Impact assessment of high penetration of rooftop PV in municipal electrical networks

by

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Declaration

I,***Mziwamadoda Timothy Tsholoba*** , declare that the contents of this thesis represent my own unaided work, and that the thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

Signed by candidate

Signed: ______________________

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Date: 23/03/2020

Dedication

...To my Father and my late Mother

Acknowledgement

Research can be exciting, fulfilling and even lonely journey at times. Thanks to the creator of the universe for bringing these people to my life and which made this journey to be more bearable. As a result, I would like to extend my greatest gratitude the following people and entities:

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Research Outputs

Publications

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Abstract

There is an increasing global trend of grid connected distributed generation, mainly based on renewable energy sources such as wind and photovoltaic (PV) systems. The proliferation of these intermittent energy sources into the existing networks may subject the network into technical challenges such as voltage rise, equipment overload, power quality and protection scheme violations. With increased PVDG (mainly rooftop PV) uptake occurring mostly on Low Voltage (LV) feeders, characterised by lack of network visibility and controllability, these technical challenges may be exacerbated. In the absence of government incentive, current uptake of rooftop PVDG is reliant on customer preference and financial means. Thus make PVDG integration on the network be randomly placed and sized, of which the network distribution operator (NDO) will have no control over. The lack of regulations and interconnection studies conducted on South African networks has resulted in a growing concern amongst utilities on how the increasing customer-owned rooftop PV systems uptake will impact the existing networks.

This study aims to investigate technical impact high penetration of rooftop PV system will have on the existing LV networks. The load flow (LF) computation is pivotal in determining power system state when subjected to high penetration of rooftop PV. Monte-Carlo based Probabilistic Load Flow (PLF) was proposed and input variables were modelled using Beta probabilistic distribution function (PDF). The proposed impact assessment framework was applied on real LV urban residential network situated in Cape Town, South Africa. Simulations were conducted on DIgSILENT PowerFactory and the PDF for input variables (Load demand and PV generation) were derived from historic data. Four scenarios were simulated and system performance parameters were recorded such as; voltage magnitude, voltage unbalance factor and equipment thermal loading.

Simulation results in the test network indicated thermal loading violation as the main limiting factor in urban residential network. PV system topology (either three-phase or single phase) proved to have significant effect on network hosting capacity, were higher PV penetration can be achieved for a three-phase system. Penetration level as low as 12% were recorded, which is significantly lower than the prescribed

guidelines in simplified criteria in NRS097-2-3 standard and therefore raises a concern on the relevance of this standard on all types of networks (in urban network in particular). However, penetration level above NRS097-2-3 limits may be achieved depending on feeder characteristics.

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Abbreviations

AC	Alternating Current
ACP	Active Power Curtailment
CCT	City of Cape Town
CDF	Cumulative Distribution Function
DC	Direct Current
DG	Distributed Generator
DGT	Distributed Generator Technology
DNO	Distribution Network Operator
DLF	Deterministic Load Flow
FL	Fault Level
GMM	Gaussian Mixture Model
GoF	Goodness of Fit
IEA	International Energy Agency
IRP	Integrated Resource Plan
$K-S$	Kolmogorov Smirnov
LV	Low Voltage
MCS	Monte Carlo Simulation
MV	Medium Voltage
NRS	National Rational Specification
PDF	Probability Distribution Function
PLF	Probabilistic Load Flow
PV	Photovoltaic
PVDG	Photovoltaic Distributed Generator
QOS	Quality of Supply
$r.v$	Random Variable
SCADA	Supervisory control and data acquisition
SCR	Short circuit ratio
SSEG	Small-Scale Energy Generation
STC	Standard test condition
V	Volts
WWF	World Wildlife Foundation

Nomenclature

α	Alpha, shape parameter of Beta distribution	
β	Beta, shape parameter of Beta distribution	
P	Real power	[W]
P_L	Load power	[W]
P_G	Active power generated by PV	[W]
Q	Reactive power	[VAr]
S	Apparent power	[VA]
S_k	short circuit ratio	[VA]
I_{sc}	short circuit current	[A]
σ	Standard deviation	
μ	Mean value	
χ^2	Chi-Squared	

Chapter 1

Introduction

1.1 Research Background

The current global electricity requirements are mostly supplied by depleting and environmental unfriendly fossil fuel based energy resources. In addition, the global electricity demand is increasing and countries are now looking for alternative electricity generation sources that will also reduce the global carbon emissions. Recently, renewable resources, which are abundance and clean have been preferred alternative to conventional fossil fuel for electrical energy generation. As a result, there has been an increasing growth in renewable energy markets. In 2018, non-renewable sources accounted for about 73.8% of electricity production and the remaining 26.2% contributed by renewable sources[1].

South Africa, like many other countries, has set its own renewable energy targets formulated in the Integrated Resource Plan (IRP) for electricity 2010, which laid out the proposed electricity generation fleet for South Africa for the period 2010 to 2030 [2, 3]. The IRP 2010 estimated that electricity demand by 2030 would require an increase in additional generation capacity to 52GW, of which, 17.8GW would be from renewable sources. As seen on the current trends, large scale renewable installations are expected to have majority contribution on this target. However, the IRP 2010 also estimated a significant increase in small-scale embedded generation (SSEG) for residential and commercial applications, with a forecast of 30GW of rooftop PV by 2050 [2].

SSEGs in the form of rooftop photovoltaic (PV) systems are increasing rapidly in many countries arounnd the world, including South Africa. The reason for this can be mainly attributed to above inflation rate increasing electricity tariffs, abundant sunshine, load shedding experience in 2008 and 2015 as well as the decreasing price of PV technologies[4]. These factors, and many others, have led to customer being involved in the electricity market as both a producer and consumer (also known as pro-sumer) of electricity. Although the South African power utility, Eskom, does not allow integration of rooftop PV into their grid, number of municipalities (including City of Cape Town (CCT)) do allow integration of rooftop PV into their grids through a defined and documented application process[5]. As a result, the rooftop PV generation is expected to continue increasing in the municipal grids, and thus introducing different technical impacts on the existing municipal grids.

1.2 Problem statement

The application process for integrating rooftop PV into the municipal grids requires site layout, written approval by registered Engineer or Technologist, NRS 097-2-3 and SA renewable power plants grid code compliance [6]. This increased administrative burden result in customers installing their rooftop PV without the knowledge of the distributors and reducing the ability of the utility to regulate the impact these source of generation will have on the existing network.

In the past, network monitoring was restricted to MV network (particularly at main substations) to reduce the infrastructure investment costs and the lack of measuring infrastructure in the LV network has made it difficult for the distributor to monitor the impact of PV systems on existing LV network. In practice, the customer is only limited by the available roof space and personal financial constraints. However, the possibility of high penetration lies in the flexibility of the existing network to seamlessly accommodate these intermittent electricity generators, which is also referred to as network hosting capacity[7, 8]. Network hosting capacity is dependent on the placement, size and output power profile of a PV system [9], which utility has no control over for a customer owned PV system [10, 11]. Proliferation of uncontrolled high penetration of PV systems will subject the existing to challenges like Voltage rise, overloading, deter power quality and protection issues.

Most of the PV - Grid integrated research work conducted thus far, has focused mainly on the voltage rise impact existing grids will be subjected to as a result of high PV penetration[12, 13]. Similar trend is observed in studies conducted in South Africa[14, 15, 16], which may be suitable for long feeders such as rural networks. However, for urban networks characterised by electrically short radial feeders, thermal overload may have greater influence than voltage rise.

Considering that proliferation of rooftop PV is expected at LV level, consisting of predominantly single-phase loads, voltage unbalance performance parameter is bound to be affected by this distributed generation.

Due to the possible high PV penetration, the distributor may have to invest in mitigation solution to increase grid hosting capacity. Therefore, it is important the distributor to investigate the impact high PV system penetration will have on the existing distribution network.

1.3 Research questions

To address the research problem presented in Section 1.2, the research questions are formulated as follows:

- RQ1: *Will the integration of rooftop PV technically impact (e.g Overvoltage, voltage unbalance and equipment loading) the existing urban residential network and to what extent?*

- RQ2: *What methods have been adopted to investigate DG impact on existing networks?*

- RQ3: *Is overvoltage performance parameter adequate to assess PVDG impact on urban residential networks?*

- RQ4: *How is network hosting capacity affected by rooftop PV system connection topology?*

The aim of this thesis will be addressed by finding answers to the above mentioned research questions.

1.4 Research objectives

These objectives set below are intended to find answers to research questions listed in Section 1.3 above. To determine the potential renewable energy that can be harvested within the municipal area of supply.

- Conduct literature review to identify:

– Technical impact on distribution network when subjected to high penetration of PVDG.

– applied impact assessment methods and their advantages.

- Determine the installable rooftop PV capacity of a given test network and maximum power injection in typical feeders.
- Model existing network and determine technical challenges based on the potential penetration levels.
- Determine PV hosting capacity and evaluate effects of different connection methods (single-phase and three phase).

1.5 Research approach

The impact of high penetration of grid-connected rooftop PV will have on the existing network can be evaluated by either conducting a pilot project collect field measurements or by conducting a simulation study. Although pilot project will provide most accurate results, this method of research is expensive and therefore simulation method was adopted for this study.

The procedure illustrated in Figure 1.1 was employed to meet the objective of this

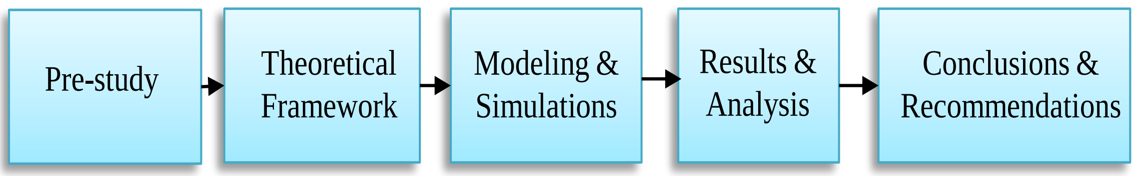


Figure 1.1: Research Approach

research work. Pre-study phase entails mainly literature review in a quest to understand the possible impacts that a high penetration of rooftop PV can have on the existing electrical network and methods applied to used to quantify these impacts. Theoretical framework was developed to guide the study, with a focus on the operating principle of the distribution networks and the rooftop PV systems and their integration/interconnection. The impact study methodology was developed and a real network test system selected for simulation. Once main variables were Modelled and real networks were used as a test network to evaluate main impact parameters of the study (i.e. Voltagerise, voltage unbalance factor and equipment overload violation). DigSilent Power Factory software [17] was used as a main simulation platform. The main inputs variables (load and PV generation) were modelled into DigSilent Power Factory and simulations conducted for different penetration levels. Where network violations were observed and PV hosting capacity were determined. Conclusions and recommendations for future studies were made.

1.6 Delimitation

Considering the size of the project, only rooftop PV renewable technology will form part of this thesis due to their technological maturity and solar resource abundance in South Africa.
It is acknowledged that the of integrating high share of rooftop PV has multiple impacts such as technical, economical, environmental and social issues. Although these issues are equally important, they are large areas of research in themselves and as result, this study will only investigate technical impact only.
The scope of the study will be limited as follows:

- Technical impact analysis will be based on steady state analysis only; focusing on voltage rise, voltage unbalance and equipment loading violations.
- The rooftop PV integration point will be at LV networks only, focusing main on urban residential network.
- It is assumed that all rootop PVs do not have a storage system and the supplers power is injected to the network.
- Data sets will be based on conditions prevailing in Cape Town, South Africa.

1.7 Research Contribution

IRP in 2013, with rooftop PV targets of 21.6GW in 2030 and 29.8GW in 2050[2]. The City of Cape Town has set its own renewable energy target of 20% in 2020 and rooftop PV systems can be a major contributor in meeting these targets. The increased interest by consumers to install rooftop PV systems requires system engineers need to know if the existing network will be able to withstand the increased capacity of the intermittent PV system. This research is aimed at understanding of the technical impact of high rooftop PV penetration into the existing municipal electrical network. This work is also intended to contribute in rooftop PV integration literature based on conditions and philosophy pertaining to South Africa.
The benefits of this work are based on stakeholders as follows:

- Network operator: determining the hosting capacity of typical feeder within the City of Cape Town area.
- Policy/Decision maker: provide insight on network limits and contribute to enabling pathways to increase rooftop PV penetration into the network.

The outcome of this work can be used as bases for the decision making in the approval process of customer owned grid integrated rooftop PV system applications.

1.8 Research overview

The balance of this thesis is outlined as follows:

- In Chapter 2 a literature review was conducted on grid integration impact research. To understand the future possibilities of high solar PV integration, the global trends of PV uptake are reviewed. Benefits and technical impact on high DG penetration on distribution grids are reviewed. impact assessment methods
- In Chapter 3 the main theoretical frame work that guided the research study is provided, focusing on the characteristics of distribution system, PV systems and their integration.
- Chapter 4 presents impact assessment methodologies adopted in this thesis based on Monte-Carlo based Probabilistic modeling of input variables and PowerFactory software as the main simulation platform.
- In Chapter 5, probabilistic impact assessment framework presented Chapter 4 is applied on real low voltage urban residential network. Simulation results of both three phase and single phase rooftop PV integration are presented and the hosting capacity of the test network is determined. Results are analyzed and discussed in relation to previous work on the subject of this thesis.
- Chapter 6 presents main findings of this research and draws conclusion on the research problem. Followed by answers to the research question posed and lastly, recommendations for future research are proposed.

Chapter 2

Literature Review

This chapter presents a literature review that is in line with the subject of integration of DGs (rooftop solar PV system) into an existing grid. To understand the future prospects of high solar PV integration, the global and local trends of PV uptake are reviewed. Followed by the impact (benefits and drawbacks) of grid-tied DGs reviewed, including the impact assessment methods adopted in the literature. Lastly, the applicable integration standards and grid codes are presented.

2.1 Global uptake of solar PV

Global electricity production is been dominated by fossil fuels, accounting for 73.8% of electricity production in 2018 and renewable energy accounting for the remaining 26.2% [1]. As illustrated in Figure 2.1, Hydro-power contributed 15.8% and accounting for 60% of total RES share. While the balance is shared between wind, solar PV,Bio-power and others (Geothermal,CSP, and ocean power). Solar PV, which is focal energy of this study, accounted for approximately 2.4% of global electricity and its adoption has grown drastically over the preceding decade. Solar PV represented about 55% of newly installed renewable power capacity in 2017[1],an improvement from 47% in 2016[1].

Figure 2.2 showed an exponential global adoption of solar PV capacity, from estimated 15GW in 2008 to record accumulated capacity of 505.5GW in 2018[1]. In 2018, China accounted for for 45% annual market addition, which is the decline from 54% in previous year. Therefore, continuing to lead in solar PV market with total PV capacity of 131GW, followed by United State (51GW), Japan (49GW), Germany (45.3GW) and Italy (19.7GW)[1]. Based on the current trend, the global uptake of solar PV is expected to increase.

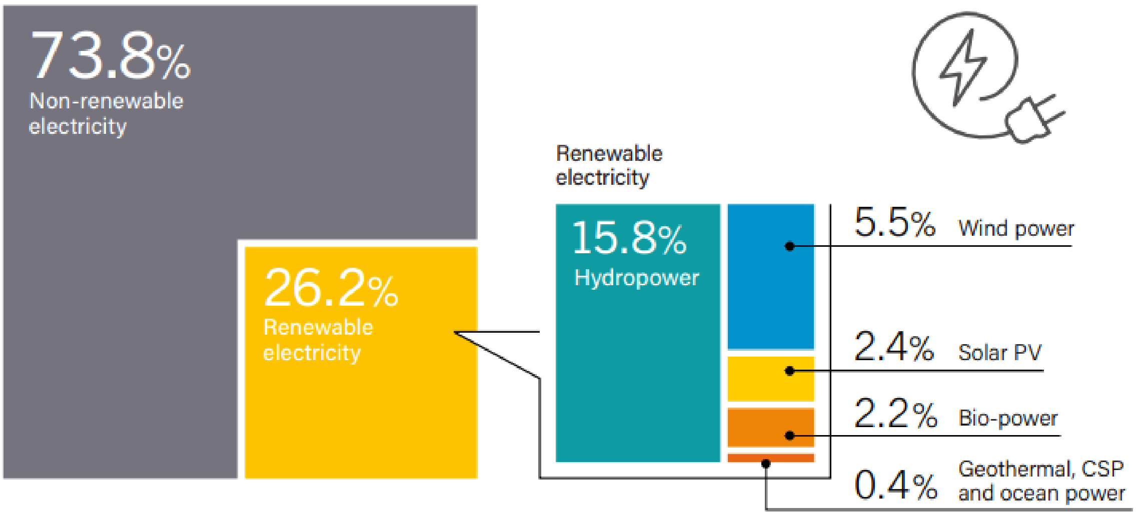


Figure 2.1: Electricity Energy share in end 2017[1]

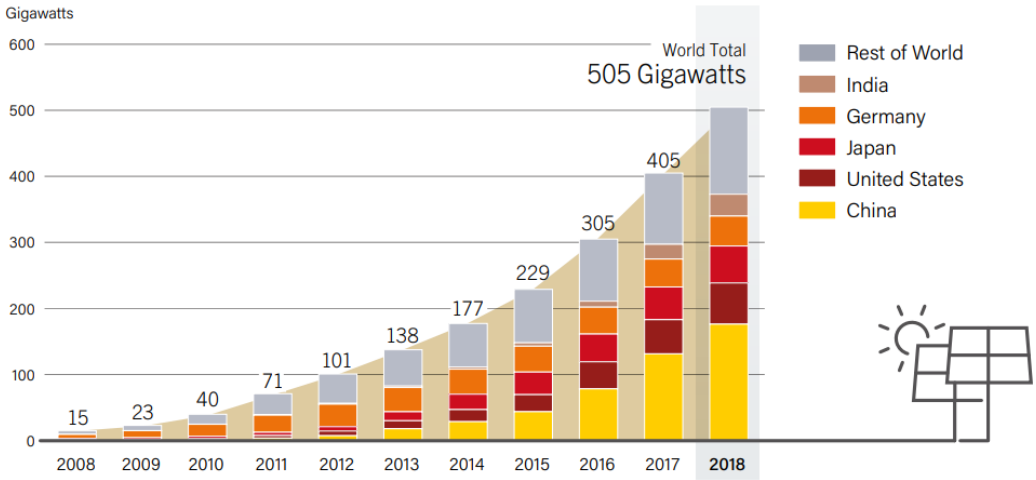


Figure 2.2: Global cumulative installed PV capacity,2008-2018[1]

2.1.1 PV uptake in South Africa

In South Africa, solar PV capacity targets set in the initial Integrated Resource Program (IRP) were low when compared to other RE technologies with rooftop PV system excluded in the target projections due to high module price at the time.

In 2017, South Africa has seen about 13MW of new PV installation and resulting in accumulated capacity of 1.8GW[1]. Figure 2.3 presents the provincial installation of recorded rooftop PV, which places the Western Cape as the second highest rooftop PV installation province in the country at the time. In the later part of 2017, Salga indicated there is 34 municipalities that allows installation SSEGs. These factors have influenced the inclusion of rooftop PV target in the updated IRP in 2013, with rooftop PV targets of 21.6GW in 2030 and 29.8GW in 2050[2]. These targets show the in-

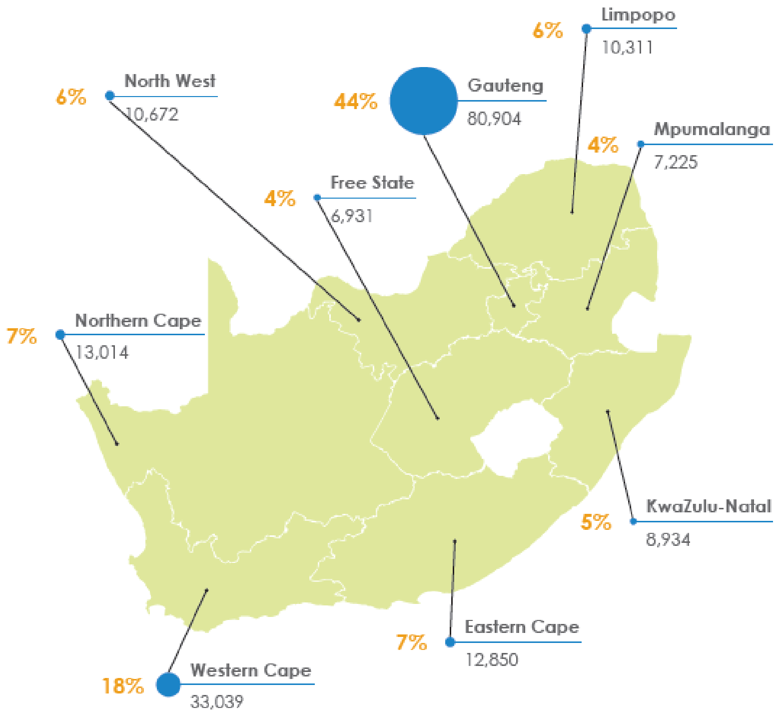


Figure 2.3: Provincial rooftop PV installations in 2017 [5]

tentions by the decision makers to evolve the country's energy mix. With more PV installations, high PV penetration has been recently awarded more attention among researchers. Although the adoption of rooftop PV may be beneficial to the customers by a reduction in electricity bill, on the other hand the DNOs will have to retain or upgrade the electrical infrastructure while revenues are declining.

2.1.2 Motivation for Distributed PV uptake

Utilisation of distributed generation (DG) technologies has increased for electricity generation applications and they are expected to play crucial part in future energy mix. The adoption of DG technologies has been driven by both global and regional factors. According to the review conducted by Pecas Lopes et al.,[18], the main drivers for increased adoption DG can be categorised into Environmental, Economical and national/regulations. According to International Energy Agency[19] report, major drivers of DG are:

- Advancements in DG technologies
- Constraint in construction of new transmission lines
- Increased customers demand for reliable electricity

- Electricity market liberalisation
- Climate change concerns

In South African context, WWF [4] reported additional factors like electricity tariffs increasing above inflation rate, abundant sunshine, load shedding experience in 2008 and again in 2015 have triggered an increased uptake of solar PV systems in South Africa. These factors have lead in customer being involved in the electricity market as both the producer and consumer (pro-sumer) of electricity were permissible. Although the power utility Eskom does not allow integration of small scale generation into their grid, number of municipalities like City of Cape Town and Ethekwini allow small scale generation into their grids. With the requirement the consumer has to be a net-consumer (Consume more than the energy they inject into the grid). These arrangements provide the opportunity for consumers to off-set their electricity bill with SSEGs. As a result, the impact of high share of DG is expected to manifest first in municipal grids.

2.2 Solar PV as a distributed generation

DGs are relatively smaller scale compared to the conventional centralised power generators. Other names like “dispersed generation” [15] and “small scale embedded generators (SSEG)” [15, 20] are also used in literature to refer to these type of generators. Definition of these generators also differs in literature. Kaundianya et al. [21] defined DGs as generators ranging from few kilowatts (kW) to Megawatts (MW) and they are mainly installed closer to the load centre. However, this definition will not be suitable for future application when DG capacity can be greater than the capacity range provided in this definition. On the other hand, the definition by Ackermann et al. [22] is widely adopted in literature[23],[14], which defines DG as “*the electric power generation source that is connected directly to the distribution network or on the customer side of the meter*”. Distributed generation technologies (DGTs) are categorised into [24],[25]:

- Renewable DG and
- Non-Renewable DG

Non-Renewable DGT consists of reciprocal engines, Gas turbine, combustion turbine, micro turbine and fuel cell. Renewable DGT consists of hydro, wind, solar, geo-Thermal, biomass and tidal. Factors like free energy resource, environmental friendly and sustainability of renewable resources make renewable DGT a favoured option than

non-renewable DGT.
Micro-geothermal and micro-hydro systems are not suitable technologies for urban areas. Thus make solar PV and micro-wind systems the two suitable DGTs for electricity generation application in urban areas. Solar irradiance is more predictable than wind and PV has less visual disturbance as compared to wind turbines as they can be rooftop installed. Therefore, this work will be focused on rooftop PV solar system.

2.2.1 Rooftop PV application

The application of PV system can either be ground mounted, Building Integrated (BIPV) or a rooftop PV system. Ground mounted system are unfavourable in urban areas, as they occupy land. BIPV systems are mainly for new establishments and thus make it costly exercise for integrating into an existing building. Therefore, Rooftop PV is the preferred application in existing buildings due to its short implementation period, no extra land required and their out of sight. PV systems are categorized into two, either as grid connected system (with or without batteries system) or off-grid system (mainly with batteries system) [26] and these systems are further explained in the below subsections.

The installation of rooftop PV system is reliant on the roof inclination and the orien-

(a) Rooftop PV without structure

(b) Rooftop PV with structure

Figure 2.4: Typical rooftop PV installations

tation. Above Figure 2.4 illustrate typical rooftop PV installations, where Figure 2.4a is a rooftop PV system installed on a pitched roof and the installation on Figure 2.4b is a PV installation on a flat roof. This shows that the roof design cannot be used as the only limiting factor for PV uptake, however the installation on a flat roof will require additional structures to incline PV arrays for optimal PV generation and thus resulting in increased installation costs.

2.2.2 Off-grid PV systems

Off-grid or standalone PV systems are PV systems that are not connected to the electrical grid. Off-grid system has been employed to providing energy for remote areas that does not justify network expansion [21]. With the sun only shining during the day, off-grid systems consist of energy storage system that includes battery and battery management system to store excess energy for use when the sun is not available[27]. The additional storage system makes off-grid system more expensive when compared to the grid-connected system, as they require additional capital and maintenance cost. Off-grid systems are competitive when compared to diesel generated electricity and network expansion[28]. However, relatively cheap coal based electricity generation in South Africa makes off-grid PV system to be less viable within urban areas where grid supply is available.

2.2.3 Grid connected PV Systems

Grid connected PV systems are a systems that are integrated with the existing grid and they are able to supply energy into the grid. The main objective of this system is to supply local load and feed excess energy into the grid [21]. With electrical grid operating on alternating current (AC), inverters are employed to convert direct current (DC) produced by PV system into AC [29]. Depending on the connection level, the transformers may be required to produce the voltage level to that of the level of common coupling. The ability to receive power from the grid when PV system is not generating power makes storage system an optional part of the system, as the grid is used as storage system [21]. Customers with potential PV uptake already have access to grid electricity; as a result their PV system will impact the existing network by either reducing load and/or injecting current into the grid.

In the presence of electrical grid, grid–connected PV system is the viable option for consumers and it is even more economically viable when there is an incentive for consumer for the excess power supplied to the grid. There are three billing concept,ie. Net metering, Net billing and reverse blocking[30].

Therefore, it is assumed in this study that all rooftop PV installations are grid-connected systems.

2.3 Benefits of distributed PV systems

DGs can assist in reducing inherent negative attributes of traditional centralised fossil fuel based generation and especially when employing renewable DGs. Benefits of DG are presented in Table 2.1 and the can be grouped into technical, Economical and environmental benefits as briefly discussed in the following subsections.

2.3.1 Technical benefits

The increase in load demand amounts increased current flow and therefore resulting in high system losses.this situation more prevalent in distribution networks have an inherent transmission loss due to their low X/R ratio characteristic (predominantly resistive). The introduction of DG (PV) at the load point will lead in to the reduction of power demanded from the grid and thus reducing system losses. The system losses reduction benefit can be achieved at low penetration and exacerbated at high penetration levels[32]. The reduction in system losses constitutes economic benefit to the distributor.

DGs can be used in voltage profile improvement as presented in literature [33][34]. Masoum et al.[33] found that moderate to high penetration of rooftop PV can have a significant voltage profile and transformer loading improvement in residential networks. Voltage profile improvement can be optimised by having capability of injecting reactive or active power into the grid as and when required[34]. This technical benefits of PVDG systems can be economically quantified to inform holistic decision making in power system planning, operation and infrastructure investments.

2.3.2 Economic benefits

Power system infrastructure has to be upgrade over time due to end of life of equipment or increasing capacity as energy demand increases. Due to high capital costs if this infrastructure, utilities may want ways to defer this investment cost and DG can assist in this regard. Literatures by [35][36], concur that the integration of DG has a potential to be strategically utilised to defer network infrastructure investment. The other benefit of DG integration can result in reduction in system losses, which can be economically quantified. Also DG can free up system capacity, which can provide DNO with an opportunity to connect additional customers without increasing generation requirements. However, in order for capital cost deferral to be realised,

Table 2.1: Technical and Economic benefits of DGs[31][24]

Technical	**Economic**	**Environmental**
reduced line losses;	deferred investments for upgrades of facilities;	Reduction of emission pollutants
voltage profile improvement;	reduced O&M costs of some DG technologies;	Encouragement to RES based generation
reduced emissions of pollutants;	enhanced productivity;	
increased overall energy efficiency;	reduced health care costs due to improved environment;	
enhanced system reliability and security;	reduced fuel costs due to increased overall efficiency;	
improved power quality;	reduced reserve requirements and the associated costs;	
relieved T&D congestion.	lower operating costs due to peak shaving;	
	increased security for critical loads.	

distribution generation has to be incorporated into the grid operator's planning[37].

2.3.3 Environmental benefits

The conventional fossil fuel based generators emits greenhouse gasses that negatively affect climate change which is been linked to the detrimental weather patterns in recent decades. The introduction of renewable based DG reduces the consumer load and thus result into reduction in power generated from centralised fossil fuel based power stations.

The realisation of the aforementioned benefits is dependent on number conditions that must be satisfied [38][37],such as:

1. Strategic placement of the distributed PV system,
2. Penetration level, and
3. Grid characteristic.

If one or more of these factors are not satisfied, then the benefits might turn into adverse impacts on the performance of the feeder [38] and these negative impacts will be reviewed in the next section.

2.4 Impact of PVDG integration on distribution networks

Historically, the electrical network was designed based on the unidirectional flow of power from a centralized power source to the load. Integrating high share of DGs into the network, especially renewable DGs (wind and solar), will alter operation of the existing grid and resulting into number of technical challenges. These impacts are briefly reviewed in this section.

2.4.1 Voltage Rise

Voltage profile is one of the most important parameter used to determine the network reliability, ensure quality of supply; voltage variation has to be kept within stipulated range of nominal/declared voltage. According to the national rational standard (NRS) governing the quality of supply (QOS) [39], the LV voltage variation should not vary more than ±10% of rated voltage at customer point of supply. Thus make voltage regulation an integral part of network design to ensure compliance with the QOS and it is managed in the two ways in the conventional electrical network, resistance minimisation and voltage transformation.

The introduction of PV at the customer busbar alters the voltage profile of a given feeder, especially where power injection without voltage control capability is permitted. Voltage rise occur when the power generated is greater than the local load and the excess power is injected into the grid.This effect is demonstrated by Figure 2.5, where the absence of PVDG result in voltage drop due to local load. Meanwhile, the introduction of PVDG will result in voltage rise especially at the end of the feeder. In residential area, this situation occurs on a sunny day resulting in PV system generating to their maximum capacity and low load when occupants are at work. The concern of voltage rise has drawn attention of researcher to investigate the potential voltage rise [14, 12, 41]and voltage profile due to the increased penetration of distributed PV systems [42, 43].

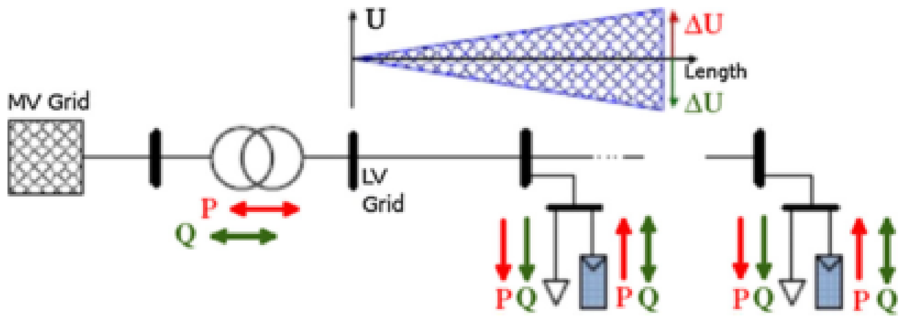


Figure 2.5: Voltage change[40]

Thomson, Infield and Member[44] conducted a study based on the real city-centre Leicester network topology with 50% penetration of PV and 100% of micro combined heat and power systems (CHP). The authors found that 50% only voltage violation occurs when both PV and CHP are at penetration of PV does not exceed voltage limits and the maximum penetration (50% and 100% respectively). Furthermore, the advantage of DG is noted as network losses decrease with an increase in penetration level. Liu et al.[45] conducted a distribution system voltage performance at high PV penetration and the reactive power flow. The study indicated that utilisation of inverter reactive power capabilities improved voltage profile on the network.

