the different voltage compensating schemes would be found effective for low voltage mitigations (voltage regulations or corrections) as a result of high EV penetration.

This research considered only low voltage distribution network but did not address medium voltage networks. Therefore, a further study can consider to assess the impact of EV charging in medium voltage networks.

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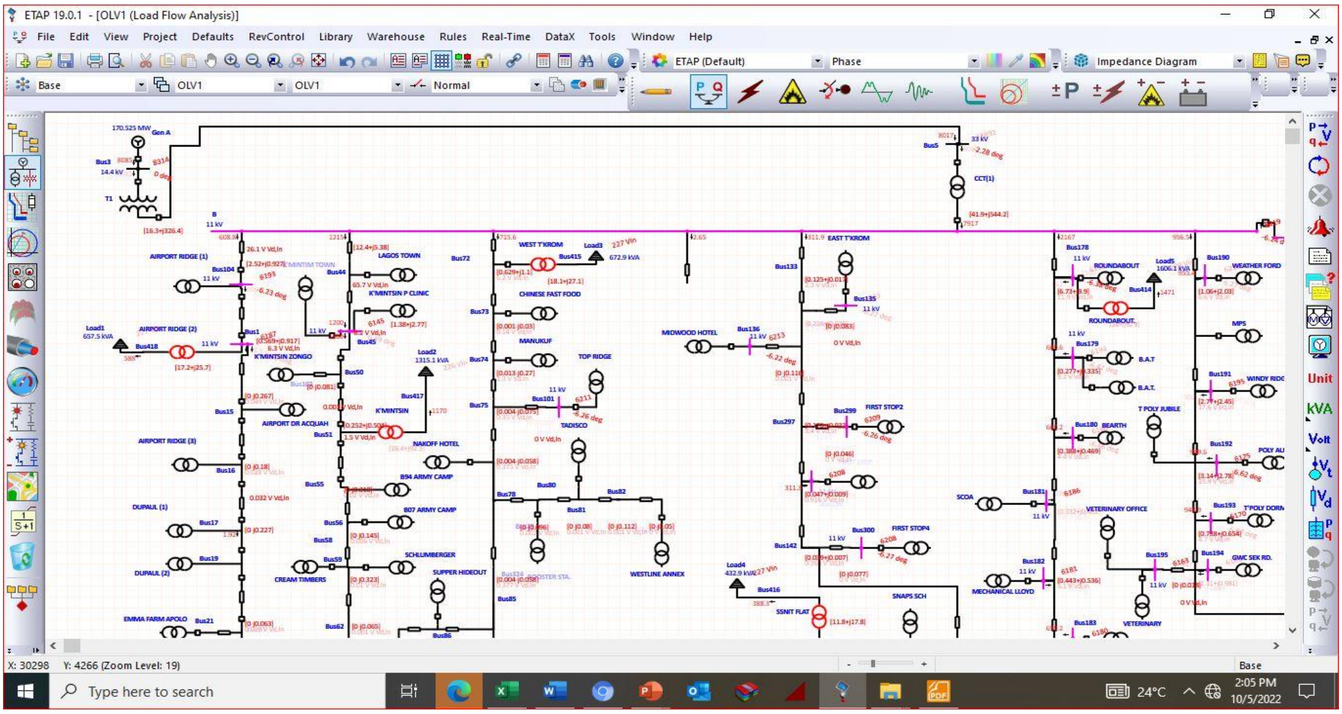
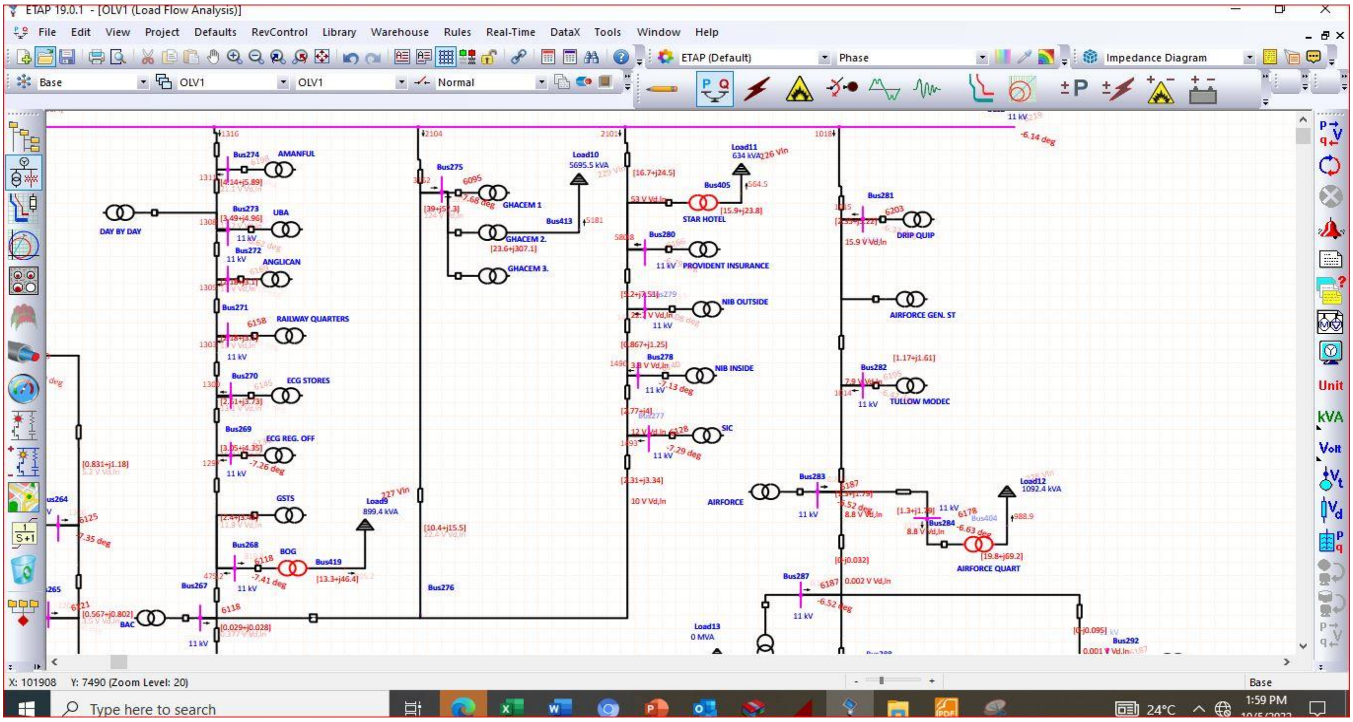
APPENDICES

