DUT
DURBAN
UNIVERSITY OF
TECHNOLOGY

FACULTY OF
ENGINEERING
& THE BUILT
ENVIRONMENT

DEPARTMENT OF
ELECTRICAL
POWER
ENGINEERING

Hosting Capacity Assessment of Electric Vehicle Charging in Residential Low Voltage Distribution Networks

By

Vincent Bassey Umoh
Student No: 22280333

A dissertation submitted in fulfillment of the requirements for the degree of Master of Engineering in the Department of Electrical Power Engineering, Faculty of Engineering and the Built Environment at Durban University of Technology

Supervisor: Dr. A. A. Adebiyi
Co-Supervisor: Dr. K. Moloi

August 2023

DECLARATION 1

I, **Vincent Bassey Umoh,** declare that;

1. The research reported in this thesis, except where otherwise indicated, is my original work.
2. This thesis has not been submitted for any degree or examination at any other university.
3. This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.
4. This thesis does not contain other persons' writing unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:
    a) their words have been re-written but the general information attributed to them has been referenced;
    b) where their exact words have been used, their writing has been placed inside quotation marks, and referenced.
5. This thesis does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source is detailed in the thesis and the References sections

Signed:………………………….. Date: 11 August 2023
Vincent Bassey Umoh

Approved for submission.

Signed……………………………. Date: 11/08/2023
Dr. A. A. Adebiyi

Signed…………………………….... Date: 11 – 08 – 2023
Dr. Katleho Moloi

ACKNOWLEDGEMENT

I am grateful to God for the wisdom and understanding to undertake this Masters programme.
I sincerely appreciate Dr. Abayomi Adebiyi for supervising this work, providing guidance, advice, and unreserved support, and for putting additional time to sharpen my technical and writing skills.

My profound gratitude to my co-supervisor Dr. Katleho Moloi for his immense support. I would also like to thank colleagues and the entire staff of the department for the knowledge imparted and the adequate environment provided for this work to thrive.

I would like to thank Prof Innocent Davidson for inviting me to South Africa to undertake this study, enabling me to settle in, and granting insight into the foundation of this study.

Finally, I want to acknowledge Prof. and Dr. Andrew Eloka-Eboka and Mrs. Iniabasi Edoho for their unwavering support towards the success of my studies. I also appreciate my friends, Joseph Akpan, Elutunji Buraimoh and Iyiola Comfort, Favour Agbajor for their encouragement and moral support.

ABSTRACT

The necessity for environmentally friendly transportation systems and the ongoing energy crisis have incited the proliferation of electric vehicles (EVs) in low voltage (LV) distribution networks. However, large-scale integration and simultaneous charging of EVs can have a huge negative impact on the distribution network, disrupting the standard operating conditions by creating several technical challenges for the distribution grid such as voltage violations, transformer and lines overloading, and an increase in electrical losses. These challenges make it important to carry out studies that will assess the impact of connecting multiple EVs simultaneously for charging in existing low voltage electrical networks and further determine the hosting capacity (HC) of such networks. This study assesses the impact of three-phase and single-phase EV charging in an eThekwini residential network, determines the HC from the assessment, investigates how the three-phase EV charging HC changes based on different circumstances, and also estimates the single-phase HC for different EV charging power. To achieve this, a residential low voltage distribution network containing 21 households is modeled using DIGSiLENT PowerFactory with the network parameters obtained from the utility. The deterministic and time series method is used for the three-phase HC determination while a stochastic method based on a simplified Monte Carlo simulation method is adopted for single-phase HC analysis. Voltage drop and equipment loading are the performance indices (PI) considered for the study and their limit is set according to the South African standard NRS097. The impact assessment result shows that increasing EV charging penetration will result in a corresponding movement of the PI toward the allowable limits. The HC results show that 5-8 three-phase connected EVs can charge simultaneously for the worst-case and 9-13 EVs for the best-case. Furthermore, the single-phase HC for the popular 3.7 kW EV charger is 15 and 8 EVs for the best-case and worst-case scenarios respectively. The result showing the seasonal variation in HC and for other EV charging power is also presented. It is observed that three-phase EV charging HC of the network is highest during the summer and the lowest during the winter season, while the difference in HC for the worst-case and best-case scenarios portrays the effect that the location of charging has on the HC.

DECLARATION 2 - PUBLICATIONS

This study has produced the following peer-reviewed publications:

1. **V. Umoh**, I. Davidson, A. Adebiyi, and U. Ekpe, "Methods and Tools for PV and EV Hosting Capacity Determination in Low Voltage Distribution Networks; A Review," Energies, vol. 16, no. 8, p. 3609, 2023. [Online]. Available: https://www.mdpi.com/1996-1073/16/8/3609.

2. **V. Umoh**, A. Adebiyi, and K. Moloi, "Hosting Capacity Assessment of South African Residential Low-Voltage Networks for Electric Vehicle Charging," Eng, vol. 4, no. 3, pp. 1965-1980, 2023. [Online]. Available: https://www.mdpi.com/2673-4117/4/3/111.

3. **Vincent Umoh,** A. Adebiyi, and K. Moloi “Electric Vehicles Hosting Capacity Assessment for a South African Low Voltage Distribution Network” in proceeding of 3rd International Conference on Electronic and Electrical Engineering and Intelligent System, Indonesia, pp. 1 – 6, 2023.

Table of Contents

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AC	Alternating Current
BEV	Battery electric vehicles
DC	Direct Current
DG	Distributed Network
DN	Distribution Network
DNO	Distribution Network Operator
DPF	DiGSILENT PowerFactory
DSO	Distribution System Operator
DU	Distribution Unit
EG	Embedded Generation
EV	Electric Vehicles
EVSE	EV Supply Equipment
FCEV	Fuel cell electric vehicle
HC	Hosting Capacity
HEV	Hybrid Electric Vehicles
LV	Low Voltage
MCS	Monte Carlo simulation
MV	Medium Voltage
N	Number of MCS scenarios
OLTC	On-Load Tap Changer
OPF	Optimal Power Flow
PDF	Probability Distribution Function
PHEV	Plug-in hybrid electric vehicles
PI	Performance Indices
PLF	Probabilistic Load Flow
PV	Photovoltaic
TDD	Total demand distortion
THD	Total Hamonic Distortion
VUF	Voltage Unbalance Factor

CHAPTER 1: INTRODUCTION

1.1 Background of the Study

The existing power grid in many parts of the world is overloaded due to rapid urbanization and a corresponding increase in the number and magnitude of grid-connected loads. Environmental safety concerns and the ongoing energy crisis make it imperative that alternative sources of electricity and transportation should be clean [1, 2]. These concerns are progressively being alleviated by the rapid increase in the use of environmentally friendly solar photovoltaic systems and electric vehicles (EVs) [2, 3]. The growing sales of plug-in electric vehicles [3] imply that EV charging in the distribution network is increasing, and this translates to a corresponding increase in peak power consumption and changes in consumption patterns [4, 5]. Large-scale integration and simultaneous charging of multiple EVs are identified to have a high impact on the network, disrupting the standard operating condition of the grid by creating several technical challenges such as voltage violations, transformer and lines overloading, and an increase in electrical losses [6]. As a result, distribution network operators (DNOs) carry out impact assessments and perform hosting capacity (HC) analysis to determine the amount of EV charging that can be integrated into a particular distribution network. This makes the HC a useful planning tool for estimating the amount of EV charging that is possible on a distribution feeder.

Hosting capacity is defined as the amount of new production or consumption that can be connected to the network without risking the reliability or power quality of other customers [7, 8]. The HC calculation is performed using various performance indices, and defining practical limits for the indices as specified by national or international standards [9, 10]. Using appropriate methods and tools, an HC determination methodology can then be formulated to guide the choice of a maximum number of EVs that can be integrated into a distribution network without violating the operational limits of such a network. The HC determination process begins with the selection of one or more performance indices (PI) such as voltage drop, voltage unbalance, thermal overload, system losses, and harmonics. This is followed by defining a suitable limit for the selected PI as specified by regulatory standards and then applying HC determination methods to estimate the HC of EV charging. Considering the importance of this concept for the present and future grid, DNOs, researchers and industry practitioners are actively conducting research to determine the HC of different distribution networks. Studies such as [11-14] are the most recent reviews conducted on the different HC calculation methods which include deterministic, time series, probabilistic, optimization, and streamlined methods. Previous studies [2, 15-20] have adopted one or more of these methods for HC determination. For example, [20] used a deterministic method to determine the HC from survey and measurement data while [16] also estimated the HC of EV charging in a Swedish LV distribution network containing 13 family houses using the deterministic method.

It is observed that different aspects of the distribution network with EV are investigated in the reviewed literature, howbeit limited studies carried out their investigation on existing electrical networks. It therefore becomes pertinent that more practical systems be modelled and investigated to contribute directly to knowledge and economy of the locale where the distribution systems are installed. As a result, this work would investigate the impact on an existing residential low voltage distribution network in South Africa at the instance of different levels of EV charging penetration, and determine the HC from the assessment.

1.2 Statement of the Problem

Environmental safety concerns have caused a rapid increase in the use of environmentally friendly electric vehicles (EVs) as indicated by the growing sales of plug-in EVs [3]. This implies that EV charging in the low voltage distribution network is increasing. However, there are technical challenges associated with the proliferation of customer own EVs in the LV distribution network at a high level, of which voltage drop, equipment overloading, voltage unbalance and losses are the major concerns. These concerns are predominantly due to increasing load demand and variations in consumption patterns that distort the traditional operation of the grid. Although a lot of research has been conducted to ascertain the acceptable limit of EV charging that can be hosted by a network, most of this research is not carried out on an existing system. Also, high EV penetration calls for utilities to invest in solutions that mitigate the challenges and enhance the grid hosting capacity.

Considering the foregoing concerns, it is important to investigate the impact of increased EV charging penetration on an existing local distribution network and determine the hosting capacity.

1.3 Aim and Objectives of the Study

This research aims to investigate the impact of high EV penetration on an eThekwini residential low voltage distribution network and determine the EV charging hosting capacity of the network. The aim of the research would be achieved under the following objectives:

1. To conduct an extensive literature review to identify the technical impact of EV charging penetration, and hosting capacity determination methods.
2. To develop a model of an existing eThekwini low voltage distribution network and conduct power flow analysis without EV, as a base case scenario.
3. To analyze different penetration levels of EV charging in the developed model and assess its impact on voltage rise and equipment loading.
4. To evaluate and estimate the hosting capacity of the existing network from the impact assessment.

1.4 Research Questions

This study will address the following research questions;

1. What methods have been adopted to determine the EV charging hosting capacity on existing networks?
2. Will the integration of EV charging as an additional load have technical impact on the existing residential networks and to what degree?
3. How many EVs can charge simultaneously in an existing grid until the HC is attained?
4. How does the HC change throughout the year?
5. What impact do the locations of the charging have on the HC?
6. Which performance indices is the most limiting one?

1.5 Limitations and Delimitations of the Study

1. The study considers only uncontrolled charging patterns.
2. The study does not consider the charging behaviour or state of charge of the battery.
3. Only phase selection is considered for the simplified Monte Carlo simulation.
4. The study is limited to only one existing grid as a network.
5. The simulation in the study is only for one calendar year from the data obtained

1.6 Structure of the Dissertation

This report contains six chapters. Chapter One provides an introduction to the study, containing the background of the study, the statement of the problem, the aim and objective of the study, and the research questions. Chapter Two reviews extensively literature relevant to the hosting capacity methodologies and South African standard NR. Chapter Three presents the theoretical framework considered within the study for grid integration of electric vehicles. Chapter Four details the modeling and simulation method adopted in the study. Results are presented and discussed in Chapter Five while Chapter Six concludes the findings and makes recommendations for future work.

CHAPTER 2 : LITERATURE REVIEW

This chapter presents a review of literature about electric vehicles (EVs) and their integration into the existing grid. The impact of grid integration of EVs is discussed followed by a review of the hosting capacity determination methods. Finally, the acceptable integration standards and grid codes are highlighted.

2.1 Electric vehicles

The internal combustion engine (ICE) used in conventional transportation systems consume fossil fuel and contributes immensely to environmental pollution [21, 22]. Electric vehicles (EVs) are designed to relieve these environmental safety challenges with their many advantages. These advantages have led to growing adoption and sales of different types of EVs around the world [3]. This section reviews the advantages of EVs over ICE vehicles and the classification of the various types of EVs.

2.1.1 Advantages of EVs

The advantages of EVs over conventional ICE vehicles are as follows;

- Zero emission: EVs do not emit CO2 or nitrogen dioxide (NO2), and their process of manufacturing is friendly to the environment [23].
- Low maintenance cost: the cost to maintain EVs and the cost of electricity needed to power it is lower compared to the maintenance and fuel cost of conventional ICE vehicles [24].
- Comfort and efficiency: EVs are more efficient than ICE vehicles with very minimal vibration and engine noise, which makes them more comfortable to travel in [25, 26].
- Simplicity and reliability: the engines of EVs are simpler and more compact with smaller elements without needing a cooling circuit, gearshift, or clutch, which makes them cheaper to maintain. The availability of fewer and simpler components and the lack of wear and tear of the engines makes EVs highly reliable with fewer breakdowns [24].
- Accessibility: since EVs have zero emissions, they can access restricted areas unlike ICE vehicles [27].

2.1.2 Electric vehicles taxonomy

There are different types of EVs in circulation around the world and are generally classified according to the technology of their engines and their settings. Figure 2.1 shows the general classification of EVs into five types including Battery Electric Vehicles (BEV), plug-in Hybrid Electric Vehicle (PHEV), Hybrid Electric Vehicle (HEV), Fuel Cell Electric Vehicle (FCEV) and Extended Range Electric Vehicle (ER-EV).

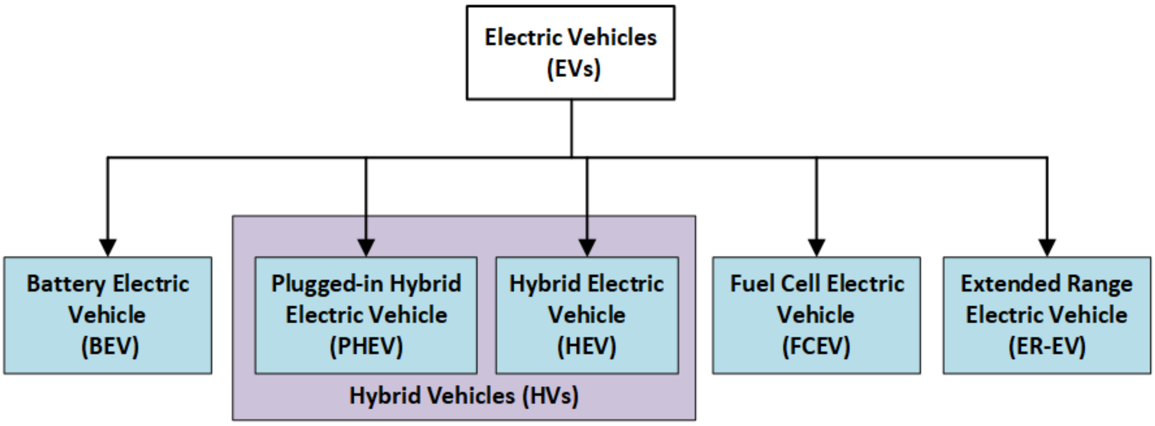


Figure 2.1: Taxonomy of Electric Vehicles

Battery electric vehicles (BEVs) do not have an internal combustion engine nor use any form of liquid fuel but are solely powered by a traction battery. The BEVs completely depend on external power from the grid for charging the battery. The BEVs are preferred for reducing fuel consumption and emissions but are limited by battery capacity as research is ongoing for improved battery technology [24, 28].

Plug-in hybrid electric vehicles (PHEVs) are a type of hybrid vehicle that has a combustion engine and an electric engine that can be charged by plugging to the external electrical grid. PHEVs can store adequate energy from the grid, reducing their fuel consumption [24].

Hybrid electric vehicles (HEVs) are hybrid vehicles with a conventional ICE and a battery powered electric engine. However, unlike the PHEVs, the HEVs cannot be plugged into the electrical grid. The battery in the electric engine side is charged by the combustion engine of the vehicle and energy generated by regenerative braking [24].

Fuel cell electric vehicles (FCEVs) are EVs that use fuel cells instead of batteries or together with batteries to power their electric engines. The FCEV uses hydrogen gas to power an electric motor exclusively by electricity that does not require fuel or charging from the grid. They are considered to have zero emissions although most of the hydrogen used is extracted from natural gas [24, 29, 30].

Extended Range Electric Vehicles (ER-EVs) are BEVs that are provided with a supplementary combustion engine that charges the battery when necessary. However, this supplementary engine is exclusively for charging and not connected to the vehicle's wheel compared to the PHEVs and HEVs. The ER-EVs charge from the grid and also use fuel [24, 30]. In this study, BEVs and PHEVs are considered and together name as EVs from here on. Moreover, grid integration of EV charging at a high level will impact the grid and cause several power quality challenges that need to be understood.

2.2 Impacts of grid-connected EV systems

Grid integration of EVs has resulted in significant changes in the design, planning and operation of the network. If the impact of this integration is not properly studied and planned, the penetration of EV charging at a high level into the traditional grid will alter its operation, resulting in several technical power quality problems such as voltage drop, voltage unbalance, harmonics, system losses, equipment overloading and voltage stability issues [31-33]. This section briefly discusses some of these impacts.

2.2.1 Voltage drop

Voltage drop is one of the main concerns that limit the integration of large-scale EV charging into the LV distribution networks. Charging EVs from the grid will cause voltage drop and voltage deviations at the point where they are connected. A high level of EV charging penetration may cause a violation of the safe voltage regulatory limit requirement on the network. As a result, utilities of different countries are saddled with the responsibility of keeping the customers′ service voltage within an acceptable range with different grid specifications. Studies such as [34] have evaluated the impact of EV charging on the voltage deviation of the network. The study in [35] shows that EV penetration rate of 50% and above will cause a violation of the standard operating voltage limit of the network.

2.2.2 Voltage Unbalance

Voltage unbalance occurs in the electrical distribution system when the phase voltages vary in amplitude or when their phase shift relationship is displaced from the typically normal 120^o or both [36]. Voltage unbalance is caused by unevenly distributed single-phase loads and impedances and is characterized by the voltage unbalance factor (VUF). VUF is the percentage ratio of the absolute values between the positive the negative sequence voltage component [36, 37]. EVs are connected to the low voltage feeders, which are dominated by single-phase loads, creating power quality concerns for operators of the distribution network. Studies reported in [38, 39] show a high voltage unbalance resulting from EV charging in the distribution network. Consequently, to ensure optimal integration of EVs with voltage unbalance, some grid codes and standards are set by utilities and impact studies need to be conducted by researchers.

2.2.3 Harmonics

Harmonics are components of voltage or current that are not at the power system frequency and are usually measured as total demand distortion (TDD) and total harmonic distortion (THD) [40]. TDD is the root mean square (RMS) ratio of harmonic content, without inter-harmonics, to the maximum demand current, while THD is the RMS ratio to fundamental current [41]. EV charging injects harmonics into the grid mainly from power electronic converters [42]. Studies reported in [43, 44] show that random EV charging at a high rate injects significant harmonics into the grid. Acceptable limits of harmonics is set by the grid codes and standards.

2.2.4 System losses

Power loss is an intrinsic characteristic of a line due to the flow of current and is proportional to the square of the current magnitude flowing through the line [45]. The Integration of EVs at high levels into the distribution system will increase the power losses due to feeder overload and changes in feeder current. The authors in [46] studied the impact of EV charging on a Danish LV distribution network and found that the system losses increased by 40% when EVs were connected. Similarly, the studies reported in [34, 35, 47] also show that grid integration of EV charging will increase system losses.

2.2.5 Equipment Overloading

Large-scale EV charging on the distribution network requires a huge amount of power to be transmitted from the grid to the load and this may cause overloading of the existing network components such as transformers and cables. The study in [48] shows the negative effect of high penetration of EV charging on the lifespan of the transformer. In [49], the author examines the impact of uncoordinated EV charging on cable loading in a Canadian distribution network. The results show that existing cables can only accommodate 25% of EV charging penetration rate for normal charging. However, the grid can only cope with 15% EV charging penetration during fast charging.

This study will investigate the impact of high penetration EV charging on voltage drop and cable loading using the operational limits set by South African standards.