2.4.2 Voltage Fluctuation

The intermittent nature of solar PV resource result in a fluctuating output power and the voltage fluctuation can be observed in point of common coupling (PCC) in a grid connected PV system. Voltage fluctuation can be grouped in two, short and long duration fluctuation. Short duration fluctuation can be a short duration change in radiation intensity as a result of cloud cover and a long duration fluctuation is based on the seasonal impact. According to Woyte et al.[46] and Ebad and Grady[47], cloud cover can result in a 30% decline in solar irradiance from the previous value and causing voltage variation of about 0.03 to 0.04 pu. Evaluating worse case of high PV generation with low load for residential feeder, Woyte et al.[46] found that voltage fluctuations is highest for scattered cloud cover and lower for clear sky and overcast sky conditions. Ebad and Grady[47] noted that the impact of voltage fluctuation is greater in a clustered area with High penetration of rooftop PV, as the effect voltage fluctuation due to moving cloud cover will be experienced simultaneously by PV systems. Conversely, the dispersed deployment of rooftop PV will result in a lesser voltage fluctuation impact due to smoothing effect as result of geographic diversity[29]. However, the utility cannot assign location of a customer owned rooftop PV system as it dependents on customer preference and this can lead to feeder congestion as a result of rooftop PV geographical density[10].

2.4.3 Voltage unbalance

Integration of single phase PVDG can pose a challenge on the feeders voltage unbalance. Power is distributed in a balanced three-phase form from transmission to distribution network and depending on the customer's notified maximum demand (NMD); consumers can either be single-phase or three-phase supplied. The single phase loads are evenly distributed in LV feeders to reduce voltage imbalance as much as practically possible, but there is an inherent degree of voltage imbalance in LV feeders due to different customer behaviour in utilisation of electrical appliances.

Integration of single-phase PVDG can either improve or deteriorate voltage imbalance in a feeder, depending on the PV rating, location and phase loading[48][49][50]. Shahnia et al [48] investigated the voltage imbalance on residential LV network due to rooftop PV. The study found that the voltage imbalance is more prominent at the end of the feeder, with a 30.19% probability of voltage unbalance violation (Based on 2% $V_{unbalance}$ limit). Similar observations were made in a study by Emmanuel and Rayudu[49]. The study by Pansakul[50] affirms that the voltage unbalance increase more when feeder PV are connected on one phase and less so when distributed across all three phases. Although it can be argued that the integration of PVDG can improve voltage unbalance provided that they are optimally placed. Although voltage unbalance is not generally a hard set, but it can still be considered as one of the limiting factor in the deployment of single-phase PV system into the grid[49]. The stochastic nature of load and PV generation complicates matters even further. LV feeders consints of predominantly single phase loads and as a result voltage unbalance will always be a QoS concern for the DNO.

2.4.4 Harmonics

Inverter based technologies like PVDG can introduce harmonic emission into the network. In the AC system, voltage and current ideally oscillates in sine or cosine waveform at standard frequency (50Hz in South African context). System harmonics refers to the presence of non-50Hz frequency to these waveforms resulting from imperfection of the generator and loads. Voltage distortion is mainly affected by generator, whilst load affect current distortion. The level of harmonic content in a signal is referred to as the total harmonic distortion (THD).

The presence of harmonics can result an increased current requirement from the system, overheating of system equipments (transformers and cables), resonance and maloperation of protection devices[51]. The grid integration of inverter based DG technologies are the main contributors of harmonics.
The thyristor based , line-commuted inverters has been the main contributor of harmonics. However,the technological advancements in the inverter industry from thyristor based converter into MOSFET and IGBT based pulse width modulated (PWM) switching converters has resulted in reduction in harmonics emitted[52].

2.4.5 Thermal overload

The design of network equipment is based on the local consumption and the introduction of PV generated power can reduce the loading of the feeder cable and as subsequently reducing losses. However, in an event where there is a mismatch of high generation and low load, power can flow from the customer to the substation. Depending on the capacity of PVs connected into a particular feeder, cables and transformers can be overloaded and their thermal limits can be violated.
Lazzeroni et al.,[53] investigated the impact of PV penetration in the distribution grid of Hebron city in the Middle East. The study found that the ideal penetration factor

was at 120%. Cable loading limits were violated at 190% penetration factor and while the voltage was still within statutory limit. In 2014, Hou et al.,[12] presented a similar study on impact on voltage rise due to high PV penetration on Sweden network, with 90% of households equipped with solar PV. It was found that in summer (high generation and low load); voltage limits were not violated owing to the constant daily commercial load and the removal of this load result in over-voltage. The main finding in the study was in summer day where PV generation may exceed cable capacity and leading into high currents.

2.4.6 System losses

Power system losses is an inherent phenomenon during power transmission from source to the load and it is related to the RMS value of the current. The flow of current through the conductor result in power losses and it can be expressed as (2.1):

$$P_{loss} = \sum_{i=1}^{n} I_i^2 R_i \tag{2.1}$$

where P_{loss} is the conductor losses, I_i is the current flowing in the conductor and R_i is the resistance of the conductor. The load demand govern the magnitude of the RMS current flowing in the conductor. The introduction of DG at the load point will reduce load demand and therefore reduction in power losses. [44] Although general expectation of DG is reduction in power losses, its effect is dependent on the injected power, location and feeder characteristic. Previous studies [32, 54, 55] has investigated the effect of PV-DG on feeder losses. Nguyen[32] investigated feeder losses the impact high penetration of PV on feeder losses on five feeders. Normalised feeder losses follow the pattern depicted in Figure 2.6 and Viawan[54] found similar results. At lower penetration level system losses can be reduced and until the generation equates to the local load demand. However, at a penetration level greater than the local load will result in surplus power injected into the network and becoming the source of increased system loss.

2.4.7 Impact on protection

Protection is essential in power system to ensure safety of personal and equipment. In the conventional network with uni-directional flow of power, protection equipment are set in such a manner that the fault is isolated quickly with minimal interrupted load.

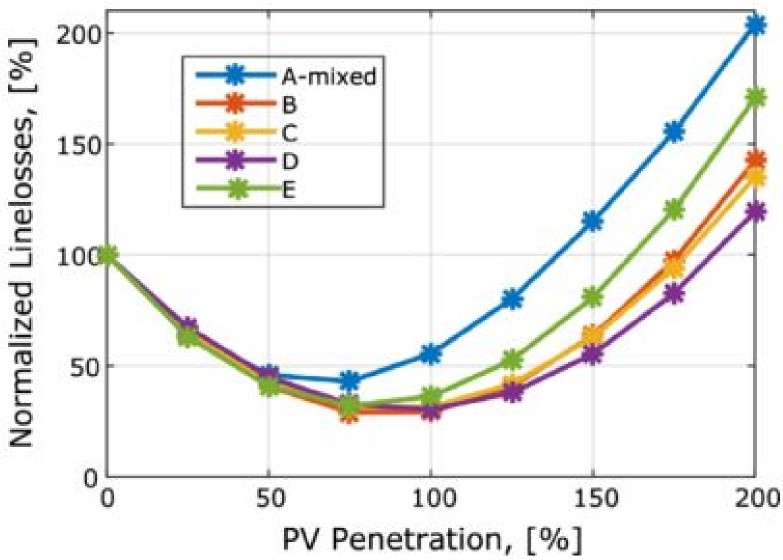


Figure 2.6: Normalised Feeder losses with increasing PV penetration[32]

Main protection issues as a result of in the LV feeder ranges from increase in fault level, islanding, reverse power flow, breaker/fuse coordination, breaker reduction of reach and sympathetic tripping[56][57]. These probable protection impacts may necessitate change in protection settings, time delays allocated per protection level and the directional protection [58]. Some of these impacts are briefly discussed.

Increase in fault level

Fault level refers to the maximum expected fault at a particular point in the network [57]. Positioning of system components is crucial, as system components (cables, overhead lines, transformers, and other equipment) are rated to withstand a given fault current for a specified duration without being damaged, while protection devices are isolating the fault. However, integration of PVDG into the grid introduces an additional source into the grid and leading into increased fault level[59]. According to [60], fault current contribution is estimated to be 110% to 150% of the inverter rating. A single PVDG may not have that much significant contribution to the overall fault current, but the aggregated impact of multiple PVDG may be of concern.

Reverse power flow

In the conventional network with unidirectional power flow and its magnitude is determined by load demand. However, integration of PVDG at the load center may result in an excessive reverse power flow from when generation is greater than the demand (when $P_{generation} \gg P_{load}$, especially at midday hour) and resulting in power propagation from LV feeder into the MV network.

Sympathetic tripping

Sympathetic tripping refers to the unnecessary operating of protection device, such as circuit breaker, for the fault that is outside of its protection zone.

2.5 PV Integration Impact assessment studies

Increased research efforts has been focused on investigating the impact distributed generation will have on the existing distribution networks. This can be attributed to the proliferation of these intermittent energy resources on the existing networks, which were not designed to accommodate such increased variation in power system parameters. These analysis are based on two main questions i.e:

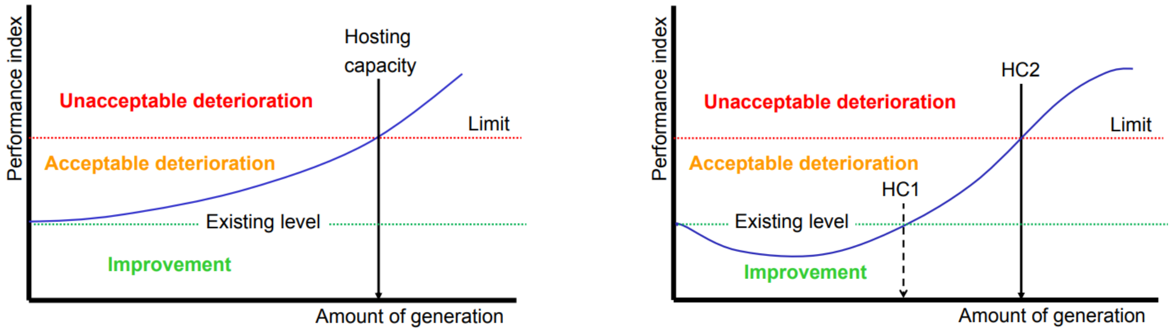
1. What power system performance parameter will be violated by increased DG penetration?

2. How much DG can be accommodated without violating system performance parameters?

2.5.1 Hosting Capacity

Initially, distributed energy generations such as solar PV have been used as an off grid systems, till recent years where they are integrated with the electrical network. Proliferation of distribute generation (including PVDG) into the electrical grid has led into a question: *how much of this Distributed Generation can be accommodated into the existing grid?*. Thus, resulting in the adoption of the term *Hosting Capacity* to quantify the amount generation that can be integrated into the grid without violating its operation and performance[7].

Bollen and Ronnberg[61] used illustration in Figure 2.7 to explains Hosting Capacity concept. Figure 2.7a represent a system were the interconnection of DG will deteriorate the performance index of the existing system even at low penetration level. While, Figure 2.7b depicts the performance improvement of the system when subjected to relatively low penetration and then increase at a high penetration level.



(a) Hosting capacity without performance improvement

(b) Hosting capacity with performance improvement

Figure 2.7: Hosting capacity illustrations[61]

The integration of PV system is likely to impact numerous performance parameters and they are also considered to determine PV hosting capacity of a given network. Figure 2.8 presents a list of technical performance parameters that can be considered to evaluate the hosting capacity of the network. The selected parameter generally under the four hosting capacity criteria, ie Thermal rating, Voltage , protection and power quality.
There has been significant work done in quantifying PV hosting capacity[62][56][7] and others considering some impact of distributed PV on one or more of these performance indices [63][13] (see Table 2.2).

Positive correlation between load and generation has a greater impact on penetration level that can be accommodated by a network/feeder[64],[65]. Based on IEEE 69- and 33-bus systems, Hung et al.[65] found penetration level on a commercial load is greater in comparison to industrial and residential loads; while residential load showed least penetration level. Similarly, the study by Hasheminamin et al.[64] also reported similar observation, when determining penetration level on a 13-bus system with comparison of industrial and residential loads. Industrial load showed a higher penetration than residential load and this can be attributed to the load correlation with the generation.

Gaunt et al. [15] applied Herman-Beta transform to investigated the penetration limits of dispersed PV on low voltage (LV) feeder. In [13], Authors investigated the voltage impact on Swedish low voltage distribution grids based on stochastic input variables. These studies has focused mainly on the voltage rise impact on existing grids due to high PV penetration[13, 12].

Because the distribution networks are not homogeneous, their hosting capacity will also vary as presented in Table 2.2. Therefore, the hosting capacity of networks can not be generalised.

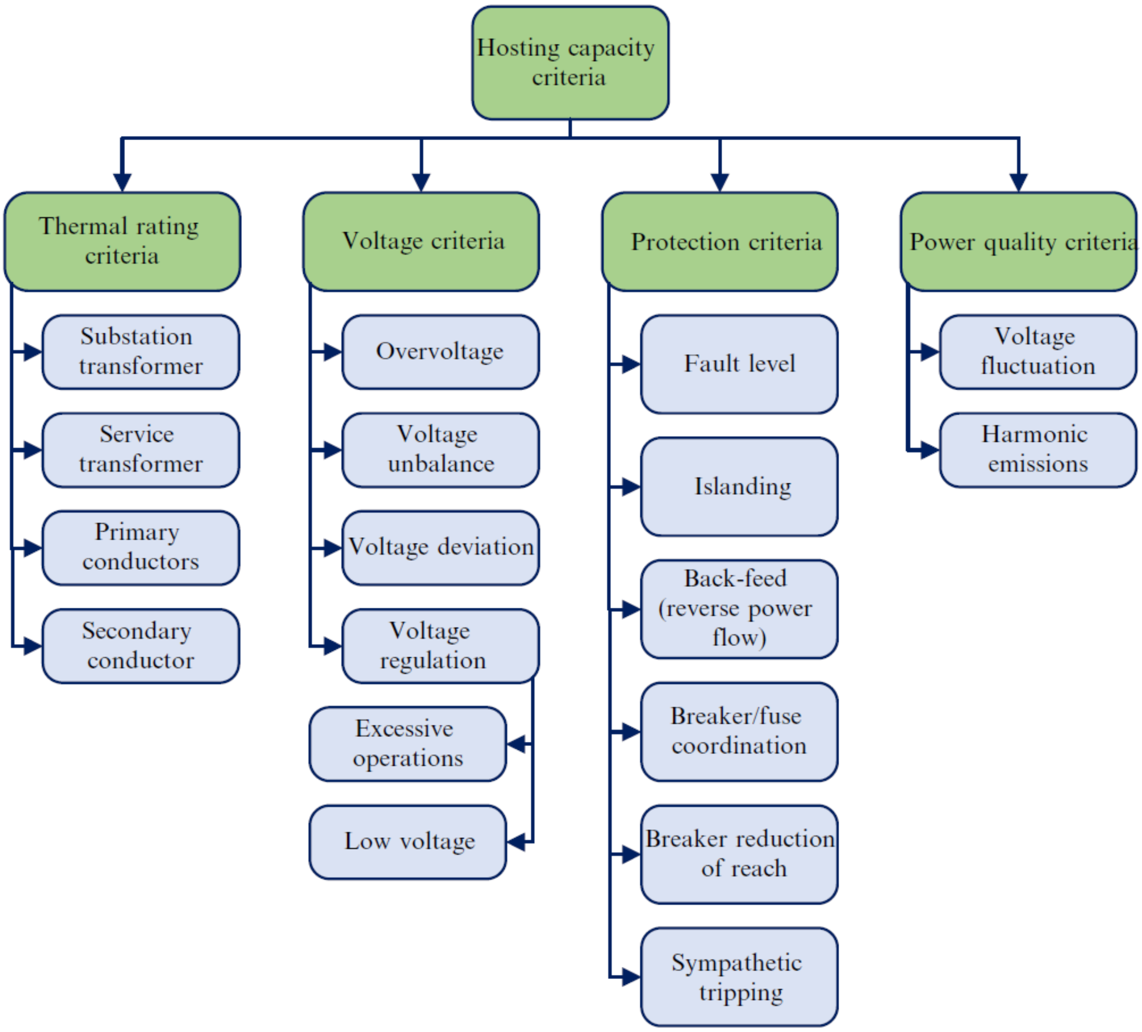


Figure 2.8: Hosting Capacity criteria[57]

Table 2.2: Hosting Capacity summary in Literature

Reference	**Test network**	**Penetration limit**	**Limiting factor**
Thomson[44]	Leicester LV network	30	Over-voltage
Jothibasu[7]		15%	Over-voltage
Tonkoski[66]	Canadian LV network	$2.5kW_{phh}$	
Tie[67]	Malaysian LV network	10%	Over-voltage
Ballanti & Ochao[62]	NW England radial urban network	60%	Over-voltage

2.5.2 Load flow methods

The impact DG has on the network is dependent on characteristic ranging from PV system size, location and system characteristics [37]. Therefore, it is crucial to evaluate the impact these DG systems will have on the existing distribution grid and load flow computation becomes pivotal for this application. The two load flow techniques (Deterministic and Probabilistic [68, 69]) are reviewed.

Deterministic load flow

Deterministic Load flow (DLF) has been used for decades for planning and operation of electrical network. DLF is a snap-shot analysis based on predetermined constant values of load, generation and network condition [70, 71]. Due to the specific value for input parameters, the DLF provide a single output value and it does not consider the uncertainty of the input parameters (load and the generation) of the system. Depending on the objective of the analysis, DLF analysis can be based on mean or worst case input parameters.

Tonkoski et al.[66] evaluated the impact of high PV Penetration on Voltage Profiles in Residential Neighbourhoods. Other studies has investigate the amount of DG that can be accommodated by the network based on worst case scenario [72]. Mahmud et.al[72] investigated voltage variation as a result of DER based on a worst case scenario. Authors considered minimum load ($P_{load} = Q_{load} = 0$) and maximum generation scenario. However, this hypothetical minimum load is not realistic and it does not consider probability of having Pmin and DGmax. This approach can be overly restrictive on the amount of DG that can be accommodated by a network.

Due to the variability of load and generation in time, the DLF can be further extended into time series analysis, where the input variables can be presented as a function of time [73, 20].

In Sydney, a study by [64] investigated the impact of High PV penetration on LV and MV networks based on residential and industrial load profile. [33]

The advantage of DLF is its quick and easy analysis method, which requires single input per list of variable. The disadvantage of this method is basing analysis that may not occur or occur for a fraction of time in a year.

Probabilistic load flow

Suitability of DLF in modern power system is inadequate, due to high level of uncertainty associated with variability in load, renewable generation integration and system operation condition [74]. In order to address this drawback of DLF, Probabilistic Load Flow evolved.

The first appearance of PLF dates back to 1974, where Borkowska [75] proposed a convolution based probabilistic load flow (PLF) to cater for the uncertainty of system load parameters. PLF is employed in power system by incorporating random variables ($r.v$) into the analysis to represent uncertainty of input parameters. These $r.v$ are based on known probability density function (PDF) or cumulative density functions (CDF) [76, 77] and developed from historic measurements, statistical data or engineering judgement [78]. Probabilistic Load Flows (PLF) are grouped into numerical/simulation (e.g. Monte Carlo Simulation) and analytical (e.g. Convolution, cumulants) approaches [70, 68, 79].

Numeric/simulation based PLF, such as MCS, make use of random assigning of values to the input variables and deterministically solve LF equations per input variable. Main features of MCS are random number generation and random sampling. MCS was applied by Arshard et al.[80] to coonduct a comprehensive assessment of PV hosting capacity and energy storage impact in realistic Finnish Low-Voltage networks. In order to determine the optimal placement of distributed generation in three-phase distribution systems with time varying load, Martinez and Guerra [81] applied Monte-Carlo approach. MCS has also been applied in conducting reliability assessment of grid-connected solar photovoltaic system[82]. However, the accuracy of MCS is dependent on large number of iteration process which leads to increase computational burden. To mitigate this drawback, other approaches such as Quasi-MCS has been proposed were iteration number are reduced to a point were the error margin on the accuracy is deemed acceptable[77]. However, the need for a solution with less computation time always been a motivation towards analytical techniques.

Analytical methods are based on the use of arithmetic based on PDF input variable and application of analytic approach such as convolution techniques to determine corresponding system output.

Monte-Carlo simulation has been widely used method in PLF application and more so as the verification method of other probabilistic approaches. Such studies include the work by Ghosh et al [83], were MCS was used to verify the proposed distribution circuit state estimation based on probabilistic approach. Ruiz-Rodriguez et.al [84] made use MCS to validate their proposed PLF consisting of combination of cumulants and Gram- Charlier expansion. Gaunt et al. [15] applied MCS as the validation method to the proposed Herman-Beta transform used to investigated the penetration limits of dispersed PV on low voltage (LV) feeder. Computational burden has been cited as the main drawback of MCS when compared to these analytical techniques, in spite of its high accuracy level [68].

The above mentioned Analytical method are intended at reducing computation burden associated with numerical/simulation method. However, these analytical methods are based on assumptions such as LF equation linearisation and complex mathematical algorithms[70, 68].

It has been established that modern power system operates under a high level of uncertainty due to variation in load, renewable generation integration and system operation condition[74]. Therefore, conventional deterministic analysis applied in passive networks will not be adequate to assess the impact of PVDG on the existing grids. In current grid integration research, probabilistic approach has been adopted to investigate the impact of PVDG integration impact on the existing grids.

2.5.3 Uncertainty Modelling

As presented in subsection 2.5.2, PLF is the preferred methods of determining the impact integration of intermittent resource into the existing grid. Thus make modelling of load and PV with their associated stochastic behaviour pivotal for this application. Statistical modelling of load and PV are reviewed below.

Uncertainty modelling of load

The Electrical load demand can vary extensively based on the time of day, day of the week, even by season. These and other factors, makes load modelling to be a challenging task. Overtime, models have been developed to represent a typical day load demand based on the type of customer, i.e domestic, commercial and industrial. Although these models are important, its application is limited when considering PLF. Statistical representation of load based on PDF has been adopted widely in the field. However, there is no agreed PDF used to represent load demand. Proposed distributions in literature include Gaussian/normal [86, 87, 88, 89], Beta [90, 16] and weibull[54].

The work by Golkar [86] propose a new probabilistic load flow for radial distribution network and made use of normal density function to represent the load demand. In their study to probabilistically model solar PV module and wind generation impact on distribution networks, Soroudi et.al [88] chose normal distribution to represent load demand. Other studies have adopted normal PDF to represent load demand in a given hour [87, 89]. The adoption of Gaussian distribution due to simplicity in attaining distribution parameter.

As Gaussian distribution at times cannot properly represent other types of loads, Carmona-Delgado et.al [91] proposed a Gaussian mixture model (GMM), which consists of combination of several Gaussian components. Application of Gaussian distribution has been driven the by the simplicity to attain the distribution parameters such as mean and standard deviation. However, its application has been limited to represent aggregated loads, mainly MV to HV, which conform to central limit theory.

However, load research studies have indicate Beta PDF as the better representation of load[90, 83]. In 1991, Herman and Kritzinger [90] conducted a load research study based on measured winter load data for grouped residential customers in South Africa. The research was intended to derive statistical representation these residential loads and they found Beta distribution as a better fit of data. Representation of load currents by Beta distribution was further applied by Herman and Gaunt [92] to propose practical probability design procedure for LV residential distribution networks.

Other load research study by Ghosh et al. [83] conducted goodness of fit using Chi-Squared χ^2 test to the load against normal, log-normal and beta distribution. χ^2 test results showed data to best fit Log-normal and less so normal distribution. due to the versatility of beta to represent skewness in data, beta distribution was chosen. As a result, beta PDF has been applied as the descriptor of load demand in other studies such as [85, 15, 16].

In conclusion of reviewed literature, it appears to be no uniformity on the type of distribution function applied to model load demand. Due to its ability to model skewness of the data, Beta distribution has been preferred to represent load PDF.

Uncertainty modelling of PV

It is well documented that the output power of PV system is inherently intermittent. Thus make it critical that the modelling of this power source incorporate this uncertainty. The generated power of a photovoltaic module depends on solar irradiance, ambient temperature of the site and the characteristics of the module itself [88, 93]. The mostly used distribution for solar irradiance modelling are Beta[94, 88, 16], Gaussian [89] and Weibull [54].

Representation of PV output using Gaussian distribution has been applied in research studies such as the work conducted by Martinez-Velasco and Guerra [89], where they investigated the impact of distributed energy resources on large distribution networks. In other instances, even Weibull distribution were fond to be close representation of solar radiation data [54].

The adoption of beta distribution as a representation of solar irradiance has been widely applied. In their study to find an optimal renewable resource mix for minimized energy loss in distribution system, Atwa et al,[94] employed Beta distribution to represent the random behaviour of solar irradiance data. Similarly in the study by Soroudi et.al [88], beta distribution was adopted to represent solar irradiance data.

It can be concluded based on literature, that there is no agreed distribution function used to represent PV generation. However, beta distribution has been a preferred distribution for representation of PV output.

Uncertainty modelling of PV location

There has been a wide research work done on the optimal placement of DG based on multiple objective such as, reduction in system losses [95, 96], voltage improvement [97]. Some of the optimisation techniques employed are particle swarm optimisation (PSO) [98], Genetic Algorithm (GA) [96]. The application of these optimisation techniques are based on the assumption that dominant impact factors (i.e. location and size) of DG can be influenced/controlled and this assumption can only hold true to the utility scale DG. However, the same assumption is not realistic for customer owned DGs like rooftop PV system, of which their adoption is dependent on the resident's financial means, preference and motivation. It is therefore apparent that the aforementioned optimisation techniques are not suitable for assessment of customer owned DGs and therefore this work will be based on random sizing and placement techniques.

2.6 Standards and Grid codes

The National Energy Regular of South Africa (NERSA) is responsible for the regulation of energy industry in accordance with the government laws, policies, standards and international best practices in support of sustainable development. The electrical distributors are obligated under distribution networks grid code to conduct distribution system impact assessment studies to evaluate the impact of additional loads or embedded generator or major modification to the Distribution System [99].

In 2014, the grid connection code for renewable power plants (RPPs) connection on transmission or distribution systems was released for implementation [100]. The grid code is intended to provide minimum requirements for connecting distributed generation into the grid. The grid code applies to various RPPs technologies (including solar Photovoltaic which is focal part of this work) that are established at the time of its release. Due to te lack of regulation on the integration of DGs with the grid, the utili-

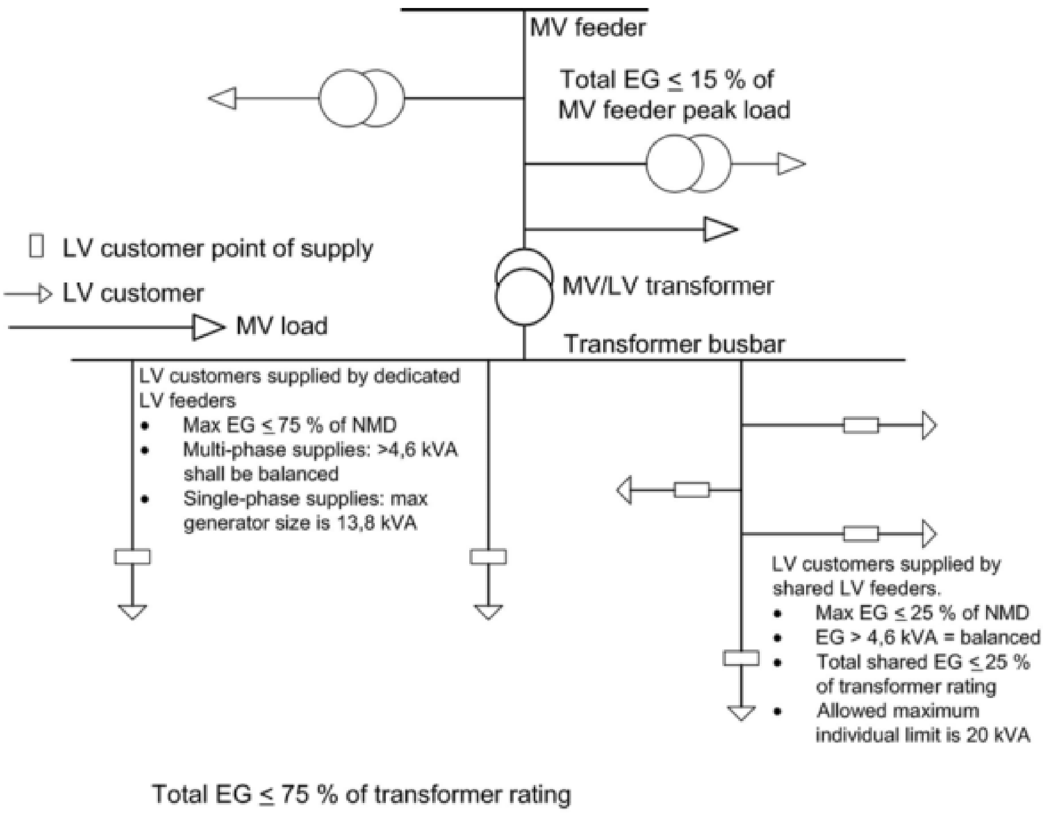


Figure 2.9: Simplified connection criteria[101]

ties has aligned themselves with the National standard NRS097-2-3[101]. NRS097-2-3 standard provides a guideline on the penetration level that can be integrated into the grid without conducting detailed studies. Figure 2.9 present the simplified connection criteria as stipulated in NRS097-2-3.

The type of feeder, either dedicated or shared feeder, has an effect on the limitation of DG capacity that can be integrated.

- In a dedicated network, Generation should be limited to 75% of NMD
- In a shared feeder, Generation should be limited to 25% of transformer rating

Table 2.3 details a NRS097-2-3 guideline on the recommended maximum individual generation limit in a shared LV feeder. In the absence of any detailed information of the specific feeder of interest, these guidelines are applied as they are and detailed

Table 2.3: Maximum individual generation limit in a shared LV (400 V/230 V) feeder [101]

Number of phases	**Service circuit-breaker size**	**NMD [kVA]**	**Maximum individual generation limit [kVA]**
1	20A	4.6	1.2
1	60A	13.8	3.68
1	80A	18.4	4.6
3	60A and 80A	41.4	13.8 (4.6 per phase)

studies are omitted. Which raises the question, does these limits applicable to all possible feeders in south Africa, considering that networks are not homogeneous? With most rooftop PV uptake occurring in urban residential networks, it important to also test applicability of these limits on urban residential networks.

Table 2.4: Relevant PV impact studies in Literature

Author(s)	**Title**	**Method**	**Local [Y/N]**	**Performance parameters**
Conti and Raiti [87]	Probabilistic load flow using Monte Carlo techniques for distribution networks with photovoltaic generators S	Deterministic and Probabilistic	N	Voltage & Current
Liu et.al[45]	Distribution System Voltage Performance Analysis for High-Penetration PV		N	Voltage
Masoum et.al[33]	Impact of Rooftop PV Generation on Distribution Transformer and Voltage Profile of Residential and Commercial Networks	Time series	N	Transformer loading and voltage profile
Tokoski et.al [66]	Impact of High PV Penetration on Voltage Profiles in Residential Neighborhoods	Deterministic	N	Over-voltage
Solanki et.al[73]	Steady State Analysis of High Penetration PV on Utility Distribution Feeder	Time series	N	voltage profiles, regulator control settings and system losses
Hasheminamin et.al[64]	Impact Study of High PV Penetration in Low and Medium-Voltage Networks When Considering Residential and Industrial Load Profile	Time-series	N	Over-voltage
Ren et.al [102]	Probabilistic Power Flow for Distribution Networks with Photovoltaic Generators	Probabilistic	N	Voltage magnitude
Punyachai et.al[42]	Impact of High Solar Rooftop PV Penetration on Voltage Profiles in Distribution Systems	Time series	N	Voltage
Mahmud et.al[72]	Voltage Variation on Distribution Networks With Distributed Generation : Worst Case Scenario	Worste case analysis	N	Voltage

Ebad and Grady [47]	An approach for assessing high-penetration PV impact on distribution feeders		N	Overvoltage, Voltage fluctuation and flicker level and Voltage regulation device operations
Watson et.al [103]	Impact of solar photovoltaics on the low-voltage distribution network in New Zealand	Probabilistic	N	Overvoltage, thermal loading and transformer reverse power
Nguyen et.al [32]	High PV penetration impacts on five local distribution networks using high resolution solar resource assessment with sky imager and quasi-steady state distribution system simulations		N	Voltage regulation, Tap changer operation,system losses and thermal loading
Gaunt, Namanya and Herman [15]	Voltage modelling of LV feeders with dispersed generation : Limits of penetration of randomly connected photovoltaic generation	Probabilistic: Analytical	Y	Voltage
Gaunt et.al [16]	Voltage modelling of LV feeders with dispersed generation : Probabilistic analytical approach using Beta PDF	Probabilistic: Analytical	Y	Voltage
Moodley et.al [20]	Impacts of SSEG on Typical South African MV networks	Time series	Y	oltage regulation, Harmonics distortion and revenue
Steyn [104]	Modelling the technical influence of randomly distributed solar PV uptake on electrical distribution networks	Time-series	Y	Voltage, Thermal overload
Lucas [105]	Single-Phase PV Power Injection Limit due to Voltage Unbalances Applied to an Urban Reference Network Using Real-Time Simulation	Deterministic	N	Voltage unbalance
Mulenga and Etherden [106]	Overvoltage due to single and three phase connected PV	Stochastic	N	Overvoltage

2.7 Closing remarks

The ever increasing uptake of PVDG into existing networks which were not designed in to accommodate high penetration of intermittent and variable generation has drawn attention of researchers to investigate future challenges that may be faced by the current networks. Similar attention has been given by power system research community in South Africa.