Appendix I: Takoradi distribution system simulated model in ETAP

(Snapshot of modelled TDS showing positions of transformers and loads)





Appendix II

Distribution of EVs (HCs) and their estimated power for minimum and maximum uptake scenarios for 2025

			Minimum uptake level				**Maximum uptake level**			
Feeder	Bus	**Substation**	**Existing load demand (A) kW**	**EV (HC)**	**EV load demand (B) kW**	**Total load demand (A+B) kW**	**Existing load demand (C) kW**	**EV (HC)**	**EV load demand (D) kW**	**Total Load demand (C+D} kW**
B01	15	Airport Ridge 2	228.5	2	14.8	243.3	228.5	3	22.2	250.7
B09	39	Kwesimintsim	368.5	2	14.8	383.3	368.5	3	22.2	390.7
B67	56	West Tanokrom	286.6	1	7.4	294	286.6	2	14.8	301.4
B11	100	SSNIT Flat	162.4	1	7.4	169.8	162.4	2	14.8	177.2
B41	106	Roundabout	538.1	3	22.2	560.3	538.1	4	29.6	567.6
B32	130	WCL	382.0	4	29.6	411.6	382.0	5	37.0	419.0
B21	148	GP Sawmill	466.1	3	22.2	488.3	466.1	4	29.2	495.7
B81	171	Raybow	344.5	3	22.2	366.7	344.5	4	29.2	374.1
B51	227	BOG	265.8	2	14.8	280.6	265.8	3	22.2	288.0
B71	229	Ghacem 2	2836.7	5	37.0	2873.7	2836.7	7	51.8	2888.5
B52	231	Star Hotel	252.0	1	7.4	259.4	252.0	2	14.8	266.8
B87	240	Airforce Quarters	303.9	2	14.8	318.7	303.9	3	22.2	326.1
		Total	**6425.1**	**29**	**214.6**	**6649.7**	**6435.1**	**42**	**310.8**	**6745.9**