2.3 Hosting Capacity

The term, "hosting capacity" has already been used in other contexts such as the capacity of web servers, watermarking of images, and settlement of refugees [7, 14], before its adoption as a term in distributed generation (DG). Hosting capacity (HC) as a concept in DG was first introduced by André Even in March 2004 during the integrated European EU-DEEP project discussion to examine the effects of distributed generation integration in the distribution network [14, 50, 51]. This concept is illustrated in Figure 2.2. The theoretical application of the concept developed in [18], is now the widely adopted methodology by network operators, regulators, and researchers to determine HC.

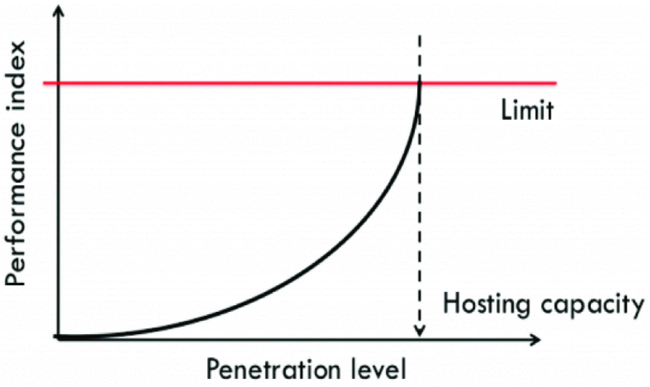


Figure 2.2: The HC concept

This development brought the first official definition of HC available in the literature as the highest amount of distributed generation that can be integrated into a power system without the performance limit being violated [52]. This definition was further refined in [53] and subsequently, the growth in the utilization of electric vehicles (EVs) made the need to evaluate the HC of distribution networks a very important endeavor [54, 55]. Thus, the definition of HC further tilted to consider the amount of new production and consumption that can be connected without compromising the reliability or quality of power supplied to other users [7, 54, 56]. This is a definition that is adopted in this study for EV charging HC assessment.

Furthermore, researchers and regulators have quantified HC in different ways depending on the different references adopted for each study, such as the proportion of customers that install PVs or the rated power from the installed PV as the percentage of the total connected load or transformer rating, or the present peak feeder load demand [57]. Table 2.1 lists the varying definitions of HC that have been presented in the literature depending on the different references adopted [13]. The reference adopted for this study is with respect to the number of customers/households with EVs.

Table 2.1: Definitions of HC based on different references adopted for defining HC [13]

Ref	Reference adopted	HC definition
[58-68]	Peak feeder load	The proportion of the PV installation's maximum capacity to the feeder's peak load demand.
[69-77]	Transformer Rating	The proportion of the overall amount of PV output to the transformer's rated capacity.
[78-82]	Customer PVs/EVs	The proportion of households in the study area that install PVs to the total number of households there.
[83-85]	Energy Consumption	The proportion of the total annual PV system energy production to total energy usage.

2.3.1 Hosting Capacity Determination Methodology

The general approach for HC determination is shown in Figure 2.3. It begins with the selection of at least one performance index (such as overvoltage, voltage unbalance, thermal overload, power quality, system losses, harmonics, or protection), defining a suitable limit for the index as specified by the national or international standards, and then applying HC determination methods to calculate the hosting capacity as a function of the amount of PV generation or EV charging [14, 86]. During the load flow calculation, the amount of PV or EV is gradually increased until the result of a performance index exceeds the allowable limit. There are five major methods for HC quantification in the distribution networks found in the literature. They include; deterministic, time series, stochastic, streamlined-stochastic, and optimization-based methods [12, 86]. Although these methods are unique in terms of actual implementation, they all use power flow calculations to find the values of the performance indices in the network and they all follow the same general approach shown in Figure 2.3.

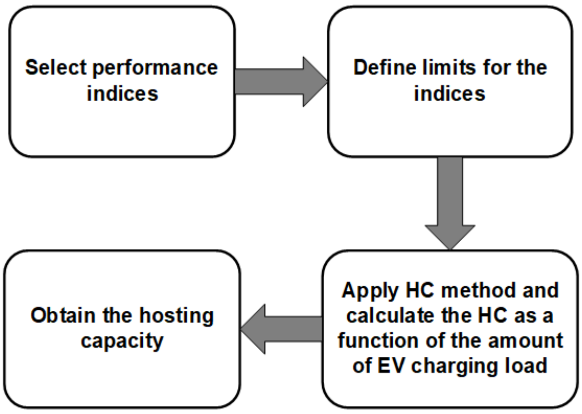


Figure 2.3: General hosting capacity approach

a. *The Deterministic method*

The deterministic method is the fundamental method for HC determination that begins with data collection of the distribution network followed by modeling of the network and load flow simulation, as shown in Figure 2.4. The deterministic method does not consider the uncertainty of the PV production, load consumption of consumers, and the size and location of the PV. Instead, these parameters are assumed to be known and assigned fixed input values before the HC calculation begins [12, 86].

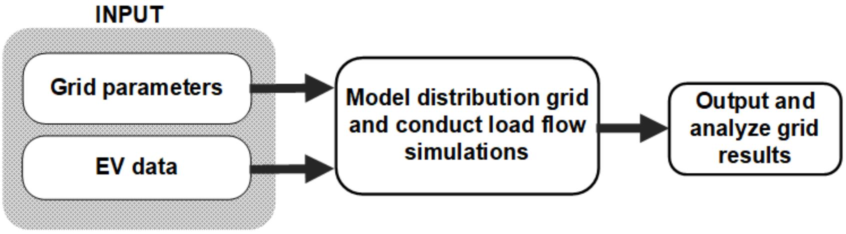


Figure 2.4: Deterministic method illustration

The deterministic method generally adopts the PV generation or EV charging approach, with the PV output or EV load as the independent variable assumed to be maximum and does not vary throughout the calculation [12, 86]. This method evaluates the system in a scenario-based fashion by iteratively increasing the size of the EV charging load unit until the first violation of a performance index is observed [69, 87-92]. The deterministic method also considers the worst-case scenarios to determine the HC due to the extreme impact of uncertain parameters [88, 91, 93].

There is also a variation in the deterministic method where the rule-based analysis is applied. This approach allows iterative increment of the EV charging load at the nodes of the grid using a forward, backward, and forward-backward method. In the end, different hosting capacity values for the distribution network are obtained, and the actual grid HC is given as a range between these values [12, 94]. This forward and backward method will be applied throughout the power flow simulations in this study.

The deterministic method is very simple and useful for quick estimation and overview of the HC of distribution networks [86]. The method is preferred for a single large installation that requires less computational burden since uncertainties are not accounted for. However, for a large number of small installations with many uncertainties that require large computations, the deterministic method becomes insufficient for HC quantification [12, 95]. Additionally, the worst-case scenario often adopted in the deterministic method can easily underestimate the HC because the minimum load consumption and maximum solar PV generation are overestimated and unlikely to happen simultaneously [86, 96].

b. The Time Series method

The time series HC calculation method illustrated in Figure 2.5 is an upgrade of the deterministic method. This method replaces the fixed values in the deterministic method with actual system measurements of base load and EV charging load for HC estimation [86]. The measurement data can be real or synthetic historical time series profiles with a long time scale and high resolution. Average values of these data on a small time scale are used for load flow calculations. During the load flow calculations, some uncertain parameters such as size, location, or the number of solar PV installations are varied until at least one of the performance indices is violated [64, 77].

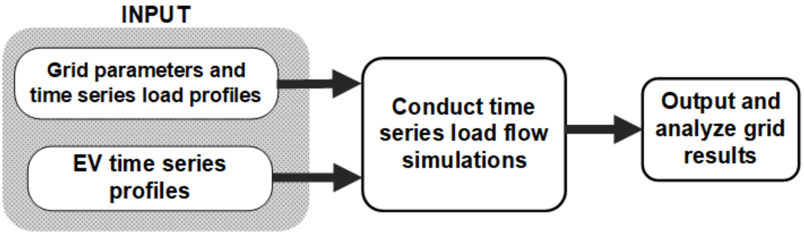


Figure 2.5: Time series method illustration

The time series method provides a more realistic value of the HC of distribution networks because it considers the time variation in the load consumption [97]. However, the method requires the availability of a large amount of measurement data, which is a challenge to acquire. Additionally, the need for high-resolution simulations in this method is time-consuming and poses a huge computational burden [12, 86]. This method will be applied to three-phase HC assessment in this study.

c. *The Stochastic method*

The stochastic method considers the uncertainties and unknown variables associated with the widespread connection of customer-owned EVs. There are several unknowns and uncertainties associated with EV charging such as charging patterns (the key determining factor of EV impact), phase connection (single-phase or three-phase), type of charging, location of EV on the feeder, and time and duration of charging. The stochastic method considers the chance of occurrence of the unknown variables and uncertainties in the distribution network by using probabilistic load flow (PLF). To begin the PLF, random scenarios for the number, location, and/or size of EV are created as input in the distribution network using probability distribution functions (PDFs) [86]. This is followed by the load flow simulation of the network and the determination of the HC based on the performance indices whose operational limits are violated [98]. Figure 2.6 shows the general process of the stochastic method of HC determination for a distribution grid.

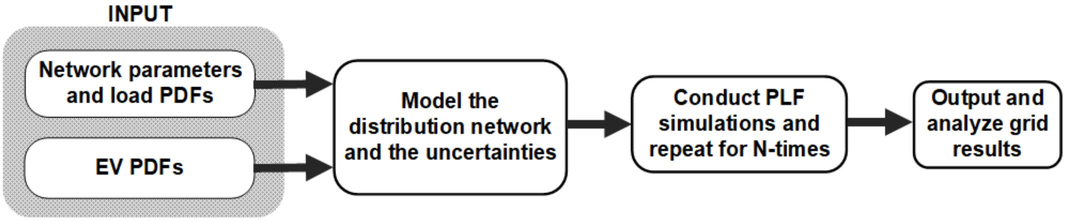


Figure 2.6: Stochastic method illustration

The key part of the stochastic method is the classification and modeling of uncertainties. Several uncertainty modeling approaches exist in the literature including the probabilistic method, robust optimization, information gap decision theory, interval-based analysis, and hybrid probabilistic and possibilistic methods [12, 99]. However, the probabilistic method is often used in the PLF with Monte Carlo Simulation (MCS) as the most common technique for generating random scenarios such as PV generation, location, size, and load profiles [100, 101]. This study adopts the stochastic method for single-phase HC assessment and the MCS method for uncertainty modelling.

d. *The Optimization-based method*

The optimization-based HC determination methods generally consider EV integration as an optimization problem. This method uses the optimal power flow technique (OPF) with the objective of maximizing the EV charging load while meeting the grid operational constraints. Figure 2.7 shows the general process of the optimization method. The most common techniques used to solve this optimization problem are Particle Swarm Optimization [102], Artificial Bee Colony [103], Robust optimization [104, 105], and

Genetic Algorithm [106, 107]. Some studies using the optimization method can define a single objective function to maximize the HC [108, 109], while other studies can set up multiple objective functions to determine the HC [100, 102].

The optimization method provides a more conservative HC result for the defined constraints and covers several numbers of scenarios but requires several iterations to obtain an optimal solution. This study adopts a combination of the deterministic and time series methods for three-phase and single-phase EV charging impact assessment and HC determination.

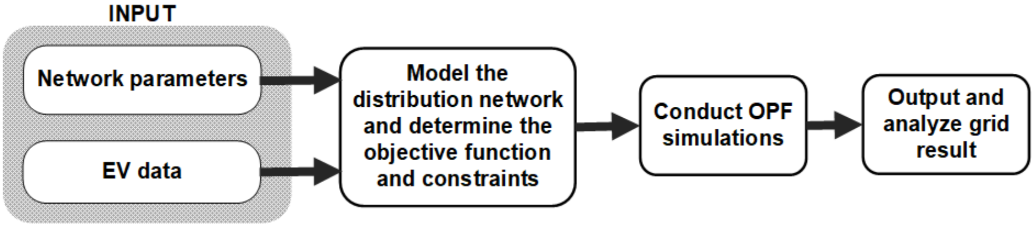


Figure 2.7: Optimization method illustration

2.3.2 EV Hosting Capacity Studies

Large-scale integration and simultaneous charging of multiple EVs have been identified to have a high impact on the network, creating several technical challenges for the grid. This makes the HC a useful planning tool for estimating the amount of EV charging that is possible on a distribution feeder. EVs on the distribution network cause violations of various performance limits including thermal limits and transformer overloading due to increased demand, harmonics, voltage drop, and voltage unbalance [2, 110, 111].

The deterministic [20], time series [112], stochastic [113], and optimization-based [114] HC calculation methods can be used to estimate the HC of EV in the distribution network. The uncertainties associated with EV charging can be addressed using the time series or stochastic method. The deterministic method is suitable for worst-case scenarios, while utilities can also view the EV HC as an optimization problem. A simple deterministic method is used to assess the impact of either average or peak load consumption from survey and measurement data in [20]. The limiting factors were applied for the charging cycle occurring between 6 pm and 10 pm. Similarly, a deterministic method is used in [16] to estimate the HC of EV charging in a real LV network containing 13 detached single-family houses. Cable loading and voltage drop were used as the limiting factor for four case studies. The results show that a maximum of 6-11 (46% to 85%) customers can charge their EVs with 11 kW simultaneously before a violation occurs.

In [2], a stochastic approach to single-phase and three-phase EV charging HC for two existing distribution networks including aleatory and epistemic uncertainties is presented. Background voltage and under-voltage are the limiting factors, with the 10th percentile of the worst-case voltage distribution as the performance index and 90% of the nominal voltage as a limit. The results show that EV charging HC is sensitive to the lowest background voltage and highest power consumption. The method can be used at any time without detailed knowledge of the charging patterns. A stochastic approach to determine the single-phase and three-phase EV charging HC considering both aleatory and epistemic uncertainties is developed in [2], while [7] applied a simplified MCS using limited input data to determine the EV charging HC. To quantify the risk of overloading in the network, [18, 19] capture the uncertainty of EV and customer loading using Poisson and Gaussian distribution models respectively.

Furthermore, different HC determination methods can be applied to EV HC studies as presented in [112]. The authors applied stochastic and time series methods to study the power quality problems of electric transportation charging of EVs on distribution systems. Stochastic measured data of EVs are used to develop stochastic harmonic analysis models and usage scenario models. The study shows transformer loading as the most violated performance limit. Also, studies such as [17, 115] assessed the combined effect of PV and EV integration in the distribution network. In the investigative study reported in [115], the authors used a stochastic method based on Monte Carlo simulations to assess the unified effect of solar PV and EV connections on a Brazilian LV network. The results show overvoltage as the most limiting factor in the distribution network.

It is necessary for key uncertainties like charging patterns and types of charging to be considered in EV HC. Therefore, [114] introduced a voltage-constrained-based approach to calculate the HC of EVs under uncontrolled charging scenarios while the authors in [19] considered both uncontrolled and controlled charging schemes. Similarly, [16] developed an EV HC tool for extremely fast charging hosting options. A summary of the EV charging HC studies highlighting different methods and performance indices is shown in Table 2.2.

Table 2.2: Summary of existing EV charging HC studies highlighting the method and performance indices

Ref	Performance Indices	HC method	Study summary
[2]	Voltage magnitude	Stochastic	Developed an approach to single-phase and three-phase EV charge HC for two existing distribution

			networks including aleatory and epistemic uncertainties.
[7]	Voltage magnitude	Stochastic	Presented a method of determining the HC of EV in an LV distribution network using limited input data and simplified MCS.
[15]	Voltage magnitude and thermal limit	Optimization	Presented a mathematical model for determining a distribution network node's marginal EV charging hosting capacity.
[112]	Harmonics, low voltage, voltage unbalance, and transformer loading	Stochastic	Studied the power quality impact of electric transportation charging including EVs on distribution systems.
[114]	Voltage magnitude, thermal limits, and losses	Optimization	Proposed a rule-based algorithm based on a holistic approach to determine the EV HC of two interlinked systems.
[16]	Voltage drop and cable overloading	Deterministic	Estimated the HC of EV charging in a Swedish LV network containing 13 detached single-family houses.
[19]	Transformer loading	Stochastic	Proposed a model that captures the EV charging and customer load uncertainties with Poisson and Gaussian distribution models respectively.
[18]	Transformer loading and Cable loading	Stochastic	Presented a user-defined, data-driven risk assessment method to evaluate the impact of high levels of EV charging and solar PV penetration.
[115]	Voltage magnitude, voltage unbalance, and cable and transformer loading.	Stochastic	Investigated how a Brazilian LV distribution network is affected by a combination of both PV and EV connections.
[116]	Losses	Stochastic and optimization method	Presented an approach to determine the HC of a distributed resource-based generation and the number of electric vehicles in isolated DC grids.
[117]	Total harmonic distortion	Stochastic	Presented the HC result on a variety of EVs from different brands under different states of charge and background distortion.
[118]	Voltage magnitude and voltage unbalance	Time series and stochastic	Formulated the EV HC assessment of two real Australian MV-LV networks by exploring multiple EV penetrations.

[119]	Voltage magnitude and thermal limit	Optimization	Proposed the concept of “EV chargeable region” to determine the EV HC for each node.
[120]	Voltage magnitude, voltage unbalance, and transformer loading	Time series and stochastic	Introduced a voltage-constrained-based approach to calculate the HC EVs under an uncontrolled charging scenario.
[121]	Voltage magnitude and thermal limit	Deterministic	Developed an EV HC tool for an extremely fast charging hosting option.
[122]	-	Time series and stochastic	Used additional available power (AAP) as an indicator in the hybrid algorithm to determine the EV HC during controlled and uncontrolled charging.
[123]	Voltage magnitude, and transformer and cable loading	Deterministic and stochastic	Carried out a wide-scale study to estimate EV HC using data readily available to utility engineers.
[124]	Voltage magnitude	Time series and stochastic	Compared how much impact the different types of EV charging can contribute to PV HC.

2.4 The South African standards and grid codes

The technical limits in the standards that place constraints on generation or additional load in the South African low voltage distribution grid are highlighted as follows [9, 125]

a) Thermal ratings of the lines and cables.
b) LV voltage regulations (±10%).
c) The maximum change in LV voltage is limited to 3%.
d) Islanding of the utility network is not allowed.
e) The fault level at the customer point of supply shall be greater than 210 A or the minimum fault level at which the generator is rated.
f) The unbalanced EG may not exceed 4,6 kVA connected between any two or different phases at an installation under normal conditions.
g) Three-phase generators may not contribute more than 0.2% voltage unbalance when connected to an LV network with impedance equal to the reference impedance

The standards give a guide for the level of penetration that can be added to the grid without undertaking in-depth research or when comprehensive information about a specific feeder of interest is lacking. However, feeders in the South African DNs are not identical, hence the need for studies to be conducted on specific residential feeders.

2.5 Chapter Summary

This chapter has presented a comprehensive literature review about EVs and their integration in the low voltage distribution network. The methods of EV charging HC determination and the previous studies that adopted the methods have been reviewed. While there is an abundance of studies about PV integration in the South African distribution network, it is observed from the review that there is a dearth of studies on EV integration, hence the relevance of this study. The deterministic method and stochastic method based on MCS are chosen due to their simplicity and ease of implementation in highly recommended electrical power systems analysis software such as DiGSILENT PowerFactory. The next chapter will present the theoretical framework that will integrate the concepts discussed in this chapter.

CHAPTER 3: THEORETICAL ANALYSIS OF GRID-CONNECTED EV CHARGERS

This chapter discusses the theoretical framework considered within this study for the integration of EV charging into the low voltage distribution network.

3.1 EV charging integration into the low voltage distribution network

An EV becomes a load and a part of the power systems when it is plugged into the LV network to charge. Large-scale integration of EVs into the power systems can present new issues because the majority of the current power grid was not built to support a lot of EV charging loads. The key challenges include under voltage problems and equipment overloading. These problems lead to a decrease in the lifetime of power grid components such as substation transformers. Generally, the higher the charging power, the more significant the impact of the EV charger on the electrical power systems. Moreover, high load variability will occur from the installation of higher power chargers because the EV charging load will ramp up and down over shorter periods. Therefore, it is important to understand the charging technologies, modes and connectors when connecting EV chargers.

3.1.1 Charging technology and strategies

There are numerous technologies for charging EV batteries. These methods are generally divided into inductive (wireless) charging or conductive charging, with the latter being the frequently used technology. Conductive charging can either be achieved with DC or AC power, but AC chargers are the most used chargers globally. However, changes in the charging profile is a major concern that is considered before EV charging is integrated into the LV network. The voltage levels are impacted in different manners depending on the charging strategies. As a result, it is important to understand the approaches and control strategies that can be employed to charge EVs. The major types of charging strategies adopted to manage the time and frequency of connection to the grid are uncontrolled and controlled charging.