There is a limited body of knowledge on PVDG impact research conducted on real South Africa networks (see Table 2.4). As a result, the scepticism by utilities to allow increased uptake of DG into the existing network has been justified. Studies that a based on real networks has applied time series approach, which has limited application as presented in the literature. The application PLF (Herman Beta transform) approach has been conducted on standard IEEE test networks, which is based on academic tool such as Matlab. However, most utilities make use of power system software such as DigSilent PowerFactory for network planning purposes. As a result, there is a need to develop a probabilistic methodology that can be applied by utility engineers for detailed impact assessment studies.

This chapter a presented a literature review relevant to the study in this thesis.

- The global PV uptake trend and motivating factors were reviewed to provide an over view of present and future prospect of Solar PV generation. Based on the exponential growth of PV uptake over the years, it is expected that future grids will be subjected to high penetration of intermittent PV systems.

- Increased uptake of DG provide both benefits and drawbacks. The benefits are dependent on size, location and characteristic of the network. Due to the inability for the utility to control these parameters, the negative impact of DG on the network may outweigh the benefits.

- The selection of network performance parameter are critical in conducting impact analysis studies, as such influencing the data resolution that can be suitably used to investigate the chosen parameter.

- Reviewed hosting capacity limits indicated that the hosting capacity of networks can not be generalised and each network will have to be analysed based on its characteristics.

- The inability of Deterministic Load Flow to account for uncertainty in input variables has makes this method not suitable for PVDG impact assessment studies.

Thus make Probabilistic Load Flow an important and necessary method for this application.

- As highlighted that PLF apply PDF to represent random input variables (load, PV generation etc.), however, in literature there seem to be no commonly preferred distribution type applied to represent these random variables. But beta distribution, due to its versatility, it has has been intensively used to represent random variable.

Therefore, highlighting the limitations of Deterministic load flow approach and justifies the increased research applying probabilistic load flow techniques to investigate the impact of high penetration of PVDG on existing networks. Firstly, impact (benefits and drawbacks) of high penetration of PVDG were reviewed, including impact assessment methods adopted by related works.

2.8 Chapter Summary

This Chapter presented detailed literature review ranging from global uptake of distributed generation, in particular solar PVDG, which has shown prospects of growth. benefits and technical drawback were presented, with the main focus on the distribution level. Due to the limitation of DLF in modelling variability of input parameters, PLF is the preferred approach in PV integration impact analysis. Although it characterised by iterative and computation burden, Monte-Carlo Simulation based PLF was chosen due to it simplicity and applicability in current power systems tools, such as DiGSILENT Powerfactory. Statistical representation of input variables(load and PV) where reviewed and Beta distribution was preferred due to its ability represent skewness in data. Next chapter will present theory analysis which will incorporate concepts highlighted in this chapter.

Chapter 3

Analysis of Grid Connected Distributed Generation

Determining characteristics of the output of a PV system and the existing electrical network is essential in impact assessment of grid integrated systems. This chapter provides a theoretical background, concepts and models that were adopted to guide the work of this thesis.

3.1 PVDG interconnection to the distribution network

The interconnection of PVDG to the existing distribution network is expected to increase and their proliferation will result into multiple technical impacts as presented in previous chapter. A typical grid-tied rooftop PV system presented in Figure 3.1 and their (PV and Grid) interaction will lead into grid performance. Bollen et al [107] classified these performances into ”primary’ and ”secondary” aims of power system. Primary aim being customer related system performances such as, reliability of supply, voltage quality, and the tariffs. While secondary aim refers DNO internal aim set to meet the primary aim such as, components Overload prevention, correct operation of the protection, current quality, operational security, and costs. It can be noted that the fulfilment of secondary aims will result in primary aim being fulfilled. Even in the presence of PVDG, DNOs are obligated by the Grid code to fulfil and maintain the primary aims[108].

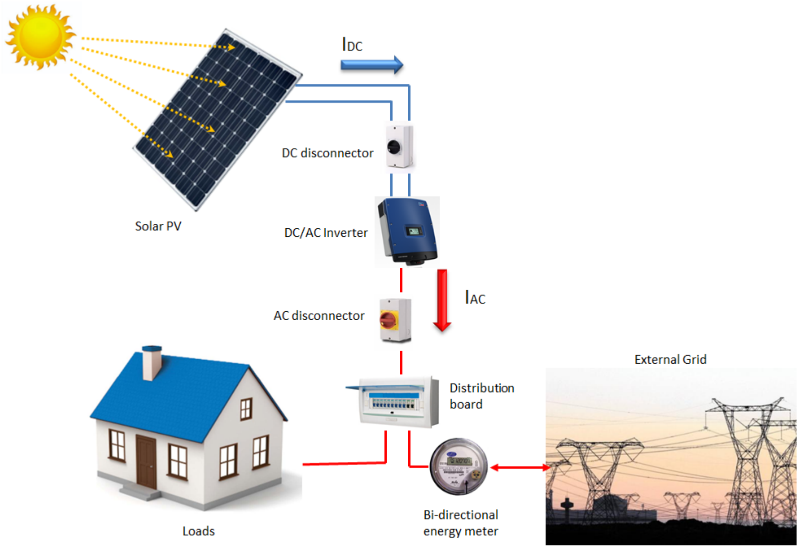


Figure 3.1: PVDG interconnection to the distribution network

3.2 Electrical Power system

Electrical power system has evolved over the years from small generation supplying local load into a centralized generation currently employed[109]. Present power systems as depicted in Figure 3.2 is made up of multiple levels i.e generation, transmission and distribution. The centralised generation power stations are situated closer to resources, i.e near coal mines for coal fired power stations. The generated electricity is stepped up by generator transformers and transmitted through high voltage transmission networks. Transmitting electricity at high voltage is an economic way of transmitting electricity while reducing system losses and voltage drop[110]. The distribution network delivers the electricity from the transmission substation to the customer[111]. Distribution level covers both medium and low voltage network, as customers can either be supplied at MV or LV level. The flow of power is from the centralized generation power station to the distribution level.

Electrical power system has evolved over time and it is emerging towards future power grid depicted in Figure 3.3. The proliferation of new technologies in the distribution network ranging from distributed generations, energy storage system and electrical vehicles has been the main driver. the possibility of bi-directional flow of power will alter the operation of the conventional power as presented in Figure 3.2.

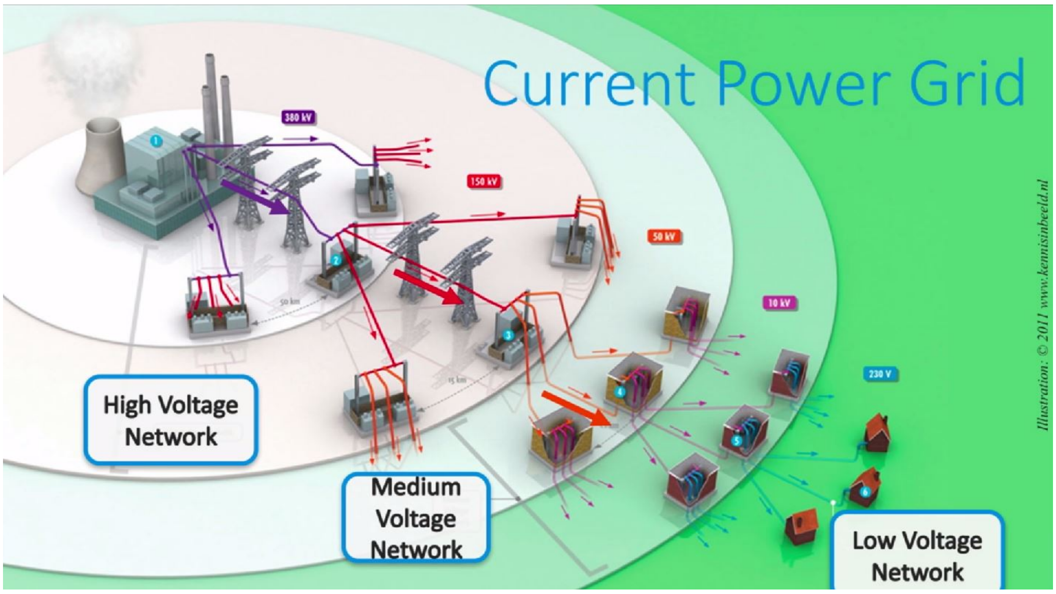


Figure 3.2: Current Power Grid [Image credit: TU Delft [112]]

3.2.1 Distribution Network topologies

The distribution network serves as the connection point for the customers access generated electricity as detailed in Section 3.2. At this level,the electrical energy is supplied at lower voltage (typically 33kV - 400V at V_{l-l}, 230V at V_{l-n}). There are three main distribution network topologies i.e. Radial, Loop/ring and meshed network as depicted in Figure 3.4[113].

- *Radial Feeder*: is characterized by a radial feeder, with a unidirectional flow of power from the source to the load. This network is popular due to simpler protection, operation and it is also less expensive. However, Radial network is less reliable compared to other network topologies.
- *Loop Feeder*: This network is based on two possible supply to the load and thus make this arrangement more reliable than the radial feeder. Planning of this feeder is slightly more complex than the radial feeder as it needs to meet all the voltage, current and protection criteria although loads are supplied from two sources.
- *Mesh Network*: is the most complex network than radial and loop feeder, but is the most reliable of the three. It is an interconnected network, with multiple paths between nodes/busbars. In most cases, this network is the most expensive.

The prevalent feeder configuration in distribution networks is the radial network due to relatively cheaper infrastructure (Power system components and protection devices) cost and less complex protection philosophy.

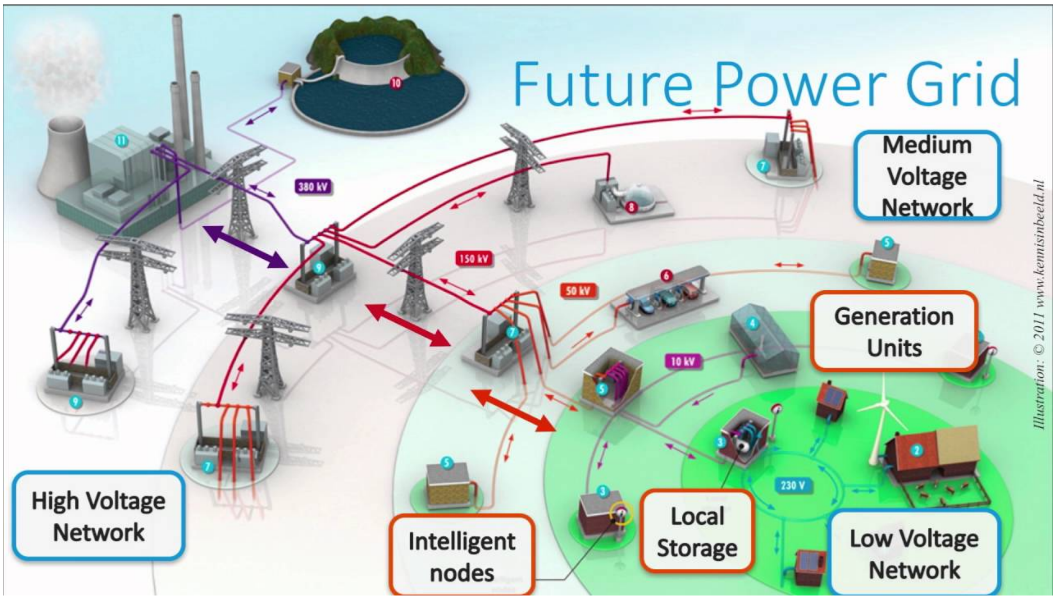


Figure 3.3: Future Power Grid [Image credit: TU Delft [112]]

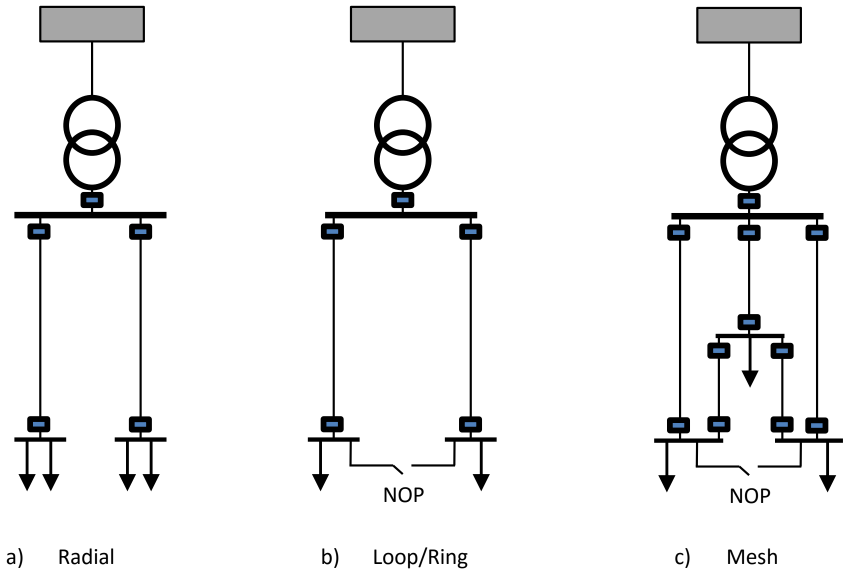


Figure 3.4: Distribution network topology

3.2.2 Low voltage feeder configuration

Typical LV network is based on a three phase four wire system, with a combined neutral and earth at the source (distribution substation). The LV network are predominantly resistive $\frac{X}{R} < 1$ and thus make Figure 3.5 relevant to represent a four wire three phase system found in LV feeders. Table 3.1, detail typical X/R ratio per voltage level.

Figure 3.5 depict a three phase cable or line connected on secondary side of the MV/LV transformer supplying single phase loads. Due to the resistive characteristic of the LV feeder, conductor phase and neutral impedance are represented by R_p and

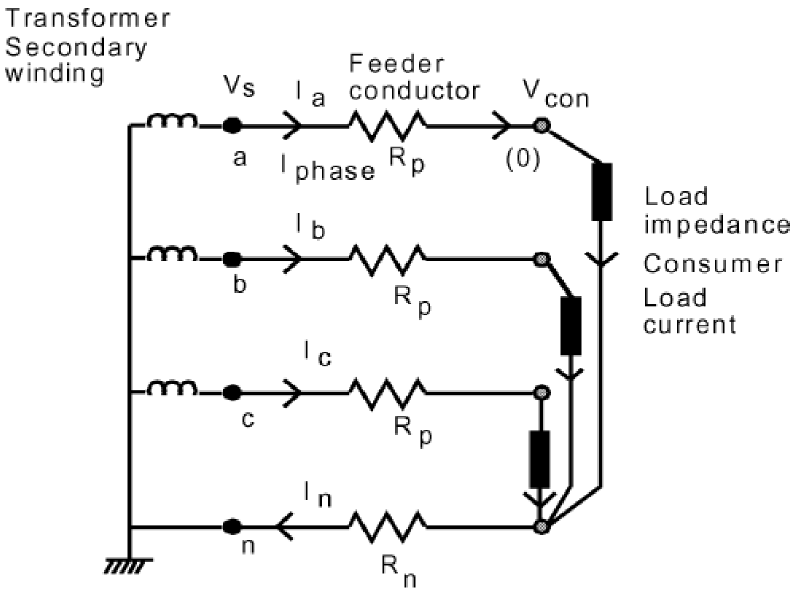


Figure 3.5: 3phase 4wire LV system[92]

R_n respectively. The single phase load connected on between a phase and the common neutral conductor. The load demand result in phase currents ($I_{a,b,c}$) drawn from the transformer and the neutral current (I_n) flowing back to the source.
The ratio of reactance over resistance determine the characteristic of the network. at the transmission level, conductors are have a small cross-section and thus reduce resistance.

Table 3.1: Typical X/R Ratio[52]

Nominal system voltage(kV)	**Typical X/R ratio**
400	16
275	10
132	6
33	2
11	1.5

3.2.3 Fault level

Short circuit current or the fault level studies are critical in the protection planning of the system. The short circuit studies apply a Thevenin equivalent network as presented in Figure 3.6 to quantify the maximum short circuit current at a given node[109]. Where thevenin voltage source V_{th} is the voltage at the point of connection

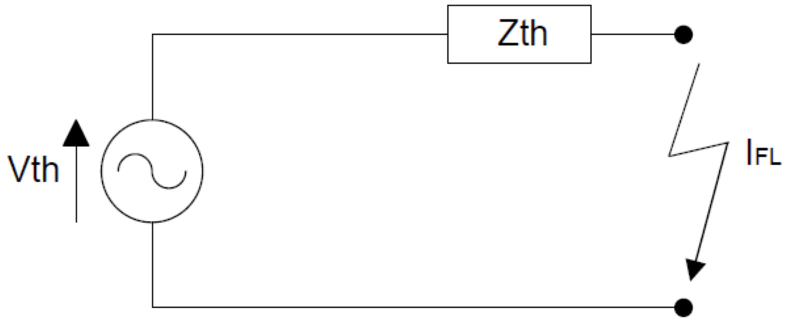


Figure 3.6: Thevenin equivalant network [52]

before the fault and Z_{th} is Thevenin impedance representing the series impedance of the network seen from the connection point. The fault level current at the connection point can be represented as:

$$|I_{FL}| = \frac{|V_{th}|}{Z_{th}} \tag{3.1}$$

SCR on a three phase network can be expressed as[52][114]:

$$S_k = \sqrt{3} V I_{sc}(VA) \tag{3.2}$$

Where S_k is the SCR at node k, V and I_{sc} are pre-fault line to line voltage and symmetrical three-phase fault current, respectively. Although high SCR seem to be the desired state for network stability, SCR should not be greater than the short circuit (I_{sc}) rating of components (cable, circuit breaker ect.) connected at a particular node.

Table 3.2: Typical fault level[52]

Nominal system voltage(kV)	**Fault level (MVA)**
132	5000-25000
33	500-2500
11	10-250

Freris and Infield [52] presented typical fault level magnitude in different voltage level as detailed in Table 3.2. Integration of the PV on a weak network points is likely to have a greater influence the voltage behaviour.

3.2.4 Short Circuit ratio

The network strength is characterised by the ability of a network to withstand voltage variation, also known as network voltage stability[114]. Short circuit ration (SCR) is a measure used determine the '*strength*' of the grid. A network with Low SCR is considered to be '*weak*', whilst high SCR characterise a '*strong*' network. SCR at a node can be expressed as:

$$SCR = \frac{FL}{P_n} \tag{3.3}$$

Where FL is the fault level

3.2.5 Distribution Network visibility

Similar to the UK, distribution network visibility is the same as in South Africa. Figure 3.7 present data limitations of the present electrical network, where the supervisory control and data acquisition (SCADA) infrastructure is limited to the high level of power system[115]. With proliferation of small scale DG systems occurring in LV feeders, the measured data is the aggregated data. The inability for the DNO to have

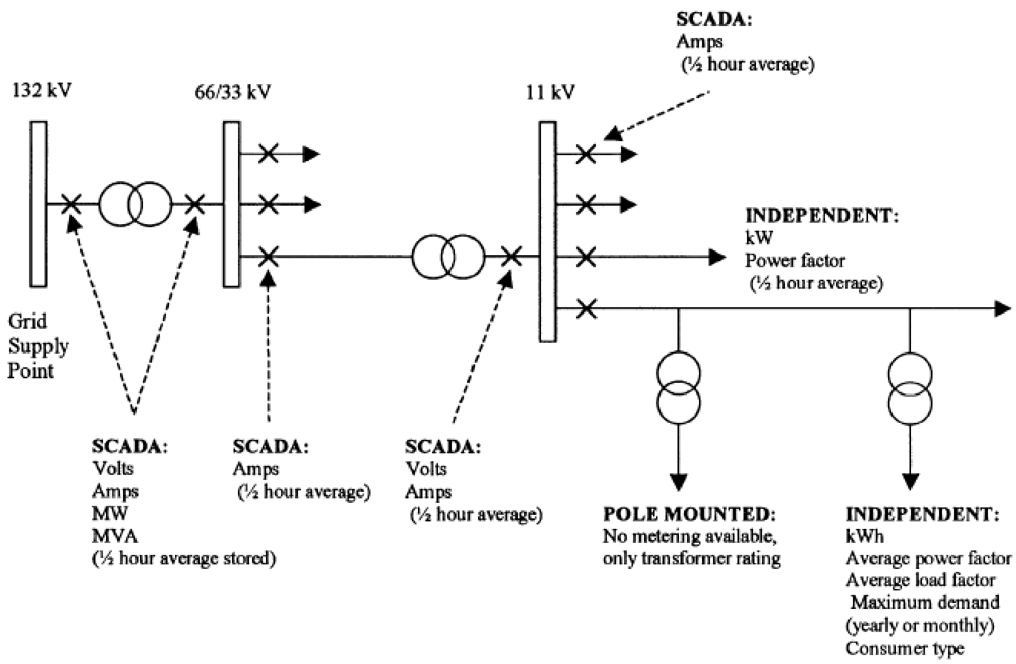


Figure 3.7: Distribution system data source[115]

visibility and controllability on the LV feeder to evaluate its performance, increases the concern on the possible challenges that may manifest when subjected to high penetration of DGs[116].

3.2.6 Voltage regulation design considerations

The electricity distributor is obligated by the distribution grid code [100] to ensure compliance with the NRS 048-2 [39]. Voltage magnitude is a critical factor in power system and it has to be maintained within a statuary limits. Voltage regulation be comes even more critical for customers who can not regulate their supplied voltage like LV customers. Therefore, voltage apportionment form part of system planning and design [117]. According to the NRS048-2[39], MV and LV voltage magnitude should be maintained within ±5% and ±10% of nominal voltage, respectively.

In the passive network, power flow is from the source to the load which result in voltage drop along the feeder and at full load the lower voltage limit should not be violated. In hypothetical condition when there is no load, the upper bound on both voltage levels is represented by a no-load graph should not be violated. In Figure.3.8, system voltage design philosophy applied by the utility is presented.

Where:

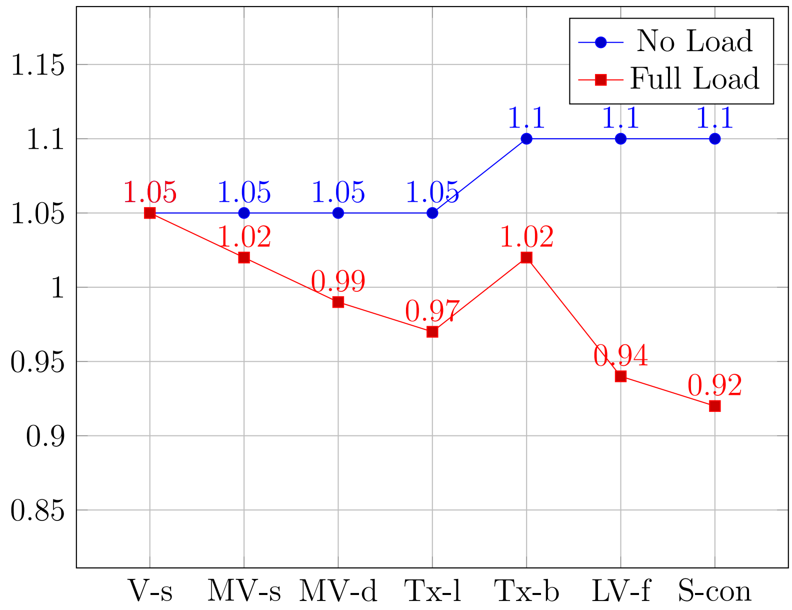


Figure 3.8: Voltage distribution

- $V - s$: is a Sending voltage,
- $MV - s$: is a MV source,
- $MV - d$: MV distributor,
- $Tx - l$: Transformer losses,
- $Tx - b$: Transformer nominal boost,

- $LV - f$: LV feeder,
- $S - con$: Service connection

Existing networks were designed based on the lower bound -8% of nominal voltage, while applying transformers voltage boost along the feeder. The 5% voltage boost of nominal voltage is adopted and applied on the secondary voltage rating of both HV/MV and MV/LV transformers. Applied voltage boost results a secondary terminals of 11.55 kV_{l-l} for HV/MV transformer and 420 V_{l-l} for MV/LV transformer. Voltage drop of 8% is allowed on the MV feeder and 10% voltage drop on the LV feeder. The MV/LV transformer voltage boost afford the lower bound to be -8% of nominal voltage, which is 2% higher than the NRS048-2 voltage drop limit at PCC.

Transformers are main voltage regulation devices in power system by providing transition between different voltage levels. Nominal voltage (V_n) for MV network is 11kV, part of voltage regulation is incorporated in the HV/MV transformer design by having a secondary voltage being designed at 1.06pu (11.660kV) of V_n.

3.3 Solar PV system

Solar cells the smallest Solar photovoltaic converts light into electric energy. Electrical characteristic of Solar PV module is determined based on standard test condition (STC), defined as a solar irradiation of $\frac{1000W}{m^2}$, module temperature of 25^0C and solar irradiation angle of 45^0.
The output power of a PV cell is influenced by many environmental factors, however, solar irradiance $I_(s)$ (W/m^2), ambient temperature T (^0C) and PV cell characteristics are the main contributors[118].
Output power of PV $P_{pv}(s)$ can formulated as:

$$P_{pv}(s) = N \times FF \times V(s) \times I_(s) \tag{3.4}$$

where N is the number of cells, FF is a fill factor, $V(s)$

$$FF = \frac{V_{mpp} \times I_{mpp}}{V_{oc} \times I_{sc}} \tag{3.5}$$

where V_{mpp} is the number of cells, I_{mpp} is a fill factor, V_{oc} I_{sc}

Power generated by a solar cell can be expressed as [**?**]:

$$P_{pv} = I_{(s)} \times cos\phi \times \eta_m \times \eta_p \times A_p \tag{3.6}$$

where:

- P_{pv} is the PV DC power (W),
- $I_{(s)}$ is the solar irradiation (W/m^2),
- ϕ is the incident angle by considering $\beta = 45^o$,
- η_m is the maximum power tracking efficiency,
- η_p is the PV panel efficiency,
- A is the PV area (m^2)

$$P_{pv,DC} = A_{Total} \times G_s \times \eta_{overall} \tag{3.7}$$

$$\eta_{module} = \eta_{STC}[1 + k_T(T_c - 25)] \tag{3.8}$$

$$T_c = T_a + \frac{G_s}{G_{s,NOCT}}(T_{c,NOCT} - 20)\left(1 - \frac{\eta_{STC}}{0.9}\right) \tag{3.9}$$

$$I_{pv} = T_{ph} - I_s.\left(e^{\frac{q.(V_{pv}+I_{pv}.R_s)}{N_s.n.k.T}} - 1\right) - \frac{V_{pv} + I_{pv}.R_s}{R_p} \tag{3.10}$$

AC conversion via solar inverter. The DC power generated by PV is converted to AC power by an inverter. the inverter has a conversion efficiency ($\eta_{PV,inverter}$) which can be expressed as:

$$P_{PV,AC} = P_{PV,DC} \times \eta_{PV,inverter} \tag{3.11}$$

Figure 3.9 depicts a solarPV characteristic between current (I) and voltage (V) and power (P) against voltage (V).

3.4 Voltage change along radial feeder

The integration of high penetration of PVDG into the grid will result in detrimental technical impact unto the existing grid as illustrated in literature [119]. In this study, the focal technical impact parameters are voltage (rise and unbalance) and equipment overloading as mentioned in Chapter 2. Theoretical background to these parameters is detailed below.

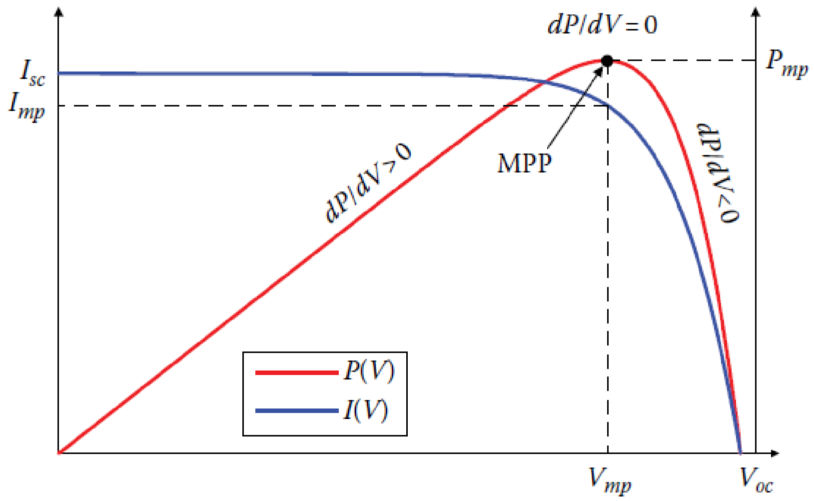


Figure 3.9: Solar PV I-V and P-V characteristic[118]

3.4.1 Voltage drop along Passive radial feeder

The conventional network is considered to be a passive network due to its uni-directional flow power, where the flow of power is from the source (transformer/substation) to the load as illustrated in Figure 3.10.

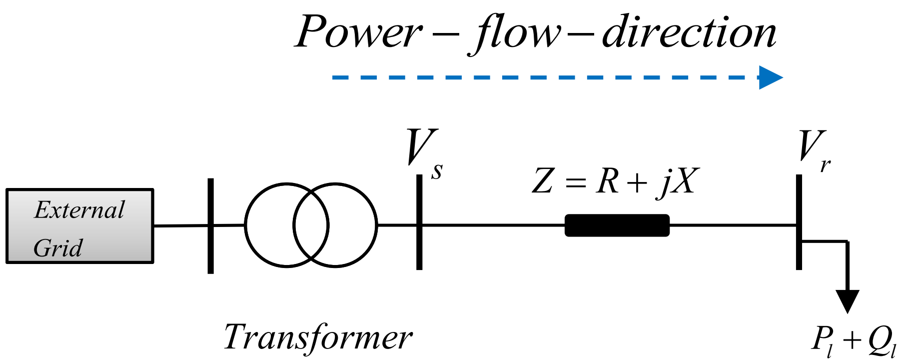


Figure 3.10: Conventional Radial feeder

Phasor diagram

The power flowing flowing from the source to load is dependent to load demand and it can be expressed as a complex power

$$S = P + jQ = V_s I^* \tag{3.12}$$

With current I from the sending node i to the receiving node j. with voltage V_i to receiving end with voltageV_j. The line between node i and j, consist of line impedance

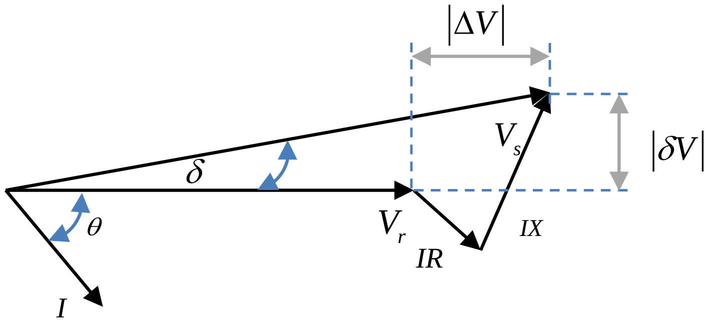


Figure 3.11: Radial phasor diagram[109][120]

Z expressed as follow:

$$Z = R + jX \tag{3.13}$$

Were R and jX are line series resistance and reactance, respectively.