Distribution of EVs (HCs) and their estimated power for minimum and maximum uptake scenarios for 2030

			Minimum uptake level				**Maximum uptake level**			
Feeder	Bus	**Substation**	**Existing load demand (A) kW**	**EV (HC)**	**EV load demand (B) kW**	**Total load demand (A+B) kW**	**Existing load demand (C) kW**	**EV (HC)**	**EV load demand (D) kW**	**Total Load demand (C+D} kW**
B01	15	Airport Ridge 2	239.1	3	22.2	261.3	239.1	6	44.4	283.5
B09	39	Kwesimintsim	385.6	4	29.6	422.6	385.6	9	66.6	452.2
B67	56	West Tanokrom	299.9	2	14.8	314.7	299.9	5	37	336.9
B11	100	SSNIT Flat	169.9	2	14.8	184.7	169.9	4	29.6	199.5
B41	106	Roundabout	563.0	4	29.6	592.9	563.0	9	66.6	629.6
B32	130	WCL	399.7	6	44.4	444.1	399.7	8	59.2	458.9
B21	148	GP Sawmill	487.7	5	37.0	524.7	487.7	10	74.0	561.7
B81	171	Raybow	360.5	4	29.6	397.5	360.5	11	81.4	441.9
B51	227	BOG	278.1	4	29.6	307.7	278.1	8	59.2	337.3
B71	229	Ghacem 2	2968	8	66.6	3034.6	2968	20	148	3116
B52	231	Star Hotel	263.7	2	14.8	278.5	263.7	5	37	300.7
B87	240	Airforce Quarters	318.0	3	22.2	340.2	318.0	10	74.0	392.0
		Total	**6733.2**	**47**	**355.2**	**7088.4**	**6733.2**	**105**	**777**	**7510.2**

Distribution of EVs (HCs) and their estimated power for minimum and maximum uptake scenarios for 2040

			Minimum uptake level				**Maximum uptake level**			
Feeder	Bus	**Substation**	**Existing load demand (A) kW**	**EV (HC)**	**EV load demand (B) kW**	**Total load demand (A+B) kW**	**Existing load demand (C) kW**	**EV (HC)**	**EV load demand (D) kW**	**Total Load demand (C+D} kW**
B01	15	Airport Ridge 2	248.7	6	44.4	293.0	248.7	40	296.0	544.7
B09	39	Kwesimintsim	401.0	10	74.0	475.0	401.0	50	370.0	771.0
B67	56	West Tanokrom	311.9	6	44.4	356.3	319.9	30	222.0	533.9
B11	100	SSNIT Flat	176.7	5	37.0	213.7	176.7	25	185.0	361.7
B41	106	Roundabout	585.5	9	66.6	652.1	585.5	65	481.0	1066.5
B32	130	WCL	415.7	11	81.4	497.1	415.7	75	555.0	970.7
B21	148	GP Sawmill	507.2	11	81.4	588.6	507.2	70	518.0	1025.2
B81	171	Raybow	374.9	12	88.8	463.7	374.9	55	407.0	781.9
B51	227	BOG	289.2	10	74.0	363.2	289.2	45	333.0	622.2
B71	229	Ghacem 2	3086.7	25	185	3271.7	3086.7	100	740.0	3826.7
B52	231	Star Hotel	274.3	6	44.4	318.7	274.3	35	259.0	533.3
B87	240	Airforce Quarters	330.7	11	81.4	412.1	330.7	60	444.0	774.7
		Total	**7002.5**	**122**	**902.8**	**7905.3**	**7002.5**	**650**	**4810.0**	**11812.5**

Distribution of EVs (HCs) and their estimated power for minimum and maximum uptake scenarios 2050

