AN ASSESSMENT OF HIGH DISTRIBUTED PV GENERATION ON ETHEKWINI ELECTRICITY DISTRIBUTION NETWORK

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In the College of Agriculture, Engineering and Science, University of KwaZulu-Natal

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DECLARATION 2 - PUBLICATIONS

Publication 1

An Assessment of Voltage Rise Phenomenon on Existing eThekwini Electricity Low-Voltage Distribution Network

Zama Goqo, Sanjeeth Sewchurran, Innocent E. Davidson, Olorunfemi Ojo

IEEE PowerAfrica 2017

Publication 2

Off-load Tap-change Transformer Impact under High Distributed PV Generation

Zama Goqo, Sanjeeth Sewchurran, David Dorrell

IEEE AFRICON 2017

Publication 3

A Review of Grid-Tied PV Generation on LV Distribution Networks

Zama Goqo, Innocent E. Davidson

IEEE PowerAfrica 2018

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NOMENCLATURE

APC	Active power curtailment
CMS	Connaught Major Substation
DG	Distributed generation
DN	Distribution network
DP	DigSILENT PowerFactory
DPVG	Distributed PV generation
HC	Hosting capacity
KZN	KwaZulu-Natal
LV	Low voltage
OLTC	On load tap changer
PF	Power factor
PV	Photovoltaic
RE	Renewable energy
RPF	Reverse power flow
SA	South Africa
SVR	Step voltage regulator
UKZN	University of KwaZulu-Natal
VD	Voltage drop
VR	Voltage rise
VU	Voltage unbalance

Abstract

Small-scale Distributed Photovoltaic Generation (DPVG) continues to grow with increasing operational challenges for electricity utilities and Distribution Network (DN) operators. In Low Voltage (LV) DNs, there are well researched potential issues that arise with high Photovoltaic (PV) penetration. These include: feeder voltage rise, voltage fluctuations and reverse power flow. Among these, the most important issue is voltage rise at the LV distribution feeder. In a broader perspective, to this point in time, there has not been more detailed research on small-scale DPVG interconnections in the LV networks in South Africa (SA) and in the KwaZulu-Natal (KZN) region. There is a great need for research in this field for ensuring network efficiency, reliability and future regulatory standards. Other network systems have been studied around the world were conditions, environment, network characteristics and electricity customer loads will be different; e.g in the North-West of England, Germany, and Queensland, Australia. Hence, the main objective of this research study is to analyze the mentioned problems, identify and test the appropriate mitigation solutions, in the event of high DPVG. This study was carried out on a typical SAn LV DN model, which represents an existing housing development estate at eThekwini Municipality. Consequently the aim is to identify solutions suitable for networks in SAn or of similar architect and characteristics. As a result, a specific application is undertaken at the KZN region, which is also representative of network characteristics of SAn networks. A voltage rise, voltage fluctuation and network power loss issues were analyzed at different PV penetration levels and varying customer loads. An innovative approach of utilization of a standard central On-Load-Tap-Change (Off-LTC) transformer for voltage regulation with high DPVG was tested. Usage of this technique has not been reported in the literature to date. National standards in SA were used as a basic guide in this study and stated the possibility of grid voltage control of distributed PV inverters. Assessment of the typical LV network showed that there is indeed voltage rise and hence possible voltage fluctuation, when PV system output power varies. The Off-LTC transformer was able to maintain network voltages within the allowed operational range and reduced the magnitude of voltage rise. This implies that there is a possibility of avoiding expensive upgrades of the existing and widespread Off-LTC transformers technology.

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1. INTRODUCTION

Solar Photovoltaic (PV) is the most environmentally friendly and efficient electrical energy resource. There have been significant focus on solar PV around the world in terms of research and development. This dissertation details a comprehensive practical assessment of Distributed PV Generation (DPVG) integration on an existing radial Low Voltage (LV) Distribution Network (DN), in South Africa (SA). In particular, an investigation on technical issues, associated with DPVG, was carried out on a case study LV DN. Thereafter, existing and innovative solutions were investigated and proposed, suitable for the considered case study network, in order to adequately address these challenges. This chapter describes the background (chapter 1.1) and objectives of the research (chapter 1.2), the context for the research (chapter 1.3), the plan of development (chapter 1.4) and finally the dissertation structure (chapter 1.5).