Voltage drop on a line is determined by the line impedance Z and the current I flowing through the line can be expressed as in equation (3.14) below.

$$V_{drop} = IZ \tag{3.14}$$

Voltage at the sending end can be expressed as:

$$V_s = V_r + \frac{P - jQ}{V_s^*}(R + jX) \tag{3.15}$$

$$V_s = V_r + \frac{RP + XQ}{V_s^*} + XP - RQV_s^* \tag{3.16}$$

Therefore, voltage drop between sending and receiving ends can be written as:

$$\Delta V = V_s - V_r = \frac{RP + XQ}{V_s^*} + \frac{XP - RQ}{V_s^*} \tag{3.17}$$

The power distribution in this network is based on the load demand depicted as active power (P_l) with unit measure of watts (W) and reactive power (jQ) with unit measure of volt-ampere-reactive (Var). The voltage difference between nodes i and j can be estimated as in:

$$\Delta V = \frac{P_l \times R + jQ_l \times X}{V_n} \tag{3.18}$$

It can be seen from (3.18) that the X/R ratio has an influence of voltage drop on the feeder.

3.4.2 Voltage drop along Active radial feeder

The introduction of a PV system at the load bus can influence the power and Voltage profile along the feeder. Consider Figure 3.12,where PV is connected at the customer side and it is able to inject power at this node. Voltage drop can be approximated by expanding equation (3.18) as follows:

$$\Delta V = \frac{(P_l - (\pm P_g) \times R) + j(Q_l - (\pm Q_g)) \times X)}{V_n} \tag{3.19}$$

Where P_g and Q_g are active and reactive power injected by PVDG, respectively.
The resultant voltage change (ΔV) at the point of common coupling is also effected by

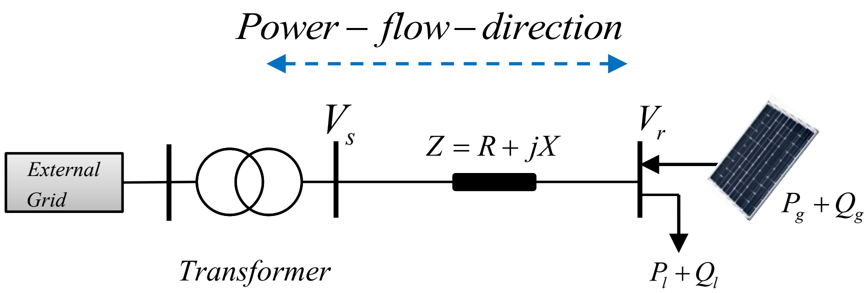


Figure 3.12: Radial feeder with PV

the type of generator connection, either single phase or three phase [106]. Considering generator injected a current I with a given power factor, the approximated ΔV can be expressed as:

$$\Delta V = R_{eq} I cos\phi + X_{eq} I sin\phi \tag{3.20}$$

Where $R_{eq} + jX_{eq}$ is the source impedance at the PCC.

Single-phase connected PV

The current injection of a single-phase PV connected between phase and neutral, will result in the voltage rise at the PCC. The voltage rise due to single phase power P_3 injection can be approximated as:

$$\Delta v_{1-\phi} = \frac{\Delta V_{1-\phi}}{V_{n1-\phi}} \approx \frac{R_{ef} x P_{1-\phi}}{V_{n1-\phi}^2} \tag{3.21}$$

Where R_{ef} is the resistive part of the earth-fault impedance, and $V_{n1-\phi}$ is the nominal phase to neutral voltage.

Three-phase connected PV

The approximated voltage rise at the PCC resulting from a three phase PV power P_3 injection can be expressed as:

$$\Delta v_{3-\phi} = \frac{\Delta V_{3-\phi}}{V_{n1-\phi}} \approx \frac{R_{sc} x P_{3-\phi}}{3 x V_{n3-\phi}^2} \tag{3.22}$$

Where R_{sc} is the resistive part of the short circuit impedance.
It is evident from the equations 3.21 and 3.22 that the voltage response will be affected differently.

3.5 Voltage unbalance

In an three phase AC network, voltage and current in a sinusoidal waveform are intended to be equal in magnitude and a displacement of 120^o between phases. The deviation from this fundamental arrangement, either voltage magnitude or phase angle or combination of the two, is referred to as voltage unbalance. Figure 3.13 depicts balanced and unbalanced voltage vectors.

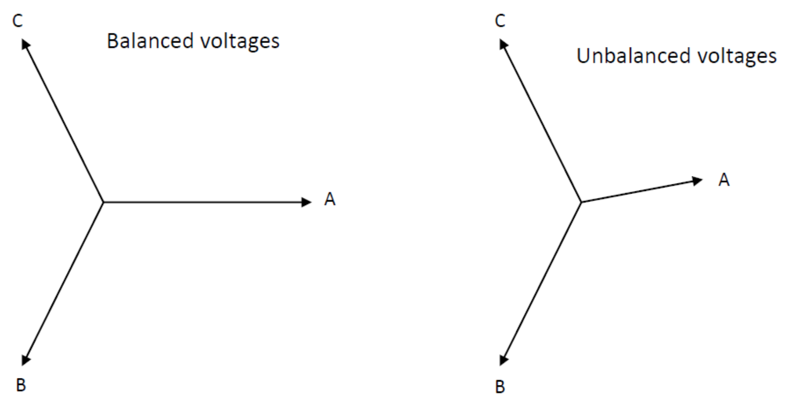


Figure 3.13: Balanced and unbalanced voltage vectors

3.5.1 Definition

Voltage unbalance has been defined in many ways and varying in parameters considered to determine if the system is unbalanced. Pillay and Manyage[121] provided voltage unbalance definitions and they are presented below. Voltage unbalance factor (VUF) is defined as the ratio of the negative sequence voltage components V_{neg} to the positive sequence V_{pos} components

$$\%VUF = \frac{V_{neg}}{V_{pos}} * 100 \tag{3.23}$$

Symmetrical components for V_{neg} and V_{pos} can be presented as follows:

$$V_{pos} = \frac{V_{ab} + aV_{bc} + a^2V_{ca}}{3} \tag{3.24}$$

$$V_{neg} = \frac{V_{ab} + a^2V_{bc} + aV_{ca}}{3} \tag{3.25}$$

Where a = $1\angle 120^0$ and a^2 = $1\angle 240^0$.
This can be expressed as follows:

NEMA based definition of voltage unbalance is

$$\%LVUR = \frac{\text{max voltage deviation from the avg line voltage}}{\text{avg line voltage}} * 100 \tag{3.26}$$

IEEE definition is based on phase voltage.

$$\%PVUR = \frac{\text{max voltage deviation from the avg phase voltage}}{\text{avg phase voltag}} * 100 \tag{3.27}$$

According to NRS048-2[39], the voltage unbalance on LV, MV and HV three-phase networks should be limited to 2%. While for planning purpose, NRS048-4 recommends the voltage unbalance per individual installation to be limited to 0.2% for 95% of the time in weekly sample[131]. With the aim of this study is to investigate the impact in the network, the 2% voltage unbalance limit will be considered in the analysis.

3.6 Equipment overloading

Power system components (lines and transformers) are intended to transmit electrical energy from the generating plant to the consumer. The bi-product of this process is the joule effect (thermal overload) as a result of resistance characteristic of these components. the balance of this section is based on the book by Bollen [107]. The maximum apparent power (S_{max}) demand on a passive feeder can be represented in a complex form as follows:

$$S_{max,1} = \sqrt{P^2_{l,max} + Q^2_{l,max}} \tag{3.28}$$

where $P_{l,max}$ and $Q_{l,max}$ are maximum active and reactive power of the load, respectively. It is assumed that the both the active and reactive power maximum demands occur at the same time, therefore equating to the maximum apparent power at the same time.

The introduction of distribution generation into the feeder and assuming the DG produce active power, the maximum apparent power on an active feeder can be written as follows:

$$S_{max,2} = \sqrt{(P_{g,max} - P_{l,min})^2 + Q_{l,min}^2} \tag{3.29}$$

The permissible maximum apparent power on the active feeder should not be greater than the passive feeder:

$$S_{max,2} < S_{max,1} \tag{3.30}$$

Therefore, the power limit can be expressed as:

$$P_{g,max} < P_{l,min} + \sqrt{P_{g,max}^2 + Q_{l,max}^2 - Q_{l,min}^2} \tag{3.31}$$

Considering the maximum feeder ampacity limit, the permissible maximum current allowed to flow through the feeder should be maintained. based on the nominal voltage, the permissible apparent power can be expressed as follows:

$$P_{g,max} < P_{l,min} + \sqrt{S_{max,limit}^2 - Q_{l,min}^2} \tag{3.32}$$

These limits must be maintained to ensure system performance and reduce equipment insulation degradation due to thermal limit violation.
The other aspect that is closely related to the thermal limit when the network is subjected to high penetration of DG is the system losses. However, this system performance indicator is not considered in this research work.

3.7 Load flow

The research method adopted in this study involves simulation studies of investigating the impact high penetration rooftop PV systems will have on the existing network and load flow computation is critical in conducting such investigation. Power flow, commonly referred to as load flow (LF), is the technique employed to determine the steady state of power systems for planning and operation purposes [70][110][122]. Load flow is 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 [110]. Firstly we consider a complex power inject at node$i$, expressed as follows:

$$S_i = V_i I_i^* \tag{3.33}$$

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

$$I_i = \sum_{j=1}^{n} Y_{ij} V_j \tag{3.34}$$

where, Y_{ij} is the admittance matrix elements. Substituting the I_i^* term into equation (3.33), equation (3.33) can be re written as follows:

$$S_i = V_i (\sum_{j=1}^{n} Y_{ij} V_j)^* = V_i \sum_{j=1}^{n} Y_{ij}^* V_j^* \tag{3.35}$$

$$I_i = \sum_{j=1}^{n} Y_{ij} V_j \tag{3.36}$$

Basic load flow equations are as follows:

$$P_i = \sum_{j=1}^{n} V_i V_j Y_{ij} \cos(\delta_i - \delta_j + \theta_{ij}) \tag{3.37}$$

$$Q_i = \sum_{j=1}^{n} V_i V_j Y_{ij} \sin(\delta_i - \delta_j + \theta_{ij}) \tag{3.38}$$

$\forall i = 1, ...n$ Equation 3.37 can be expressed in a rectangular form as follows.

$$P_i = V_i \sum_{j=1}^{n} V_j [G_{ij} \cos(\delta_i - \delta_j) + B_{ij} \sin(\delta_i - \delta_j)] \tag{3.39}$$

$$Q_i = \sum_{j=1}^{n} V_i V_j V_j [G_{ij} \sin(\delta_i - \delta_j) - B_{ij} \cos(\delta_i - \delta_j)] \tag{3.40}$$

$\forall i = 1, ...n$ Solving these equations, two of the four variables have to be specified. Table 3.3 gives the bus classification based on specified and unknown variables. These are non-linear equations requiring iteration methods to solve. there are mainly three load flow solving methods [110][122]:

- Newton-Raphson method
- Gauss-Seidel method
- Fast decoupled method

These LF methods are applied by simulation software as algorithm. Simulation software adopted for this study, DiGSILENT PowerFactory, employ Newton-Raphson method to solve Non-linear AC load flow equations[17].

Table 3.3: Bus specification

Bus	**Specified variable**	**Unknown variable**
Slack bus	V_i,θ_{ij}	P_i,Q_i
Voltage controlled bus (PV bus)	P_i,V_i	Q_i,θ_{ij}
Load bus (PQ bus)	P_i,Q_i	V_i,θ_{ij}

These system buses can be specified as follows:

1. *Slack bus*: this node serves as a reference node, with a specified voltage magnitude V_i. The voltage angle at this bus, typically $\angle 0^0$, serves as a reference voltage angle to other buses.

2. *Voltage controlled buses (PV bus)*: generators are connected to this node. At this node the real power and voltage magnitude are specified.

3. *Load buses (PV bus)*: loads are connected to these buses and known quantities (P_i,Q_i) are specified based on measurements or historic data.

These busbars specifications are to be considered when modelling and simulating power system performance.

3.8 Monte Carlo simulation

Monte Carlo simulation (MCS) are numerical methods used in many fields to solve complex problems by providing a statistical probability of the expected observation [123]. This technique can also be employed to analyse power system performance due to stochastic behaviour of input parameters. This is achieved by random selection of input variables from their probability distribution function and solving deterministic load flow to obtain output parameters.[84]. This process is iterated multiple times based on multiple input combination. The output results can be statistically represented based on their PDF or CDF. MCS is based on the random sampling and large number generation.

Figure 3.14 shows a MCS outline and associated steps.

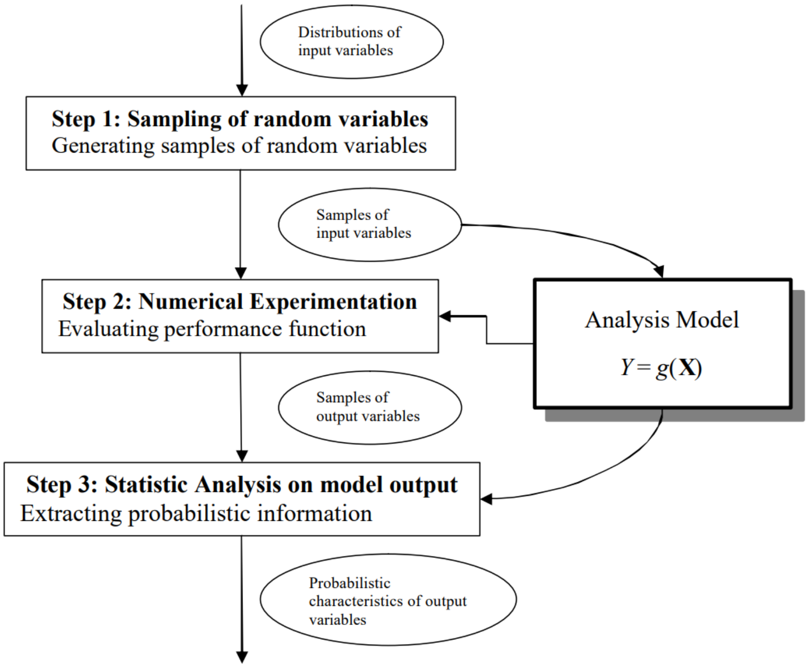


Figure 3.14: Monte Carlo Simulation [123]

The expected observation can be formulated as:

$$E(Y) = \frac{1}{N}\sum_{i}^{N} Y_i \tag{3.41}$$

where Y is the observation based on Monte-Carlo trails of N. Y_i is the independent observation governed by the solution function and probability constraints of input variables $x_{1,2}$,. ..$_{,M}$.

3.8.1 Random variables

Variable are randomly select to represent their uncertainty. To ensure the variables mimic the expected probability extracted from known data, probability distribution functions are employed.

Random variables can either be discrete or continuous. where discrete variable

Random variable X can be expressed based on it distribution function, denoted as follows[124]:

$$F(x) = P(X \leq x) \tag{3.42}$$

Where $F(x)$ is the probability a variable X is taking on a value less or equal to x.

Uniform distribution

Uniform distribution is one of the simplest continuous distribution

$$f(x) = \begin{cases} \dfrac{1}{b-a} & \text{if } x\in\ \alpha,\beta \\ 0 & \text{otherwise} \end{cases} \tag{3.43}$$

mean and standard deviation of uniform distribution are expressed as:

$$\mu = \frac{a+b}{2} \tag{3.44}$$

and

$$\sigma = \frac{b-a}{\sqrt{12}} \tag{3.45}$$

Normal/Gaussian distribution

Normal distribution is a bell-shaped curve

$$f(x) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\dfrac{(x-\mu)^2}{2\sigma^2}}; \tag{3.46}$$

Weibull distribution

Weibull distribution Function is

$$f(x;\lambda,k) = \begin{cases} \left(\dfrac{k}{\lambda}\right)\left(\dfrac{x}{\lambda}\right)^{k-1} e^{-(x/k)^k} & x \geq 0 \\ 0 & x < 0 \end{cases} \tag{3.47}$$

where $k > 0$ and $\lambda > 0$ are the shape and scale parameters of the distribution.

Beta distribution

Beta distribution function is used to represent a continuous random variables with distribution parameters of alpha (α) and beta (β). Were parameters are real numbers (α,$\beta \in \Re$).Beta distribution function can be expressed as (3.48) below.

$$f(x) = \begin{cases} \dfrac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)+\Gamma(\beta)} s^{\alpha-1} \times (1-s)^{\beta-1} & if\ 0 \leq \text{x} \leq 1, 0 \leq \alpha,\beta \\ 0 & \text{else} \end{cases} \tag{3.48}$$

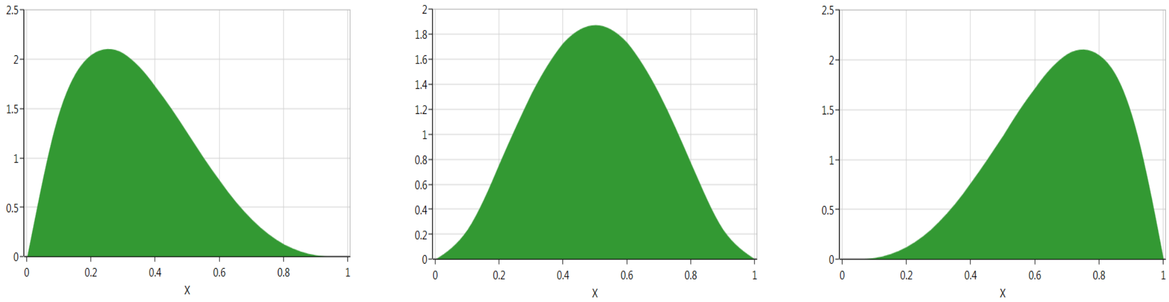
Beta parameters are calculated based on mean (μ) and standard deviation (σ), as denoted in (3.49)

$$\beta = (1-\mu)(\frac{\mu(1+\mu)}{\sigma^2} - 1); \alpha = \frac{\mu \times \beta}{1-\mu} \tag{3.49}$$

Distribution mode represent the peak of of the distribution, which represents the quantile (x-axis value) with higher probability.

$$\frac{\alpha - 1}{\alpha + \beta - 2} for \alpha, \beta > 1 \tag{3.50}$$

Consider Figure 3.15 to illustrate Beta distributions based on different mode points.



(a) Beta distribution-Right skewed

(b) Beta distribution-centered

(c) Beta distribution-Left skewed

Figure 3.15: Beta distributions

The mode influence the skewness on the distribution function. Figure 3.15a present a right skewed distribution where lower variables have a high probability. While Figure 3.15b represent a symmetrical variable as a higher probability and Figure 3.15c depicts higher probability for the upper bound.

3.9 Goodness of fit

Goodness of Fit (GOF) test is a statistical hypothesis test to test how well the sample data fit a distribution from the population. Some of such type of tests are Chi-square (χ^2) and Kolmogorov Smirnov ($K - S$)
The Chi-square (χ^2) formula is expressed as followed:

$$\chi^2 = \Sigma \frac{(O_i - E_i)^2}{E_i} \tag{3.51}$$

Where O_i and E_i are the observation and expected frequency,respectively.
The kolmogorov-Smirnov is based on the largest vertical difference between the theoretical and empirical cumulative distribution function:

$$D = max\left(F(x_i) - \frac{i-1}{n}, \frac{i}{n} - F(x_i)\right) \tag{3.52}$$

These tests are conducted using computer based tool, such as Easyfit software. Three methods used in by Easyfit software, i.e. Kolmogorov Smirnov (K-S), Anderson Darling and Chi-square.

3.10 Chapter Summary

This chapter presented theoretical background of the electrical power system, with in depth focus on the distribution network which is where PVDG integration is prevalent. Characterization and impact factors that influence the behaviour of the network were presented, such as network topology, fault level and short circuit ratio. The PV system operation and characteristics were presented to give fundamental background to be considered in system modelling. Monte-Carlo simulation and random variable compilation were presented. Lastly, Goodness of Fit tests were presented and explained. The presented theoretical background will be applied in the next chapter.

Chapter 4

Modelling and Simulation

This chapter presents the proposed impact assessment methodology including variables modelling and data analysis intended to address the objectives of this study. Proposed modelling and analysis are based on theoretical background established in Chapter 3.

4.1 Introduction

Model is the mathematical representation of the system, which allows for the simulation and analysis of the system. This approach allows engineers and planners to predict the response of the power system when subjected to the change in system state. Figure 4.1 represent the the basic modelling approach in power system analysis and it is the same approach is adopted in this thesis.

Firstly, the two stage impact assessment framework consisting of time-series and probabilistic analysis is presented and detailed. Followed by presentation of study area and processing of available data (Load and generation), including modelling on simulation platform. Lastly, detailing method of deriving statistical information from the supplied data and their application in probabilistic analysis.

4.2 PV impact assessment methodology

In order to analyse the impact rooftop PV system on the existing distribution network, methodology shown in Figure 4.2 is adopted. The methodology consists of two types of analysis, i.e. time-series and probabilistic analysis.

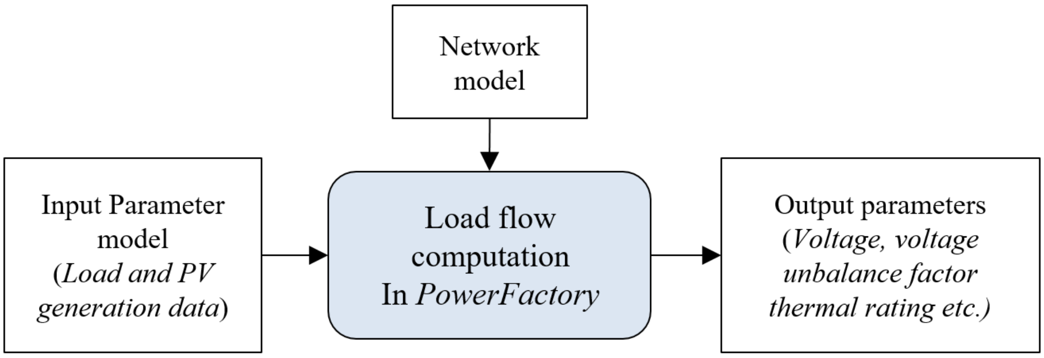


Figure 4.1: Basic modelling approach

4.2.1 Time-series analysis:

Prior to the PV integration analysis, a base case is determined to establish the initial state of the test network. The base case is conducted on an annual time-series load flow simulation and it is assumed that there are no PV systems connected. Once the initial state of the network is established, the annual time-series load flow simulation with installable PV capacity is conducted to determine critical point (greatest load PV generation difference) for further analysis. When the critical point is identified, probabilistic impact assessment described in subsection 4.2.2 is conducted for that particular point.

Time Series Simulation procedure

1. Acquire annual load demand and PV generation and save as .csv file with time stamp
2. Create load and PV characteristic in DIgSILENT PowerFactory as described in Appendix A.3
3. Run a load flow using a *Quasi-Dynamic command* in PoweFactory
4. Plot results (Voltage, voltage unbalance factor and equipment loading) for te simulation duration

4.2.2 Probabilistic analysis

There is high level of uncertainty in customer owned PV uptake and thus require a randomised analysis. In this study, Monte Carlo Simulations (MCS) are conducted to generate random variables to effect location and size of PV system as depicted in . It is assumed that all households are PV candidates with equal chances of installing PV

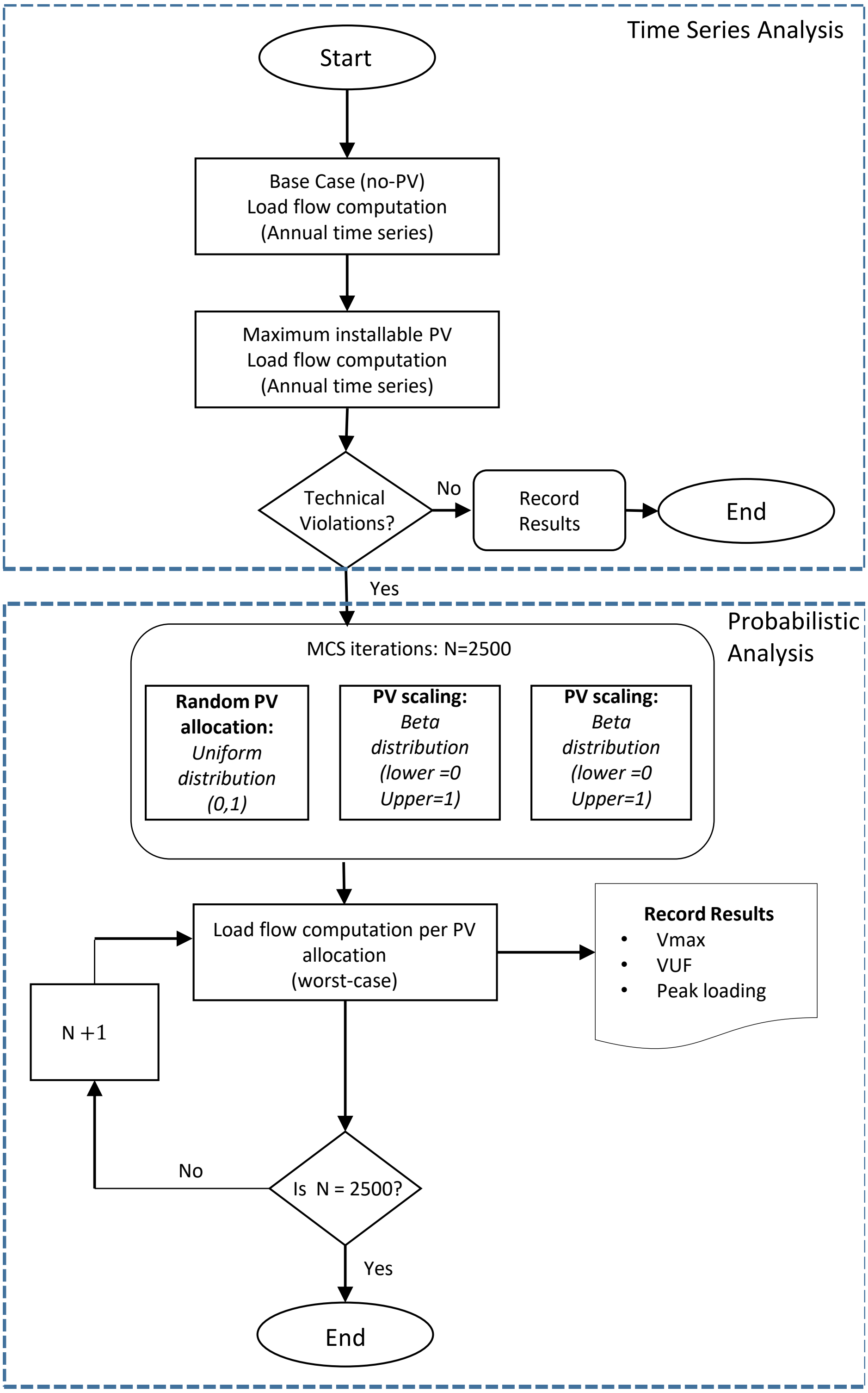


Figure 4.2: Proposed impact assessment methodology

system. To generate random locations and number of PV systems in a scenario, PV out of service parameter in Powerfactory is assigned a switching characteristic based on random variables following uniform probability distribution function (PDF) of 0 and 1 (where, 0 = in service and 1 = out of service). PV size is varied based on a potential rooftop PV limited by available roof space. PV scaling factor parameter is assigned a characteristic based on random variables following a beta PDF between 0 and 1.

These input variables are generated in Microsoft excel and saved as *.csv* file which

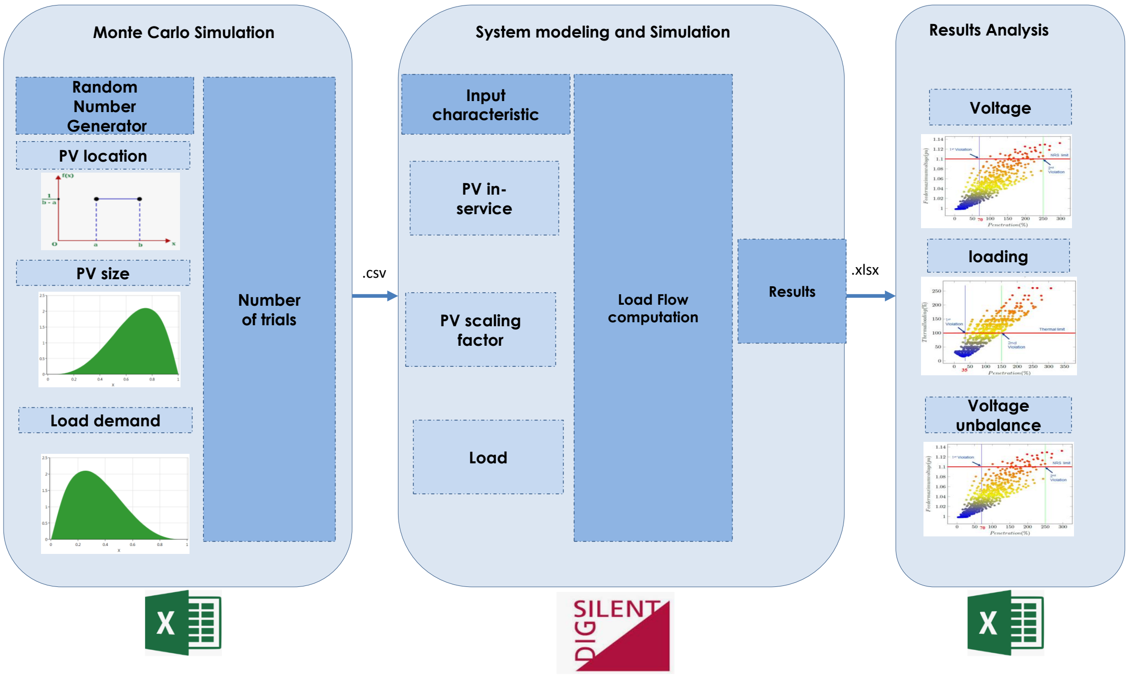


Figure 4.3: Probabilistic Load flow

can be read by Powerfactory. Each scenario is assigned a time step with a total step equal to number of MCS iterations and 2500 iterations was adopted for this study. Once *.csv* file is updated, load flow simulations are conducted for all possible scenarios in Powerfactory and results (voltage and equipment loading) are stored for further analysis. Load flows can either be balanced or unbalanced depending on how the test system was modelled. The output peak values per scenario are plotted into scatter plot for further analysis.

Probabilistic Simulation procedure

1. Identify instance of excess generation ($P_{net} = P_{generation} - P_{load}$)
2. save as .csv file with time stamp
3. Create load and PV characteristic as described in Appendix A.3
4. Run a load flow using a *Quasi-Dynamic command* in PoweFactory

4.2.3 Variables compilation

As presented in Figure 4.3, PV location, size and load demand are the three variables to be randomly varied based on PDF. Random number generator is critical in creating random variables and Microsoft Excel is used in this study. A standard excel function RAND() is used to generate a random number between 0 and 1. These random numbers are generated based on software internal algorithm, which makes them pseudo-random. However, for the balance of this work, the term *'Random-number'* is used to refer to this pseudo-random number.

Load

Customer owned PV capacity is considered to be random as its adoption is reliant many factors that can not be modelled with certainty. In this study, PV capacity is varied by applying a scaling factor to the rated capacity of individual customer load.

$$f(x) = BETA.INV(RAND(), \alpha, \beta, [A], [B]) \tag{4.1}$$

where

- α and β are beta distribution parameters
- $[A]$ is the lower bound
- $[B]$ is the upper bound

Probability distribution function for a specific load will be derived from historic data of a given network. Equation 4.1 set out to generate stochastic load inputs that follow a PDF that represent load population.

PV Allocation

The adoption of customer owned PV is governed by many factors as detailed in literature and their adoption is random. In order to represent this randomness, PV systems are switched in and out of service. to effect a uniform distribution with equal chances of either 0 or 1, the formula (4.2) was applied in excel to generate random PV allocations.

$$f(x) = IF * (RAND() < 0.5, 0, 1) \tag{4.2}$$

as a result, all random number below 0.5 will be rounded off to 0 and the applicable PV will be switch on. While, any random number above 0.5 will rounded up to 1 and the applicable PV will be switched out. This allocation is independent of the state of other PVs in the feeder.

PV capacity

Similar approach used for load modelling is also adopted in modelling input parameters for customer owned PV capacity. is considered to be random as its adoption is reliant many factors that can not be modelled with certainty. In this study, PV capacity is varied by applying a scaling factor to the rated capacity of individual PV system.

$$f(x) = BETA.INV(RAND(), \alpha, \beta, [A], [B]) \tag{4.3}$$

where

- α and β are beta distribution parameters
- $[A]$ is the lower bound
- $[B]$ is the upper bound

Potential rooftop PV and notified maximum demand are the two types of PV systems capacity boundaries considered in this study.