			Minimum uptake level				**Maximum uptake level**			
Feeder	Bus	**Substation**	**Existing load demand (A) kW**	**EV (HC)**	**EV load demand (B) kW**	**Total load demand (A+B) kW**	**Existing load demand (C) kW**	**EV (HC)**	**EV load demand (D) kW**	**Total Load demand (C+D} kW**
B01	15	Airport Ridge 2	257.5	22	162.8	420.3	257.5	195	1443.0	1700.5
B09	39	Kwesimintsim	415.1	23	170.2	585.3	415.1	350	2590.0	771.0
B67	56	West Tanokrom	322.9	18	133.2	456.1	322.9	190	1406.0	1728.9
B11	100	SSNIT Flat	182.9	15	111.0	293.9	182.9	100	740.0	9229.0
B41	106	Roundabout	606.1	33	244.2	850.3	606.1	400	2960.0	3566.1
B32	130	WCL	430.4	35	259.0	689.4	430.4	500	3700.0	4130.4
B21	148	GP Sawmill	525.1	30	222.0	747.1	525.1	450	3330.0	3855.1
B81	171	Raybow	388.1	25	185.0	573.1	388.1	250	1850.0	2238.1
B51	227	BOG	299.4	24	177.6	477.0	299.4	200	1480.0	1779.4
B71	229	Ghacem 2	3195.5	50	370	3565.5	3195.5	1000	7400.0	10595.5
B52	231	Star Hotel	284.0	19	140.6	424.6	284.0	170	1258.0	1542.0
B87	240	Airforce Quarters	342.4	23	170.2	512.6	342.4	220	1628.0	1970.4
		Total	**7249.4**	**317**	**2345.8**	**9595.2**	**7249.4**	**4025**	**29785.0**	**37034.4**

Distribution of EVs (FCs) and their estimated power for minimum and maximum uptake scenarios for 2025

			Minimum uptake level				**Maximum uptake level**			
Feeder	Bus	**Substation**	**Existing load demand (A) kW**	**EV (FC)**	**EV load demand (B) kW**	**Total load demand (A+B) kW**	**Existing load demand (C) kW**	**EV (FC)**	**EV load demand (D) kW**	**Total Load demand (C+D} kW**
B01	15	Airport Ridge 2	228.5	1	50.0	278.5	228.5	1	50.0	278.5
B09	39	Kwesimintsim	368.5	1	50.0	418.5	368.5	2	100.0	468.5
B67	56	West Tanokrom	286.6	1	50.0	336.6	286.6	1	50.0	336.6
B11	100	SSNIT Flat	162.4	1	50.0	212.4	162.4	1	50.0	212.4
B41	106	Roundabout	538.1	2	100.0	638.1	538.1	3	150.0	688.1
B32	130	WCL	382.0	2	100.0	482.0	382.0	3	150.0	532.0
B21	148	GP Sawmill	466.1	2	100.0	566.1	466.1	3	150.0	616.0
B81	171	Raybow	344.5	1	50.0	394.5	344.5	2	100.0	444.5
B51	227	BOG	265.8	1	50.0	315.8	265.8	1	50.0	315.8
B71	229	Ghacem 2	2836.7	4	200.0	3036.7	2836.7	5	250.0	3086.7
B52	231	Star Hotel	252.0	1	50.0	302.0	252.0	1	50.0	302.0
B87	240	Airforce Quarters	303.9	1	50.0	353.9	303.9	2	100.0	403.9
		Total	**6425.1**	**18**	**900.0**	**7335.1**	**6425.1**	**25**	**1250.0**	**7685.1**

Distribution of EVs (FCs) and their estimated power for minimum and maximum uptake scenarios for 2030

			Minimum uptake level				**Maximum uptake level**			
Feeder	Bus	**Substation**	**Existing load demand (A) kW**	**EV (FC)**	**EV load demand (B) kW**	**Total load demand (A+B) kW**	**Existing load demand (C) kW**	**EV (FC)**	**EV load demand (D) kW**	**Total Load demand (C+D} kW**
B01	15	Airport Ridge 2	239.1	1	50.0	289.1	239.1	3	150.0	389.1
B09	39	Kwesimintsim	385.6	2	100.0	485.6	385.6	5	250.0	635.6
B67	56	West Tanokrom	299.9	1	50.0	349.9	299.9	3	150.0	449.9
B11	100	SSNIT Flat	169.9	1	50.0	219.9	169.9	2	100.0	269.9
B41	106	Roundabout	563.0	3	150.0	713.1	563.0	7	350.0	913.0
B32	130	WCL	399.7	3	150.0	549.7	399.7	8	400.0	799.7
B21	148	GP Sawmill	487.7	3	150.0	637.7	487.7	6	300.0	787.7
B81	171	Raybow	360.5	2	100.0	460.5	360.5	5	250.0	610.5
B51	227	BOG	278.1	2	100.0	378.1	278.1	4	200.0	478.1
B71	229	Ghacem 2	2968	8	400.0	3368.0	2968	13	650.0	3618.0
B52	231	Star Hotel	263.7	1	50.0	313.7	263.7	2	100.0	363.7
B87	240	Airforce Quarters	318.0	2	100.0	418.0	318.0	4	200.0	518.0
		Total	**6733.2**	**29**	**1450.0**	**8183.2**	**6733.2**	**62**	**3100.0**	**9833.2**