Uncontrolled or uncoordinated charging allows the batteries of EVs to begin charging as they park. There is no intelligent scheduling done in this type of charging strategy, but the vehicle owners are allowed to connect their EVs to the grid for charging at any time and disconnect at any time irrespective of the peak hours or price. Uncontrolled charging approach at different penetration levels has the greatest impact on the distribution network by increasing the load on the network parameters such as transformers and cables, increasing the losses and hence reducing the efficiency and reliability of the grid [126, 127]. The controlled or coordinated charging strategy uses intelligent control and communication between the EVs and the grid to allow the EVs to charge during off-peak hours when the demand is low in order to get technical and economic benefits. The approach mostly involves optimization and communication algorithms, and specific demand side management. Controlled charging has a reduced impact on the peak capacity, decreases power losses, minimizes voltage variations and load surge in transformers, and provides room for higher operating efficiency [126, 127]. This study will adopt the uncontrolled charging strategy where the EV charging is added as a simple electrical load. However, EVs connected to the grid have different modes and levels of charging that needs to be understood.

3.1.2 Charging modes

The International Electrotechnical Commission (IEC) is a body that has created international standards (IEC-62196 and 61851) for EV charging. They have defined four charging modes in the standards for AC and DC charging of EVs. Mode 1 is for slow charging and is defined as a domestic charging mode mostly used in homes with a varying current limit of 8A to 16 A depending on the country. This mode allows EVs to be connected to the grid via the regular single-phase or three-phase power outlet with phase(s), neutral, and protective earth conductors. Mode 2 is for semi-fast charging that can be used at homes or public places. EVs can be connected with a maximum of 32 A current via regular single-phase or three-phase power outlets with phase(s), neutral, and protective earth conductors.

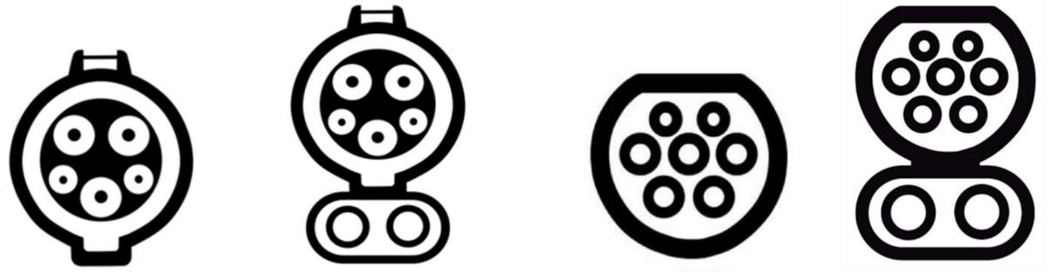
Mode 3 is used for slow or fast charging with a varying current limit between 32 A and 250 A. The single-phase or three-phase EV is connected to the grid via a specific outlet with the controllers called the EV Supply Equipment (EVSE). The cable has earth and control pilot that allows adequate communication between the EV and the grid. Mode 4 uses ultra-fast charging via fixed EVSE with 600 V DC power. The connection cable has an earth and control pilot to allow a maximum current of 400 A. Table 3.1 shows a comparison of these four modes according to the IEC standard.

Table 3.1: Comparison of the different charging modes [24, 128]

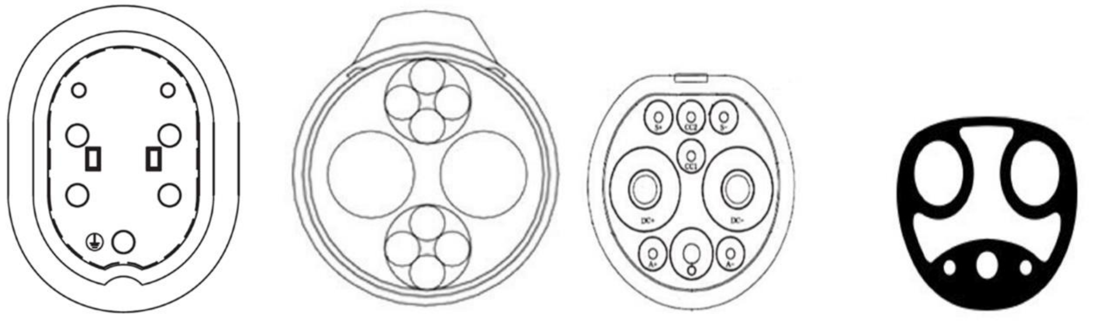
Charge Mode	Phase	Current (max)	Voltage (max)	Power (max)	Specific Connector
Mode 1	1-ϕ AC	16 A	230–240 V	3.8 kW	No
	3-ϕ AC		480 V	7.6 kW	
Mode 2	1-ϕ AC	32 A	230–240 V	7.6 kW	No
	3-ϕ AC		480 V	15.3 kW	
Mode 3	1-ϕ AC	32 – 250 A	230–240 V	60 kW	Yes
	3-ϕ AC		480 V	120 kW	
Mode 4	DC	250 – 400 A	600 – 1000 V	400 kW	Yes

3.1.3 Charging ports and connectors

EV charger components (including power outlets, connectors, cords, and attached plugs) are the main components of EVSE which provide reliable charging, discharging and protection for the charging system. There are commercially available AC and DC connectors shown in Figure 3.1 for charging EVs following their specifications and standards.



(a) J1772-2009 Type 1 for AC charging (b) J1772-2009 Type 2 for AC/DC charging (c) IEC-62196 Type 2 (Mennekes) (d) IEC-62196 Type 2 (Mennekes CCS)



(e) IEC-62196 Type 3 (Scame) (f) IEC-62196 Type 4 (CHAdeMO) (g) GB/T 20234 fast charging connector (h) Tesla connector for United States

Figure 3.1: Different EV connectors adopted by the different standards [24, 128]

3.2 Load flow

Load flow computation will be conducted in this study to examine the impact that integrating EV charging at a high will have on the present low voltage network. This will be done via simulation in DiGSILENT PowerFactory power system software. Load flow also called power flow is the technique for power system planning and operations to determine the steady state conditions [129, 130]. The process involves the computation of voltage magnitude (V) and phase angle (θ) at each bus of the power system, along with determining the active (P) and reactive (Q) power flowing on the line segment of the system [129]. Consider a complex power inject at node i, which can be expressed as;

$$S_i = V_i I_i^* \tag{3.1}$$

where, S_i represent the complex apparent power, V_i is the voltage and I_i^* is the conjugate of the current at node i.

$$I_i = \sum_{j=1}^{n} Y_{ij} V_j \tag{3.2}$$

where, Y_{ij} represent the admittance matrix element. Substituting equation (3.2) into equation (3.1) will allow equation (3.1) to be written as;

$$S_i = V_i (\sum_{j=1}^{n} Y_{ij} V_j)^* = \sum_{j=1}^{n} Y_{ij}{}^* V_j{}^* \tag{3.3}$$

$$I_i = \sum_{j=1}^{n} Y_{ij} V_j \tag{3.4}$$

Also, the primary load flow expressions are:

$$P_i = \sum_{j=1}^{n} V_i V_j Y_{ij} \cos{(\delta_i - \delta_i + \theta_{ij})} \tag{3.5}$$

$$Q_i = \sum_{j=1}^{n} V_i V_j Y_{ij} \sin{(\delta_i - \delta_i + \theta_{ij})} \tag{3.6}$$

Equations (3.5) and (3.6) can be represented in a rectangular form as:

$$P_i = \sum_{j=1}^{n} V_j [G_{ij} \cos{(\delta_i - \delta_j)} + B_{ij} sin(\delta_i - \delta_j)] \tag{3.7}$$

$$Q_i = \sum_{j=1}^{n} V_i V_j [G_{ij} \sin\left(\delta_i - \delta_j\right) - B_{ij} cos(\delta_i - \delta_j)] \tag{3.8}$$

These equations are solved by specifying two of the four variables at either the slack bus, PV bus or the PQ bus. The non-linear equations can be solved using either Newton-Raphson, Gauss-Seidel or Fast decoupled iterative methods [129, 130]. Moreover, these methods are applied as algorithms in power systems simulation software. In this study, the Newton-Rapson method is used since it is the method employed in DiGSILENT PowerFactory software.

3.3 Monte Carlo simulation

Monte Carlo simulation (MCS) is a numerical method used to resolve intricate physical and mathematical problems by presenting a statistical probability of the anticipated observation. This method can also be adapted to evaluate the behavior of the power system as a result of the unpredictable nature of the inputs. The method is realized by randomly selecting input variables and solving the deterministic load flow to generate the output [131]. The process is iterated numerous times based on numerous input combinations. Figure 3.2 shows the outline and steps involved in MCS with the anticipated observation expressed as;

$$E(Y) = \frac{1}{N} \sum_{i}^{N} Y_i \tag{3.9}$$

where Y represents the observation based on Monte-Carlo trails of N, Y_i represent the independent observations ruled by the solution function and probability constraints of input variables $x_{1,2,3,\dots\dots,N}$.

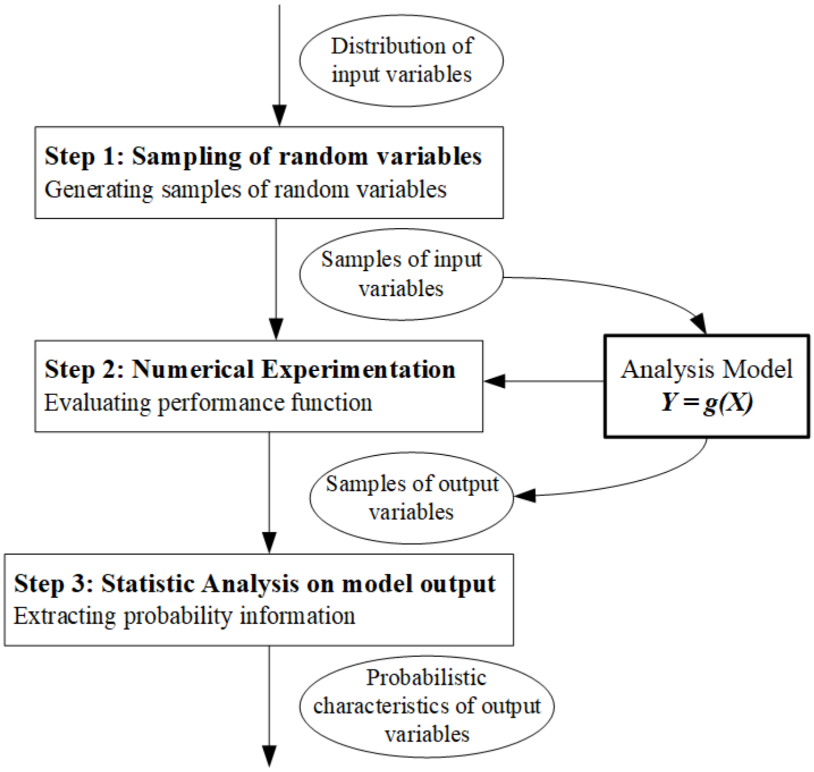


Figure 3.2: Monte Carlo simulation process

3.4 Chapter summary

This chapter discussed the theoretical framework considered within this study for grid integration of electric vehicles. The charging technologies and strategies, modes, and types of ports and connectors have been highlighted, with the uncontrolled charging scheme adopted for this study. Also discussed are the load flow method and Monte Carlo simulation process adopted for this study. The outlined theoretical framework will be applied to the modelling and simulation process discussed in the following chapter.

CHAPTER 4: MODELLING AND SIMULATION

This chapter presents the proposed methodology for the impact assessment and subsequent hosting capacity determination. The modelling of the different components of the system and the simulation technique adopted based on the theoretical framework established in Chapter 3 is presented.

4.1 EV Charging impact and hosting capacity assessments methodology

The overview of the modelling approach adopted for the impact assessment and hosting capacity determination is shown in Figure 4.1. The residential and EV load profiles are imputed into PowerFactory software where the network is also modelled and the load flow calculation performed. The results of the system parameters of interest are exported and analyzed in Microsoft Excel. The simulation procedure for three-phase and single-phase EV charging HC assessment follows the flowchart in Figure 4.2. Deterministic-time series and stochastic method based on a simplified MCS are the two types of analysis performed in the methodology for three-phase and single-phase EV charging HC assessment respectively.

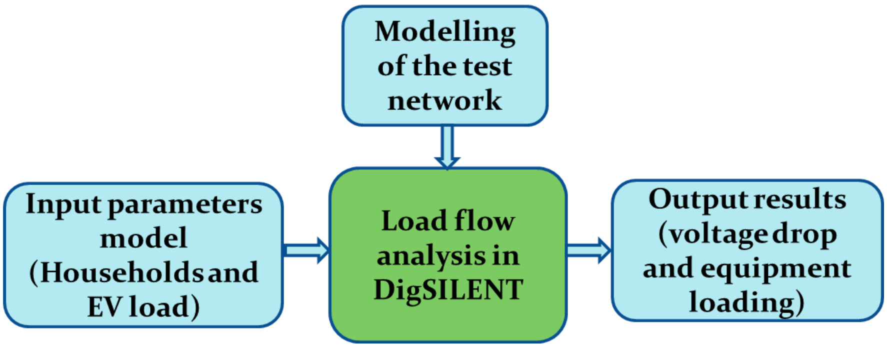


Figure 4.1: Overall modelling approach

4.1.1 Deterministic-time series method

A baseline annual time series load flow simulation is used to first identify the initial state of the network before EV charging is connected. A deterministic method is used to determine the location of EV charging. This is done by creating a priority list from the result of the power flow and applying the list in both forward and backward positions to decide which customer the EV charging load will first be added to and so on. The forward application of the list is termed the “worst case” and begins with the customers having the highest voltage drop. The backward application is termed the “best case” and begins with customers having the lowest voltage drop. Thereafter, the historical time series load data is applied to carry out the simulation.

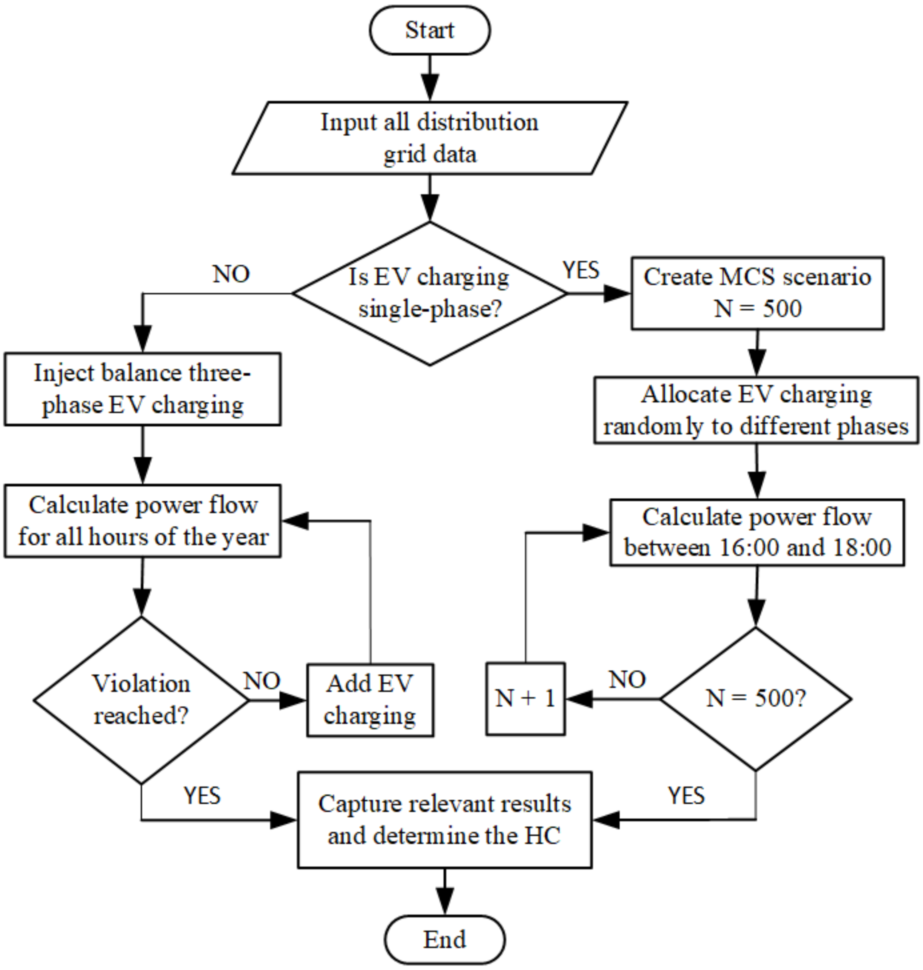


Figure 4.2: Simulation methodology

Deterministic simulation procedure to create a priority list for the location of EV charging

1. Acquire historical annual time series load demand data and save as .csv file with time stamp.
2. Generate the customer load profile in PowerFactory as shown in Appendix A.2
3. Run baseline load flow in Powerfactory using the Quasi-Dynamic command.
4. Make a list of the voltages at the different buses in the forward (worst case) and backward (best case) directions.

Time series simulation procedure

1. Obtain historical yearly time series load demand data and EV charging load data and save as .csv file with time stamp.
2. Generate the customer and EV load profiles in PowerFactory as shown in Appendix A.2

3. Run the time series load flow using the Quasi-Dynamic tool in PowerFactory
4. Acquire and analyze the results of voltage drop and equipment loading for the period of simulation as shown in Appendix A.3.

4.1.2 Stochastic method

A stochastic method is used for EV charging analysis to account for uncertainties and random variables. In this study, a stochastic method is used for single-phase EV charging analysis. All customers are assumed to be EV candidates with equal chances of owning an EV. A simplified MCS first introduced in [71] for PV hosting capacity studies that use minimum available data and reduced simulation time is adapted and used in this study. It is used to randomly assign the phase to each customer at every addition of the EV charging load. The input variables are generated in Microsoft Excel and saved as a PowerFactory compatible format. Time steps are assigned to every scenario equivalent to the number of MCS iterations and 500 iterations is adopted for this study. Load flow simulations are conducted and the result for voltage drop and equipment loading is obtained, which is used for further analysis.

Stochastic method simulation procedure

1. Identify the critical day with the highest load consumption.
2. Save all input data with time stamp as .csv file
3. Create customer and EV load profiles in PowerFactory as shown in Appendix A.1
4. Run the load flow using the Quasi-Dynamic command in PowerFactory

4.2 Simulation software

The method described in section 4.1 needs to be carried out using an appropriate power system software package. The 2022 version of PowerFactory, developed by DIGital SImuLation of Electrical NETworks (DIgSILENT), is the primary power system software tool used for simulation in this study. DIgSILENT PowerFactory (DPF) is a widely used power system analysis software tool for highly sophisticated and advanced applications in the investigation of generation, transmission, distribution and industrial electrical power systems [132]. Studies such as [64, 133, 134] have previously used the software for impact assessment and HC studies. DPF software is easy to use and has a library of the component required for this study and a module dedicated to HC studies. The software has a function known as “Quasi-Dynamic Simulation”, which can be used for both deterministic and time series load flow computations. This Quasi-Dynamic simulation function is used in this study since the load demand is a function of time.

4.3 System constraint

Performance indices (PI) need to be selected and their limits set for impact assessment and HC determination. For this study, voltage drop and equipment thermal limits are performance indices selected for the assessments with respect to the high penetration of EV charging. The distribution network must operate within the standard set by NRS048-2 [9, 125].

The acceptable voltage limits need to be followed for the stability of the network. This range can be expressed thus:

$$V_i^{min} \leq V_i^t \leq V_i^{max} \tag{4.1}$$

where, V_i^{min} and V_i^{max} are the upper and lower limits of the voltage at the terminal i. The South African standard set this voltage limits as ± 10% of the nominal voltage, which is adopted for this study.

Similarly, there is an increase in the thermal characteristics of electrical equipment such as transformers and cables when current flows through them because of the joule effect [135]. The thermal loading of equipment often stated by the manufacturer can be expressed thus:

$$I_t \leq I \tag{4.2}$$

where, I_t is the current flowing through the conductor at a given time and I is the current rating of the conductor. In this study, 100% equipment loading is the assumed limit.

4.4 System modelling

The system models required for the simulation are created in PowerFactory in order to assess the impact and HC of the EV charging on an existing low voltage network. The details of how the system components were modelled are described in this subsection.