4.3 Simulation packages

Simulations are the integral part of this work and selection of proper simulation tool contribute in the accuracy of the analysis entailed in a study.

4.3.1 PowerFactory

DIgSILENT PowerFactory (DPF) version 2018 was selected as the main simulation platform for this study due to its wide adoption by utilities. PowerFactory was developed by DIGital SImuLation of Electrical NETworks (DIgSILENT). DPF is a computer-aided engineering tool for the analysis of transmission, distribution and industrial electrical power systems [17]. It has been widely used in previous research work for planning and operation analysis of power systems [125][126]. This software has a library of components necessary for the analysis required in this study and their characteristics can be modified for the representation of practical component. This software consists of load flow functionalities for both snapshot (Deterministic) or time series (know as Quasi-Dynamic) simulations. Computing this loaf flow simulations, system state can be established by recording the values for voltage, voltage unbalance factor and equipment loading. Due to the change in PV generation and Load demand are function of time, Quasi-Dynamic simulation will be used in this study.

4.4 System constraint

The distribution networks has to operate within set of prescribed parameters to ensure system security and quality of supply. For he purpose of this study, over voltage, voltage unbalance and equipment thermal limits will form part of network performance parameters considered to interpret the network response when subjected to high penetration of rooftop PV.

4.4.1 Voltage constraint

Voltage quality is crucial in LV network due to the inability of the customer to regulate supply voltage. As result, voltage limit range can be expressed as follows:

$$V_i^{min} \leq V_i^t \leq V_i^{max} \tag{4.4}$$

where, V_i^{min} and V_i^{max} are lower and upper bound of voltage in node$i$. The threshold for V_i^{min} and V_i^{max} are prescribed by NRS048-2 [39], where LV voltage variation should not vary outside of $\pm 10\%$ of rated voltage at customer point of supply.

4.4.2 Voltage unbalance

According to NRS048-2 [39], compatibility level of Voltage unbalance in three phase networks is restricted to 2% and 3% for predominantly single phase or bi-phase networks, respectively.

$$V_{unbalance} \geq 2\% \tag{4.5}$$

The voltage unbalance limit of 2% is adopted in this study.

4.4.3 Thermal constraint

The flow of current in the electrical equipment (conductor or transformer in this study) results in the increase in thermal characteristic of the equipment due to joule effect [85]. Thermal loading of equipment is specified by the manufacturer and it can be represented by (4.6).

$$I_i^t \leq I_{rated} \tag{4.6}$$

Where I_i^t is the current flowing on the conductor and I_{rated} current rating of the conductor.

4.5 System modelling

The proposed methodology is applied to asses the impact of rooftop PV to the real urban LV network. In order to run simulations, system models had to be created in DIgSILENT PowerFactory and the required models are:

- Test network model
- Load model
- PV generation model

The following subsections will provide details on the selected study area and how system components were models.

4.5.1 Test network Description and modelling

Impact assessment is conducted on a real LV urban residential feeder located in Cape Town, South Africa. The test LV feeder is supplied by an 11kV feeder supplied from HV/MV substation all modelled in PowerFactory. A single line diagram of the test feeder is depicted in Figure 4.4. This test feeder consists of a single 315kVA Dyn11 11.66/0.42kV transformer and it supplies 18 households. The feeder consists of 4-wire LV underground cables, with a conductors size range of $35 - 300m2$. A single load and PV are modelled to represent the summated load and generation of the customers supplied from the particular node.

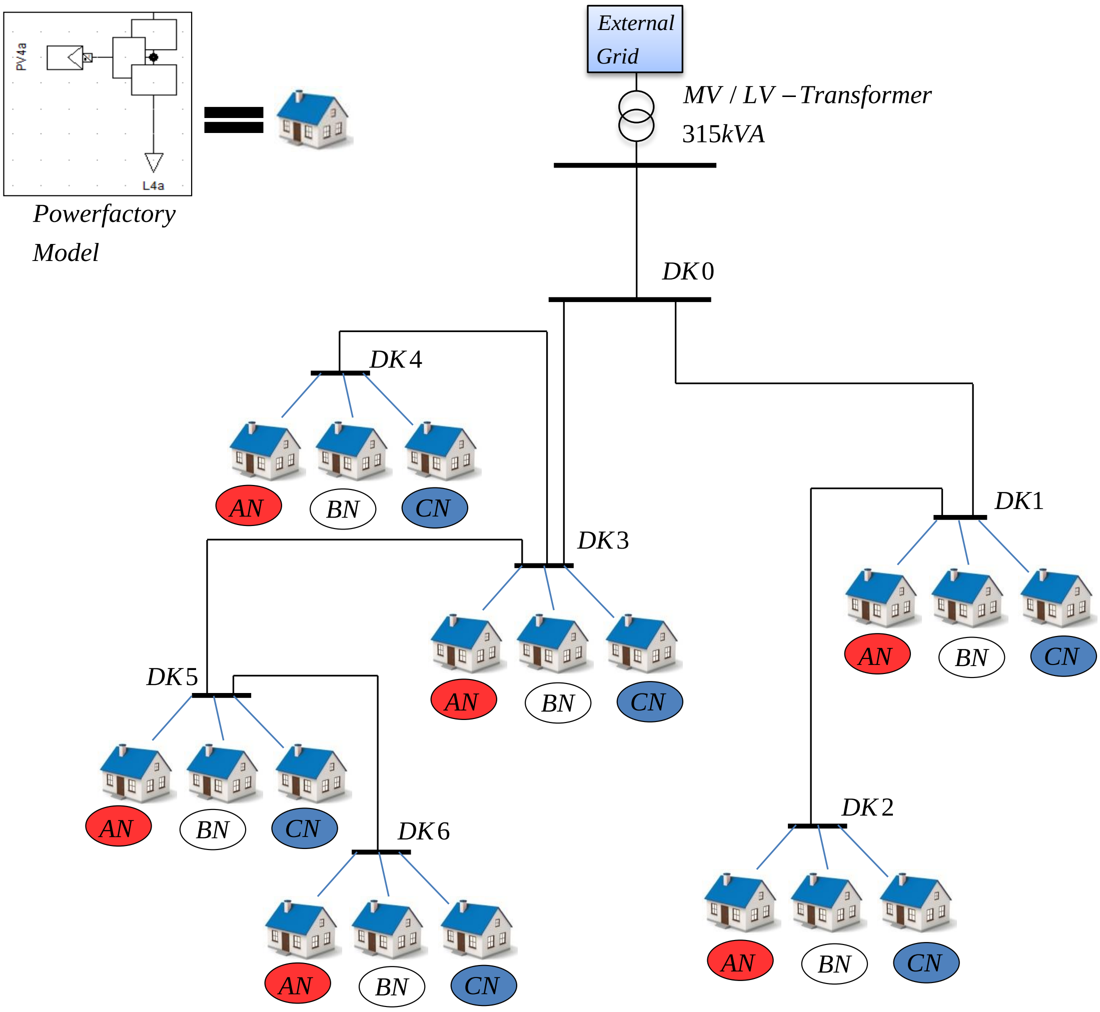


Figure 4.4: LV test network

Major network assumptions

Due to the absence of information relating to the real network,some modelling assumptions where made as follows:

- Households are assumed to be evenly distributed on each node and resulting into three house per node.
- Each household is considered to be rooftop PV candidate.

The cable parameters of the test feeder are detailed in Figure4.1. Urban feeders are relatively short and the cable capacitance are negligible[110]. Therefore, cable modelling include resistance, reactance and ampacity.

The test LV feeder is supplied by a 315kVA Dyn11 transformer and its details are of interest for modeling purposes.

Table 4.1: Test network cable data

Cable *Description*	**Length** *(km)*	R_1 (Ω)	X_1 (Ω)	I_{rated} (kA)
Linetx-0	0.014	0.023	0.001	0.270
Line0-1	0.014	0.023	0.001	0.270
Line1-2	0.065	0.056	0.005	0.105
Line0-3	0.046	0.012	0.003	0.210
Line3-4	0.087	0.039	0.006	0.155
Line3-5	0.063	0.028	0.005	0.155
Line5-6	0.108	0.094	0.008	0.105

Table 4.2: MV/LV Transformer details of test network

Tx Rating kVA	**Count** *no.*
200	1
315	7
500	4
800	2
6005	14

Table 4.3: MV/LV Transformer details for LV feeder

Parameter	**Value**	**Unit**
S_{rating}	315	kVA
Voltage Ratio	11.66/420	kV
Vector group	Dyn11	
X/R ratio	22	

4.5.2 Load modelling

Customer load data with appropriate resolution is critical in evaluating the impact of customer-owned PV system on the network. As Discussed in section 3.2.5, this data is not easily available especially for the LV level were PV uptake is prevalent.
The same data issues are available in the test system, where only the aggregated 30 minute average RMS load data measured at HV/MV substation for individual feeder are available and there are no further data recording downstream.
A historic load demand data from January to December 2016 was obtained from the utility and it presented in Figure 4.5. The yearly load curve can be observed, with

annual peak load demand of 4.3 MVA occurring in winter season.

To illustrate seasonal profiles, a sample of daily loads curves for winter and summer

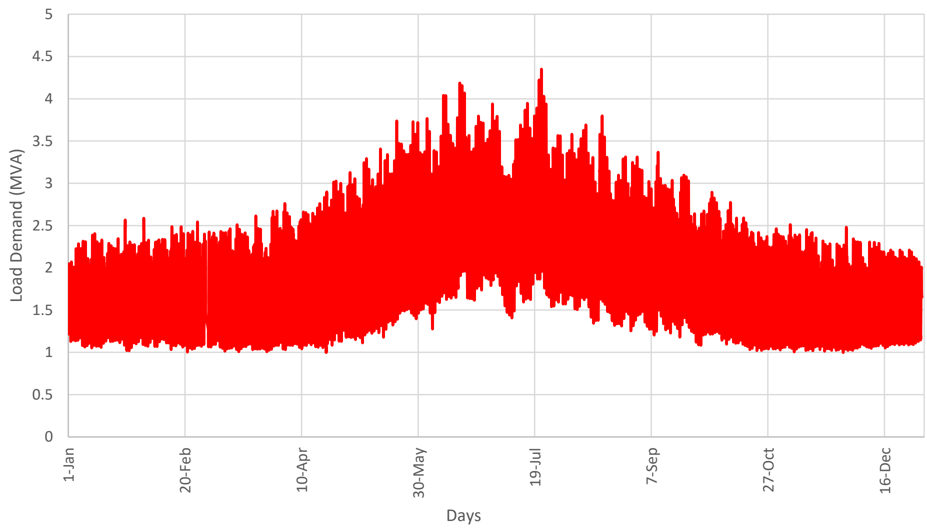


Figure 4.5: MV feeder annual load demand

day is presented in Figure 4.6 below.

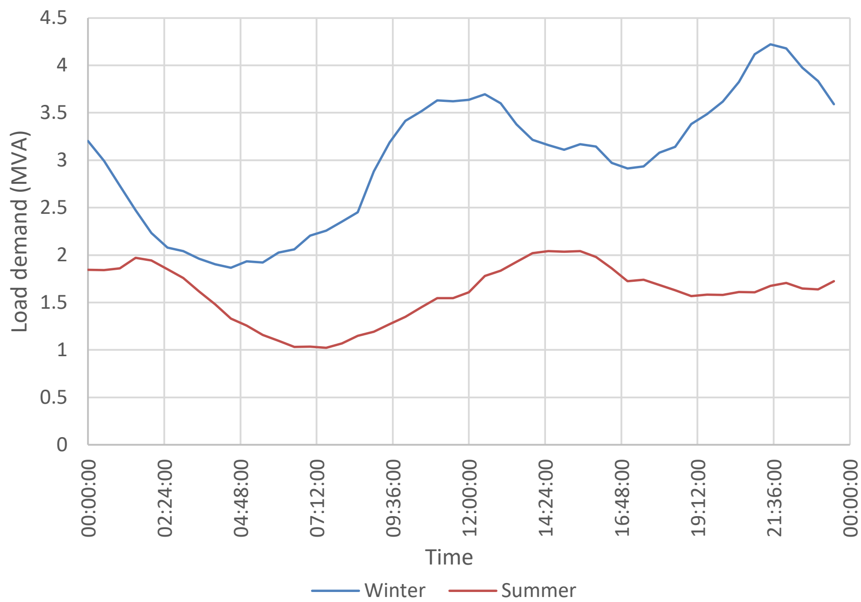


Figure 4.6: Typical load for winter and Summer day

With the adoption of rooftop PV occurring at customer premises, it is crucial to represent this data at the load point and load disaggregation have to be applied as detailed in Subsection 4.5.2 below.

Load Allocation

In order to conduct simulations, load demand has to be assigned to the individual load point in the model. Load scaling method was utilized to estimate load at points were consumption data is unknown. Load scaling is a top-down method of estimating load allocation along the feeder to sum up to the known measurement at the beginning of the feeder (typically at the HV/MV substation) and it is a standard feature in DIgSILENT PowerFactory software[17]. Load scaling is conducted in two phases, i.e. MV and consumer load scaling. This method is preferred for the same customer group, as it retains the load profile of the group.

The industry approach is to employ proportion of a MV/LV transformer in relation to the total installed capacity along an MV feeder is used to estimate the MV load of a given transformer and this approach was adopted in [127]. Load scaling at each transformer can be determined by equation (4.7) below.

$$P_x = \frac{S_x}{S_{total}} \times P_{feeder} \tag{4.7}$$

Where P_x is the scaled load at transformer x, S_x is the transformer rated capacity, S_{total} is the total installed transformer capacity along the feeder and P_{feeder} is the total feeder load measured at the beginning of feeder. By employing equation (4.7) with the MV/LV transformer details in Table 4.2, load scaling factor of the test LV feeder was estimated as follows:

$$P_x = \frac{315}{6005} \times P_{feeder} = 0.0524 \times P_{feeder}$$

Further load disaggregation was required at the load points along the LV feeder. The concept by Heunis and Dekenah [128] is applied, where they found that the high income customers has a high electricity consumption and has a direct correlation with the property floor space. By applying this technique, the estimate load at point of common coupling can be determined by modifying the previous Equation (4.7) into:

$$P_{pcc} = \frac{A_{pcc}}{A_{total}} \times P_x \tag{4.8}$$

Where P_{pcc} is the scaled load at point of common coupling, A_{pcc} is the summated property floor area on properties supplied at pcc, A_{total} is the total floor area of properties connected along the feeder and P_x is the scaled load at transformer x.

ArcGIS tool was used to quantify property floor area by building polygons, as depicted in Figure 4.7. By employing equations (4.7) and (4.8), resulting load scaling factor for the test network are presented in table 4.4 below. Load at each node is allocated

Figure 4.7: Study area property footprint

Table 4.4: Load scaling factor details

Bus	**Property area**	**Scaling factor**
Bus 1	1169	0.169
Bus 2	1481	0.214
Bus 3	839	0.121
Bus 4	1232	0.178
Bus 5	1143	0.165
Bus 6	1049	0.152

based on the appropriate scaling factor.

Table 4.5: Summated floor size per node point

Bus no	**Bus1**	**Bus2**	**Bus3**	**Bus4**	**Bus5**	**Bus6**
Property 1 (m^2)	300	562	190	479	340	316
Property 2 (m^2)	393	448	351	431	413	343
Property 3 (m^2)	476	471	298	322	390	390
Area(m^2)	1169	1481	839	1232	1143	1049

By applying the prescribed methodology, the load demand details are summarized in Table 4.6. The limitation of this approach is that during planning stage, the over-rated (high capacity) transformer may be installed with the anticipation of future load and this may result in some of the network transformers being lightly loaded. This

Table 4.6: Load demand summary

Bus number	**Phase**	$S_{1-phase}(kVA)$	$S_{3-phase}(kVA)$	$Cos\theta$
	a	3.4645		0.95
DK1	b	4.538494	13.50	0.95
	c	5.497006		0.95
	a	6.526941		0.95
DK2	b	5.202971	17.20	0.95
	c	5.470088		0.95
	a	2.196663		0.95
DK3	b	4.058045	9.70	0.95
	c	3.445292		0.95
	a	5.559821		0.95
DK4	b	5.002679	14.30	0.95
	c	3.7375		0.95
	a	3.926509		0.95
DK5	b	4.769554	12.20	0.95
	c	3.5		0.95
	a	3.675119		0.95
DK6	b	3.98913	12.20	0.95
	c	4.535748		0.95

method is also not that effective for the combination of different load classes (commercial and residential), as it does not eliminate the residential characteristic from the load measurements (morning and afternoon peaks for residential load).

Phase allocation

Phase allocation is crucial in single phase system and DNO are allocating customers on a busbar as balanced as possible. Although customers are evenly allocated on a busbar (3per busbar), the overall feeder phase allocation is considered.

4.5.3 PV generation Modelling

The Photovoltaic system considered for this study is a rooftop PV system, installed at customer premises consisting of PV modules and inverter converting DC power from PV to AC power. The output power is based on the I-V characteristic of the PV module and dependent on solar irradiance, ambient temperature and the characteristics of the module itself [88, 93]. PowerFactory software has a standard PV model (.$ElmPvsys$), with input variable modelled as[17]:

- Active Power Input, or
- Solar calculation

Active power input provides an opportunity to model a production profile of a reference PV system, where the this data is available. while on the other hand solar calculation is used in an a case where the data of the solar panel type, the arrangement of the solar array, the local time and date, and optionally irradiance data, with the option[17]. In this study, the active power input model was adopted and active power production was generated with PVsyst software for Cape Town area.

The PV generation profile used in this study is based on the typical meteorological year (TMY) data derived from PVsyst for a typical PV installation Cape Town, South Africa. PVsyst has built in METEONORM meteorological database, with res

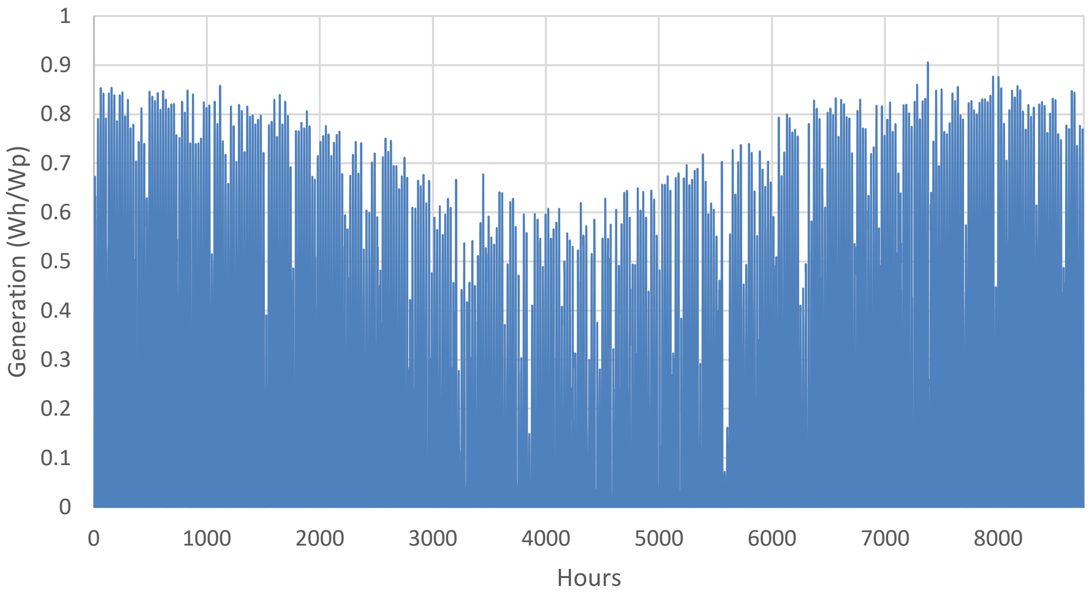


Figure 4.8: Typical Cape Town PV generation

Details of a PV module used for generating test PV system are detailed in table4.7.

PV potential

The rooftop PV system is the considered for this study and the PV potential of the study area has to be quantified. There are many techniques presented in literature on how to quantify rooftop PV potential. By considering equation (3.6), output power of

Table 4.7: PV module characteristics

Parameters	**Specification**
Make	Yingli solar
Model	YL290P-35b
Cell type	Si-poly
Maximum power (P_{max})	290 W
Open circuit voltage (V_{oc})	44.8 V
Short circuit current (I_{sc})	8.68 A
Voltage at maximum power (V_{mp})	35.8 V
Current at maximum power (I_{mp})	8.11 A
Number of cells in a module	72

a PV system can be expressed as follows:

$$P_{pv} = I_{(s)} \times cos\phi \times \eta_m \times \eta_p \times A_p \tag{4.9}$$

The potential installable area is based on the available roof space. The PV potential of all the houses supplied by the test feeder/s is modelled based on the available roof space, inclination and orientation. The roof features were modelled in ArcGIS software and details for the area are depicted in Figure 4.9.

Figure 4.9

Roof areas are modelled based on the available area as seen from the aerial image and the obvious obstacles (trees, fire chimney etc.) are excluded in the model. The available roof areas are traced out by building polygons on ArcGIS with area feature in order to quantify the available area.

The roof inclination is based on the angle of the roof in relation to the horizontal plane. Properties with the same area consist of different roof inclination and some assumptions had to be made for modelling simplification. It is assumed in this study that all inclined roofs have inclination of 33^o and the flat roofs have inclination of 0^o.

The roof orientation (Azimuth) refers to the direction the roof is facing and for optimal PV orientation . The study area is situated at the southern side of the equator; the south facing roofs will not be considered in the model. There are five orientations considered in the study, i.e. North, North east, North West, East and West. Different colours are allocated to each orientation in order to easily differentiate between orientations.

Table 4.8: Available roof space

Orientation *Description*	**Area** m^2
North	1499
North East	119
North West	0
East	881
West	805
Flat	1857
Total Area	5161
Installable PV capacity	757

The same approach is used to determine the installable PV capacity per point of common coupling. the potential roof area of properties supplied from a given node used to quantify the installable PV capacity on a node. Table4.9 provided a summary of summated rooftop area and installable PV capacity per node.

4.6 Preliminary Simulations: Critical time identification

Computing annual power flow simulation provides detailed insight on the Grid integration impact of PV generation due to their dependency on weather which varies

Table 4.9: Installable PV capacity per node point

Bus no	Bus1	Bus2	Bus3	Bus4	Bus5	Bus6
Property 1 (m^2)	146.67	292.47	330.99	195.52	484.60	231.20
Property 2 (m^2)	366.67	389.96	289.61	146.64	302.89	462.39
Property 3 (m^2)	220	194.98	206.87	146.64	424.04	231.20
Area(m^2)	733.34	974.91	827.47	488.81	1211.54	924.78
Installable PV capacity(kWp)	109.06	144.99	123.06	72.69	180.18	137.53

based on time of the day and season. Considering vast possible scenarios that has to be investigated, running annual time step simulation constitute high computational burden. Therefore, some assumptions had to be made to reduce computational time by identifying critical time that lead to worst case violation. This scenario is intended to identify the critical time where the deference between the load and PV generation is at its highest in a sample period (P_G - P_L = P_{max}). This point is identified by the following network condition:

- Year peak voltage
- Equipment overload (i.e. Cable segment and transformer)

To determine the day with worst parameter violation, a 30minute interval Quasi-dynamic balanced three-phase load flow simulation for a year was conducted using PowerFactory software. The resultant annual voltage profile for the furthest busbar is presented in Figure 4.10 and the peak voltage for the year was found to be 30/11/2016 at 12:00pm (Wednesday), with peak voltage violation of 1.13pu. Due to this statutory limits violations, PV penetration impact on test LV network will be further investigated.

Figure 4.11 presents a full day profile of the aggregated load and PV generation. It can be seen that the potential generation is greater than the load demand, thus resulting in voltage rise on the test feeder. therefore, the worst case analysis will be conducted based on this state of the network.

4.7 Probabilistic parameter modeling

The proposed Probabilistic methodology presented in Figure 4.3 require three variables (load, PV size and PV location) to be presented in a statistical form using probability density functions.

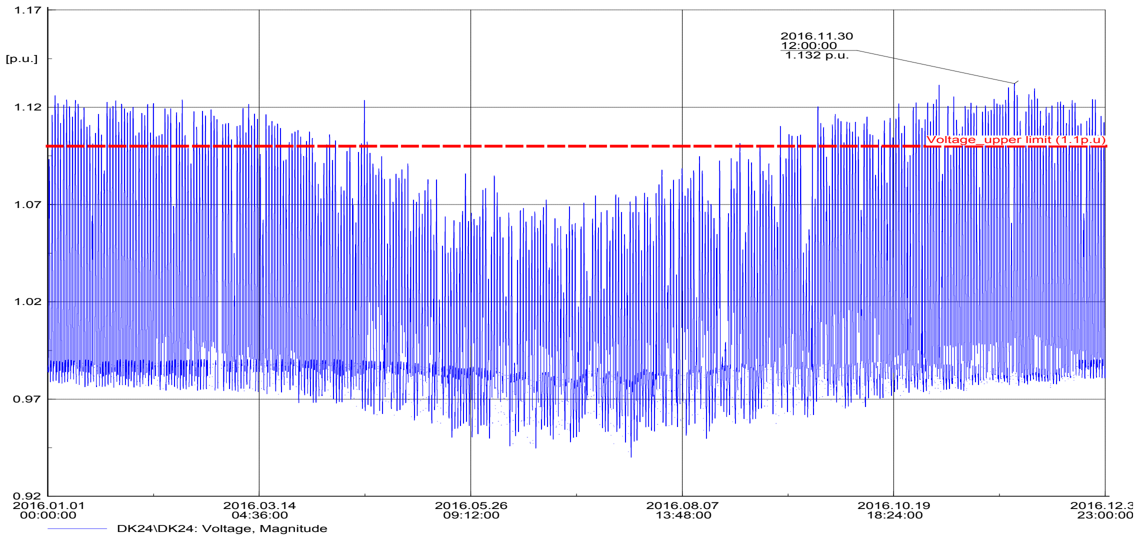


Figure 4.10: Annual voltage distribution of DK6

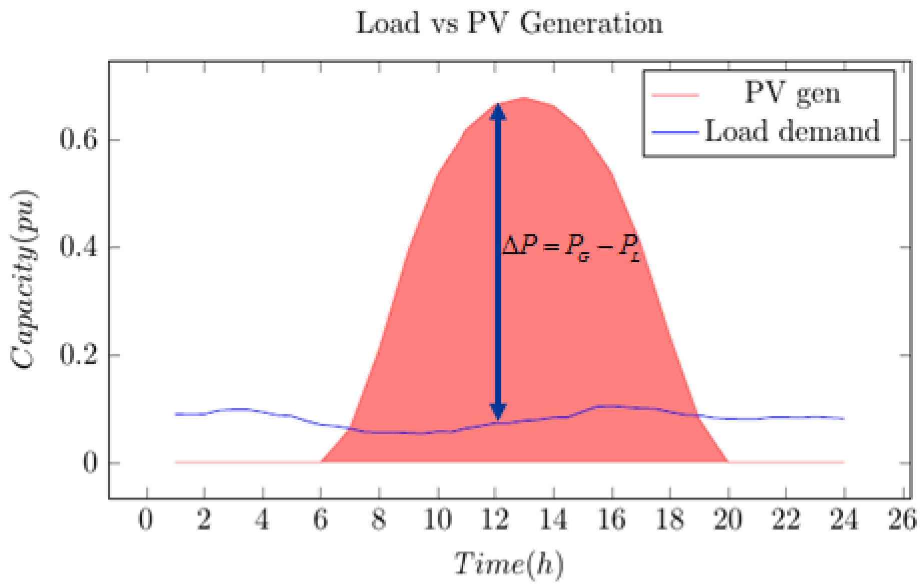


Figure 4.11: Load vs PV Hour of interest

4.7.1 Probabilistic load modelling

Although the load demand probability has been well documented that the LV load follows beta pdf[15][92], for the purpose of this study, PDF will be derived from the supplied load data from the utility. From Figure 4.11, 12 O'clock appear to be the hour of interest where ΔP between load and generation is at its highest. With the load data being a 30minute average value, Beta PDF is fitted on the histogram of hour of interest (11:30am to 12:30pm)load data for three months period (October to December) and making up 184 sample points ($N = 92 \times 2$). Figure 4.12 present the resulting load PDF derived for *load4a* and data fitting of beta distribution is applied.

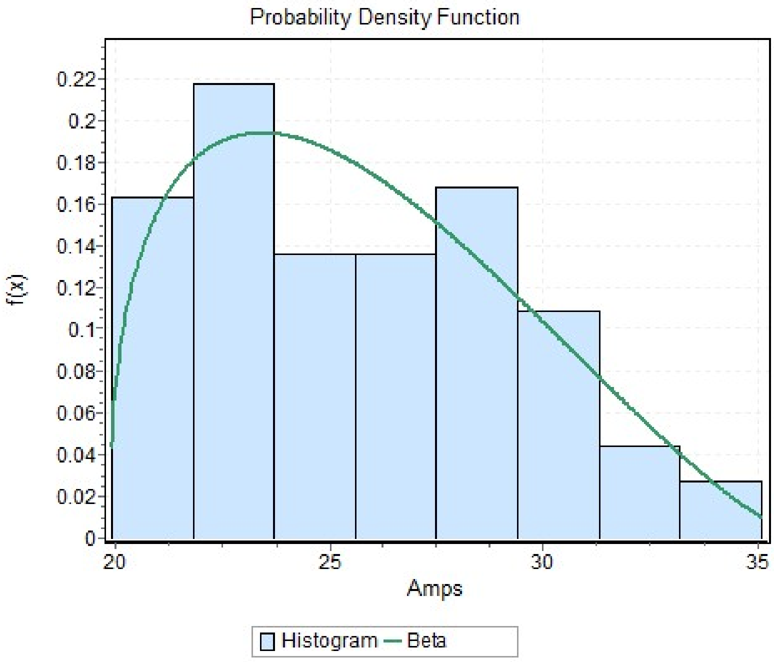


Figure 4.12: Load demand pdf

The resulted Beta parameters (α, β) per load are detailed in Table B.1.

4.7.2 Probabilistic PV output modelling

Similar to the load modelling, the PV output power PDF is compiled based on the 12 O'clock generation data. Figure 4.13 depicts the 12 O'clock PV generation histogram fitted with multiple distributions and Beta PDF was found to be the best fit (see Figure 4.14).

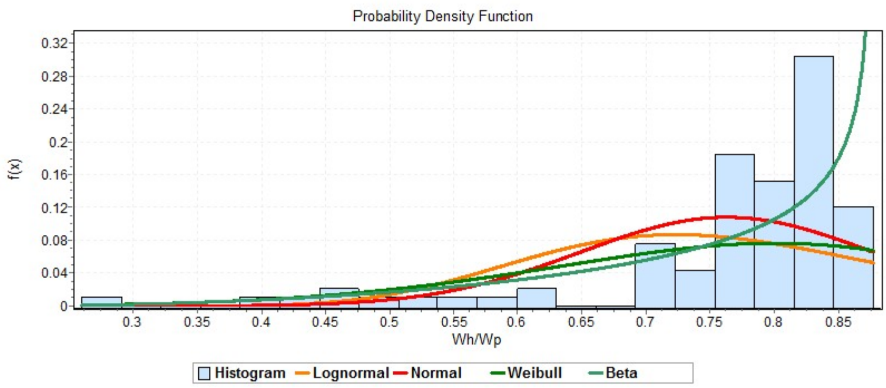


Figure 4.13: Distribution fitting on 12 pm PV output (Oct - Dec period)

Graphs | Summary | Goodness of Fit

Goodness of Fit - Summary

#	Distribution	Kolmogorov Smirnov		Anderson Darling		Chi-Squared	
		Statistic	Rank	Statistic	Rank	Statistic	Rank
1	Beta	0.19356	1	9.8305	2	N/A	
2	Lognormal	0.27687	5	11.847	4	42.621	1
3	Normal	0.23728	2	8.8824	1	47.629	2
4	Uniform	0.24677	3	34.862	5	N/A	
5	Weibull	0.27522	4	10.485	3	90.727	3

Figure 4.14: Goodness of Fit results for 12 pm PV output (Oct - Dec period)

The resulted parameter per PV are detailed in Table

4.8 Results interpretation

The projected adoption of PV systems is expected to increase and as a result, its share into the existing electrical network will increase as well. Before exploring further on impacts of DG integration into the grid, it is critical to understand the two commonly used terms in grid integration literature, penetration level and hosting capacity.