1.1. Background to the study

Currently, the world experiences high amount of electric power production from solar PV systems, and will see more in the coming years [1]. A main driver of this production is climate change and increasing energy demand. In recent years, the solar PV sector growth has been showing signs of stagnation in its most mature markets and more growth opportunities in emerging markets [2]. In particular, SA, as one of emerging markets, has challenges in the electricity sector of providing adequate power supply to meet rapidly increasing and unpredictable electricity demand [3]. In addition, population growth and illegal connections have increased grid connectivity and power demand, respectively. Moreover, economic growth fuels energy consumption and have often led to frequent load shedding in order to meat global demand [4]. There is high probability of load shedding, by Eskom, in the near future due to depleting coal stockpile and ever increasing electricity demand. Hence, alternative energy resources have been considered by municipalities and Eskom to address load shedding and high power demand.

A challenge to produce additional power, in line with environmental compliance to clean energy to reduce CO_2 emissions and minimize reliance on fossil fuels; led to the South African electricity utility, Eskom, establishing a Renewable Energy Independent Power Producers Procurement Programme (REIPPPP) [4, 5, 6]. However, the scope of the REIPPPP is limited to utility-scale Renewable Energy (RE) installations. Alternatively, Eskom and most municipalities planned independent small-scale RE projects, and have been inundated with consumer applications to connect Distributed Generation (DG) resources (mainly solar PV systems) to low and medium voltage DNs.

Solar PV panels generate electricity by using PV technology, and are an integral part of solar PV systems. Solar energy, from the sun, is stored and converted into electric energy by PV panels. Increased solar PV generation would reduce the burden on conventional coal power stations. Germany is currently the world leader with 7.6 GW of newly installed PV capacity. The most important factors driving the market growth is that, it reduces CO_2 emissions and saves coal and natural gas reserves. As a result, electricity utilities support installation of solar PV systems through regulations, tax rebates and feed-in-tariffs plans. Distributed PV market share currently increases at a rapid rate [7]. These systems are by large installed as rooftop or ground mounted PV systems. The main focus of this study is to assess and address challenges introduced by high distributed solar PV generation on radial LV DNs; mainly in SA. There exist well researched problems that arise with large-scale integration of DG onto the grid. These will be assessed in a typical radial DN, situated in the region of KwaZulu-Natal (KZN), SA.

1.2. Objectives of this study

1.2.1. Problems to be investigated

Traditional DNs in SA were designed such that electricity flow from the transmission subsystem onto the DN, and finally to end consumers. When rooftop PV (and other DG forms) are connected onto a DN, there is a possibility of a change in direction of power flow and DN becoming active. A main problem arise when PV generation capacity is greater than load demand, on the DN. This results in net power flow toward central transformer and in circulation on the DN, which existing power networks were not designed to manage, and may raise voltage levels beyond acceptable operational limits [8]. Consequently, a Voltage Rise (VR) phenomenon occurs and may lead to failure of DN equipment and customer home appliances.

Most electricity customers require financial compensation for power exported onto the grid. Nonetheless, eThekwini Municipality has made an effort to address this through exploration of a pilot Net-Metering Programme to motivate costumers to invest in PV systems [4]. DG schemes (landfill gas, wind, solar) integration in DNs, considering energy losses and voltage stability (including VR), has attracted attention of electricity suppliers, and is an issue to be investigated [8].

Grid connection of any form of modular generation introduces a disturbance in normal grid operation. Distributed solar PV systems are no exception and more likely to cause problems for utilities, due to intermittent nature of solar irradiance. These problems include; VR, voltage fluctuation, power losses and Reverse Power Flow (RPF), and are investigated as part of this study, on an existing radial LV DN. The DPVG forms considered in this work are conventional rooftop and ground mounted PV systems. The main questions of interest are:

- Do challenges (VR, RPF . . . etc.) exist once DPVG is connected on the case study DN?
- What is the degree of these problems?
- What are suitable mitigation measures for the case study network?
- Is the high uptake of DPVG realizable in SA, and KZN?

1.2.2. Purpose of the study

Rising energy costs, growing public concern about environmental impacts of fossil fuel energy generating resources and energy constraints of utilities across the globe have increased the relevance and need for alternative RE resources. Residential solar PV market growth introduces technical and economic concerns for municipalities and electricity utility network operators. In SA, there is strong interest, from electricity suppliers and customers, on grid-connected DPVG, in contrast to utilization of expensive conventional energy storage and generation devices. Electricity utilities (including Eskom and municipalities), have concerns over DG interconnection, partially because of a lack of intensive published studies, and therefore do not feel able to guarantee reliability and quality to customers once they allow connection of DG without strict requirements. Part of this research aim is to address these concerns through a simulation and experimental study of a case study local DN, at eThekwini municipality. Among challenges, the most important limiting issue is over and under voltage in LV DNs, in the presence of DG [9].