4.4.1 Low voltage distribution network modelling

The test LV distribution network used for this study is part of an eThekwini power grid and the grid data obtained from eThekwini municipality. The studied area is a housing development in Durban, South Africa consisting of 21 high-income homes, each with the potential for EV charging. Figure 4.3 shows a single line diagram of the studied grid. The grid is supplied by a 350 kVA 11/0.41kV Dyn11 transformer, and the cable characteristics are detailed in Table 4.1. Every household represents a customer and is evenly allocated on a customer distribution unit (DU) resulting in three customers per DU. The initial load flow simulation shows that the feeder operates within the allowable limits, validating the obtained grid data. It is assumed that each customer can connect only one EV to the grid. The detailed line diagram implemented in PowerFactory can be found in Appendix A.1.

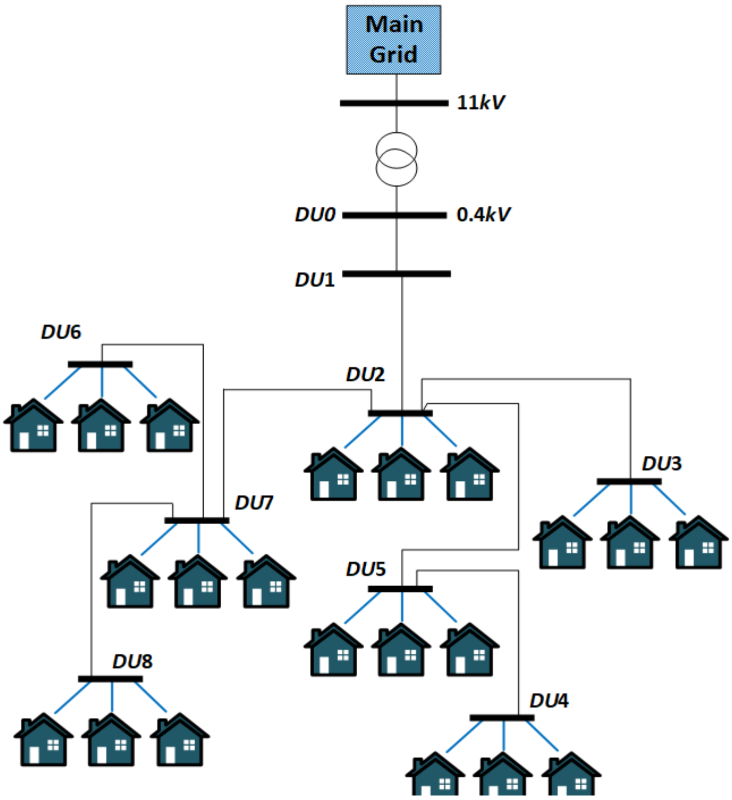


Figure 4.3: Low voltage distribution network

Table 4.1: Cable properties

Cable ID	Length *(m)*	R1 *(Ω)*	X1 *(Ω)*	Rated current *(A)*
DU0-1	98	0.019	0.007	282
DU1-2	64	0.025	0.005	242
DU2-3	79	0.091	0.007	122
DU2-5	81	0.092	0.007	122
DU2-7	72	0.081	0.006	122
DU5-4	77	0.090	0.006	122

DU6-7	63	0.074	0.005	122
DU7-8	66	0.076	0.005	122

4.4.2 Load modelling

The historical time series load data available for the studied grid is a one calendar year (2021) measured hourly average active energy (kWh) for all the 21 customers in the distribution network obtained from the utility. Figure 4.4 shows the aggregated historical time series load data used to model the studied grid with peak consumption observed in July. Figure 4.5 shows the seasonal load profile for the day with the highest consumption across each season. It can be observed that the highest consumption occurs during the winter season with the day (15 July 2021) having the highest load demand set as the critical day, which is subsequently used as the simulated period for single-phase EV charging HC assessment. Since information about the load consumption of individual households is not available and all customers are assumed to be of the same class with the same consumption pattern, load scaling method is applied to estimate the load for each consumer. Load scaling is a top-down method of estimating the load distributed along a feeder, to sum up to the known measurement at the beginning of the feeder. It is a standard feature in DIgSILENT PowerFactory software.

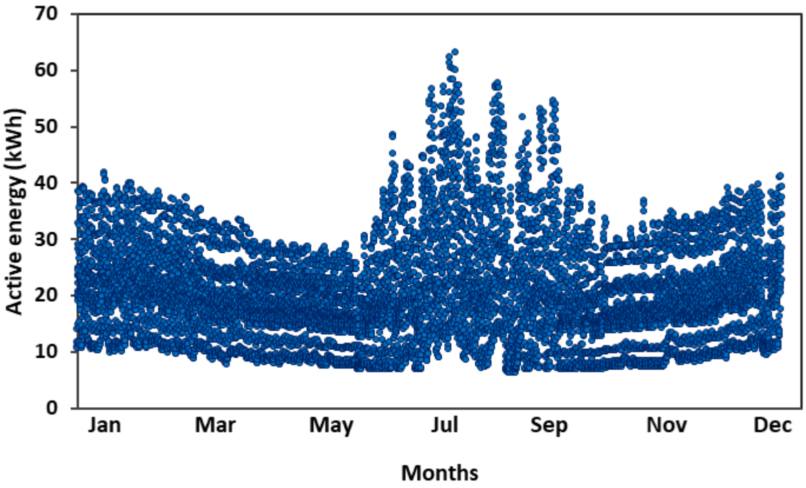


Figure 4.4: Aggregated historical time-series load for the year 2021

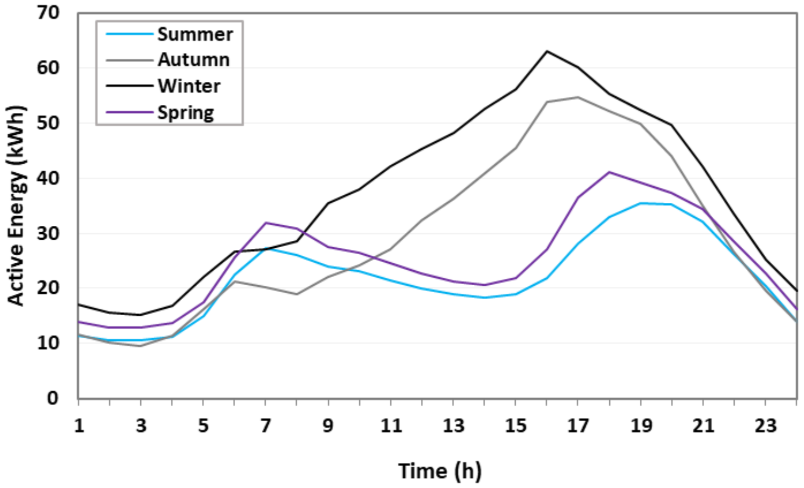


Figure 4.5: Seasonal load profiles

4.4.3 EV charging power modelling

The impact and hosting capacity is initially assessed for the most popular EV chargers with charging power of 3.7kW single phase and 11kW three-phase, corresponding to a 16-A fuse. Since utilities in South Africa have not yet specified the allowable chargers on the grid, other single-phase connected charging powers shown in Table 4.2 are also assessed. EV charging is modelled as an addition to the domestic load, and each customer on the network is modelled as an EV candidate with equal chances of installing any of the chargers. An uncontrolled EV charging pattern is also assumed for all customers.

Table 4.2: EV charging power and the corresponding fuse

EV charging power (kW)	Corresponding fuse (A)
3.7	16
4.6	20
5.75	25
6.9	30
9.2	40
11.5	50

4.5 Deterministic simulation and priority list

An initial baseline load flow simulation without the addition of EV charging is conducted to assess the voltages at different buses and create a priority list. This procedure, described in section 4.1.1, is used to determine how the EV charging is assigned to each household during subsequent simulations. The simulation is conducted on the day (15 July 2021) with the highest load demand obtained from the historical data. The result of this simulation and the priority list starting with the bus with the lowest voltage drop for single-phase and balanced three-phase load is shown in Table 4.2. This is termed the “best-case” scenario while the reverse is the “worst-case” scenario.

Subsequently, historical load data for all hours of the year (2021) is used to conduct the power flow simulations with EV charging power (11 kW) added to each household as a constant power load, balanced across the three phases. EV charging power is added to one customer at a time for every simulation based on the priority list for either the worst-case or best-case scenarios. The process is iterated until the first violation of either voltage or loading limits, and the HC is obtained.

Table 4.3: Priority list used for placement of EV charging load

Three-phase		**Single-phase**	
Bus number	**Voltage (p.u.)**	**Bus number**	**Voltage (p.u.)**
DU1	0.9893	DU1	0.9871
DU2	0.9796	DU2	0.9754
DU3	0.9748	DU3	0.9705
DU5	0.9699	DU5	0.9656
DU4	0.9650	DU4	0.9647
DU7	0.9649	DU7	0.9627
DU8	0.9618	DU8	0.9616
DU6	0.9608	DU6	0.9579

4.6 Stochastic variable modelling and simulation

The proposed stochastic method described in section 4.1.2 requires the modelling of uncertainties and random variables. There are two major random variables (location of EV and phase connection) accounted for in this study for single-phase HC assessment. The priority list for the best-case and worst-case is used to determine EV placement while a simplified MCS method is used to assign the phases randomly during simulation. The randomness of the phase connection is generated in Excel using equation (4.3) and applied during the simulation. The equation returns a uniform distribution between phases a, b, and c, with each customer having equal chances of connecting their EVs to any of the phases.

$$f(x) = CHAR(RANDBETWEEN(97{,}99)) \tag{4.3}$$

Figure 4.6 shows the load profile for the critical day (15 July 2021) and the period of interest used for the simplified MCS. Three power flow simulations are performed for each scenario for the period of interest (critical day) using1-hour resolution from 16:00 and 18:00. Since EV charging will have the greatest impact on the distribution grid when there is peak demand [136], this period with the highest consumption throughout the year is chosen. It is assumed that if there is no violation during this period it is unlikely that there would be at other periods. MCS is used to randomly assign the phase to each customer at every addition of the EV charging load. The procedure is repeated for 500 MCS scenarios. This number of simplified MCS scenarios is adopted for this study because it has been validated by [71] The result of interest is captured, which includes voltage drop and equipment loading.

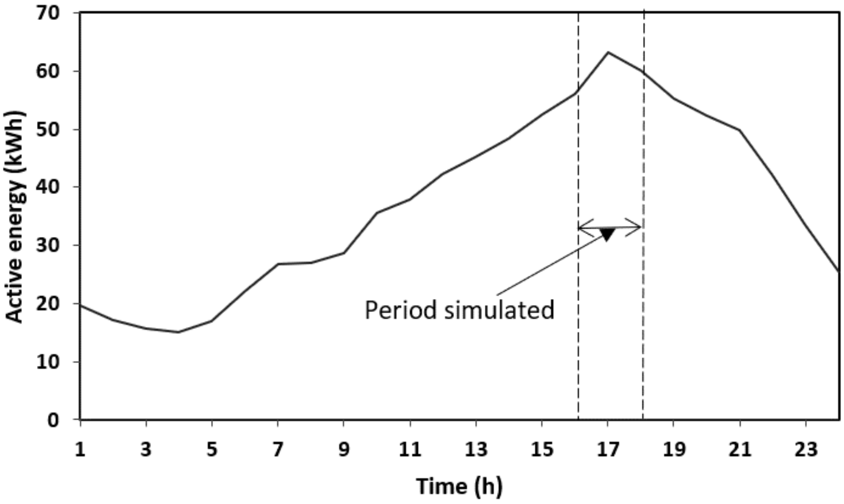


Figure 4.6: Hourly load profile for the critical day (15/07/2021) with the highest consumption

4.7 Scenario development

There are two case studies formulated for this study for three-phase and single-phase EV charging impact assessment and HC determination. Each scenario highlights certain aspects of the impact of high penetration of EV charging in the distribution network. Case study 1 is concerned with the impact assessment and HC of a balanced three-phase EV charging (11 kW and 22 kW load). This case study uses the deterministic method to examine how the network performance is impacted by seasonal load variations. It also evaluates how the HC changes throughout the year and across the different seasons, and how the location of EV charging affects the change.

Case study 2 evaluates the impact of single-phase EV Charging in an unbalanced network using the simplified MCS based stochastic method. In this case study, the HC of different EV charging power is assessed to help utilities in South Africa plan effectively for the integration of EVs. The system parameters of interest (voltage drop and equipment loading) for each case study are recorded for every load flow iteration and analyzed.

4.8 Penetration level and hosting capacity definition

To understand the results, the penetration level (PL_{EV}) and HC with reference to EV charging must be defined. In this research, EV penetration level is defined as the ratio total number of customers equipped with EVs to the total number of customers in the area under study as formulated in equation (4.3). Hosting capacity in this study is defined as the total number of customers on the LV distribution network that can charge their EV simultaneously without violating any operational limit. The performance indices considered are voltage drop and cable loading with their operational limit is set according to the South African standard. The equipment loading limit is set to 100% while the voltage drop must not be below 0.90 p.u. of the nominal voltage.

$$PL_{EV} = \frac{\sum Customers\ charging\ their\ EVs}{Total\ number\ of\ customers\ on\ the\ network}\ 100\% \tag{4.3}$$

4.9 Chapter Summary

This chapter has proposed a methodology for modelling and simulation in order to assess the impact of EV charging penetration in the distribution network. The deterministic method and the stochastic method based on a simplified MCS are applied to the three-phase and single-phase HC determination respectively. The test network was modelled in DiGSILENT PowerFactory using aggregated historical time series load data. The different charging power for EV charging impact investigation was also modelled. The next chapter will apply the models and methods presented to assess the technical impact and determine the hosting capacity of residential networks with EV charging.

CHAPTER 5: RESULTS AND DISCUSSION

The key objective of this research is to assess the impact of high penetration of EV charging on a South African residential LV network and quantify the hosting capacity. This chapter presents the results of the simulation conducted based on the model and methodology described in Chapter 4 to evaluate the impact of EV charging an eThekwini residential LV distribution network. An investigation is made to evaluate the performance of the distribution grid pre and post EV charging penetration by assessing the network parameters such as voltage drop and equipment loading. The HC for three-phase and single-phase EV charging on the network is also determined. Part of the results presented in this chapter have been published in [137]

5.1 Case study 1: Impact of grid-connected EV charging in a balanced three-phase network

This case study is to evaluate the impact of three-phase EV charging on the grid, quantify the HC, examine how the HC changes throughout the year and how the location of EV charging affects the change. All the analyses are based on historical load data for all hours of the year (2021) and uncoordinated EV charging power of 11 kW. The EV charging is added to each household and simulated as a constant power load, balanced across the three phases.

5.1.1 Impact on voltage drop

Test network without EV charging load

The voltage profile at different busbars along the feeder of the balanced three-phase network, when no EV load is connected, is shown in Figure 5.1. It can be observed that the bus closest to the transformer, DU1, has the lowest voltage drop with the highest voltage magnitude of 0.989 p.u (395.6 V). The busbar, DU6, has the highest voltage drop with the lowest voltage magnitude of 0.961 p.u (384.4V). The voltage magnitude at all the busbars is within the acceptable operational limit.

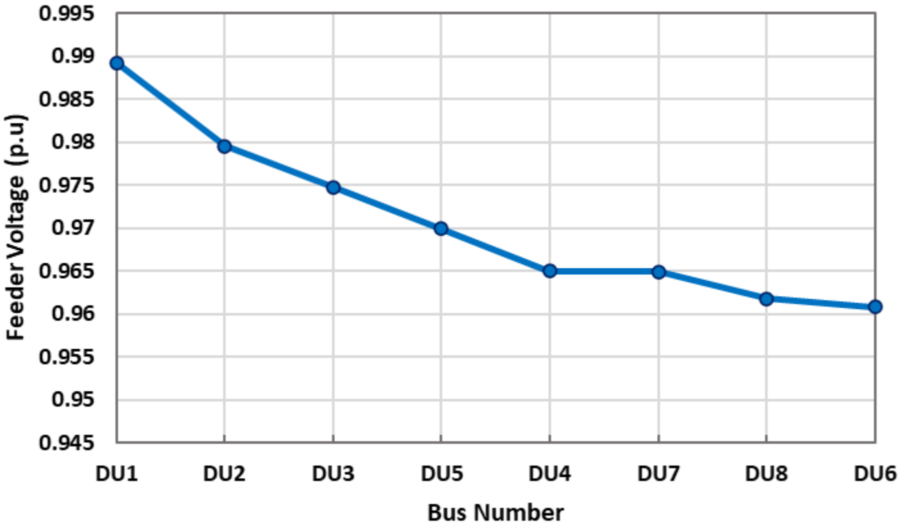


Figure 5.1: Bus voltages without EV

Test network with EV charging load

The voltage profile in the network when EV charging load is connected for the worst case and best case scenario is shown in Figure 5.2 and 5.3 respectively. A scattered plot is used to demonstrate the relationship between the maximum and minimum feeder voltages at each busbar and the penetration of EV charging in the test LV network. Each dot in the figures shows maximum and minimum voltages at the different busbars in the network as the allocation of EV charging is gradually increased. It is observed that an increase in the penetration level of EVs (PL_{EV}) decreases the feeder voltages towards the lower limit. For the worst case scenario shown in Figure 5.2, considering the lower voltage limit of 0.90, the first violation is observed at 29% PL_{EV} when 6 customers are simultaneously charging. Due to load variations, more customers can charge at hours of lower household load demand until both minimum and maximum voltages exceed the limits when 9 EVs (43% PL_{EV}) are simultaneously charging. At this point, there will always be a violation irrespective of the time of the year. Figure 5.3 shows the best case scenario where the first violation is observed at 57% PL_{EV} when 12 EVs are simultaneously charging. At 71% PL_{EV} (15 EVs simultaneously charging) and beyond, there will always be a violation for every hour of the year.

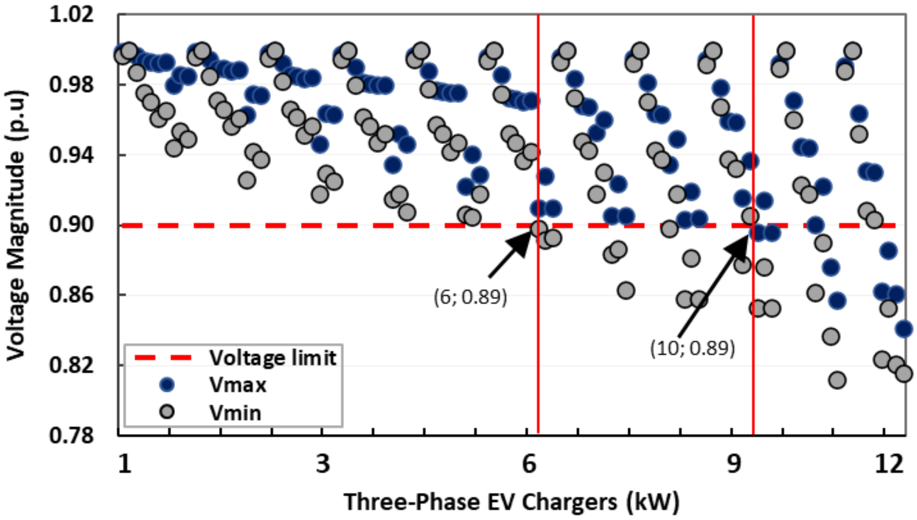


Figure 5.2: Worst case voltage

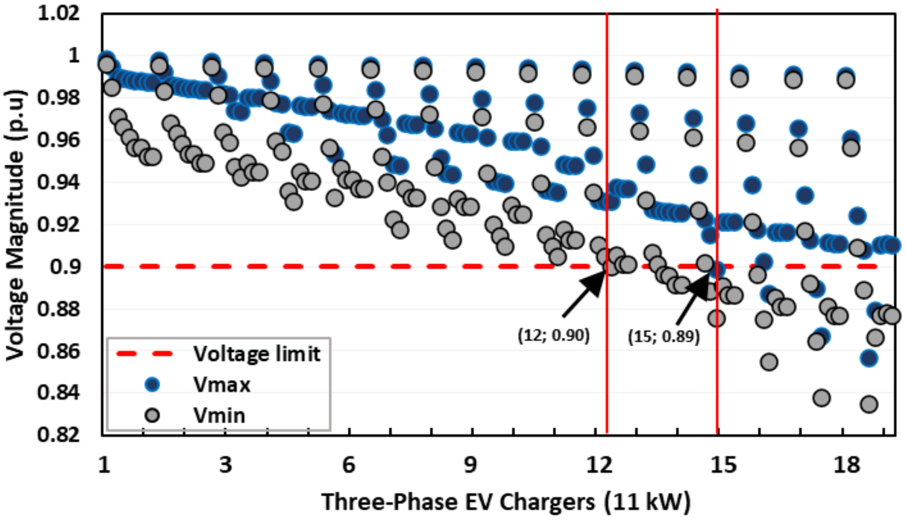


Figure 5.3: Best case voltage

5.1.2 Impact on equipment loading

Test network with EV charging load

The scatter plot in Figures 5.4 and 5.5 shows the maximum and minimum equipment loading for the worse case and best case respectively for all the hours of the year simulated as the PL_{EV} is varied. The equipment considered are the cables and the transformer and the dots represent the maximum and minimum values for each equipment during the period of simulation. It is observed that increasing the penetration level results in a corresponding increase in the equipment loading toward the allowable limit. In the worst case scenario shown in Figure 5.4, the first violation at 108% equipment loading is observed at 29% PL_{EV} when 6 customers are simultaneously charging their EVs. More customers can charge at hours of lower household load demand until both minimum and maximum equipment loading exceed the limits when 9 EVs (43% PL_{EV}) are simultaneously charging. The best case scenario in Figure 5.5 shows the first violation at 107% equipment loading when 10 customers (48% PL_{EV}) are simultaneously charging. At 67% PL_{EV} (14 customers) and beyond, there will always be a violation for every hour of the year.