The term *'penetration level'* has been a widely used in literature to refer to the increasing uptake trend of PV into the existing electrical network. However, many authors have applied this term in many ways depending on the assumptions made on the study. The term is used to illustrate the proportion of units equipped with PV system [129] and the assumption is that the PV capacity is known. The other application is proportion of the installed PV capacity to the peak load of the feeder [130][73]. This definition incorporates the possible uncertainty relating to the size of the PV system to be installed at a given PCC. These two applications of the term 'penetration level' in literature make it crucial to define the application of this term in a given study as it has an impact on the interpretation of the findings.

Hosting capacity of a distribution feeder is the maximum amount of distributed generation (Rooftop PV in this study) that can be integrated without violating the thresholds of any impact criteria [61]. The integration of PV system is likely to impact numerous performance parameters; this study is limited to the impact on voltage magnitude and equipment loading.

The performance indicators will be based on the thresholds stipulated in the grid code governing the Quality of Supply (QOS). According to [131], the MV and LV voltage variation should not vary more than ±5% and ±10% of rated voltage at customer point of supply respectively.

Penetration level

$$PL_{PV} = \frac{\sum_{i=0}^{n} PV_{rated}}{FMD} \tag{4.10}$$

4.9 Scenario planning

The simulated case studies are formulated into four sections as detailed below. Each scenario is intended to highlight a certain aspect that will provide insight on the network performance when subjected to high penetration of rooftop PV. In general, first set of case studies (Case1 and 2) are based on balanced three phase analysis and the rooftop PV are limited by the potential roof space. while the other set (Case3 and 4) are based on unbalanced three phase analysis and the single-phase rooftop PV system are limited by circuit breaker current carrying capacity ($I = 80A$ for this study). The other aspect is to investigate how the network performance is influence different load modelling in the analysis, i.e. constant load with varying PVDG parameters (size and location) *vs.* varying load with varying PVDG parameters (size and location).

- Case1: The impact of three-phase grid-connected PVDG (constant load)
- Case2: The impact of three-phase grid-connected PVDG (probabilistic load)
- Case3: The impact of single-phase grid-connected PVDG (constant load)
- Case4: The impact of single-phase grid-connected PVDG (Probabilistic load)

Each case consists of two scenarios, 1) base scenario representing a passive network performance in the absence of PV and 2) the second scenario representing active network with PV. In each scenario, system parameters such as voltage magnitude, voltage unbalance factor and equipment loading are recorded per each load flow iteration. These results will be further analysed to understand the response of the test network.

4.10 Limitations of time series and probabilistic modelling

The adopted type of system modelling consists of both positive and negative attributes. The chosen method will be dependent on the parameter to be investigated. The time series analysis expands from deterministic (Snap-shot approach) to incorporate time dependency of the input variables, which will illustrate time of the day to seasonal pattern.

On the other hand, probabilistic modelling incorporate the associated uncertainty of input variables, influenced by many myriad of factors.

4.11 Chapter summary

In this chapter, a simulation framework to investigate impact assessment of high rooftop PV penetration into distribution network is proposed. The proposed simulation methods are time series and the probabilistic modelling. Time series analysis was applied to identify the point of interest where the impact of PV to the distribution network will be at its highest. For the identified point, the historic data is used to generate probability distribution functions for the input variables (load and generation) and Goodness of Fit technique was applied to determine beta parameters for input variables. The test network was presented and their history data were used to generate PDF for probabilistic load flow analysis. In the next chapter, models and procedures presented will be applied to assess the technical impact PV on the urban residential network.

Chapter 5

Impact of Rooftop PV on Cape Town Urban Residential Feeder

This chapter presents simulation results on the impact of integration of high penetration level of rooftop PV on the Cape Town urban residential low-voltage network and the analysis are based on the probabilistic impact assessment methodology presented in Chapter 4. The results presented in this chapter are intended to investigate the impact of PV integration by evaluating the network parameters i.e over voltage, voltage unbalance and equipment loading. Lastly, the hosting capacity of the test network is quantified.

5.1 Introduction

The main objective of this study is to investigate the impact of high penetration rooftop PV in the existing electrical network. To achieve this objective, analysis has to be made to determine distribution network performance pre and post PV integration. Simulations were conducted based on models and methods presented in Chapter 4. The system analysis are based on solely three phase or single phase system. Some of the results in this chapter are published in [132]

5.2 Penetration level definition

Results in this Chapter are referenced in relation to the penetration level and thus need to be defined. In this study, penetration level is defined as the total summated PV ratings in relation to the feeder maximum demand (FMD) as formulated in Equation 5.2.

$$PL_{PV} = \frac{\sum_{i=0}^{n} PV_{rated}}{FMD}$$

Prior to the analysis, FMD had to be quantified for the test feeder. The design FMD was determined by gradually increasing loads on all load points, until the first violation of either voltage or overloading is reached and a load resulting in this violation is considered a FMD. Therefore, PV penetration level is feeder specific. The first violation was due to overload violation at 210kVA, thus the FMD for the test feeder is assumed to be 210kVA.

5.3 Case1: The impact of three-phase grid-connected PVDG (Constant load)

This case investigates impact of integrating a three phase PV system into a balanced three phase network. Powerflow simulations for prior and post PV integration are conducted in DIgSilent PowerFactory and network state (Voltage profile and equipment loading) is recorded. All analysis are based on Load and PV generation profile for the critical day identified in Section 4.6 of previous chapter. Throughout this case it is assumed that the loads are constant.

In this subsection the network status is evaluated in the absence of the PV generation. All customer loads are modelled as three-phase loads and balanced load flow if computed to establish the network status (Voltage magnitude and equipment loading).

5.3.1 Impact on voltage

Passive feeder

The voltage profile along the test feeder is presented in Figure 5.1. Dot represent a busbar and a line joining dots represents a cable between busbars. It can be observed that in absence of PV, the feeder experiences voltage drops as the busbar is further from the transformer and the steepness between busbars indicate high voltage drop. The closest busbar to the transformer, DK0, showed the highest voltage magnitude of 0.998p.u (399.2 V).The furthers busbar from the transformer, DK6, showed the lowest voltage magnitude of 0.984p.u (393.6 V). Voltage magnitude for other busbars are within the two bounds and they are detailed in Table.B.3.

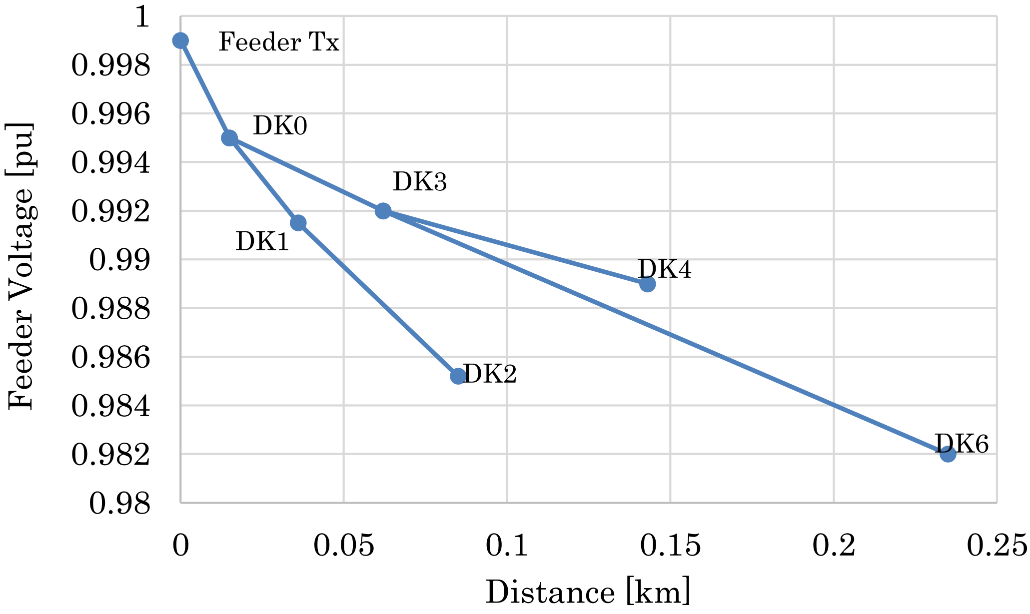


Figure 5.1: Balanced feeder voltage profile without PV

Active feeder

In this scenario, a scatter plot was used to illustrate the relationship between feeder peak voltage and penetration of rooftop PV system into test LV feeder. Figure 5.2 depicts peak voltages anywhere in the network based on varied size and allocation of PV systems (each dot represent a scenario). It is observed with an increases in PL_{pv} feeder voltage improves and move towards voltage upper limit.

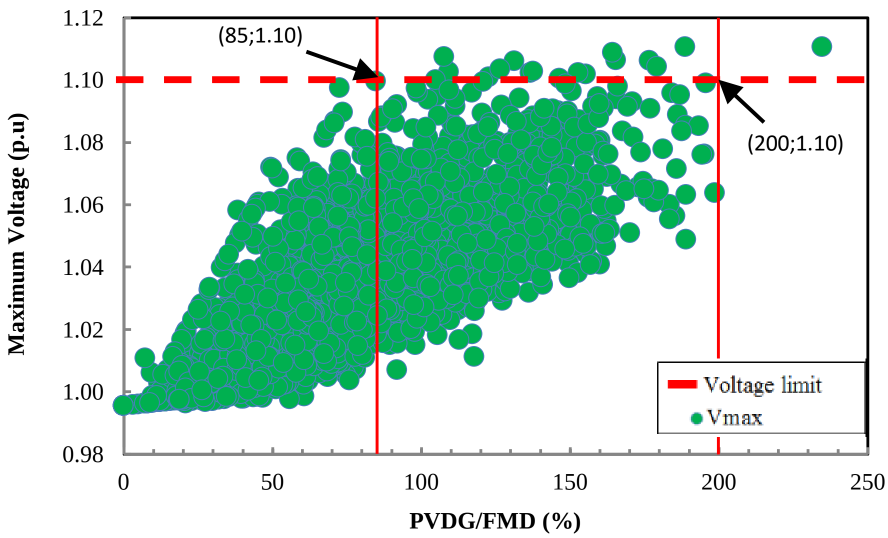


Figure 5.2: Maximum voltage

By considering the voltage upper limit of 1.10 pu, the first violation is observed at 85% penetration level (178.5kW). Beyond this point, probability of violation increases based on the PV capacity and location.

5.3.2 Impact on Loading

Active feeder

Scatter plot in Figure 5.3 presents maximum cable loading anywhere in the network based on varied penetration level.

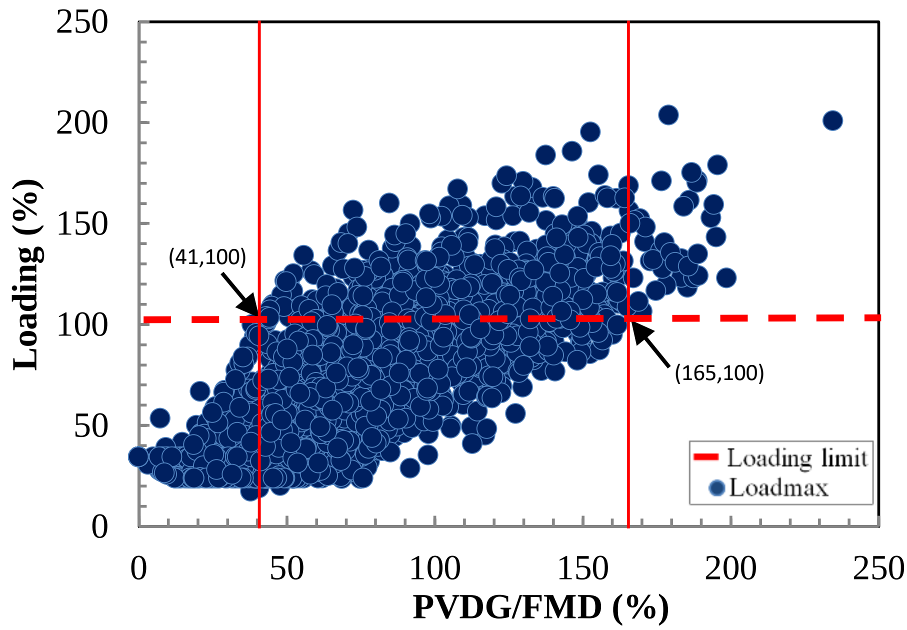


Figure 5.3: Maximum feeder loading (3-phase)

Scatter plot indicate an increase in cable loading with an increase in penetration level. However, there are scenario that actually results reduction in feeder loading. The initial drop in feeder loading can be observed from the plot with an increase in PL_{pv} as from 0% to about 40% and this represent load-generation equilibrium. From this point on, there is a ramping up of feeder loading due to reverse power flow.
The maximum feeder loading threshold is reached at 41% penetration level (86 kWp) and it is regarded as the first violation point. Beyond this penetration level, the probability of thermal violation increases and resulting in conditional hosting capacity. Beyond 165% PL_{pv} (346.5 kWp), any combination will result in feeder loading violation.

5.4 Case2: The impact of three-phase grid-connected PVDG (probabilistic load)

This case is intended to investigate impact of integrating a three phase PV system into the balance three phase network. The difference from the previous case is that loads, PV output and location are statistically represented based on PDF characteristics developed in Chapter 4.

5.4.1 Impact on voltage

Passive feeder

The voltage drop is the main concern on a passive feeder, as result the feeder minimum voltage is presented in Figure 5.4. The voltage drops with an increase in load demand ranging from 0.975 to 0.935 pu (390V to 375V (V_{l-l})). For a sampled load data from load demand PDFs, feeder voltage drop is still within a permissible minimum voltage limit.

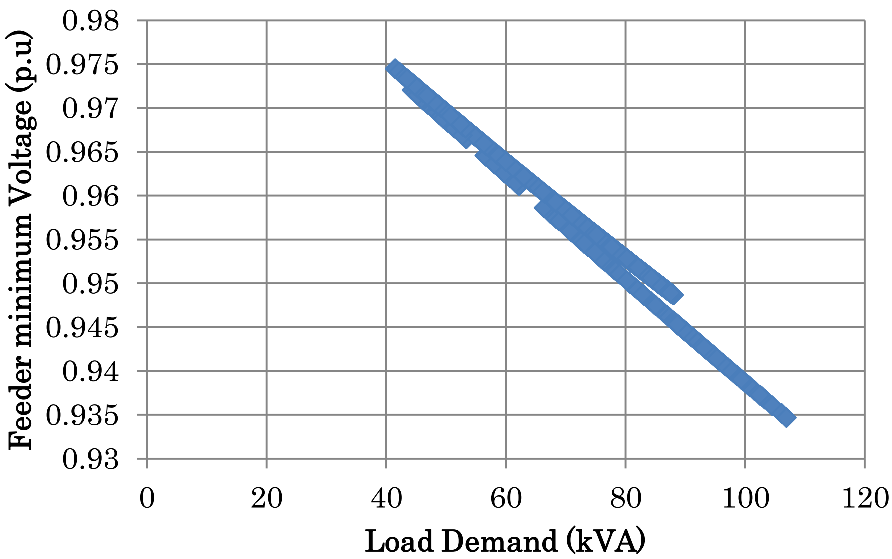


Figure 5.4: Feeder minimum voltage

Active feeder

The effect of PV integration on feeder voltage is shown by scatter plot in Figure 5.5 which illustrate feeder maximum voltage impact of integrating PV into the balanced test feeder. It is observed that the feeder maximum voltage increase with an increase in PL_{pv}.

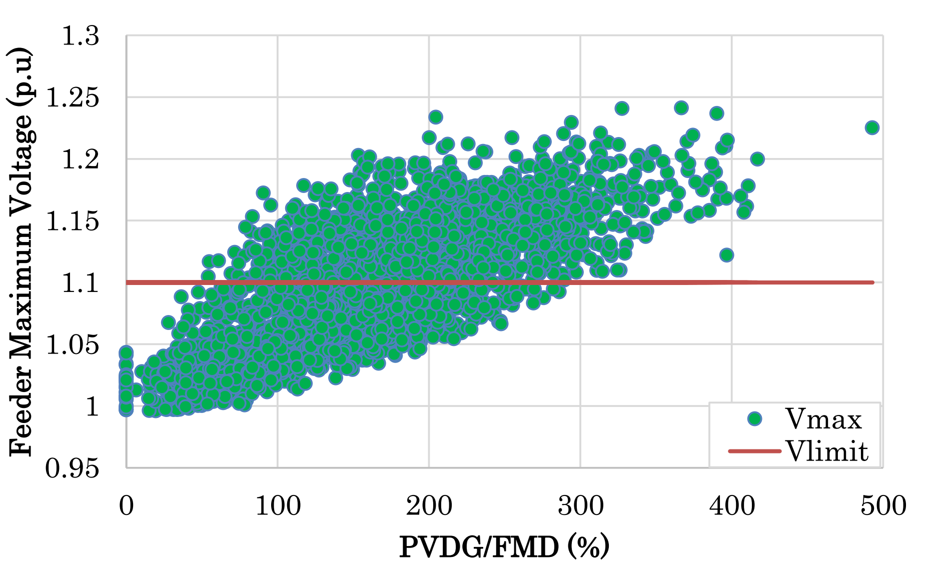


Figure 5.5: Feeder maximum voltage due to three phase PV integration

At a zero penetration level, feeder maximum voltage ranges between 0.99 p.u to about 1.04 pu (396V to 416V (V_{l-l})). Increase in PL_{pv} improves feeder voltage and until voltage upper limit is reached at 50.2% (105.4kWp) penetration level. Beyond this point to 300% (630 kWp) penetration level, voltage violation probability increases. Beyond 300% PL_{pv}, any combination will result in voltage violation.

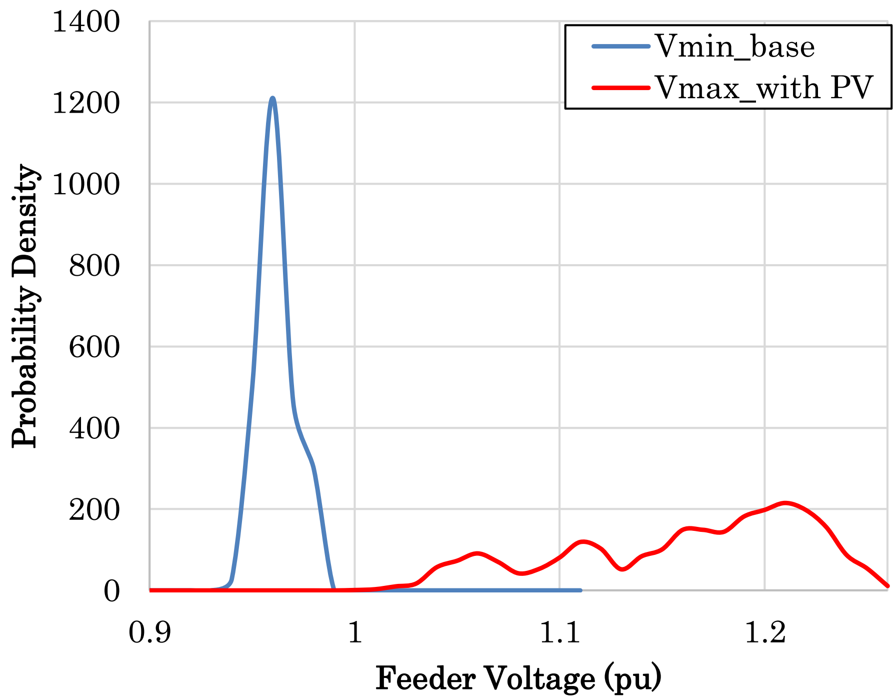


Figure 5.6: Feeder voltage comparison

Figure 5.6 illustrates voltage violation probability with and without PV integration. Base minimum feeder voltage PDF with mean value of 0.955 pu (382V). While, base feeder maximum is constantly at 1.0 pu which is the voltage transformer secondary busbar. Integration of PV results in Feeder maximum voltage PDF skewed to the left, with mode value of 1.21pu.

5.4.2 Impact on Loading

Active feeder

Figure 5.7 shows a feeder maximum loading against load demand in the absence of PV system. It is observed that feeder loading increase with an increase load demand, ranging from 16.6% to 42.6% for minimum and maximum feeder loading.

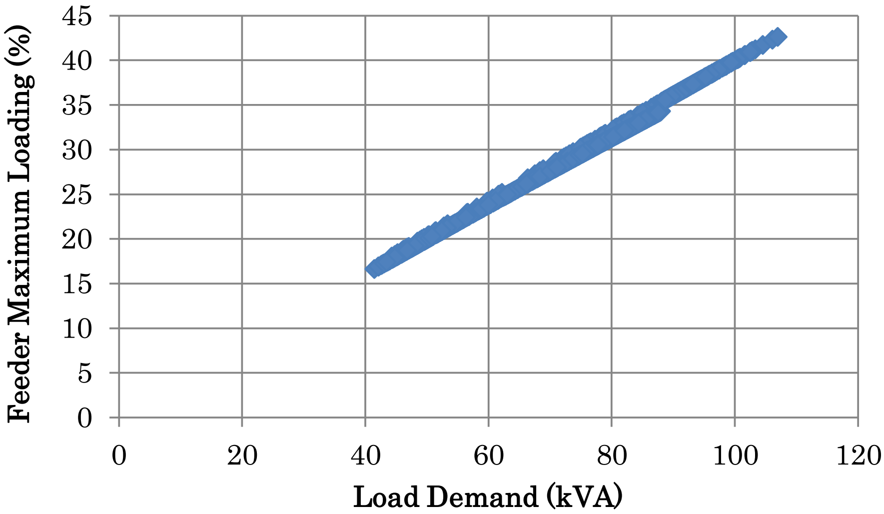


Figure 5.7: Baseline feeder minimum loading

The impact of PV integration on feeder loading is presented by scatter plot in Figure 5.8, which presents maximum cable loading anywhere in the network based on varied penetration level. It can be observed that feeder loading increase with an increase in PL_{pv}, ranging from minimum feeder loading of 12.6% (24% less than baseline minimum loading) to maximum of 199.5% (468% above baseline maximum loading). The loading violation is recorded at penetration level of 60% and from this point the loading violation probability increases with an increase in PL_{pv}. Any location combination beyond PL_{pv} of 357% will result in feeder loading violation.

To evaluate the effect of PV integration, maximum feeder loading PDFs with and without PV were compared as presented in Figure 5.9. The baseline feeder maximum loading is more to the right with a mean value of 42% and stDEV of 5.9%. Introduction of PV results in PDF being skewed to the right, with mean value of 100% and

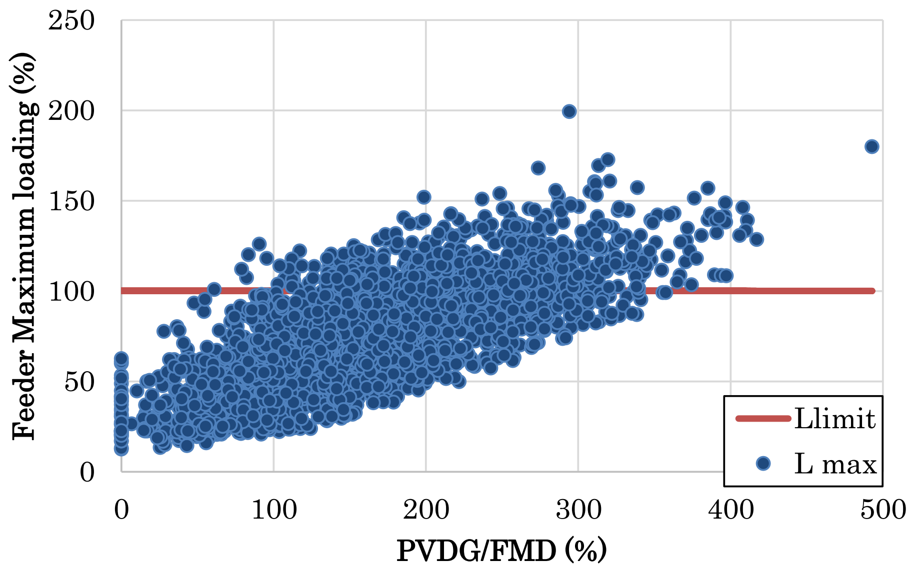


Figure 5.8: Feeder maximum loading due to three phase PV integration

stDEV of 29.8%.

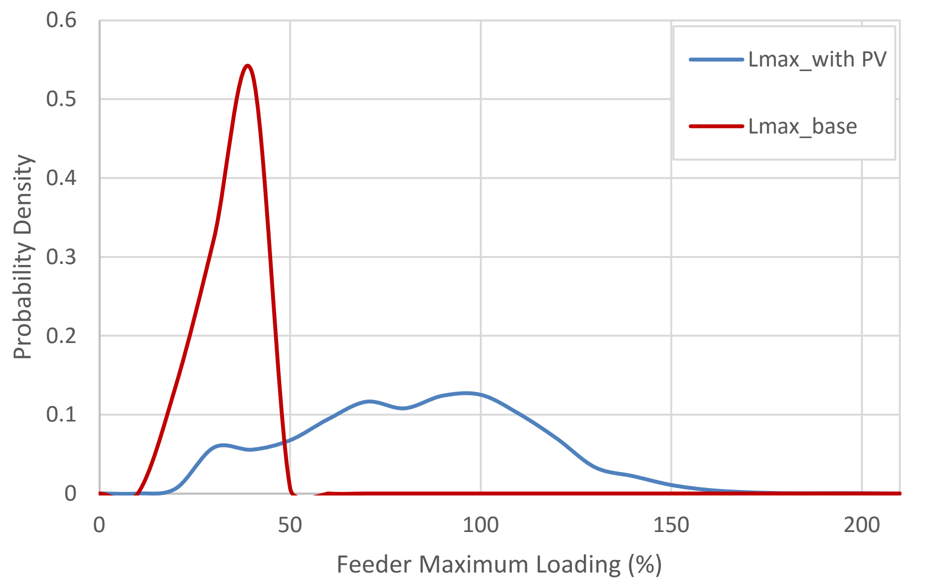


Figure 5.9: feeder-loading-comp

5.5 Case3: The impact of single-phase grid-connected PVDG (Constant load)

This case is intended to investigate impact of integrating a single phase PV system into the unbalanced three phase network. A typical residential loads are single phase supply and each household is assumed to be supplied by a single phase 80A circuit breaker. This case is intended to evaluate the impact of single phase PVDG,Therefore, PV capacity per property is rated at 18.4 kWp (equivalent to the assumed NMD).

Simulations in this section are based on the procedure presented in Figure 4.3 and un-balanced load flow computation is conducted. The network state (Voltage profile, voltage unbalance factor and equipment loading) with and without PV integration is recorded. Throughout this case it is assumed that the loads are constant.

5.5.1 Impact on voltage

Passive feeder

Figure 5.10 presented feeder voltage profile without PV based on the deterministic load and each phase voltage is presented by a different colour code. It can be observed that the voltage drops as the busbar is further from the transformer and the lower voltage drop is on blue phase with 0.98pu (225.4V (V_{l-n})). Phase voltages disperse significantly at the end of the feeder.

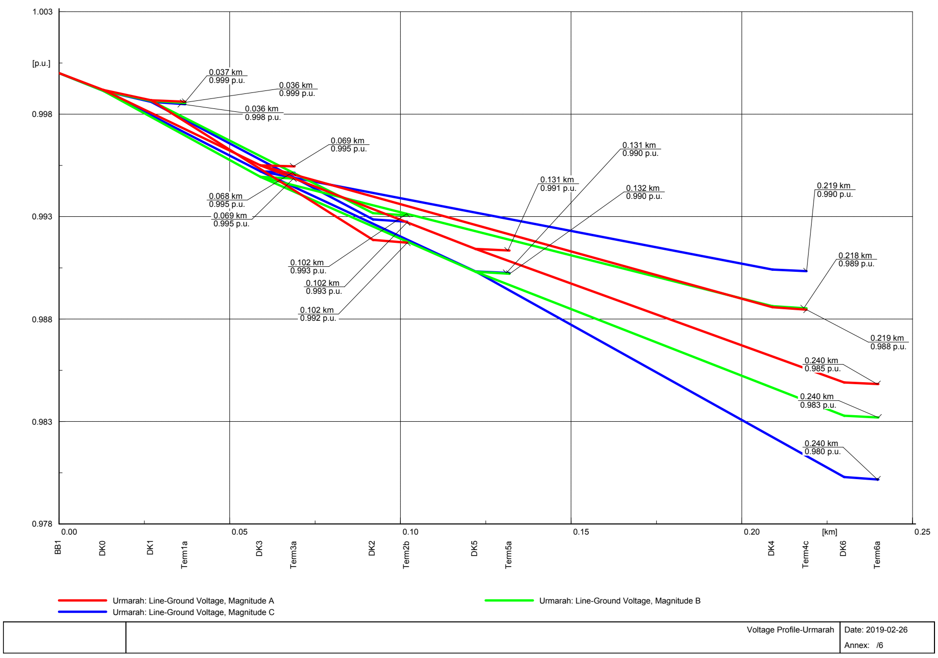


Figure 5.10: Unbalanced feeder voltage profile

Active feeder

Scatter plot in Figure 5.11 presented peak voltages anywhere in the network against an increase in PL_{pv}. It is observed that the voltage magnitude increase with an increase in penetration level. Peak magnitude of 1.08pu (248.4V (V_{l-n}))) at 83% PL_{pv} is observed, which is considerably below voltage upper limit (1.1pu).

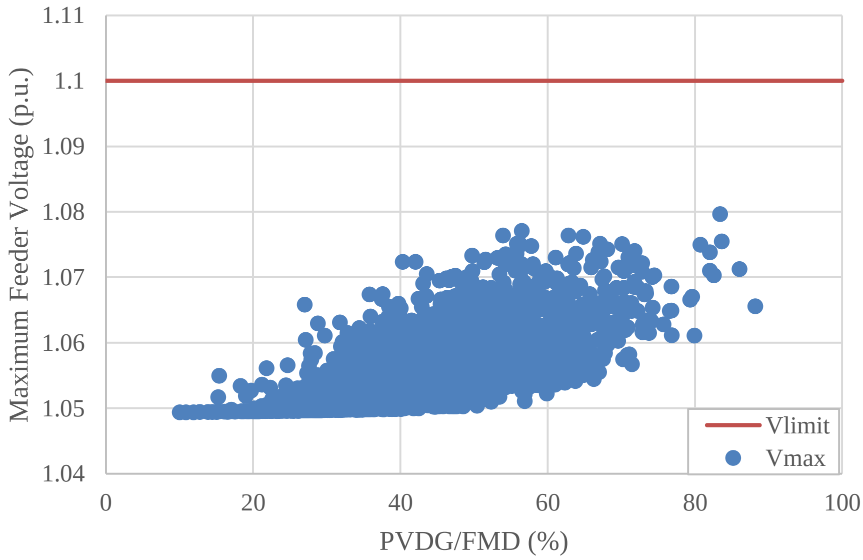


Figure 5.11: Vmax Single phase

5.5.2 Impact on Voltage unbalance

Passive feeder

Voltage unbalance impact resulting from single phase PVDG considered in this subsection. Figure 5.12 present a baseline voltage unbalance at customer point of connection (i.e at a distribution kiosk). It can be observed that there is no VUF violation in a baseline case. Busbar near the transformer, DK0, showed least VUF value of 0.008% and the furthest busbar, DK6, showed highest VUF value of 0.152% (this value is still significantly lower than the VUF limit).

Active feeder

PV integration impact on feeder maximum VUF was evaluated and the results shown in a scatter plot in Figure 5.13. Each dot represent a feeder maximum VUF based on

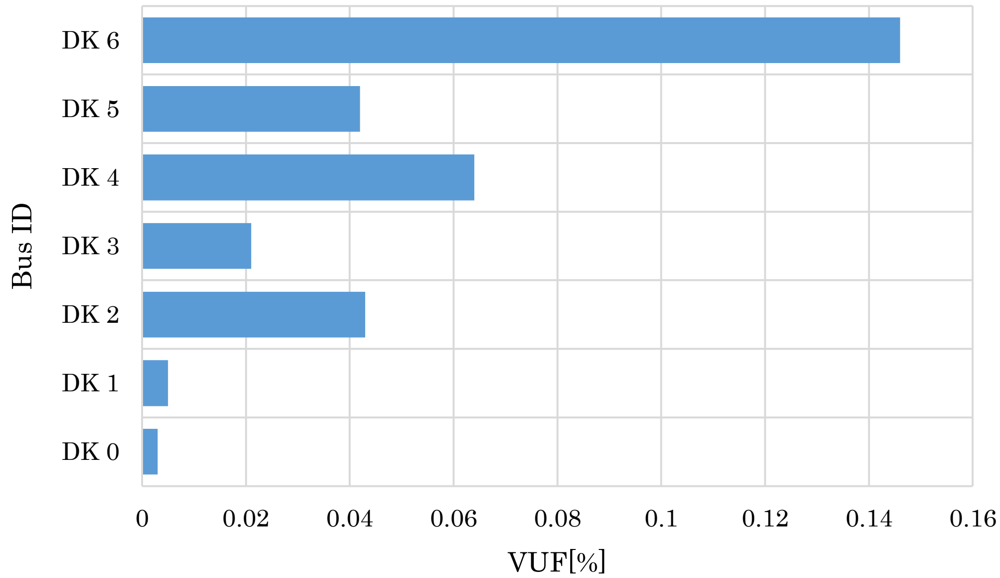


Figure 5.12: Baseline feeder VUF

varied PV location and capacity. The general observation of the scatter plot results show that the PV integration will mostly increase VUF of the feeder. The VUF limit of 2% was reached at approximately 45% penetration level, while higher penetration level result in decrease in feeder VUF.