Distribution of EVs (FCs) and their estimated power for minimum and maximum uptake scenarios for 2040

			Minimum uptake level				Maximum uptake level			
Feeder	Bus	**Substation**	**Existing load demand (A) kW**	**EV (HC)**	**EV load demand (B) kW**	**Total load demand (A+B) kW**	**Existing load demand (C) kW**	**EV (FC)**	**EV load demand (D) kW**	**Total Load demand (C+D} kW**
B01	15	Airport Ridge 2	248.7	3	150.0	398.7	248.7	17	850.0	1098.7
B09	39	Kwesimintsim	401.0	5	250.0	651.0	401.0	25	1250.0	1651.0
B67	56	West Tanokrom	311.9	3	150.0	461.9	311.9	15	750.0	1061.9
B11	100	SSNIT Flat	176.7	2	100.0	276.7	176.7	6	300.0	476.7
B41	106	Roundabout	585.5	7	350.0	935.5	585.5	40	2000.0	2585.5
B32	130	WCL	415.7	10	500.0	915.7	415.7	50	2500.0	2915.7
B21	148	GP Sawmill	507.2	9	450.0	957.2	507.2	45	2250.0	2757.2
B81	171	Raybow	374.9	6	300.0	674.9	374.9	30	1500.0	1874.9
B51	227	BOG	289.2	4	200.0	489.2	289.2	18	900.0	1189.2
B71	229	Ghacem 2	3086.7	20	1000.0	4086.7	3086.7	100	5000.0	3618.0
B52	231	Star Hotel	274.3	2	100.0	374.3	274.3	16	800.0	1074.3
B87	240	Airforce Quarters	330.7	4	200.0	530.7	330.7	22	110.0	1430.7
		Total	**7002.5**	**75**	**3750**	**10752.5**	**7002.5**	**384**	**19200.0**	**26202.5**

Distribution of EVs (FCs) and their estimated power for minimum and maximum uptake scenarios for 2050

			Minimum uptake level				Maximum uptake level			
Feeder	Bus	**Substation**	**Existing load demand (A) kW**	**EV (HC)**	**EV load demand (B) kW**	**Total load demand (A+B) kW**	**Existing load demand (C) kW**	**EV (FC)**	**EV load demand (D) kW**	**Total Load demand (C+D} kW**
B01	15	Airport Ridge 2	257.5	8	400.0	657.5	257.5	50	2500.0	2757.5
B09	39	Kwesimintsim	415.1	18	900.0	1315.1	415.1	150	7500.0	7915.1
B67	56	West Tanokrom	322.9	7	350.0	672.9	322.9	80	4000.0	4322.9
B11	100	SSNIT Flat	182.9	5	250.0	432.9	182.9	20	1000.0	11829.0
B41	106	Roundabout	606.1	20	1000.0	1606.1	606.1	200	10000.0	10606.1
B32	130	WCL	430.4	22	1100.0	1530.4	430.4	250	12500.0	12930.4
B21	148	GP Sawmill	525.1	17	850.0	1375.1	525.1	190	9500.0	10025.1
B81	171	Raybow	388.1	14	700.0	1088.1	388.1	123	6150.0	6538.1
B51	227	BOG	299.4	12	600.0	899.4	299.4	100	5000.0	5299.4
B71	229	Ghacem 2	3195.5	50	2500.0	5695.5	3195.5	1000	50000.0	53195.5
B52	231	Star Hotel	284	7	350.0	634	284.0	90	4500.0	4784.0
B87	240	Airforce Quarters	342.4	15	750.0	1092.4	342.4	125	6250.0	6592.4
		Total	**7249.4**	**195**	**9750.0**	**16999.4**	**7249.4**	**2378**	**118900.0**	**126149.4**