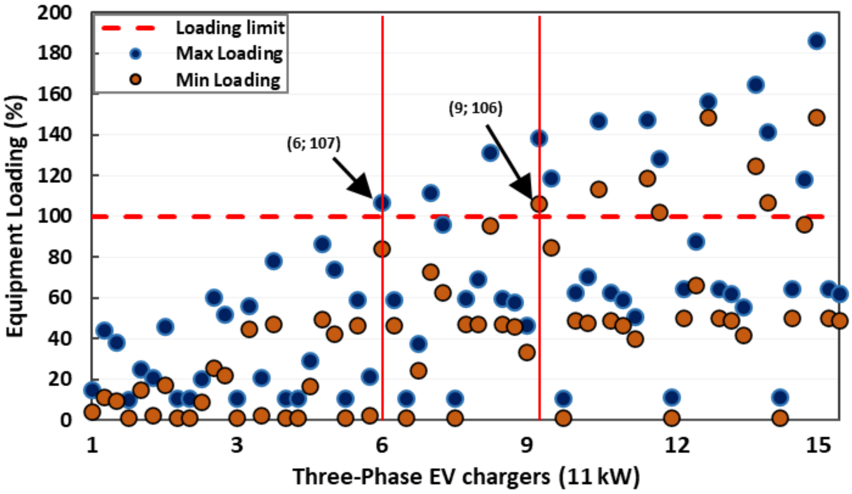


Figure 5.4: Worst case loading

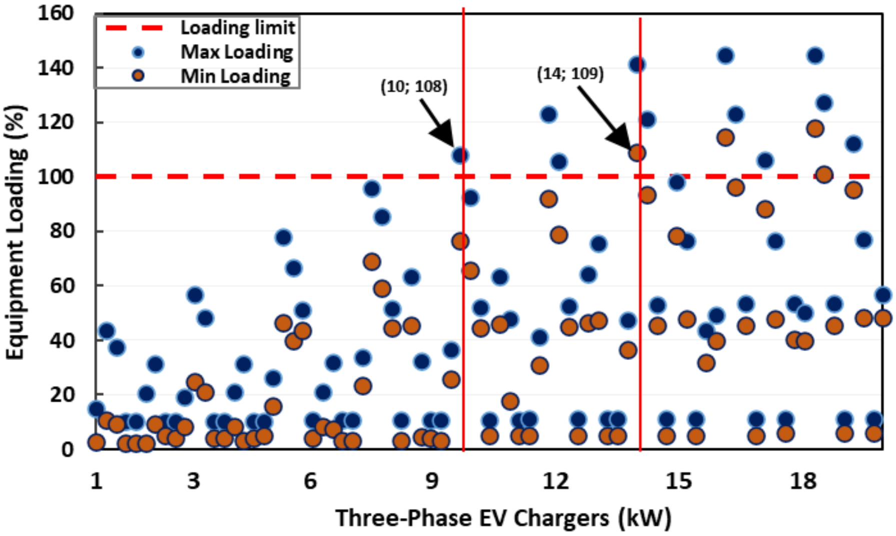


Figure 5.5: Best case loading

5.1.3 Hosting capacity estimation

Hosting capacity in this study is defined as the total number of customers on the LV distribution network that can charge their EV simultaneously without violating any operational limit. The range of value for the hosting capacity of the balanced three-phase network obtained from the impact assessment conducted is given as 5-8 customers and 9-13 customers for the worst case and best case scenario respectively. This range of value is general considering all hours of the year and all the performance indices. However, further analysis is carried out to estimate the seasonal and yearly variations in HC values.

Figures 5.6 and 5.7 show the seasonal variation in HC for the 11 kW and 22 kW chargers respectively. It is observed that the test network can host more customers with EVs during the summer while the least number of EVs can be connected during the winter. Figure 5.8 show the fraction of the year with the number of EVs that can be hosted simultaneously in the test network without the violation of a performance limit. The pie charts include results from all hours of 2021. It is shown that during the best case scenario, 9 and 10 customers can be hosted simultaneously for 85% and 70% of the hours respectively. For the 22 kW charger shown in Figure.9, the HC is 4-6 customers and 2-4 customers for the best case and worst case respectively. During the worst case scenario, 5 and 6 customers are hosted simultaneously for 85% and 60% of the year without violating the limit of any PI.

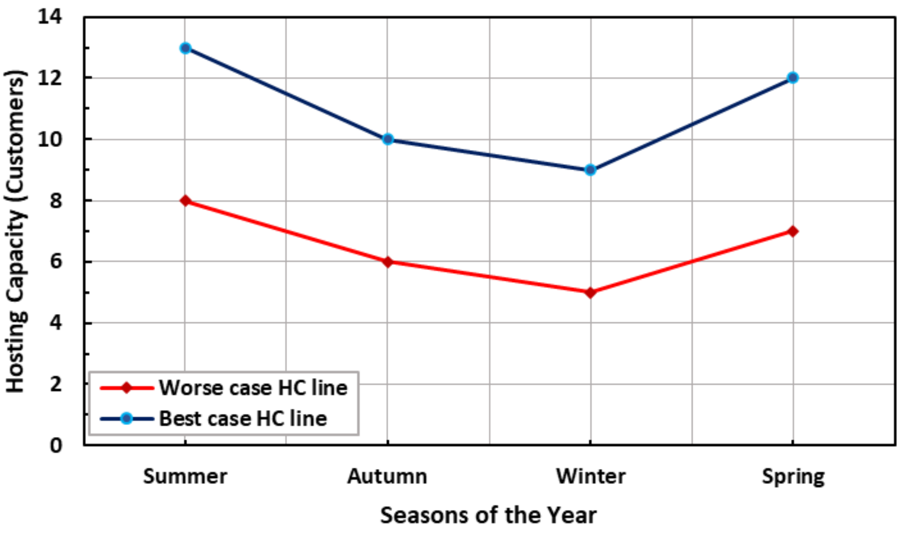


Figure 5.6: Seasonal hosting capacity for 11 kW chargers

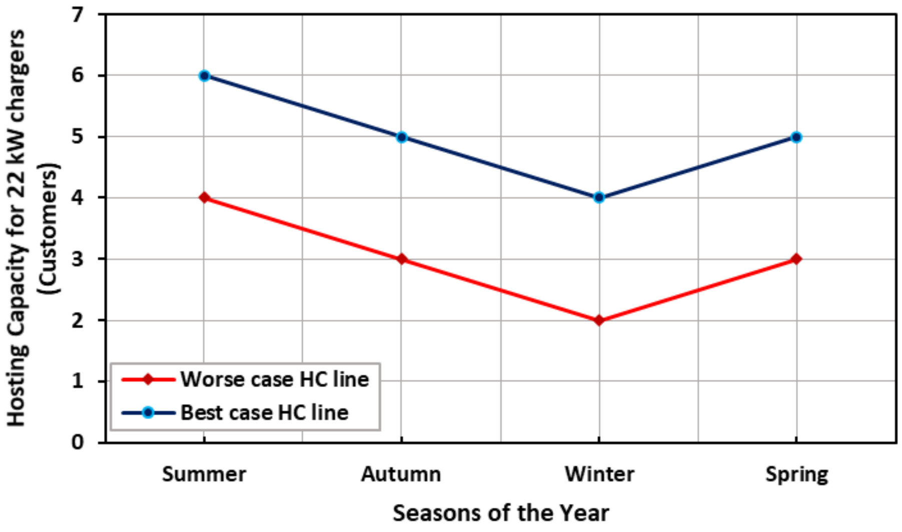


Figure 5.7: Seasonal hosting capacity for 22 kW chargers

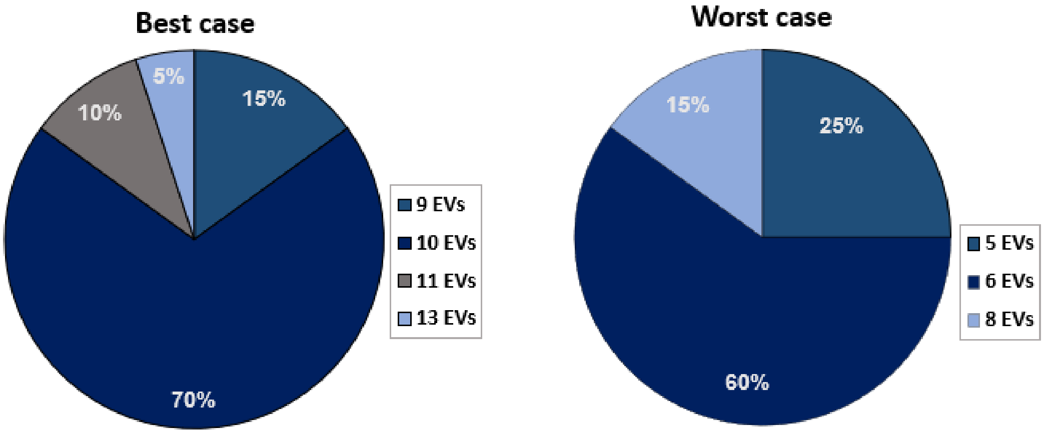


Figure 5.8: Fraction of the year with the given number of EV that can charge without a violation of any PI for EV charging power of 11 kW

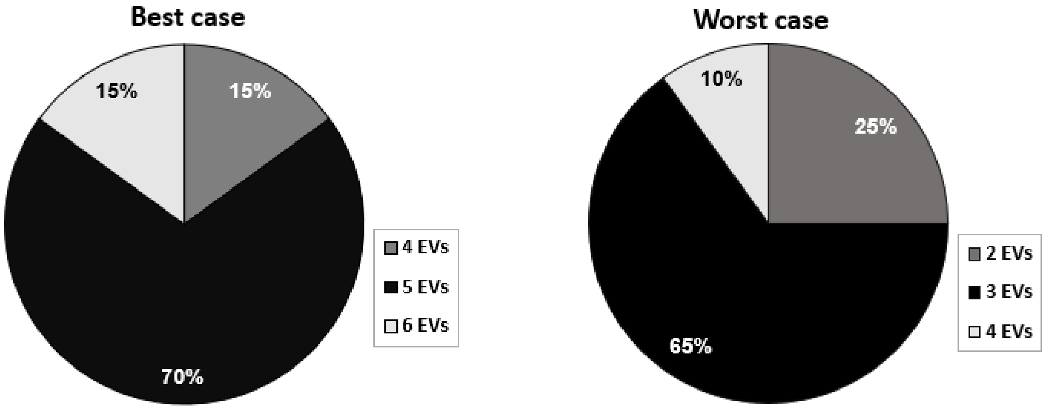


Figure 5.9: Fraction of the year with the given number of EV that can charge without a violation of any PI for EV charging power of 22 kW

5.2 Case study 2: Impact of single-phase EV charging in an unbalanced Network

This case study is to assess the impact of single-phase EV charging on an unbalanced LV distribution network and estimate the hosting capacity. All the analysis is based on the identified critical day using a simplified MCS for the stochastic assessment, and uncoordinated EV charging is assumed. Firstly, the popular 3.7 kW charging power corresponding to 16 A fuse is used for the impact assessment.

5.2.1 Impact on voltage drop

Test network without EV charging load

The voltage profile at different busbars along the feeder of the unbalanced single-phase network without EV load is shown in Figure 5.10. It can be observed that the feeder closest to the transformer, DU1, has the lowest voltage drop with the highest voltage magnitude of 0.987p.u (394.8 V). The busbar, DU6, has the highest voltage drop with the lowest voltage magnitude of 0.957p.u (382.8 V). The voltage magnitude at all the busbars is within the acceptable operational limit.

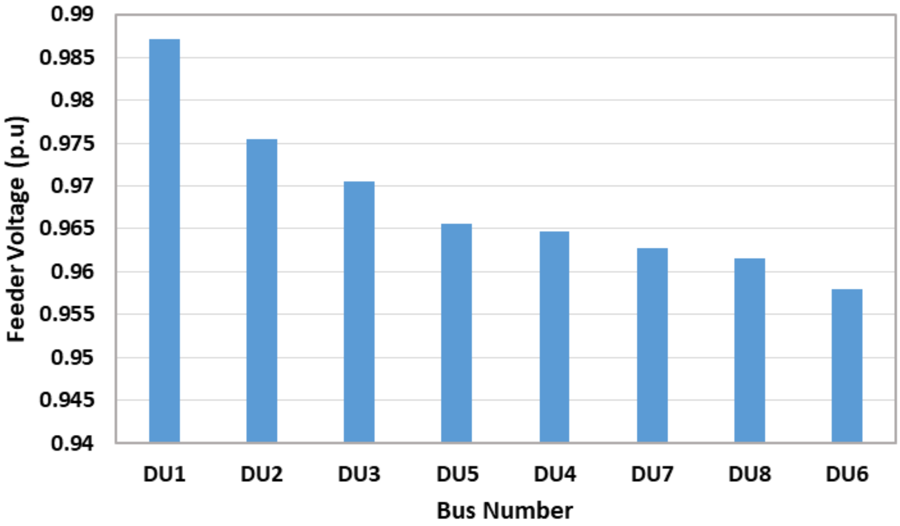


Figure 5.10: Bus voltages without EV

Test network with EV charging load

The voltage profile in the network when EV charging load is connected for the worst case and best case scenario is shown in Figures 5.11 and 5.12 respectively. A scattered plot is used to demonstrate the relationship between the minimum feeder voltages and the penetration of EV charging in the test LV network. Each dot in the Figures represents an MCS scenario and shows the minimum voltages anywhere in the network based on the increasing EV charging load and random phase allocation. It is observed that an increase in the penetration level of EVs (PL_{EV}) decreases the feeder voltages towards the lower limit. For the worst case scenario shown in Figure 5.11, considering the lower limit of 0.90, the first violation is observed at 52% PL_{EV} when 11 customers are simultaneously charging. The probability of a violation increases from this point as more EVs are connected. Figure 5.12 shows the best case scenario where the first violation is observed at 76% PL_{EV} when 16 EVs are simultaneously charging.

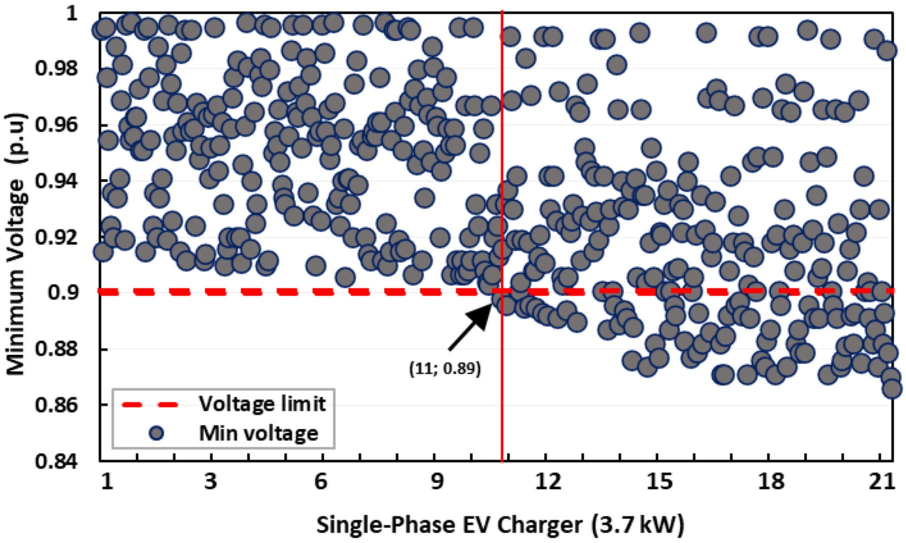


Figure 5.11: Worst case minimum voltage

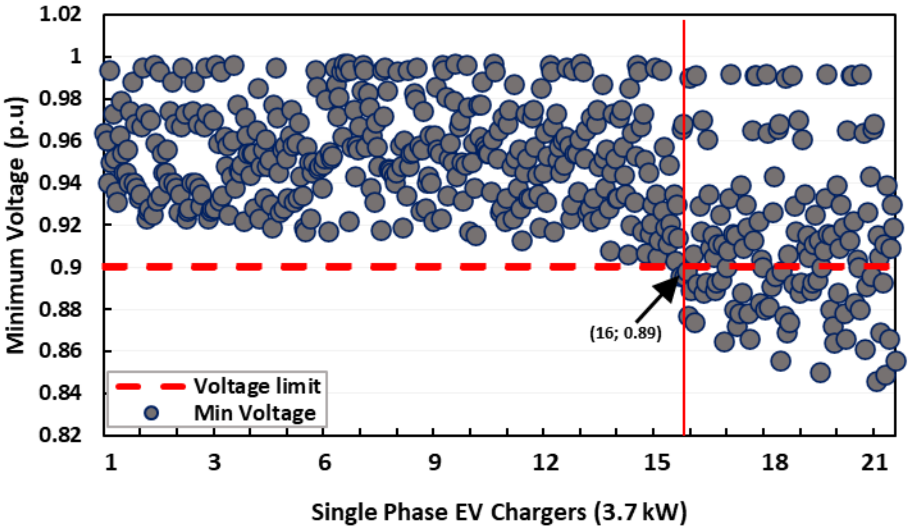


Figure 5.12: Best case minimum voltage

5.2.2 Impact on equipment loading

Test network with EV charging load

The scatter plot in Figures 5.13 and 5.14 shows the maximum equipment loading anywhere in the network for the worse case and best case scenarios respectively for increasing penetration levels. The equipment considered are the cables and the transformer and each dot represents a MCS scenario. It is observed that increasing the penetration level results in a corresponding increase in the equipment loading towards the allowable limit. In the best case scenario in Figure 5.13, the first violation at 100% equipment loading is observed at 43% PL_{EV} when 9 customers are simultaneously charging their EVs. The best case scenario in Figure 5.14 shows the first violation at 102% equipment loading when 11 customers (52% PL_{EV}) are simultaneously charging.