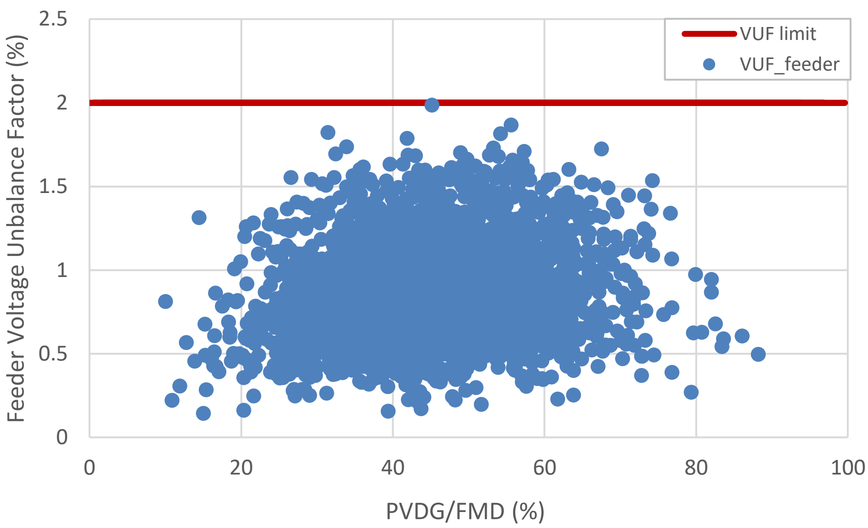


Figure 5.13: Feeder peak voltage unbalance factor

5.5.3 Impact on Loading

Active feeder

Figure 5.14 presents a scatter plot of maximum cable loading anywhere in the network based on varied size and allocation of PV systems. There was no loading violation observed, although one scenario loser to the threshold. The feeder loading increase with an increase in PL_{pv}.

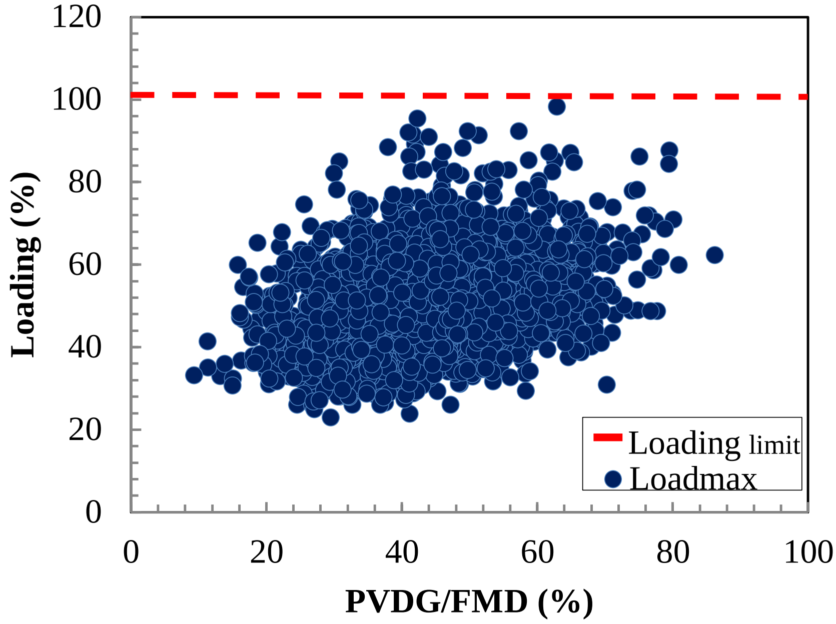


Figure 5.14: Maximum feeder loading (1-phase)

5.6 Case4: The impact of single-phase grid-connected PVDG (Probabilistic load)

This case is intended to investigate impact of integrating a single phase PV system into the unbalanced three phase network. A typical residential loads are single phase supply and each household is assumed to be supplied by a single phase 80A circuit breaker. This case is intended to evaluate the impact of single phase PVDG and it is assumed that PV capacity per property is rated at 18.4 kWp (equivalent to the assumed NMD).

5.6.1 Impact on voltage

Passive feeder

The minimum feeder voltage is the most interesting measurement for the a passive feeder (without PV). Figure 5.15 shows minimum feeder voltage against load demand. It is apparent that the drops with an increase in load demand. The lower and upper voltage is 0.983 pu and 0.976 pu respectively. Therefore, no voltage violation was recorded in a baseline scenario.

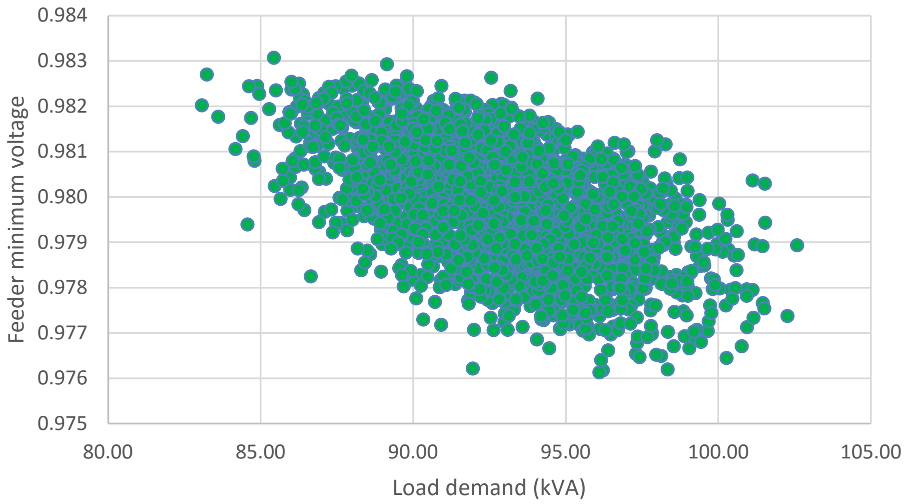


Figure 5.15: Minimum feeder voltage without PV

Active feeder

In Figure 5.16, the effect of PV introduction on feeder maximum voltage is presented. The overall feeder voltage is improved and the peak voltage of 1.04 pu is significantly below he voltage limit.

5.6.2 Impact on Voltage unbalance

Passive feeder

The voltage unbalance effect was evaluated based on voltage unbalance factor. Figure 5.17 shows the feeder maximum VUF without PV integration. It can be observed that feeder VUF increase with an increase in load demand. The maximum feeder VUF value of 0.43% as recorded, which is significantly lower than the limit.

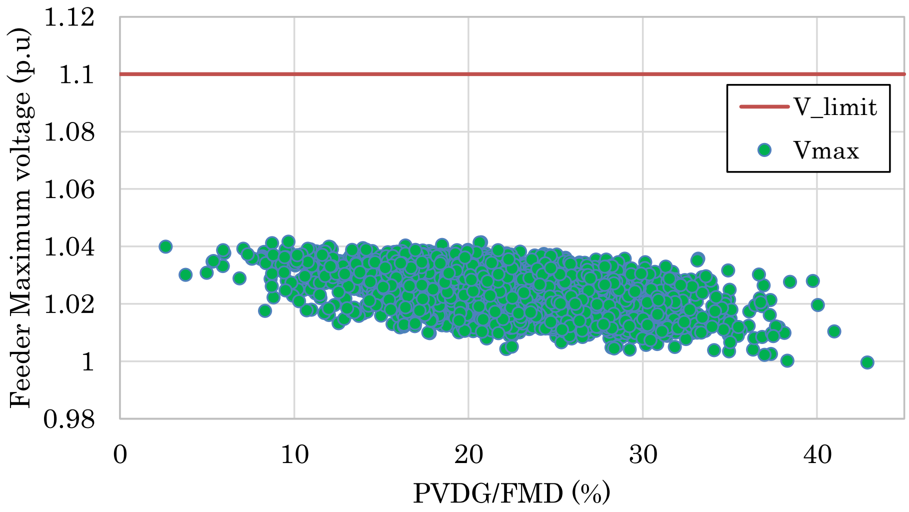


Figure 5.16: Maximum feeder voltage with PV

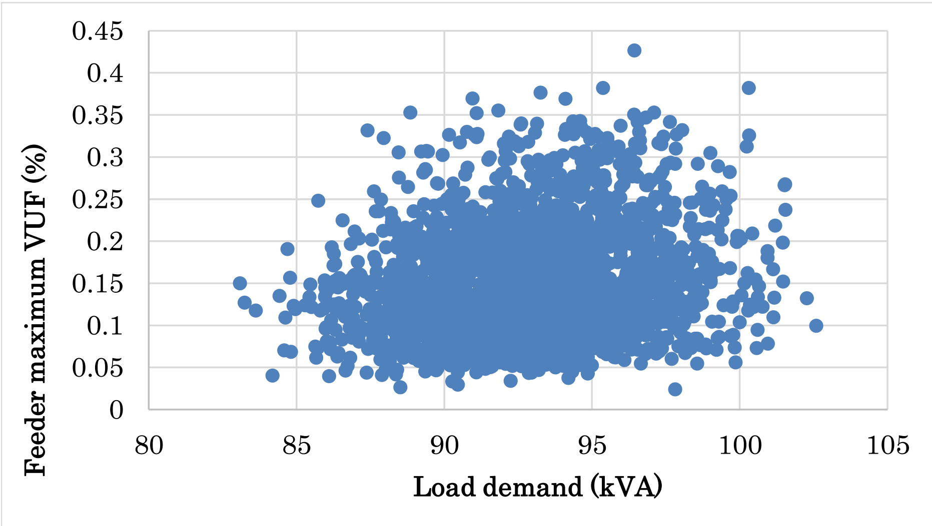
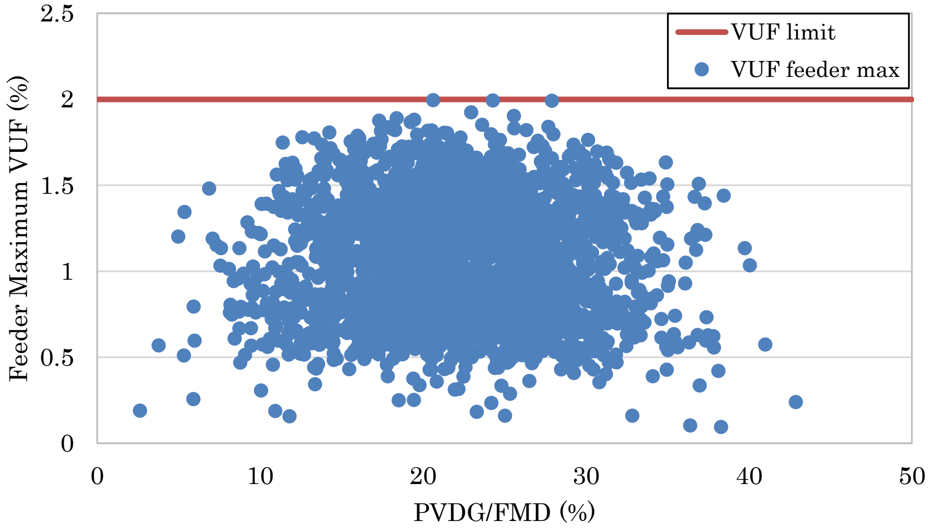


Figure 5.17: Maximum feeder VUF without PV

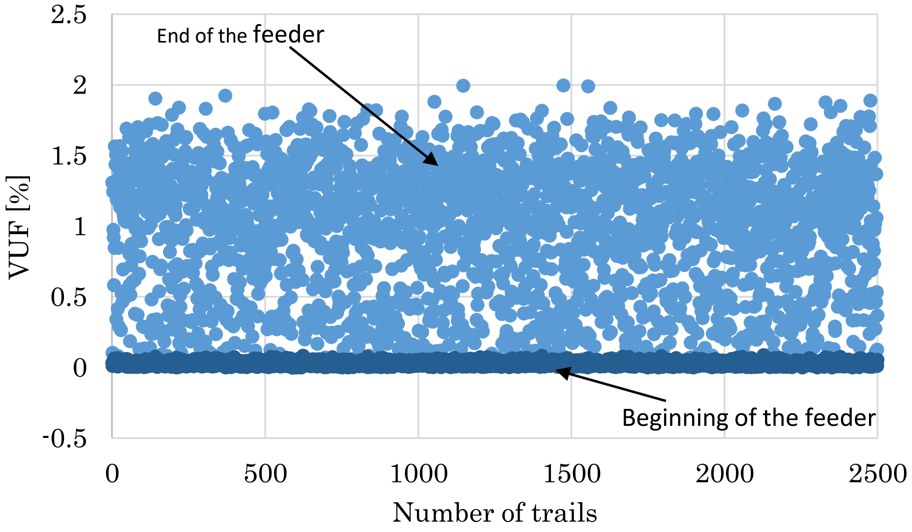
Active feeder

To evaluate the VUF impact of integrating PV into te network, simulations were conducted with PV system. Figure 5.18a shows the feeder maximum VUF with PV integration. It can be observed that feeder VUF increase with an increase in PL_{pv}. The VUF limit (2%) was reached three times out of 2500 scenarios. It is clear that the feeder VUF with PV is significantly higher than without PV.

The attention is drawn to Figure 5.18b, where VUF is compared between bus at the beginning against the bus at the end of the feeder. It can be seen that the bus at the beggining of the feeder showed less VUF change, ranging between 0.0 - 0.087%. While VUF of the bus at end of the feeder showed most change, ranging between 0.023 - 1.99%.



(a) Maximum feeder VUF with PV



(b) Maximum feeder VUF with PV

Figure 5.18: Feeder VUF with PV integration

5.6.3 Impact on Loading

Passive feeder

Feeder loading impact was also considered.Figure 5.19 presents the feeder loading impact against the load demand (without PV). it is observed that feeder maximum loading increase with an increase in load demand. The recorded values ranges between 36% and 52%, which are lower than the loading limit. Therefore, no loading violation was experienced in the absence of PV system.

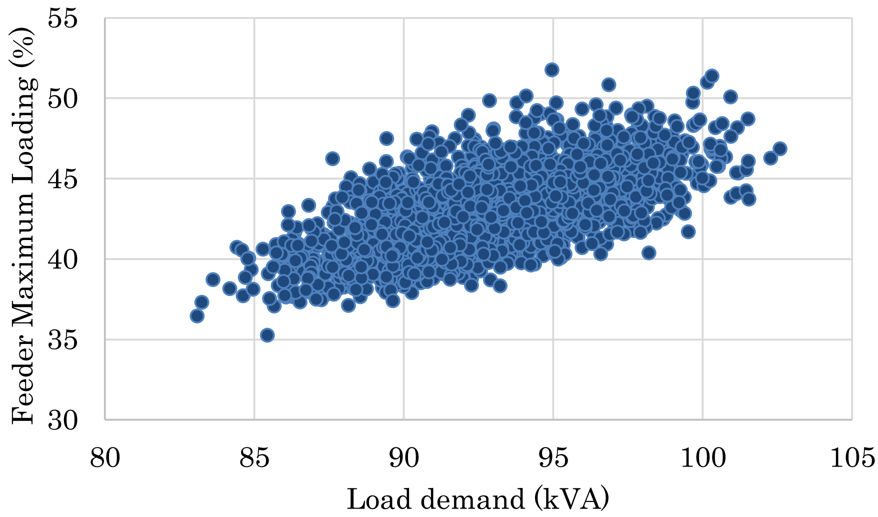


Figure 5.19: Maximum feeder loading without PV

Active feeder

To evaluate the feeder loading impact due to PV integration into the network, PV systems were introduced and simulations were conducted. Figure5.20 shows feeder maximum loading against penetration level. There is a general decrease in feeder load with an increase in penetration level and it is highlighted by the trend line. however,there was a loading violation occurred around 11% PL_{pv}.

To evaluate the impact on feeder thermal loading, comparison between passive and

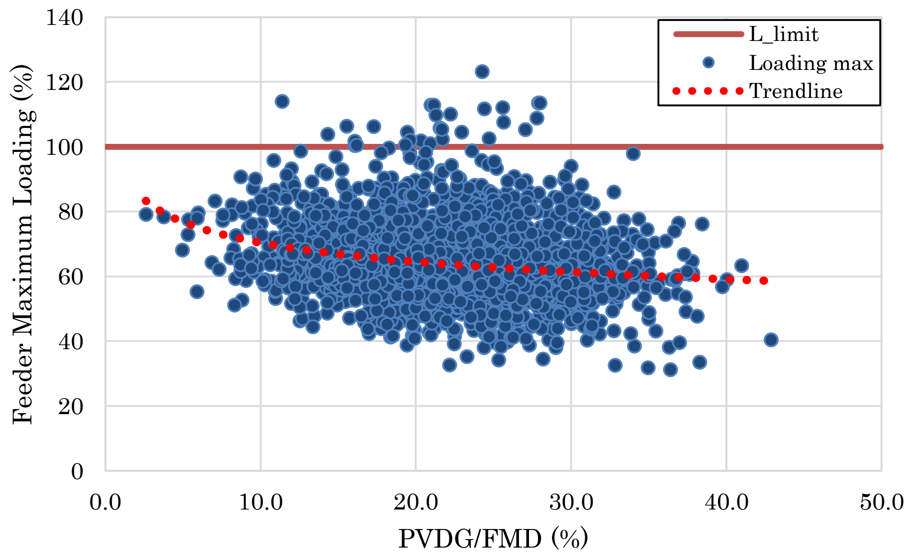


Figure 5.20: Maximum feeder loading with PV

active scenario are presented in Figure 5.21. It can be seen that for a passive feeder loading PDF has a mean value of around 50%. While the introduction of PV will increase feeder loading, with a PDF mean of around 75% and peak value 123%. Therefore, there is a risk of thermal violation in the active feeder.

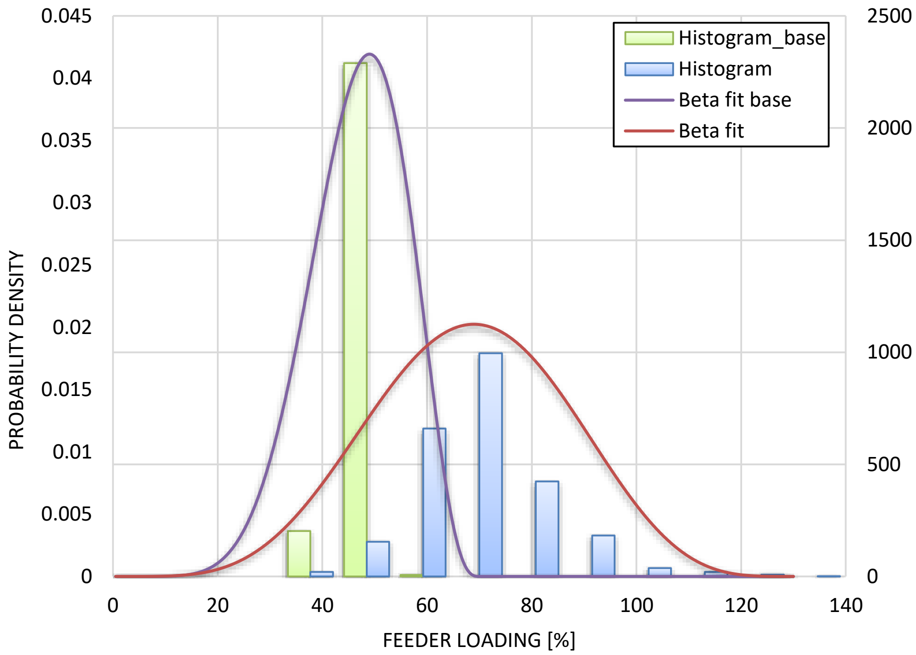


Figure 5.21: Feeder loading PDF comparison with and without PV

5.7 Determination of grid hosting capacity

Determination of grid hosting capacity is crucial for the system engineers, as it provides an insight on network performance limits when subjected to high PV penetration. Electrical networks are not homogeneous and they are expected have varying hosting capacity as highlighted in Table 2.2, in subsection 2.5. The adopted definition of Hosting capacity of a distribution feeder is the maximum amount of distributed generation (Rooftop PV in this study) that can be integrated without violating the thresholds of any impact criteria. Although high penetration of rooftop PV into the grid will likely result in numerous impacts as reviewed in Chapter 2, for the purpose of this study, only steady state overvoltage, voltage unbalance factor and equipment thermal loading were considered as impact analysis parameters. Therefore, Hosting capacity will be the penetration level that result in the first violation of one of the three parameters considered in this study.

The results of the scatter plots presented in Section 5.3 to 5.6 were considered and the penetration level resulting first violation per performance parameter were recorded (see Table 5.1).

It can be observed that overcurrent threshold is the limiting factor for the hosting

Table 5.1: Test feeder hosting capacity

System topology	HC factor	Case 1 (%)	Case 2 (%)	Case 3 (%)	Case 4 (%)
3-phase	Over voltage	85	50	N/A	N/A
	Over loading	41	55	N/A	N/A
1-phase	Over voltage	N/A	N/A	-	-
	Voltage unbalance	N/A	N/A	45	21
	Over loading	N/A	N/A	63	12

capacity of test LV feeder, due to the short feeder length. As a result, it can be concluded that the hosting capacity for a 3-phase PV integration to the test LV feeder is 41% Penetration level, which is equivalent to 87.5kWp (equating to 7.25kWp per household). The last hosting capacity (HC2) is not considered in determining the feeder hosting capacity as it depends on numerous capacity and location combination the network operator/utility has not control over. When considering a single phase PV integration on the hosting capacity, it was found that the test network can only accommodate 12% penetration level and limited by thermal limit. For the test LV feeder supplying 18 households, it can be deduced that only 1.4kWp can be installed per household and no statutory limits will be violated. Effect of type of connection is clearly illustrated in Table 5.1 and it can be concluded that the three phase PVDG uptake can result in high hosting capacity.

5.8 Violation probability analysis

In some instances, Network planner may want to assess the risk of integrating a PVDG into the network and decide whether the risk is acceptable or not. In this subsection, the risk analysis is conducted by applying cumulative distribution functions (CDF) to test probability of performance parameter violation.

To quantify the risk associated with these performance parameters (voltage, voltage unbalance factor and equipment thermal loading) violation, two modelling techniques were evaluated, i.e. constant load (denoted by 1ph_const and 3ph_const) and stochastic load (denoted by 1ph_st and 3ph_st).

Firstly, Figure **??** presents Cumulative distribution functions (CDF) of voltage violation comparing single and three phase systems. A 1-phase system is within voltage limit, while there is 99.36% confidence of operating with in voltage limit for 3-phase system. The balance of 0.64% represents statistical risk of voltage violation in $3 - phase_{const}$system. This voltage violation risk is very low and it can be acceptable risk.While, Voltage $3 - phase_{st}$ showed high probability of violation at approximately 50% risk. This risk is too high to be accepted.

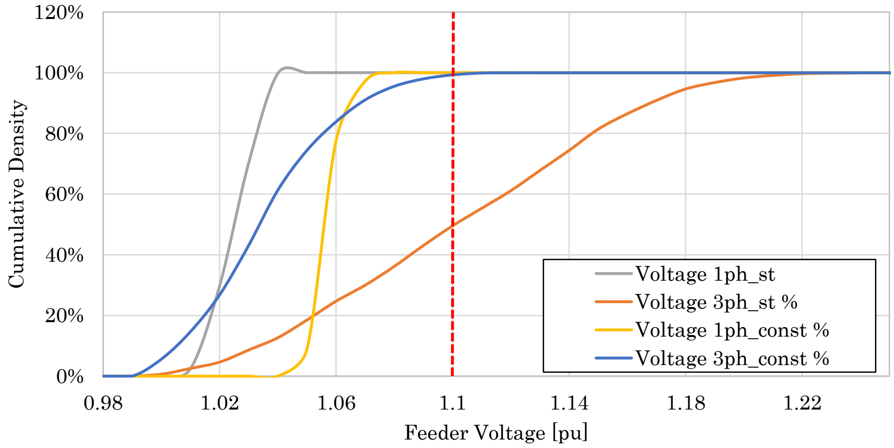


Figure 5.22: Single phase vs Three phase feeder voltage CDF plot

To assess the impact of PV integration on feeder VUF violation analysis was conducted and plotted in Figure 5.23. the plot consists of VUF impact based on constant load ($VUF1ph_{const}$) against the impact based on statistical load ($VUF1ph_{st}$). No violation was recorded,

The other critical parameter, especially in urban network, is equipment loading. Figure 5.24 presents probability of loading violation comparing 1-phase and 3-phase systems.

A 1-phase system is within voltage limit, while there is 73% confidence of operating with in thermal loading limit for 3-phase system. The remaining 27% represents statistical risk of thermal loading violation in 3-phase system and it applies to both types of modelling (Loading $3 - phase_{const}$ and Loading $3 - phase_{st}$). As it stands, 27% risk is too high and it is unacceptable risk.

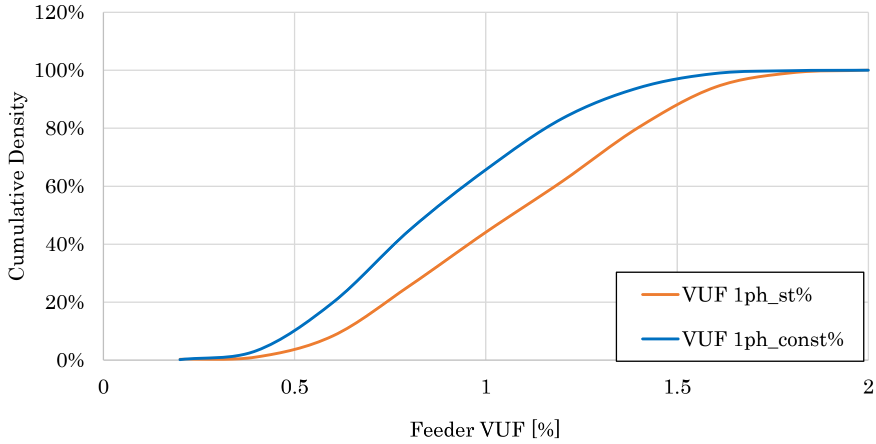


Figure 5.23: Single phase vs Three phase feeder voltage unbalance factor CDF plot

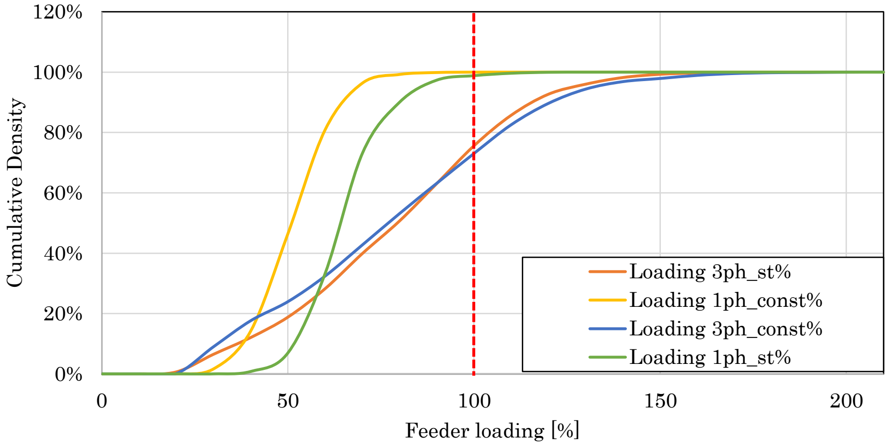


Figure 5.24: Single phase vs Three phase feeder loading CDF plot

5.9 Discussion and implications

The current study was to investigate the impact of high penetration of Rooftop PV into the existing electrical network, specifically on the urban residential network. This section interprets results of this study in relation to the research questions (specifically RQ1, RQ3 and RQ4) and position them in relation to the existing body of knowledge from literature.

The voltage rise limits are stipulated in NRS048[39], where voltage has to be within ±10% of nominal voltage, for 95% of the weeks period. The voltage impact of PV integration was observed in all integration scenarios. All voltage impact test results suggests that the introduction PV will improve the feeder voltage and this is reflected in all voltage impact result [16, 104]. However, the interesting results are that of Section 5.6 (PV integration in unbalanced LV network (Probabilistic load)), where increase in penetration level results in feeder voltage drop. This response can be attributed to the independence of input variables (load and generation), which in this case there is a negative correlation between load demand and generated power. The transformer secondary voltage was assumed to be at nominal voltage of 400V (Vn = 400V = 1.0pu) and the present voltage apportionment presented in Section 3.2.6 will lead in voltage violation. Considering that CoCT transformers are designed based on a 5% nominal voltage boost on the transformer secondary busbar (refer to Section 3.2.6), the voltage rise range will decreased and leading in reduced penetration level. The implication of this scenario is that the DNO will have to revisit their transformer infrastructure and operate them at a lower tap for feeders with high proliferation on PVDGs.

The feeder voltage unbalance resulting from the integration of single-phase grid-connected rooftop PV into a residential LV network was presented in Section 5.5 and 5.6. The results suggests that the introduction of PV into the system will result in an increased feeder voltage unbalance and this was shown in Figures 5.13 and 5.18a. It is interesting to observe that the VUF violation can occur even at medium penetration levels (21% to 45%) and feeder VUF decrease when approaching high penetration levels. This can be due to phase cancellation. Although this general observation was made by other authors [48, 105], this study provided a probability of occurrence (see Figure 5.23) which will be crucial for quantifying risk of VUF violation during network planning stage.

The VUF variation (ΔVUF) also depends on the position of the busbar in relation to the source. This is presented in Figure 5.18b, where ΔVUF is minimal at the beginning of the feeder and more at the end of the feeder. The same observation was reported by [48]. The reason for this situation is linked to the fault level which is higher closer to the source (transformer secondary busbar in our case), which leads into resistance in voltage change and the opposite is true at the end of the feeder.

Considering that customer load demands are not homogeneous and they are affected by many factors including weather, occupancy and activity profile. The load modelling (either constant or stochastic) effect can be observed when comparing the VUF results in Figures 5.13 and 5.18a. Constant load with varying PV generation only illustrate the worst impact of the current injection to VUF, which disregard the correlation impact between load and generation. However, there are times where PV injection occurs on the phase with higher load relative to other phases and therefore improving busbar VUF (refer to Figure 5.18b). Thus make statistical approach to be the most realistic representation of VUF.

The equipment loading is one of the concerning factors for the utility and loading impact results of this study seem to justify the concern. Introduction of PV into the network can either improve or worsen the system loading. The feeder loading results (Figures 5.3, 5.8, 5.14 and 5.20) indicates that feeder loading is improved at lower penetration levels and this can be attributed to the PV generated power being lesser or equivalent to the local load (self consumption). PV can reduce feeder loading at lower penetration levels, while at high penetration level inverse is also true and similar observations were made by Watson et al [103]. As stated in literature, system losses are directly proportional to the system loading. The loading trends are in line with the normalised system losses trend reported in other studies, such as [32, 103, 54].

System topology (Single-phase vs three-phase) effect on the performance of distribution network was evaluated and it was fond to have a significant impact on the performance of the network. In general, the hosting capacity results presented in Section 5.7 (see Table 5.1) affirms recommendations made in NRS097-2-3 [101], where three phase DG can result in higher hosting capacity. However, hosting capacity results for urban residential feeder used in this study, are not in line with the NRS 097-3-2 recommended quantities for shared networks. NRS097-2-3 [101] recommends the following thresholds before detailed studies can be conducted, where single phase capacity limit is 4.6kW (on NMD 18.4kVA) and three-phase capacity limit is 13.8kW (on NMD 41.4kVA) in shared networks. However, the current study were found to be below NRS07-3-2 recommended threshold.

Although penetration level has an impact on feeder performance, results of this study indicated also the influence of location.

5.10 Chapter summary

In this chapter, impact assessment of high penetration of rooftop PV on real urban residential feeder were investigated. The analysis were based on three performance indicators,i.e voltage rise, voltage unbalance and thermal loading. The system topology (single-phase vs three-phase) was also considered in order to understand their overall impact on network performance. Although most research on PV integration has been focused mainly on the voltage impact, it is observed that over-current violation is reached before voltage violation. This is due to electrically short feeder characteristic of urban feeders, resulting in lesser impedance. In light of the simulations, analysis and discussions conducted thus far, the overall conclusions of this thesis are presented in the next chapter.