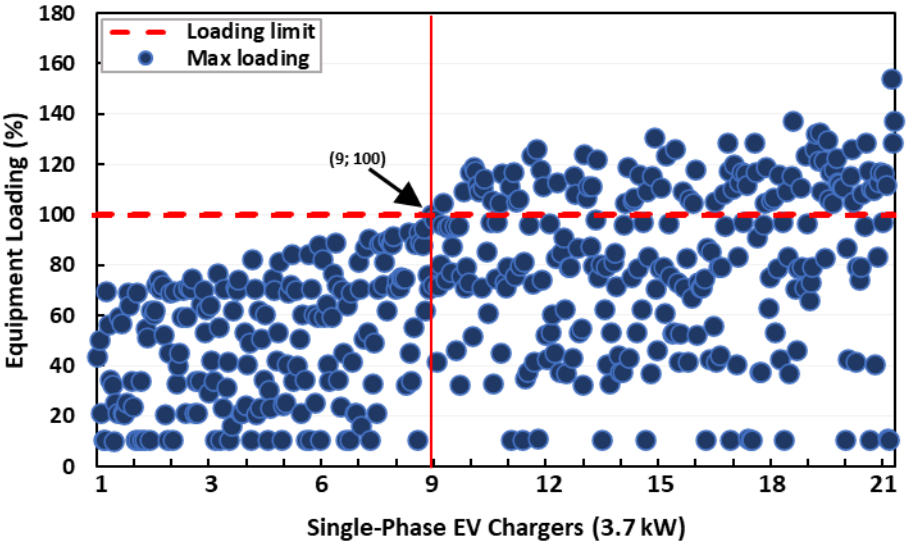


Figure 5.13: Worst case maximum loading

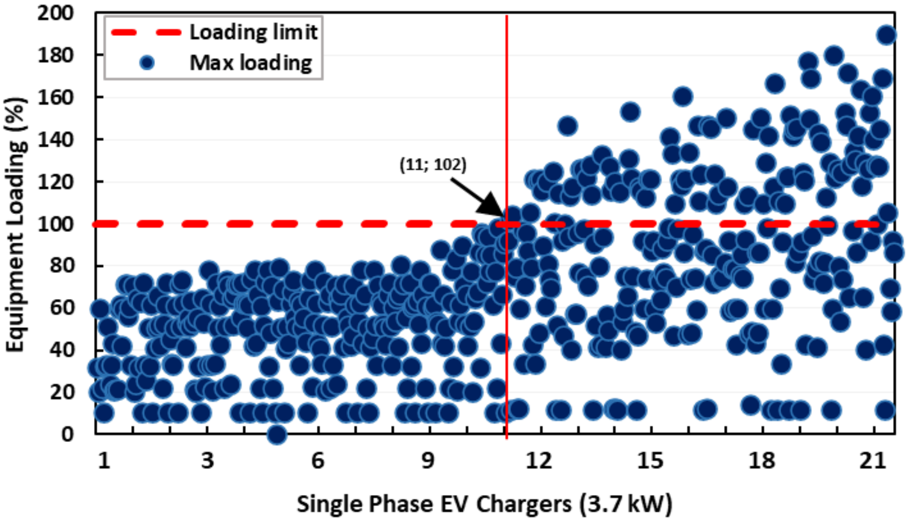


Figure 5.14: Best case maximum loading

5.2.3 Hosting capacity estimation

The hosting capacity of the unbalanced single-phase network obtained from the impact assessment conducted for different charging power is shown in Figures 5.15 and 5.16 for voltage drop and equipment loading respectively. In Figure 5.16, the HC with charging power of 3.7 kW is 48% and 71% (10 and 15 customers) for the worst case and best case respectively, when voltage drop is the PI considered. The HC reduces to 9.5% and 57% at 6.9 kW charging power.

When considering equipment loading as PI, the result in Figure 5.16 shows that with a charging power of 11.5 kW, none of the customers can charge their EVs for the worst case while 5 customers can charge during the best case. The HC is 0 and 5 customers for the worst case and best case scenario respectively. Moreover, for the popular charging power of 3.7 kW, the HC is 8 customers for the worst case and 10 customers for the best case. Table 5.1 shows a comparison of the HC values for the worst case and best case scenarios when considering both PIs, with equipment loading as the most limiting PI. The difference in HC values between the two scenarios in this case study also highlights the effect of charging location on the HC of single-phase EV charging.

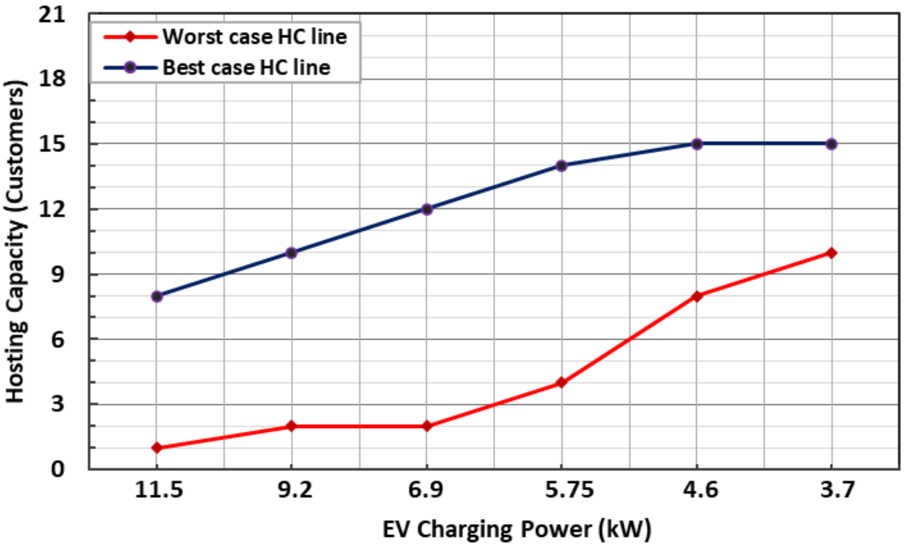


Figure 5.15: Single-phase hosting capacity results for different charging power when considering voltage drop as the PI

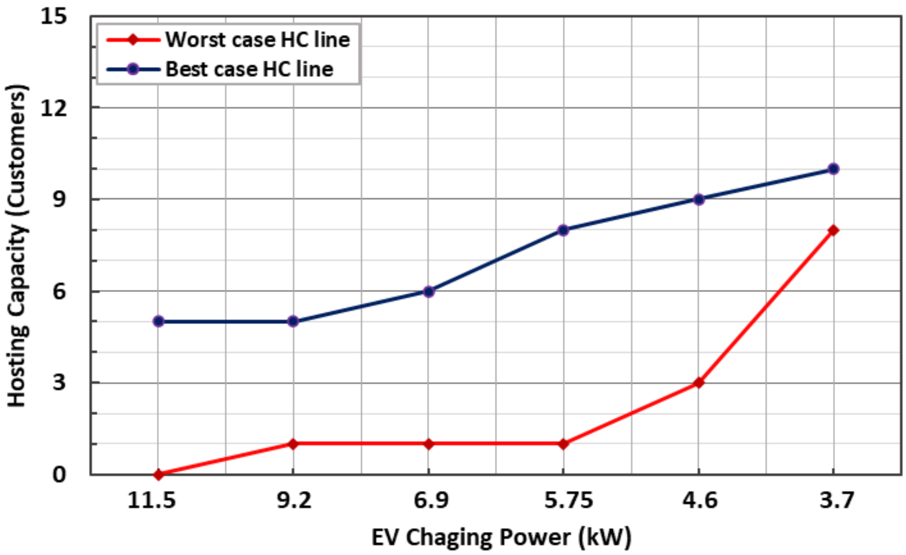


Figure 5.16: Single-phase HC results for different charging power when considering cable loading as the PI

Table 5.1: HC comparison of both performance indices

Charging Power (kW)	HC When Voltage Drop Is PI (Customers)		HC When Equipment Loading Is PI (Customers)	
	Worst Case	Best Case	Worst Case	Best Case
11.5	1	8	0	5
9.2	2	10	1	5
6.9	2	12	1	6
5.75	4	14	1	8
4.6	8	15	3	9
3.7	10	15	8	10

5.3 Discussions and Implication

The main objective of this research is to assess the impact of different levels of EV charging penetration in an eThekwini low voltage distribution network and estimate the network hosting capacity. This section discusses results and its implication in the South African electrical networks according to the South African standard. The limit of voltage drop specified in NRS 097 [9] is that voltage must be within ±10% of the nominal voltage for 95% of the weeks. The impact of EV charging integration in the LV network was observed in all the case studies with the results (Figure 5.2, 5.3, 5.9, and 5.10) signifying that the increased penetration of EV charging will result in feeder voltage drop.

The impact of EV charging on equipment loading is one of the major concerns for the DSOs, which has been supported by the result of this study. The feeder loading results (Figures 5.4, 5.5, 5.13, and 5.14) indicate that equipment loading of the feeder increases as the penetration levels increase. This can be credited to the increased power flowing through the cables and transformers, which is higher than what the network was traditionally designed to accommodate. The implication of this is that the DNOs will have to increase the cable sizes and adjust the transformer to operate them at an appropriate tap for feeders with high spread of EV charging loads.

The system topology and location of EVs on the feeder also impact the hosting capacity. The results show that the network accommodates more single-phase EV charging compared to three-phase EV charging. Furthermore, the difference in HC values shown in the results between the best case and worst case scenarios highlights the effect of charging location on the HC of both three-phase and single-phase EV connections. This implies that DNOs, in their planning, should consider the effect of the location of charging bearing in mind that customers could plug in their EVs at any point in the network.

5.4 Generality of result

The HC method adopted in this study can readily be used by operators to get an immediate estimate of the EV charging penetration in the distribution network for planning and expansion purposes. However, the results presented are for a specific grid, PI, and the PI limits, and cannot be immediately transferred to another grid. This is because distribution grids are non-homogenous. Also, this study uses uncontrolled EV charging without considering the charging behaviour and state of charge, but the EV load is added to all the hours of the year. This approach may underestimate the HC but generates a result that shows the variation in HC throughout the year. In reality, there may be a higher probability of more EVs charging simultaneously if the charging is distributed in time.

5.5 Chapter Summary

This chapter has investigated the impact of EV penetration in existing residential networks and estimated the network hosting capacity based on the results obtained. The evaluation was conducted for three-phase and single-phase EV charging integration for holistic performance assessment. Voltage drop and equipment loading are the performance indices assessed with equipment loading seen to be the most limiting factor. The methodology, results and discussion thus far form the basis for the overall conclusions that will be presented in the next chapter.

CHAPTER 6: CONCLUSION AND FUTURE WORK

This chapter presents the conclusions based on the study objectives and offers recommendations for possible future research direction.

6.1 Conclusions

This dissertation has examined the technical impact of EV charging integration in South residential electrical networks and used the results obtained to estimate the network hosting capacity. The impending proliferation of EV charging in the secondary distribution network due to the growing sales of EVs is of concern to the utilities, which made this study very important. According to the objectives of the studies, the model of an existing eThkwini low voltage residential network was implemented using the DigSILENT PowerFactory software. From the extensive literature review conducted to identify the existing HC determination methods, the deterministic method was applied for the three-phase impact assessment and HC determination while a stochastic method that uses a simplified MCS was adapted for the single-phase impact assessment and HC estimation. Only phase selection was considered as the random variable for the single-phase HC assessment due to its impact in an unbalanced electrical network and to reduce the simulation time. Voltage drop and equipment loading were the PI considered and their limit was set using the South African standard NRS097. From the impact assessment, it can be seen that high penetration of uncontrolled EV charging will negatively impact the existing residential networks, with equipment loading violations observed to be the most limiting factor.

The three-phase HC results show that 5-8 customers can charge their EVs simultaneously in the worst case scenario without a violation while 9-13 customers can connect their EVs at the same time in the best case scenario. The single-phase HC result presented shows that 48% to 71% of the customers can charge simultaneously when the voltage drop is the PI considered. Seasonal variations in HC values throughout the year were also studied, with the three-phase EV charging HC at the highest during the summer and lowest during the winter. The difference in HC values between the best case and worst case scenarios in the study highlights the effect of the location of charging on the HC for both three-phase and single-phase EV charging. The method applied in this study can be employed in other studies to evaluate other PI and is relevant to help utilities make planning for future EV connections. The method is non-specific and can be applied at any time of the year without elaborate knowledge of the customers’ charging patterns.

6.2 Future works

This dissertation has fulfilled its objective of assessing the potential behaviour of residential electrical networks as EV charging is connected. However, further studies can be conducted in the following areas.

1. This study is limited to one residential feeder which does not account for all possible network characteristics. Further studies can be conducted on different residential networks in South Africa, to access their potential behaviour at different levels of EV charging penetration. This will generate a streamlined approach for HC estimation.
2. Only one uncertainty was accounted for in this study. Future work should consider MCS scenarios with more uncertainties.
3. The load modelling and allocation in this study was done using the load scaling technique at the beginning of the feeder due unavailability of individual load demand data. Future work should consider collecting consumer load data for more precise models and accuracy of results.
4. Investigating mitigating solutions and methods that can improve the EV hosting capacity of the network according to the South African standard is another area for future research.

References

[1] M. M. Haque and P. Wolfs, "A review of high PV penetrations in LV distribution networks: Present status, impacts and mitigation measures," *Renewable and Sustainable Energy Reviews,* vol. 62, pp. 1195-1208, 2016/09/01/ 2016, doi: https://doi.org/10.1016/j.rser.2016.04.025.

[2] E. Mulenga, M. Bollen, and N. Etherden, "Adapted Stochastic PV Hosting Capacity Approach for Electric Vehicle Charging Considering Undervoltage," (in eng), *Electricity,* article vol. 2, no. 3, pp. 387-402, 2021 2021, doi: 10.3390/electricity2030023.

[3] "EV Sales." https://cleantechnica.com/tag/ev-sales/ (accessed 11 November, 2022).

[4] J. Ping, Z. Yan, and S. Chen, "A two-stage autonomous EV charging coordination method enabled by blockchain," *Journal of Modern Power Systems and Clean Energy,* vol. 9, no. 1, pp. 104-113, 2020.

[5] M. Shepero, J. Munkhammar, J. Widén, J. D. Bishop, and T. Boström, "Modeling of photovoltaic power generation and electric vehicles charging on city-scale: A review," *Renewable and Sustainable Energy Reviews,* vol. 89, pp. 61-71, 2018.

[6] P. T. Ogunboyo, R. Tiako, and I. E. Davidson, "Effectiveness of Dynamic Voltage Restorer for Unbalance Voltage Mitigation and Voltage Profile Improvement in Secondary Distribution System," *Canadian Journal of Electrical and Computer Engineering,* vol. 41, no. 2, pp. 105-115, 2018, doi: 10.1109/CJECE.2018.2858841.

[7] M. H. Bollen and S. K. Rönnberg, "Hosting capacity of the power grid for renewable electricity production and new large consumption equipment," *Energies,* vol. 10, no. 9, p. 1325, 2017.

[8] V. Umoh, I. Davidson, A. Adebiyi, and U. Ekpe, "Methods and Tools for PV and EV Hosting Capacity Determination in Low Voltage Distribution Networks—A Review," *Energies,* vol. 16, no. 8, p. 3609, 2023. [Online]. Available: https://www.mdpi.com/1996-1073/16/8/3609.

[9] *NRS 097-2-1: Grid Interconnection of Embedded Generation* 2017.

[10] "EN 50160:2010, Voltage Characteristic of Electricity Supplied by Public Electricity Networks, Standard, European Commitee for Electrotechnical Standardization (CENELEC), 2010."

[11] A. Rajabi, S. Elphick, J. David, A. Pors, and D. Robinson, "Innovative approaches for assessing and enhancing the hosting capacity of PV-rich distribution networks: An Australian perspective," *Renewable and Sustainable Energy Reviews,* vol. 161, p. 112365, 2022/06/01/ 2022, doi: https://doi.org/10.1016/j.rser.2022.112365.

[12] E. Mulenga, M. H. J. Bollen, and N. Etherden, "A review of hosting capacity quantification methods for photovoltaics in low-voltage distribution grids," *International Journal of Electrical Power & Energy Systems,* vol. 115, p. 105445, 2020/02/01/ 2020, doi: https://doi.org/10.1016/j.ijepes.2019.105445.

[13] S. Fatima, V. Püvi, and M. Lehtonen, "Review on the PV hosting capacity in distribution networks," *Energies,* vol. 13, no. 18, p. 4756, 2020.

[14] S. M. Ismael, S. H. E. Abdel Aleem, A. Y. Abdelaziz, and A. F. Zobaa, "State-of-the-art of hosting capacity in modern power systems with distributed generation," *Renewable Energy,* vol. 130, pp. 1002-1020, 2019/01/01/ 2019, doi: https://doi.org/10.1016/j.renene.2018.07.008.

[15] M. Alturki and A. Khodaei, "Marginal hosting capacity calculation for electric vehicle integration in active distribution networks," in *2018 IEEE/PES Transmission and Distribution Conference and Exposition (T&D),* 2018: IEEE, pp. 1-9.

[16] M. Sandström, C. Bales, and E. Dotzauer, "Hosting Capacity of the Power Grid for Electric Vehicles-A Case Study on a Swedish Low Voltage Grid," in *IOP Conference Series: Earth and Environmental Science*, 2022, vol. 1050, no. 1: IOP Publishing, p. 012008.

[17] R. Fachrizal, U. H. Ramadhani, J. Munkhammar, and J. Widén, "Combined PV–EV hosting capacity assessment for a residential LV distribution grid with smart EV charging and PV curtailment," *Sustainable Energy, Grids and Networks,* vol. 26, p. 100445, 2021.

[18] A. Palomino and M. Parvania, "Data-driven risk analysis of joint electric vehicle and solar operation in distribution networks," *IEEE Open Access Journal of Power and Energy,* vol. 7, pp. 141-150, 2020.

[19] A. Palomino and M. Parvania, "Probabilistic impact analysis of residential electric vehicle charging on distribution transformers," in *2018 North American Power Symposium (NAPS)*, 2018: IEEE, pp. 1-6.

[20] R.-C. Leou, C.-L. Su, and C.-N. Lu, "Stochastic analyses of electric vehicle charging impacts on distribution network," *IEEE Transactions on Power Systems,* vol. 29, no. 3, pp. 1055-1063, 2013.

[21] S. F. Tie and C. W. Tan, "A review of energy sources and energy management system in electric vehicles," *Renewable and sustainable energy reviews,* vol. 20, pp. 82-102, 2013.

[22] H. S. Das, M. M. Rahman, S. Li, and C. W. Tan, "Electric vehicles standards, charging infrastructure, and impact on grid integration: A technological review," *Renewable and Sustainable Energy Reviews,* vol. 120, p. 109618, 2020/03/01/ 2020, doi: https://doi.org/10.1016/j.rser.2019.109618.

[23] Z. Li, A. Khajepour, and J. Song, "A comprehensive review of the key technologies for pure electric vehicles," *Energy,* vol. 182, pp. 824-839, 2019/09/01/ 2019, doi: https://doi.org/10.1016/j.energy.2019.06.077.

[24] J. A. Sanguesa, V. Torres-Sanz, P. Garrido, F. J. Martinez, and J. M. Marquez-Barja, "A review on electric vehicles: Technologies and challenges," *Smart Cities,* vol. 4, no. 1, pp. 372-404, 2021.

[25] C. C. Chan, "The state of the art of electric, hybrid, and fuel cell vehicles," *Proceedings of the IEEE,* vol. 95, no. 4, pp. 704-718, 2007.

[26] A. Albatayneh, M. N. Assaf, D. Alterman, and M. Jaradat, "Comparison of the overall energy efficiency for internal combustion engine vehicles and electric vehicles," *Rigas Tehniskas Universitates Zinatniskie Raksti,* vol. 24, no. 1, pp. 669-680, 2020.

[27] OECD., *Non-exhaust Particulate Emissions from Road Transport An Ignored Environmental Policy Challenge*. OECD Publishing, 2020.

[28] C. Yang, M. Zha, W. Wang, K. Liu, and C. Xiang, "Efficient energy management strategy for hybrid electric vehicles/plug-in hybrid electric vehicles: review and recent advances under intelligent transportation system," *IET Intelligent Transport Systems,* vol. 14, no. 7, pp. 702-711, 2020.

[29] X. Sun, Z. Li, X. Wang, and C. Li, "Technology development of electric vehicles: A review," *Energies,* vol. 13, no. 1, p. 90, 2019.

[30] S. S. Acharige, M. E. Haque, M. T. Arif, and N. Hosseinzadeh, "Review of Electric Vehicle Charging Technologies, Configurations, and Architectures," *arXiv preprint arXiv:2209.15242*, 2022.

[31] C. Dharmakeerthi, N. Mithulananthan, and T. K. Saha, "Overview of the impacts of plug-in electric vehicles on the power grid," in *2011 IEEE PES Innovative Smart Grid Technologies*, 2011: IEEE, pp. 1-8.

[32] R. C. Green II, L. Wang, and M. Alam, "The impact of plug-in hybrid electric vehicles on distribution networks: A review and outlook," *Renewable and sustainable energy reviews*, vol. 15, no. 1, pp. 544-553, 2011.

[33] J. Y. Yong, V. K. Ramachandaramurthy, K. M. Tan, and N. Mithulananthan, "A review on the state-of-the-art technologies of electric vehicle, its impacts and prospects," *Renewable and Sustainable Energy Reviews*, vol. 49, pp. 365-385, 2015/09/01/ 2015, doi: https://doi.org/10.1016/j.rser.2015.04.130.

[34] H. Wang, Q. Song, L. Zhang, F. Wen, and J. Huang, "Load characteristics of electric vehicles in charging and discharging states and impacts on distribution systems," 2012.

[35] H.-l. Li, X.-m. Bai, and W. Tan, "Impacts of plug-in hybrid electric vehicles charging on distribution grid and smart charging," in *2012 IEEE International Conference on Power System Technology (POWERCON)*, 2012: IEEE, pp. 1-5.

[36] Á. Borrell, M. Velasco, M. Castilla, J. Miret, and R. Guzmán, "Collaborative Voltage Unbalance Compensation in Islanded AC Microgrids With Grid-Forming Inverters," *IEEE Transactions on Power Electronics*, vol. 37, no. 9, pp. 10499-10513, 2022.

[37] M. F, x00F, ller, and J. Meyer, "Survey of voltage unbalance and unbalanced power in German public LV networks," in *2022 20th International Conference on Harmonics & Quality of Power (ICHQP)*, 29 May-1 June 2022 2022, pp. 1-6, doi: 10.1109/ICHQP53011.2022.9808568.

[38] P. Richardson, D. Flynn, and A. Keane, "Impact assessment of varying penetrations of electric vehicles on low voltage distribution systems," in *IEEE PES general meeting*, 2010: IEEE, pp. 1-6.

[39] R. Liu, L. Dow, and E. Liu, "A survey of PEV impacts on electric utilities," in *ISGT 2011*, 2011: IEEE, pp. 1-8.

[40] O. Gandhi, D. S. Kumar, C. D. Rodríguez-Gallegos, and D. Srinivasan, "Review of power system impacts at high PV penetration Part I: Factors limiting PV penetration," *Solar Energy*, vol. 210, pp. 181-201, 2020/11/01/ 2020, doi: https://doi.org/10.1016/j.solener.2020.06.097.

[41] I. S. Association, "519-2014-IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems," *New York, IEEE*, 2014.

[42] N. Garwa and K. R. Niazi, "Impact of EV on integration with grid system–a review," in *2019 8th international conference on power systems (ICPS)*, 2019: IEEE, pp. 1-6.

[43] V.-L. Nguyen, T. Tran-Quoc, and S. Bacha, "Harmonic distortion mitigation for electric vehicle fast charging systems," in *2013 IEEE Grenoble Conference*, 2013: IEEE, pp. 1-6.

[44] S. Deilami, A. S. Masoum, P. S. Moses, and M. A. Masoum, "Voltage profile and THD distortion of residential network with high penetration of Plug-in Electrical Vehicles," in *2010 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT Europe)*, 2010: IEEE, pp. 1-6.

[45] K. A. Alboaouh and S. Mohagheghi, "Impact of Rooftop Photovoltaics on the Distribution System," *Journal of Renewable Energy*, vol. 2020, p. 4831434, 2020/01/04 2020, doi: 10.1155/2020/4831434.

[46] J. R. Pillai and B. Bak-Jensen, "Impacts of electric vehicle loads on power distribution systems," in *2010 IEEE Vehicle Power and Propulsion Conference*, 2010: IEEE, pp. 1-6.

[47] K. Clement-Nyns, E. Haesen, and J. Driesen, "The impact of charging plug-in hybrid electric vehicles on a residential distribution grid," *IEEE Transactions on power systems,* vol. 25, no. 1, pp. 371-380, 2009.

[48] Q. Yan and M. Kezunovic, "Impact analysis of electric vehicle charging on distribution system," in *2012 North American Power Symposium (NAPS)*, 2012: IEEE, pp. 1-6.

[49] E. Akhavan-Rezai, M. Shaaban, E. El-Saadany, and A. Zidan, "Uncoordinated charging impacts of electric vehicles on electric distribution grids: Normal and fast charging comparison," in *2012 IEEE power and energy society general meeting*, 2012: IEEE, pp. 1-7.

[50] N. Hatziargyriou, E. Karfopoulos, A. Tsitsimelis, D. Koukoula, M. Rossi, and V. Giacomo, "On the der hosting capacity of distribution feeders," in *Proc. CIRED 23rd International Conference on Electricity Distribution*, 2015.

[51] J. Deuse, D. Benintendi, P. Agrell, and P. Bogetoft, "Power system and market integration of der, the eu-deep approach," in *CIRED 2005-18th International Conference and Exhibition on Electricity Distribution*, 2005: IET, pp. 1-4.

[52] M. Bollen, Y. Yang, and F. Hassan, "Integration of distributed generation in the power system-a power quality approach," in *2008 13th International Conference on Harmonics and Quality of Power*, 2008: IEEE, pp. 1-8.

[53] M. H. Bollen and F. Hassan, *Integration of distributed generation in the power system*. John wiley & sons, 2011.

[54] S. Cundeva, A. K. Mateska, and M. H. Bollen, "Hosting capacity of LV residential grid for uncoordinated EV charging," in *2018 18th International Conference on Harmonics and Quality of Power (ICHQP)*, 2018: IEEE, pp. 1-5.

[55] A. Rodriguez-Calvo, R. Cossent, and P. Frías, "Integration of PV and EVs in unbalanced residential LV networks and implications for the smart grid and advanced metering infrastructure deployment," *International Journal of Electrical Power & Energy Systems,* vol. 91, pp. 121-134, 2017.

[56] A. E. Avila-Rojas, D. Oliveira-De Jesus, and M. Alvarez, "Distribution network electric vehicle hosting capacity enhancement using an optimal power flow formulation," *Electrical Engineering,* vol. 104, no. 3, pp. 1337-1348, 2022.

[57] S. Fatima, V. Püvi, and M. Lehtonen, "Comparison of Different References When Assessing PV HC in Distribution Networks," *Clean Technologies,* vol. 3, no. 1, pp. 123-137, 2021.

[58] A. Y. Saber, T. Khandelwal, and A. K. Srivastava, "Fast feeder PV hosting capacity using swarm based intelligent distribution node selection," in *2019 IEEE Power & Energy Society General Meeting (PESGM),* 2019: IEEE, pp. 1-5.

[59] S. Kikuchi *et al.*, "Hosting capacity analysis of many distributed photovoltaic systems in future distribution networks," in *2017 IEEE Innovative Smart Grid Technologies-Asia (ISGT-Asia),* 2017: IEEE, pp. 1-5.

[60] P. Mohammadi and S. Mehraeen, "Challenges of PV Integration in Low-Voltage Secondary Networks," *IEEE Transactions on Power Delivery,* vol. 32, no. 1, pp. 525-535, 2017, doi: 10.1109/TPWRD.2016.2556692.

[61] H. V. Haghi *et al.*, "Feeder impact assessment of smart inverter settings to support high PV penetration in California," in *2019 IEEE Power & Energy Society General Meeting (PESGM),* 2019: IEEE, pp. 1-5.

[62] H. V. Padullaparti, S. Jothibasu, S. Santoso, and G. Todeschini, "Increasing feeder PV hosting capacity by regulating secondary circuit voltages," in *2018 IEEE Power & Energy Society General Meeting (PESGM),* 2018: IEEE, pp. 1-5.

[63] I. A. Essackjee and R. T. A. King, "Maximum Rooftop Photovoltaic Hosting Capacity with Harmonics as Limiting Factor–Case Study for Mauritius," in *2019 International Conference on Advances in Big Data, Computing and Data Communication Systems (icABCD)*, 2019: IEEE, pp. 1-6.

[64] A. F. Steyn and A. J. Rix, "Modelling the technical influence of randomly distributed solar PV uptake on electrical distribution networks," in *2019 International Conference on Clean Electrical Power (ICCEP)*, 2019: IEEE, pp. 690-698.

[65] F. Ding and B. Mather, "On distributed PV hosting capacity estimation, sensitivity study, and improvement," *IEEE Transactions on Sustainable Energy*, vol. 8, no. 3, pp. 1010-1020, 2016.

[66] M. Asano *et al.*, "On the interplay between svcs and smart inverters for managing voltage on distribution networks," in *2019 IEEE Power & Energy Society General Meeting (PESGM)*, 2019: IEEE, pp. 1-5.

[67] H. Yao *et al.*, "Possibilistic evaluation of photovoltaic hosting capacity on distribution networks under uncertain environment," *Applied Energy*, vol. 324, p. 119681, 2022/10/15/ 2022, doi: https://doi.org/10.1016/j.apenergy.2022.119681.

[68] C. Gaunt, E. Namanya, and R. Herman, "Voltage modelling of LV feeders with dispersed generation: Limits of penetration of randomly connected photovoltaic generation," *Electric Power Systems Research*, vol. 143, pp. 1-6, 2017.

[69] D. P. Guevara, C. A. Correa-Florez, and G. Ordóñez-Plata, "Assessment of harmonic distortion associated with pv penetration in a low voltage distribution network," in *2020 IEEE PES Transmission & Distribution Conference and Exhibition-Latin America (T&D LA)*, 2020: IEEE, pp. 1-6.

[70] W. Martin, Y. Stauffer, C. Ballif, A. Hutter, and P.-J. Alet, "Automated quantification of PV hosting capacity in distribution networks under user-defined control and optimisation procedures," in *2018 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, 2018: IEEE, pp. 1-6.

[71] R. Torquato, D. Salles, C. O. Pereira, P. C. M. Meira, and W. Freitas, "A comprehensive assessment of PV hosting capacity on low-voltage distribution systems," *IEEE Transactions on Power Delivery*, vol. 33, no. 2, pp. 1002-1012, 2018.

[72] S. Pukhrem, M. Basu, M. F. Conlon, and K. Sunderland, "Enhanced network voltage management techniques under the proliferation of rooftop solar PV installation in low-voltage distribution network," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 5, no. 2, pp. 681-694, 2016.

[73] N. K. Singh, M. Wanik, A. A. Jabbar, and A. Sanfilippo, "Enhancing PV hosting Capacity of a Qatar Remote Farm Network using Inverters Ability to Regulate Reactive Power-a Case Study," in *2019 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe)*, 2019: IEEE, pp. 1-5.

[74] M. M. Rahman, G. Shafiullah, A. Arefi, H. Pezeshki, and S. Hettiwatte, "Improvement of voltage magnitude and unbalance in LV network by implementing residential demand response," in *2017 IEEE Power & Energy Society General Meeting*, 2017: IEEE, pp. 1-5.

[75] A. Arshad, V. Püvi, and M. Lehtonen, "Monte Carlo-based comprehensive assessment of PV hosting capacity and energy storage impact in realistic finnish low-voltage networks," *Energies*, vol. 11, no. 6, p. 1467, 2018.

[76] M. M. Rahman, A. Arefi, G. Shafiullah, and S. Hettiwatte, "A new approach to voltage management in unbalanced low voltage networks using demand response

and OLTC considering consumer preference," *International journal of electrical power & energy systems,* vol. 99, pp. 11-27, 2018.

[77] D. Chathurangi, U. Jayatunga, M. Rathnayake, A. Wickramasinghe, A. Agalgaonkar, and S. Perera, "Potential power quality impacts on LV distribution networks with high penetration levels of solar PV," in *2018 18th International Conference on Harmonics and Quality of Power (ICHQP)*, 2018: IEEE, pp. 1-6.

[78] D. Chathurangi, U. Jayatunga, S. Perera, A. Agalgaonkar, T. Siyambalapitiya, and A. Wickramasinghe, "Connection of Solar PV to LV Networks: Considerations for Maximum Penetration Level," in *2018 Australasian Universities Power Engineering Conference (AUPEC)*, 27-30 Nov. 2018 2018, pp. 1-6, doi: 10.1109/AUPEC.2018.8757962.

[79] D. A. Sarmiento, P. P. Vergara, L. C. Da Silva, and M. C. De Almeida, "Increasing the PV hosting capacity with OLTC technology and PV VAr absorption in a MV/LV rural Brazilian distribution system," in *2016 17th International Conference on Harmonics and Quality of Power (ICHQP)*, 2016: IEEE, pp. 395-399.

[80] T. Aziz and N. Ketjoy, "PV penetration limits in low voltage networks and voltage variations," *IEEE Access,* vol. 5, pp. 16784-16792, 2017.

[81] A. T. Procopiou and L. F. Ochoa, "Voltage control in PV-rich LV networks without remote monitoring," *IEEE Transactions on Power Systems,* vol. 32, no. 2, pp. 1224-1236, 2016.

[82] C. Long and L. F. Ochoa, "Voltage control of PV-rich LV networks: OLTC-fitted transformer and capacitor banks," *IEEE Transactions on Power Systems,* vol. 31, no. 5, pp. 4016-4025, 2015.

[83] M. J. Weisshaupt, B. Schlatter, P. Korba, E. Kaffe, and F. Kienzle, "Evaluation of measures to operate urban low voltage grids considering future PV expansion," *IFAC-PapersOnLine,* vol. 49, no. 27, pp. 336-341, 2016.

[84] P. H. Divshali and L. Söder, "Improving hosting capacity of rooftop PVs by quadratic control of an LV-central BSS," *IEEE Transactions on Smart Grid,* vol. 10, no. 1, pp. 919-927, 2017.

[85] P. H. Divshali and L. Söder, "Improving PV hosting capacity of distribution grids considering dynamic voltage characteristic," in *2018 Power Systems Computation Conference (PSCC)*, 2018: IEEE, pp. 1-7.

[86] M. Zain ul Abideen, O. Ellabban, and L. Al-Fagih, "A review of the tools and methods for distribution networks' hosting capacity calculation," *Energies,* vol. 13, no. 11, p. 2758, 2020.

[87] V. Quintero-Molina, M. Romero-L, and A. Pavas, "Assessment of the hosting capacity in distribution networks with different DG location," in *2017 IEEE Manchester PowerTech*, 2017: IEEE, pp. 1-6.

[88] B. B. Navarro and M. M. Navarro, "A comprehensive solar PV hosting capacity in MV and LV radial distribution networks," in *2017 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, 2017: IEEE, pp. 1-6.

[89] E. Hartvigsson, M. Odenberger, P. Chen, and E. Nyholm, "Estimating national and local low-voltage grid capacity for residential solar photovoltaic in Sweden, UK and Germany," *Renewable Energy,* vol. 171, pp. 915-926, 2021/06/01/ 2021, doi: https://doi.org/10.1016/j.renene.2021.02.073.

[90] M. D. Braga, S. D. Machado, I. Oliveira, T. E. de Oliveira, P. F. Ribeiro, and B. I. L. Lopes, "Harmonic hosting capacity approach in a radial distribution system due to pv integration using opendss," in *2018 13th IEEE International Conference on Industry Applications (INDUSCON)*, 2018: IEEE, pp. 222-228.

[91] N. Soukaina, E. Hassane, and L. Tijani, "Hosting capacity estimation of underground distribution feeder in Urbain Areas," in *2019 International Conference on Wireless Technologies, Embedded and Intelligent Systems (WITS)*, 2019: IEEE, pp. 1-5.

[92] L. M. Putranto, "Study on Photovoltaic Hosting in Yogyakarta Electric Distribution Network," in *2018 5th International Conference on Information Technology, Computer, and Electrical Engineering (ICITACEE)*, 2018: IEEE, pp. 240-244.

[93] A. Kharrazi, V. Sreeram, and Y. Mishra, "Assessment techniques of the impact of grid-tied rooftop photovoltaic generation on the power quality of low voltage distribution network - A review," *Renewable and Sustainable Energy Reviews*, vol. 120, p. 109643, 2020/03/01/ 2020, doi: https://doi.org/10.1016/j.rser.2019.109643.

[94] F. Ebe, B. Idlbi, J. Morris, G. Heilscher, and F. Meier, "Evaluation of PV hosting capacity of distribuion grids considering a solar roof potential analysis—Comparison of different algorithms," in *2017 IEEE Manchester PowerTech*, 2017: IEEE, pp. 1-6.

[95] J. Deboever, S. Grijalva, M. J. Reno, and R. J. Broderick, "Fast quasi-static time-series (QSTS) for yearlong PV impact studies using vector quantization," *Solar Energy*, vol. 159, pp. 538-547, 2018.

[96] M. S. S. Abad, J. Ma, D. Zhang, A. S. Ahmadyar, and H. Marzooghi, "Sensitivity of hosting capacity to data resolution and uncertainty modeling," in *2018 Australasian Universities Power Engineering Conference (AUPEC)*, 2018: IEEE, pp. 1-6.

[97] T. E. Castelo de Oliveira, M. Bollen, P. F. Ribeiro, P. M. de Carvalho, A. C. Zambroni, and B. D. Bonatto, "The concept of dynamic hosting capacity for distributed energy resources: Analytics and practical considerations," *Energies*, vol. 12, no. 13, p. 2576, 2019.

[98] M. Rossi, G. Viganò, D. Moneta, and D. Clerici, "Stochastic evaluation of distribution network hosting capacity: Evaluation of the benefits introduced by smart grid technology," in *2017 AEIT International Annual Conference*, 2017: IEEE, pp. 1-6.

[99] R. H. Zubo, G. Mokryani, H.-S. Rajamani, J. Aghaei, T. Niknam, and P. Pillai, "Operation and planning of distribution networks with integration of renewable distributed generators considering uncertainties: A review," *Renewable and Sustainable Energy Reviews*, vol. 72, pp. 1177-1198, 2017.

[100] H. Sadeghian and Z. Wang, "A novel impact-assessment framework for distributed PV installations in low-voltage secondary networks," *Renewable Energy*, vol. 147, pp. 2179-2194, 2020.

[101] A. Koirala, T. Van Acker, R. D’hulst, and D. Van Hertem, "Uncertainty quantification in low voltage distribution grids: Comparing Monte Carlo and general polynomial chaos approaches," *Sustainable Energy, Grids and Networks*, p. 100763, 2022.

[102] S. Lakshmi and S. Ganguly, "Simultaneous optimisation of photovoltaic hosting capacity and energy loss of radial distribution networks with open unified power quality conditioner allocation," *IET Renewable Power Generation*, vol. 12, no. 12, pp. 1382-1389, 2018.

[103] E. R. Mmary and B. Marungsri, "Optimal Hybrid Renewable Generator for Techno-Economic Benefits in Smart Distribution Network," in *2018 International Electrical Engineering Congress (iEECON)*, 2018: IEEE, pp. 1-4.

[104] X. Chen, W. Wu, B. Zhang, and C. Lin, "Data-driven DG capacity assessment method for active distribution networks," *IEEE Transactions on Power Systems,* vol. 32, no. 5, pp. 3946-3957, 2016.

[105] X. Chen, W. Wu, and B. Zhang, "Robust capacity assessment of distributed generation in unbalanced distribution networks incorporating ANM techniques," *IEEE Transactions on Sustainable Energy,* vol. 9, no. 2, pp. 651-663, 2017.

[106] S. Sakar, M. E. Balci, S. H. A. Aleem, and A. F. Zobaa, "Increasing PV hosting capacity in distorted distribution systems using passive harmonic filtering," *Electric Power Systems Research,* vol. 148, pp. 74-86, 2017.

[107] M. Vatani, D. Solati Alkaran, M. J. Sanjari, and G. B. Gharehpetian, "Multiple distributed generation units allocation in distribution network for loss reduction based on a combination of analytical and genetic algorithm methods," *IET Generation, Transmission & Distribution,* vol. 10, no. 1, pp. 66-72, 2016.

[108] Z. Wang, X. Wang, and L. Tang, "Practical power distance test tool based on OPF to Assess Feeder DG Hosting Capacity," in *2017 IEEE Electrical Power and Energy Conference (EPEC)*, 2017: IEEE, pp. 1-6.

[109] X. Xu, J. Gunda, R. Dowling, and S. Djokic, "A Two-stage Approach for Renewable Hosting Capacity Assessment," in *2019 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe)*, 2019: IEEE, pp. 1-5.

[110] C. Guo, K. Zhu, C. Chen, and X. Xiao, "Characteristics and effect laws of the large-scale electric Vehicle’s charging load," *ETransportation,* vol. 3, p. 100049, 2020.

[111] M. R. Khalid, M. S. Alam, A. Sarwar, and M. J. Asghar, "A Comprehensive review on electric vehicles charging infrastructures and their impacts on power-quality of the utility grid," *ETransportation,* vol. 1, p. 100006, 2019.

[112] R. C. Leou *et al.*, "Stochastic analysis of electric transportation charging impacts on power quality of distribution systems," *IET Generation, Transmission & Distribution,* vol. 12, no. 11, pp. 2725-2734, 2018.

[113] Y. Zou, J. Zhao, X. Gao, Y. Chen, and A. Tohidi, "Experimental results of electric vehicles effects on low voltage grids," *Journal of Cleaner Production,* vol. 255, p. 120270, 2020.

[114] A. K. Fadi and F. Bruno, "Holistic approach for prioritizing emergency EV charging in an existing distribution network," 2022.

[115] L. E. S. e Silva and J. P. A. Vieira, "Combined PV-PEV Hosting Capacity Analysis in Low-Voltage Distribution Networks," *Electric Power Systems Research,* vol. 206, p. 107829, 2022/05/01/ 2022, doi: https://doi.org/10.1016/j.epsr.2022.107829.