Table 5.2: Simulation Results summary

Case ID	Description	Factors								
		Voltage (pu)			$Voltage_{unbalance}$(%)			Loading(%)		
		Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
Case1	Passive feeder	0.982	0.992	0.999	-	-	-	13.4	23.157	34.3
	Active feeder(3ph-PV)	0.981	1.011	1.11	-	-	-	6.04	41.49	202.62
Case2	Passive feeder	0.993	0.996	0.997	-	-	-	16.654	28.818	42.639
	Active feeder(3ph-PV)	0.989	1.101	1.241	-	-	-	12.612	78.290	199.532
Case3	Passive feeder	0.993	0.996	0.997	0.003	0.046	0.146	16.654	28.818	42.639
	Active feeder(1ph-PV)	1.049	1.056	1.079	0.003	0.046	0.146	22.09	51.11	97.08
Case4	Passive feeder	0.999	0.999	0.999	0.024	0.150	0.427	35.29	42.997	51.764
	Active feeder(1ph-PV)	1.000	1.025	1.042	0.095	1.072	1.996	31.224	65.060	123.205

Chapter 6

Conclusions and Future Works

This chapter presents conclusions of this study and provides recommendations for future studies.

6.1 Conclusions

This thesis investigated the technical impact of high penetration rooftop PV on urban residential networks. Its proliferation has resulted in increased concern from the distribution network operators due stochastic nature of PV generation and load demand variability. Uncertainty associated with these variables (Loads, PVDG size and location), has resulted in the development of impact assessment framework based on probabilistic load flow techniques and specifically Monte-Carlo simulation. Technical evaluation considered overvoltage, voltage unbalance factor and equipment thermal loading. based on the results of this research, it can be concluded that the uncontrolled high penetration of PVDG will have detrimental impact on the existing urban residential networks, leading mainly to equipment thermal violations.

List of research questions where posed in Section 1.3, intended to guide towards addressing the objective of this thesis. Main findings of this works are presented in the context of providing answers to the research questions as follows:

- **RQ1:** ***Will the integration of rooftop PV technically impact (e.g Overvoltage, voltage unbalance and equipment loading) the existing urban residential network and to what extent?***
  Integration of distributed generation has been reported to have numerous impacts on the existing network and these impacts are presented in Section 2.4. This study was limited to overvoltage, voltage unbalance and equipment loading

resulting from high penetration of rooftop PV. Unlike the rural networks, Urban networks are characterised by short feeder lengths and thus leading to less voltage change (both V_{drop} or V_{rise}). Equipment loading was violated first, thus make it the limiting factor for the adoption of rooftop PV. The extent at which the integration of PV will impact the existing network is dependent number of parameters such as the feeder configuration (feeder length/impeadance, number of branches etc.), connection

- **RQ2:** ***What methods have been adopted to investigate DG impact on existing networks?***
  Through rigorous literature review presented in Chapter 2, it was found there are lot of methods applied in investigating DG impact on existing networks. These methods can be generally grouped into deterministic and probabilistic methods. Although each method has its advantages and disadvantages, probabilistic methods are preferred as they provide a spectrum of estimated values in a statistic form (refer to Section 2.4). In Probabilistic load flow application, numeric/simulation based techniques such as Monte-Carlo Simulation are widely applied due to their simplicity in their application. However, the main drawback of MCS is the iterative process which leads to high computation burden for a desired level of accuracy. On the other hand, Analytical methods are also applied, but they are associated with complicated mathematical computation, include the requirement of mathematical assumptions, such as linearisation of equations and independence between input variables, which leads to inaccurate results [91]. As a result, the probabilistic assessment based on Monte-Carlo Simulation was adopted in his study due to its simplicity in its application.

- **RQ3:** ***Is overvoltage performance parameter adequate to assess PVDG impact on urban residential networks?***
  Unlike rural feeders, urban networks are characterised by short feeders and dense loads. In this work it was found that feeder thermal constraint is the main contributing factor when considering low voltage urban residential network and this is affirmed by loading impact results in Chapter 5. This proves the risk associated with just considering the voltage rise as the only assessment parameter when determining the hosting capacity of low voltage networks.

- **RQ4:** ***How is network hosting capacity affected by rooftop PV system connection topology?***
  PVDG system connection topology, ether single-phase or three-phase, affects the response of the network when subjected by the high penetration of PVDG. The effect of system topology on network hosting capacity was evaluated in Section

5.7. Single phase PV system results in lower hosting capacity, which conform to the recommendation of NRS097-2-3. This is also indicated simplified connection criteria formulated in NRS097-2-3 [101] (see Section 2.6), where single phase capacity limit is 4.6kW (on NMD 18.4kVA) and three-phase capacity limit is 13.8kW (on NMD 41.4kVA) in shared networks.

6.2 Future Works

This thesis made a strides in understanding the potential behaviour of urban residential network when subjected to the high penetration of grid-connected rooftop PV. However, there is still further research work that can be explored.

- Analysis conducted in this work is limited in its application as it does not cover all possible urban network characteristics. Further research is required were analysis are conducted on a number of urban network, which can lead in a taxonomy for urban network in South Africa and their potential behaviour when subjected to high penetration levels of distributed generation.
- Due to unavailability of individual customer load data, the load allocation method applied in this study has short coming in the analysis although it is a method widely used in the industry. This limitation highlight the need to collect customer load data for future research work that will improve the accuracy models used and relevance of integration studies.
- The current work was focused main on technical impact on the LV network, future work can extend the impact assessment methodology presented in this work to investigate how this high penetration of grid connected rooftop PV will propagate into the upper networks (i.e MV and HV networks).
- The work of this thesis can be extended by incorporating other forms of technologies such as electrical vehicles.
- The other possible future work can be on investigating mitigation solution that can improve Hosting capacity the test network was determined in this study.

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Appendix A

DiGSILENT PowerFactory Models

DiGSILENT PowerFactory was used as the main simulation software in this study. The following subsection provide details on how the models and variables inputs where constructed. Further details on the aspect of system modelling in DiGSILENT PowerFactory can be accessed in [17].

A.1 Test network Model

The MV network supplying the test LV feeder was modelled in DIgSILENT Powerfactory and presented as a graphical representation depicted in Figure A.1. The rectangular block represent the HV/MV substation and the big circles represent distribution substation consisting of only MV switchgear. While the small circles represent the miniature substation consisting of ring main unit (RMU) and MV/LV transformer.

The detailed simulation is conducted on the LV feeder and the single line diagram presented in Figure A.2 was modeled in PowerFactory. The single line diagram shows the interconnection of feeder components such as busbar, line/cables, loads, PV etc. Each customer is represented by both load and PV system.

A.2 Variable Models

To be able to conduct simulations, input variable (Load demand, PV generation, scaling factors etc) had to be incorporated into PowerFactory.

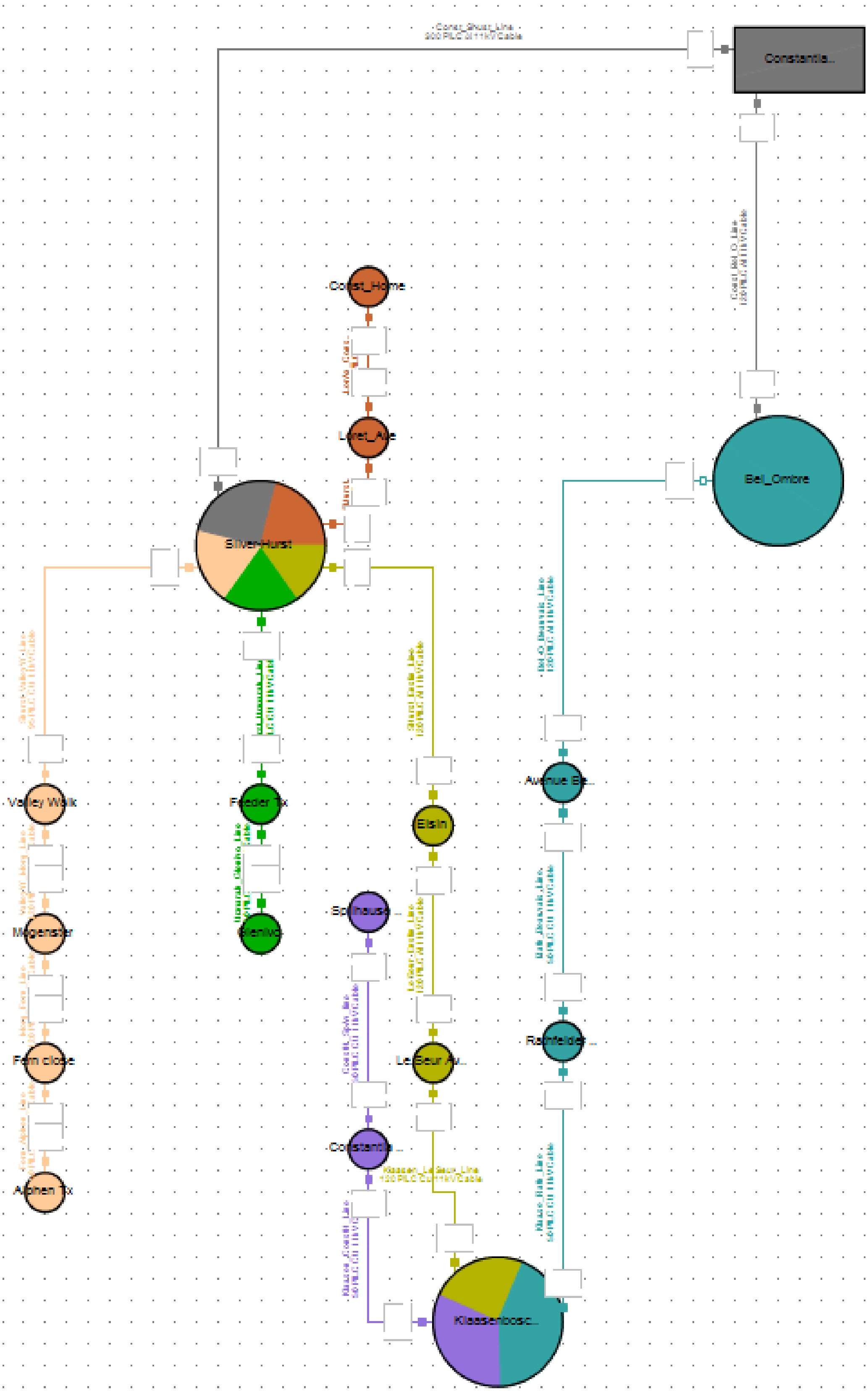

Figure A.1: MV network SLD

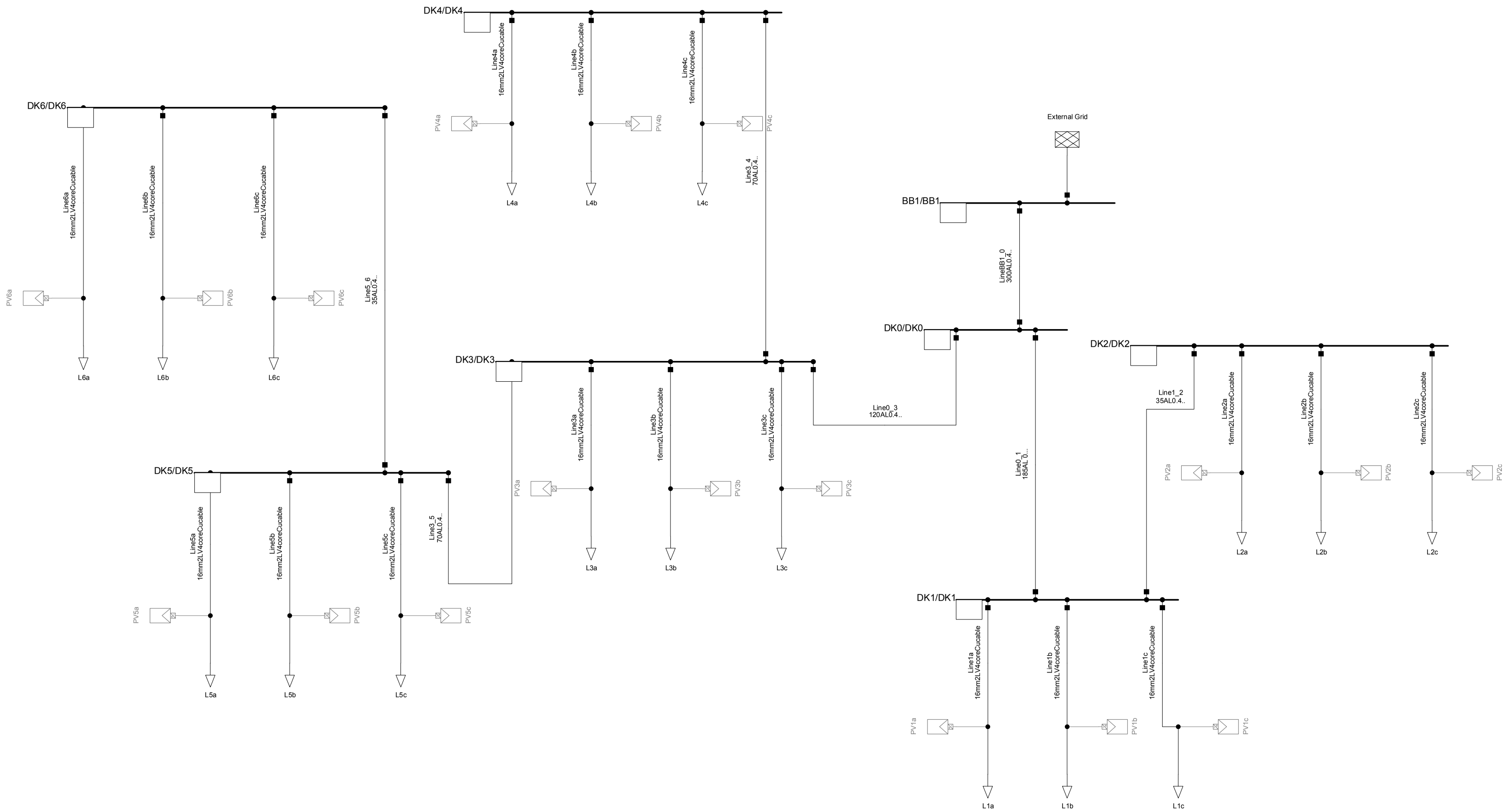

Figure A.2: Detailed test LV feeder

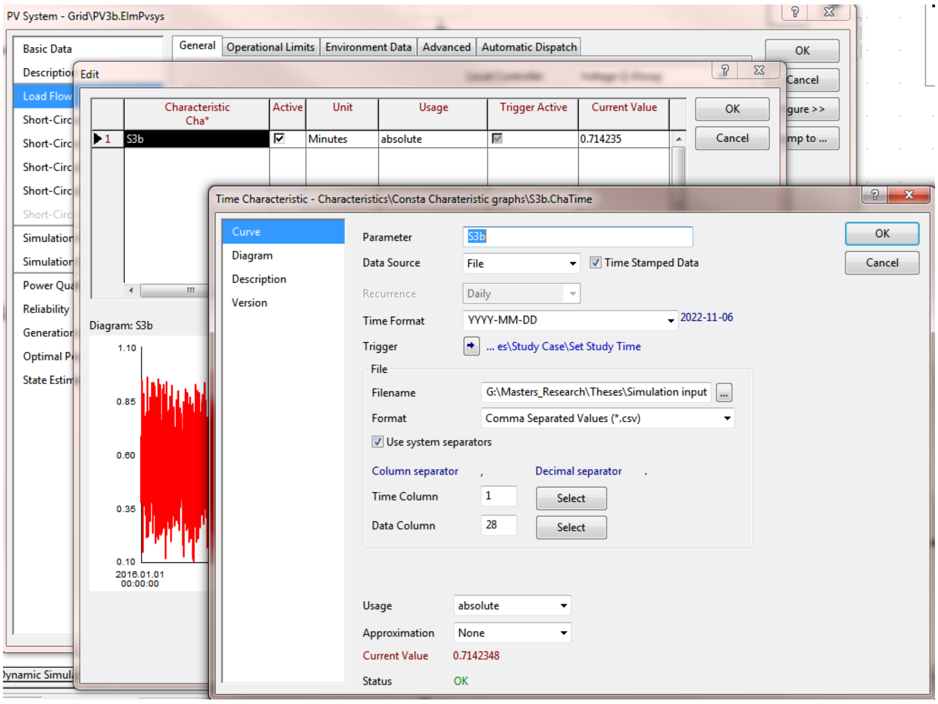

Figure A.3: PV scaling model

Appendix B

Supplementary results

Table B.1: Load demand summary

Bus number	**Phase**	α	β	A_{min}	A_{max}
	a	1.4066	2.4654	12.523	22.813
1	b	1.4067	2.4655	16.405	29.886
	c	1.4067	2.4655	19.87	36.197
	a	1.4067	2.4655	18.517	33.734
2	b	1.4067	2.4655	14.761	26.891
	c	1.4067	2.4655	15.519	28.271
	a	1.4066	2.4654	11.051	20.131
3	b	1.4067	2.4655	20.415	37.19
	c	1.4067	2.4655	17.332	31.575
	a	1.4067	2.4655	18.972	34.563
4	b	1.4067	2.4655	17.071	31.099
	c	1.4066	2.4654	12.754	23.234
	a	1.4067	2.4655	17.515	26.443
5	b	1.4067	2.4655	17.632	32.121
	c	1.4067	2.4655	16.65	30.332
	a	1.4067	2.4655	14.7	26.779
6	b	1.4067	2.4655	15.956	29.067
	c	1.4067	2.4655	18.142	33.05

B.1 Case1 Results summary

Steady state results of passive 3phase network are presented in Table B.3.

Table B.2: Load demand summary

Bus number	**Phase**	α	β	A_{min}	A_{max}
	a	1.4066	2.4654	12.523	22.813
1	b	1.4067	2.4655	16.405	29.886
	c	1.4067	2.4655	19.87	36.197
	a	1.4067	2.4655	18.517	33.734
2	b	1.4067	2.4655	14.761	26.891
	c	1.4067	2.4655	15.519	28.271
	a	1.4066	2.4654	11.051	20.131
3	b	1.4067	2.4655	20.415	37.19
	c	1.4067	2.4655	17.332	31.575
	a	1.4067	2.4655	18.972	34.563
4	b	1.4067	2.4655	17.071	31.099
	c	1.4066	2.4654	12.754	23.234
	a	1.4067	2.4655	17.515	26.443
5	b	1.4067	2.4655	17.632	32.121
	c	1.4067	2.4655	16.65	30.332
	a	1.4067	2.4655	14.7	26.779
6	b	1.4067	2.4655	15.956	29.067
	c	1.4067	2.4655	18.142	33.05

Table B.3: Voltage profile and loading without PV

Bus number	**Voltage (p.u.)**	**Line ID**	**Loading(%)**
DK0	0.999	Linetx-0	32.9
DK1	0.995	Line0-1	16.6
DK2	0.989	Line0-3	34.3
DK3	0.995	Line1-2	23.9
DK4	0.992	Line3-5	24.0
DK5	0.991	Line3-4	13.4
DK6	0.984	Line5-6	17.0

B.2 Case2 Results summary

Figure **??** presents Voltage unbalance factor output result from the Quasi-Dynamic simulation in powerFactory.

The feeder loading was examined and the probability density function is presented in Figure B.2. The measured data is fitted on Beta PDF and distribution parameters are μ of 0.97987899 and σ of 0.00125274. The singlle phase feeder loading PDF when subjected to rooftop PV is presented in FigureB.3.

The output voltage data fitted the beta distribution with μ of 0.97987899 and σ of

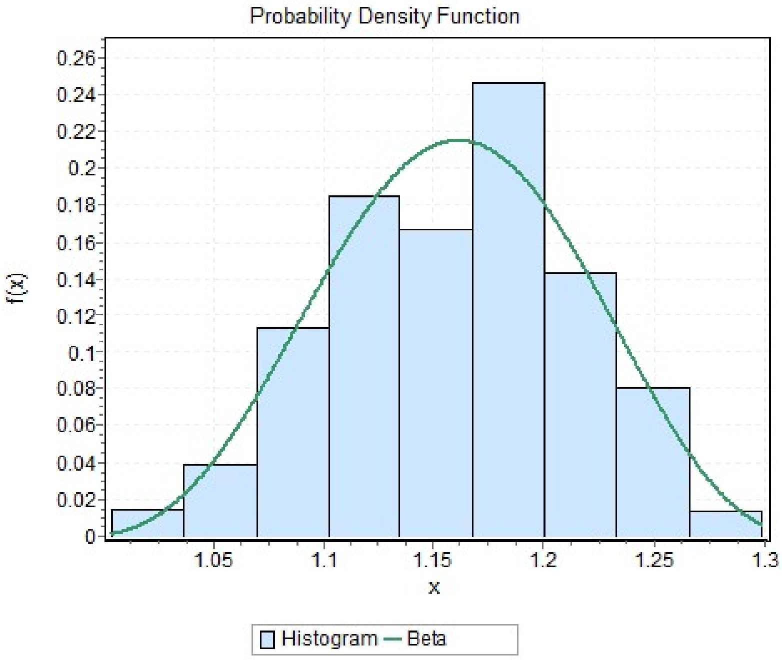

Figure B.1: Test

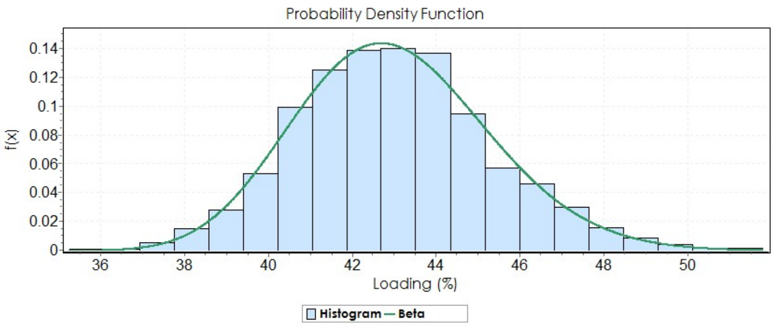

Figure B.2: Loading base

0.00125274. The minimum voltage drop of 0.975 pu which is significantly above the NRS minimum voltage limit of 0.90pu.

Voltage unbalance impact

Figure B.5 presents the feeder maximum VUF fitted with a Beta PDF. Beta PDF is skewed to the left with distribution parameters of μ of 0.97987899 and σ of 0.00125274.The recorded maximum VUF of 0.96% is significantly lower than NRS maximum VUF limit of 2%.

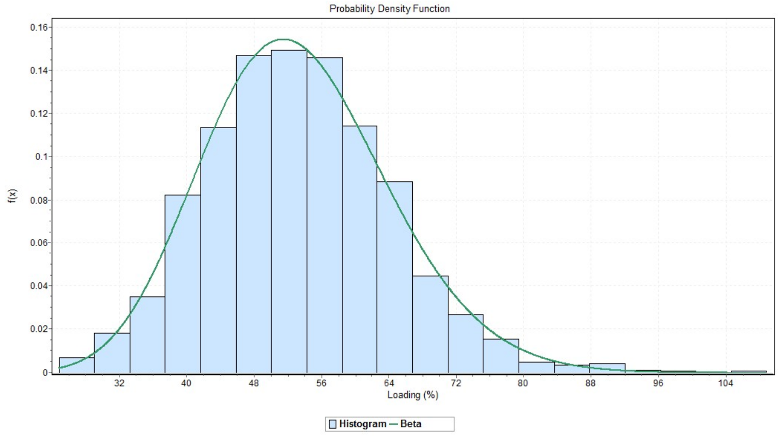

Figure B.3: Single phase feeder loading PDF when subjected to high rooftop PV penetration

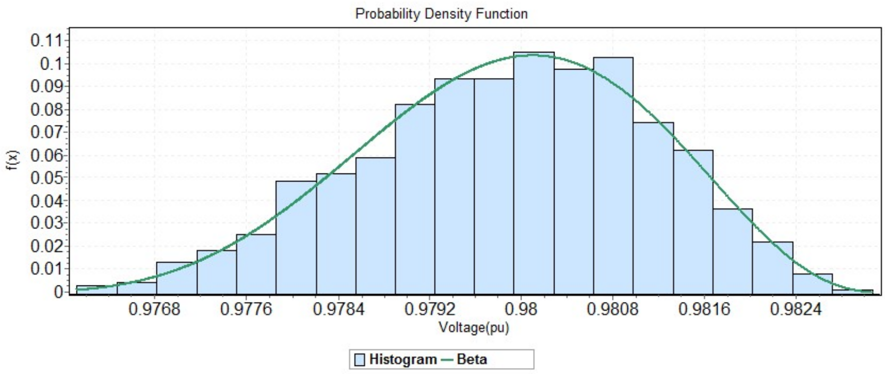

Figure B.4: Feeder voltage drop PDF-base

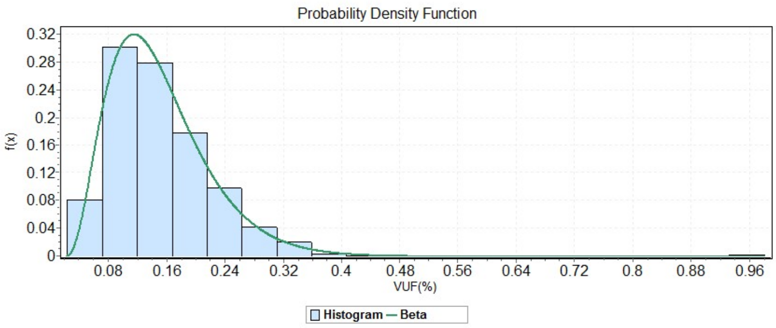

Figure B.5: VUF base-1phase

B.3 Case4

To interpret the potential of voltage violation, PDF of the active feeder is presented in Figure B.6.

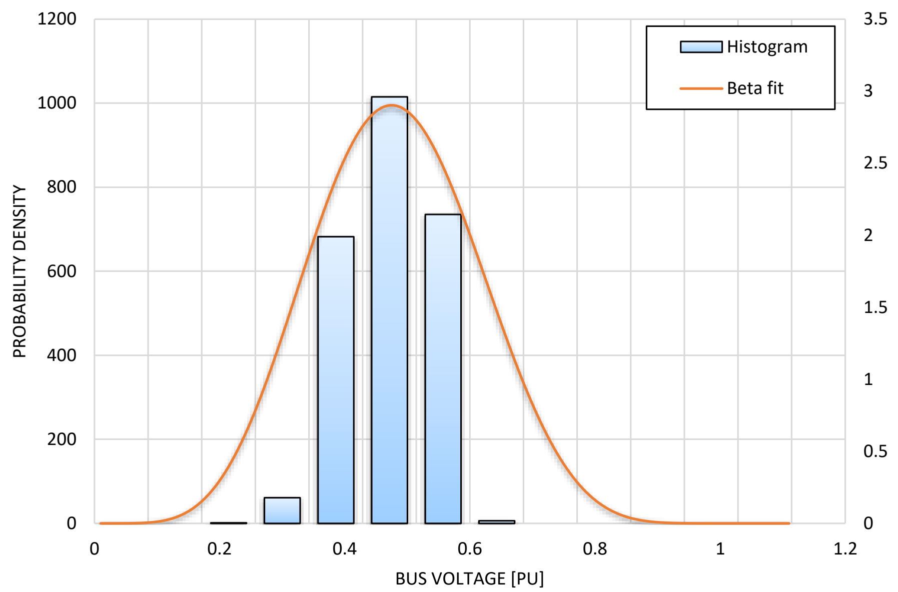

Figure B.6: Maximum feeder voltage PDF in an active feeder

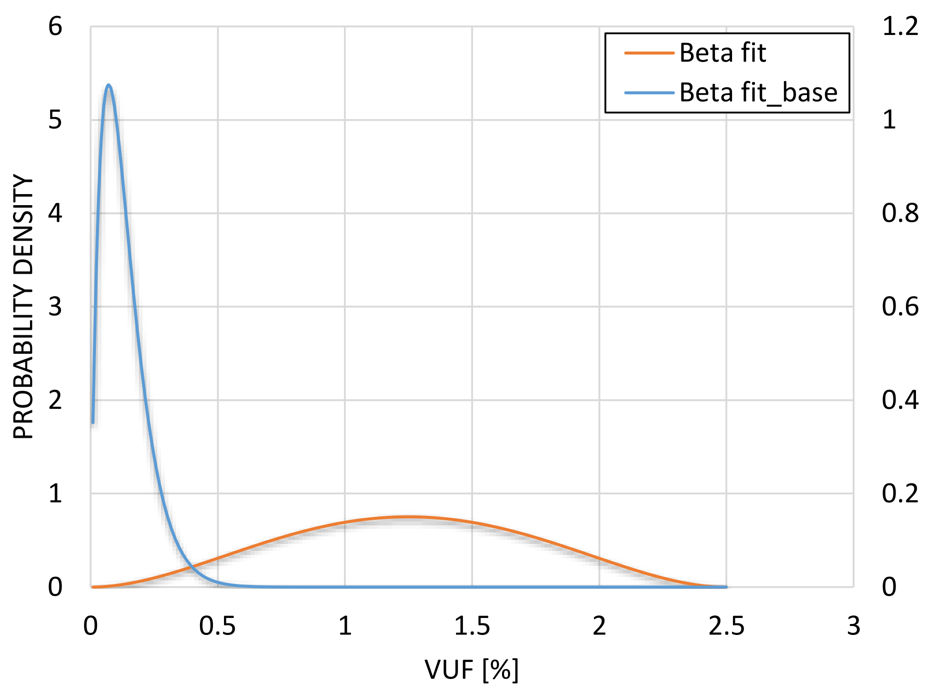

Figure B.7: Feeder VUF PDF comparison with and without PV

Appendix C

PV System specification

Specification of the Yingli 310Wp solar PV used in this thesis.

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Characteristics of a PV module

Manufacturer, model :	**Yingli Solar, YL290P-35b**
Availability :	Prod. from 2015
Data source :	Manufacturer 2015

STC power (manufacturer)	**Pnom**	**290**	**Wp**	**Technology**		**Si-poly**	
Module size (W x L)		0.990 x 1.960	m²	Rough module area	Amodule	1.94	m²
Number of cells		1 x 72		Sensitive area (cells)	Acells	1.75	m²

Specifications for the model (manufacturer or measurement data)

Reference temperature	TRef	25	°C	Reference irradiance	GRef	1000	W/m²
Open circuit voltage	Voc	44.8	V	Short-circuit current	Isc	8.68	A
Max. power point voltage	Vmpp	35.8	V	Max. power point current	Impp	8.11	A
=> maximum power	Pmpp	290.0	W	Isc temperature coefficient	muIsc	3.6	mA/°C

One-diode model parameters

Shunt resistance	Rshunt	245	ohm	Diode saturation current	IoRef	0.099	nA
Serie resistance	Rserie	0.46	ohm	Voc temp. coefficient	MuVoc	-151	mV/°C
				Diode quality factor	Gamma	0.96	
Specified Pmax temper. coeff.	muPMaxR	-0.43	%/°C	Diode factor temper. coeff.	muGamma	0.000	1/°C

Reverse Bias Parameters, for use in behaviour of PV arrays under partial shadings or mismatch

Reverse characteristics (dark)	BRev	3.20	mA/V²	(quadratic factor (per cell))	
Number of by-pass diodes per module		3		Direct voltage of by-pass diodes	-0.7 V

Model results for standard conditions (STC: T=25°C, G=1000 W/m², AM=1.5)

Max. power point voltage	Vmpp	35.8	V	Max. power point current	Impp	8.11	A
Maximum power	Pmpp	290.0	Wc	Power temper. coefficient	muPmpp	-0.42	%/°C
Efficiency(/ Module area)	Eff_mod	14.9	%	Fill factor	FF	0.746	
Efficiency(/ Cells area)	Eff_cells	16.6	%				

PV module: Yingli Solar, YL290P-35b

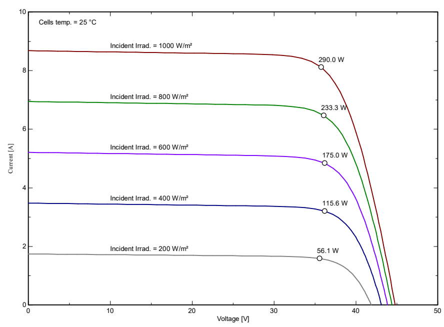

Figure C.1: Solar PV specification