[116] C. D. Zuluaga-Ríos, A. Villa-Jaramillo, and S. D. Saldarriaga-Zuluaga, "Evaluation of Distributed Generation and Electric Vehicles Hosting Capacity in Islanded DC Grids Considering EV Uncertainty," *Energies,* vol. 15, no. 20, p. 7646, 2022.

[117] N. Nakhodchi, H. Bakhtiari, M. H. Bollen, and S. K. Rönnberg, "Including uncertainties in harmonic hosting capacity calculation of a fast EV charging station," *Available at SSRN 4150376,* 2022.

[118] J. Zhu, W. J. Nacmanson, L. F. Ochoa, and B. Hellyer, "Assessing the EV Hosting Capacity of Australian Urban and Rural MV-LV Networks," *Electric Power Systems Research,* vol. 212, p. 108399, 2022.

[119] J. Zhao, J. Wang, Z. Xu, C. Wang, C. Wan, and C. Chen, "Distribution network electric vehicle hosting capacity maximization: A chargeable region optimization model," *IEEE Transactions on Power Systems,* vol. 32, no. 5, pp. 4119-4130, 2017.

[120] M. Kamruzzaman, N. Bhusal, and M. Benidris, "Determining maximum hosting capacity of electric distribution systems to electric vehicles," in *2019 IEEE Industry Applications Society Annual Meeting,* 2019: IEEE, pp. 1-7.

[121] P. Paudyal, S. Ghosh, S. Veda, D. Tiwari, and J. Desai, "EV hosting capacity analysis on distribution grids," in *2021 IEEE Power & Energy Society General Meeting (PESGM)*, 2021: IEEE, pp. 1-5.

[122] B. Zeng, Z. Zhu, X. Zhu, L. Qin, J. Liu, and M. Zhang, "Estimation of Distribution System Capability for Accommodating Electric Vehicles," *Journal of Electrical Systems*, vol. 16, no. 2, 2020.

[123] T. Barbosa, J. Andrade, R. Torquato, W. Freitas, and F. C. Trindade, "Use of EV hosting capacity for management of low-voltage distribution systems," *IET Generation, Transmission & Distribution*, vol. 14, no. 13, pp. 2620-2629, 2020.

[124] L. F. Henrique, L. A. Bitencourt, B. S. M. C. Borba, and B. H. Dias, "Impacts of EV residential charging and charging stations on quasi-static time-series PV hosting capacity," *Electrical Engineering*, vol. 104, no. 4, pp. 2717-2728, 2022/08/01 2022, doi: 10.1007/s00202-022-01513-8.

[125] *NRS 097-2-3: Grid Interconnection of Embedded Generation* 2014.

[126] S. Habib, M. Kamran, and U. Rashid, "Impact analysis of vehicle-to-grid technology and charging strategies of electric vehicles on distribution networks – A review," *Journal of Power Sources*, vol. 277, pp. 205-214, 2015/03/01/ 2015, doi: https://doi.org/10.1016/j.jpowsour.2014.12.020.

[127] J. García-Villalobos, I. Zamora, J. I. San Martín, F. J. Asensio, and V. Aperribay, "Plug-in electric vehicles in electric distribution networks: A review of smart charging approaches," *Renewable and Sustainable Energy Reviews*, vol. 38, pp. 717-731, 2014/10/01/ 2014, doi: https://doi.org/10.1016/j.rser.2014.07.040.

[128] S. S. G. Acharige, M. E. Haque, M. T. Arif, N. Hosseinzadeh, K. N. Hasan, and A. M. T. Oo, "Review of Electric Vehicle Charging Technologies, Standards, Architectures, and Converter Configurations," *IEEE Access*, vol. 11, pp. 41218-41255, 2023, doi: 10.1109/ACCESS.2023.3267164.

[129] J. D. Glover, M. S. Sarma, and T. J. Overbye, "Power System," *Analysis and Design, Stamford: Cengage Learning*, 2012.

[130] L. L. Grigsby, "Power Systems (The Electric Power Engineering Handbook)," ed: CRC Press, Boca Raton, 2007.

[131] T. T. Mziwamadoda, "Impact assessment of high penetration of rooftop PV in municipal electrical networks," MEng., Electrical Engineering, Cape Penisula University of Technology, 2019.

[132] Digsilent. "Power System Solutions." https://www.digsilent.de/en/ (accessed 08 April, 2022).

[133] S. Maharjan, D. Sampath Kumar, and A. M. Khambadkone, "Enhancing the voltage stability of distribution network during PV ramping conditions with variable speed drive loads," *Applied Energy*, vol. 264, p. 114733, 2020/04/15/ 2020, doi: https://doi.org/10.1016/j.apenergy.2020.114733.

[134] M. Hasheminamin, V. G. Agelidis, and A. Heidari, "Impact study of high PV penetration in low and medium-voltage networks when considering residential and industrial load profile," in *2013 International Conference on Renewable Energy Research and Applications (ICRERA)*, 2013: IEEE, pp. 347-352.

[135] F. Diop and M. Hennebel, "Probabilistic load flow methods to estimate impacts of distributed generators on a LV unbalanced distribution grid," in *2017 IEEE Manchester PowerTech*, 2017: IEEE, pp. 1-6.

[136] J. Dixon and K. Bell, "Electric vehicles: Battery capacity, charger power, access to charging and the impacts on distribution networks," *ETransportation*, vol. 4, p. 100059, 2020.

[137] V. Umoh, A. Adebiyi, and K. Moloi, "Hosting Capacity Assessment of South African Residential Low-Voltage Networks for Electric Vehicle Charging," *Eng*, vol. 4, no. 3, pp. 1965-1980, 2023.

APPENDICES

Apendix A: Test Network Model in DigSILENT PowerFactory

DiGSILENT PowerFactory (DPF) was used to model the test network and the carry out simulations. The simulations was conducted on the LV feeder and the single line diagram of the modeled in (DPF) is shown in Figure A.1. The diagram shows the components of the feeder such as busbar, cables, loads, etc, and their interconnections. Each customer is represented by a load and EV load is also added.

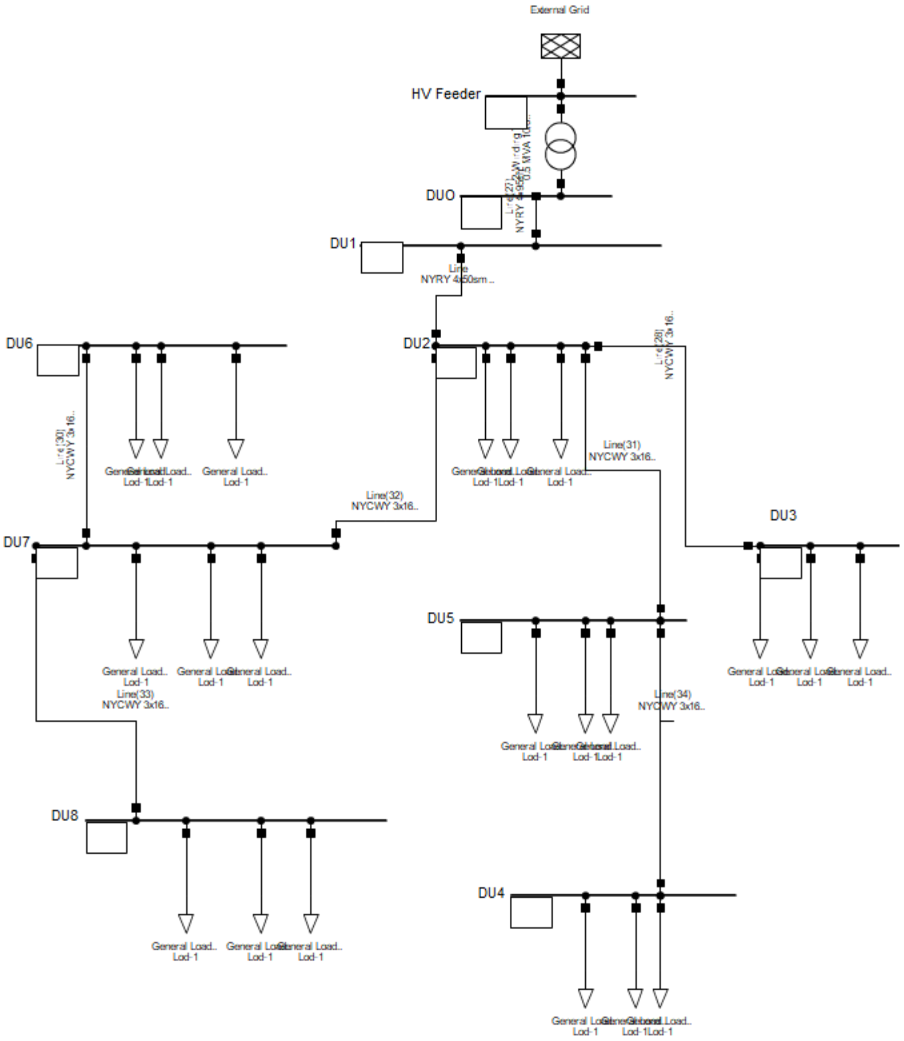
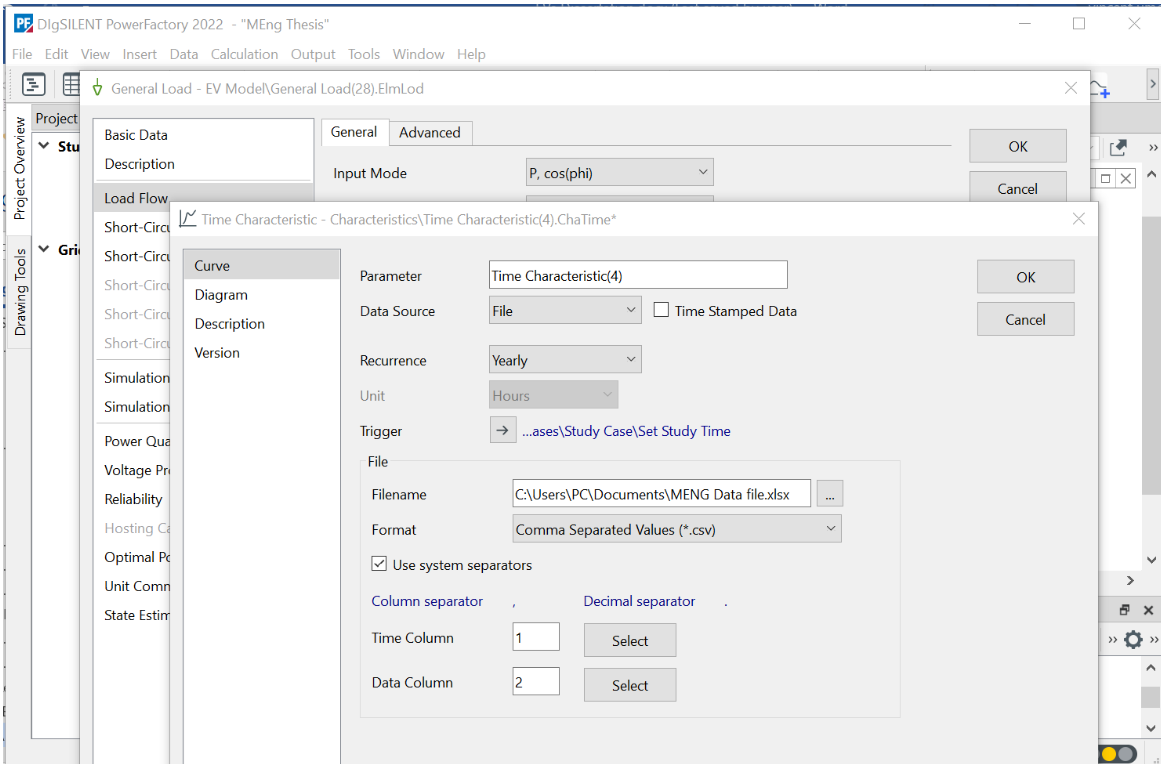


Figure A.1: Detailed model of the test network



General Load - EV Model\General Load(28).ElmLod

Input Mode: P, cos(phi)

Time Characteristic - Characteristics\Time Characteristic(4).ChaTime*

Parameter: Time Characteristic(4)

Data Source: File ☐ Time Stamped Data

Recurrence: Yearly

Unit: Hours

Trigger: → ...ases\Study Case\Set Study Time

File

Filename: C:\Users\PC\Documents\MENG Data file.xlsx

Format: Comma Separated Values (*.csv)

☑ Use system separators

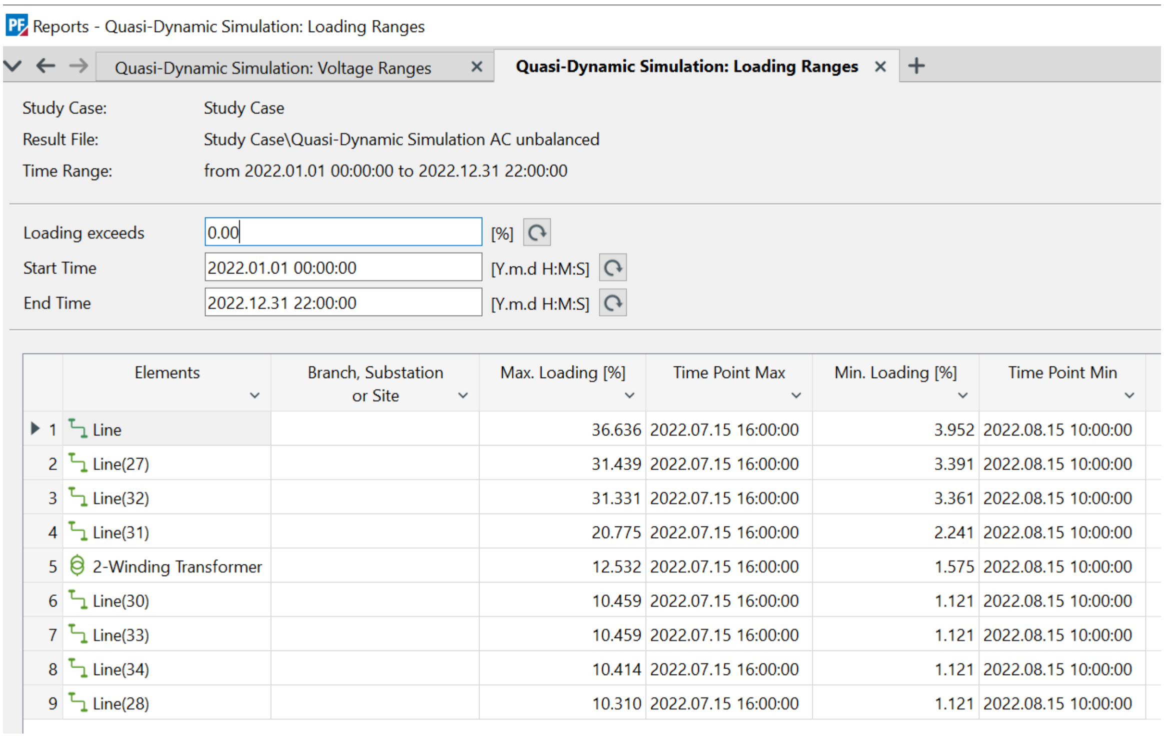
Column separator ,

Decimal separator .

Time Column: 1

Data Column: 2

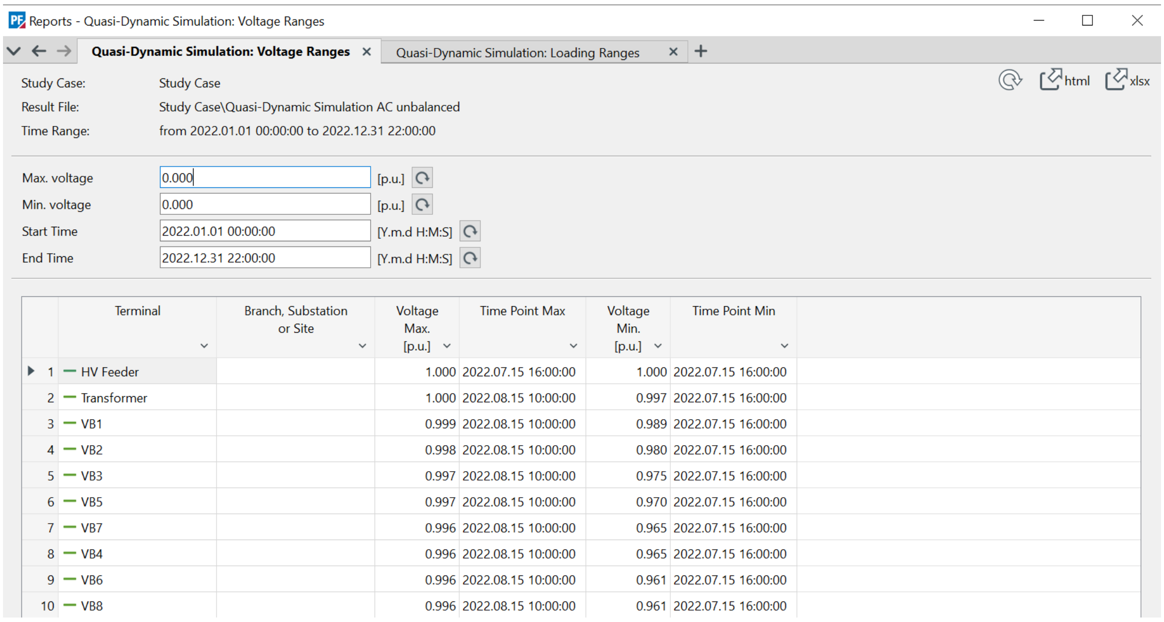
Figure A.2: Load input from Excel



Study Case: Study Case
Result File: Study Case\Quasi-Dynamic Simulation AC unbalanced
Time Range: from 2022.01.01 00:00:00 to 2022.12.31 22:00:00

Loading exceeds 0.00 [%]
Start Time 2022.01.01 00:00:00 [Y.m.d H:M:S]
End Time 2022.12.31 22:00:00 [Y.m.d H:M:S]

	Elements	Branch, Substation or Site	Max. Loading [%]	Time Point Max	Min. Loading [%]	Time Point Min
1	Line		36.636	2022.07.15 16:00:00	3.952	2022.08.15 10:00:00
2	Line(27)		31.439	2022.07.15 16:00:00	3.391	2022.08.15 10:00:00
3	Line(32)		31.331	2022.07.15 16:00:00	3.361	2022.08.15 10:00:00
4	Line(31)		20.775	2022.07.15 16:00:00	2.241	2022.08.15 10:00:00
5	2-Winding Transformer		12.532	2022.07.15 16:00:00	1.575	2022.08.15 10:00:00
6	Line(30)		10.459	2022.07.15 16:00:00	1.121	2022.08.15 10:00:00
7	Line(33)		10.459	2022.07.15 16:00:00	1.121	2022.08.15 10:00:00
8	Line(34)		10.414	2022.07.15 16:00:00	1.121	2022.08.15 10:00:00
9	Line(28)		10.310	2022.07.15 16:00:00	1.121	2022.08.15 10:00:00



Study Case: Study Case
Result File: Study Case\Quasi-Dynamic Simulation AC unbalanced
Time Range: from 2022.01.01 00:00:00 to 2022.12.31 22:00:00

Max. voltage 0.000 [p.u.]
Min. voltage 0.000 [p.u.]
Start Time 2022.01.01 00:00:00 [Y.m.d H:M:S]
End Time 2022.12.31 22:00:00 [Y.m.d H:M:S]

	Terminal	Branch, Substation or Site	Voltage Max. [p.u.]	Time Point Max	Voltage Min. [p.u.]	Time Point Min
1	HV Feeder		1.000	2022.07.15 16:00:00	1.000	2022.07.15 16:00:00
2	Transformer		1.000	2022.08.15 10:00:00	0.997	2022.07.15 16:00:00
3	VB1		0.999	2022.08.15 10:00:00	0.989	2022.07.15 16:00:00
4	VB2		0.998	2022.08.15 10:00:00	0.980	2022.07.15 16:00:00
5	VB3		0.997	2022.08.15 10:00:00	0.975	2022.07.15 16:00:00
6	VB5		0.997	2022.08.15 10:00:00	0.970	2022.07.15 16:00:00
7	VB7		0.996	2022.08.15 10:00:00	0.965	2022.07.15 16:00:00
8	VB4		0.996	2022.08.15 10:00:00	0.965	2022.07.15 16:00:00
9	VB6		0.996	2022.08.15 10:00:00	0.961	2022.07.15 16:00:00
10	VB8		0.996	2022.08.15 10:00:00	0.961	2022.07.15 16:00:00

A.3 Downloading report and exporting result