Small-scale residential solar PV projects have been implemented in LV DNs, and there are plans for large-scale future projects at a municipal level. However, there are well known researched technical issues (chapter 1.2) associated with large-scale connection of DG on the electricity grid. These have been reported and need to be assessed thoroughly and independently on existing electricity DNs [10]. In this approach all the challenges would be well understood prior commissioning of solar PV projects [3, 11]. This work aims to assess in detail and address the mentioned issues (chapter 1.2.1) in a typical radial DN in SA. This work is applicable to other networks with similar architectures and characteristics.

1.3. Scope and limitations

A case study residential LV DN of eThekwini Electricity [12] was used in this project, to study potential issues of grid-connection of solar PV systems on a typical radial SAn network. In addition, mitigation measures, utilizing network resources and PV systems, were tested. Only radial LV DN are considered in this study with LV reticulation standards used in eThekwini Electricity, SA. Mitigation techniques using SAn standards, network equipment and PV inverters were evaluated on the case study DN. The main focus was on the LV network part of the overall MV-LV DN [12], and was modeled in DigSILENT PowerFactory (DP) Service Pack 5 2016. A subset of issues associated with DG was considered in this study, and include: VR, voltage fluctuation, RPF and electrical power losses. Other issues have been studied in the literature and can be assessed in this specific case study network as future work. Only single phase home PV systems and customers are considered in this research. A three phase customer (commercial, industrial ...etc.), with a dedicated feeder, was incorporated in the LV network with no connected local PV system. Customers referred to in this work are electricity distribution customers.

1.4. Plan of development

In order to study and analyze DPVG problems, it was critical to model an existing LV network. A PhD study by Dr. Sewchurran [12], focused intensively on the modeling and analysis of the case study DN. At this point in time, is the only existing model that has been successfully implemented and tested in DP, in the SA context. The network had to be modified to suit this specific application of DPVG, in DPF. A project flow chart is included in Appendix A - Fig. A.3, and shows a broader process that was followed to arrive at the conclusions of this dissertation. Following is a summary tool-set of this project:

- DP SP5 2016
- Desktop workstation running DP
- Existing LV network model - for appropriate modification and simulation analysis
- Eskom Smart Grid lab - University of KwaZulu-Natal (UKZN), Westville

Part of these resources are available in the research facility, Eskom Center of Excellence (CoE) in HVDC and FACTS, at UKZN - Westville Campus. An existing network model was obtained from Dr. Sewchurran work [12], whom is a principal engineer at eThekwini Municipality, Durban, SA. DP is a high-quality power systems simulation tool; it includes features specifically designed for analysis of complex electrical systems, and individual components. DP was readily available and licensed at the Eskom CoE in HVDC and FACTS, UKZN.

1.5. Report outline

This report is structured as follows:

- Chapter 2: presents the field of solar PV RE, and introduces concepts of VR, VD, voltage unbalance and fluctuation. Furthermore, mitigation techniques are detailed. The chapter provides an overview of relevant research in the solar PV field and thus provides a context for, and identifies research challenges related to the dissertation.
- Chapter 3: provides an overview of goal-based and prescriptive regulation concepts, and introduces the international and SAn regulatory standards applicable in this field.
- Chapter 4: introduces research methods typically used for assessment of DPVG. It outlines the research design applied in the research and details network component models and study assumptions.
- Chapter 5: presents the most important findings and results of the research. All contributions from the papers (P1-P2, Appendix C) are described in this chapter.
- Chapter 6: the research results are discussed in the context of DPVG and contributions presented in the previous chapters. A short discussion and summary of the potential applicability of the research results is provided.

- Chapter 7: in this chapter, research results are summarized, the main conclusions are presented and some prospects for future work are briefly outlined.

2. LITERATURE REVIEW

2.1. Background

Implementation of major changes in existing electric power DNs, requires ascertainment of key issues, with respect to technical performance of the network, and include [13]:

- Voltage fluctuation
- Voltage regulation
- Electrical power losses
- DN loading and utilization

Kothari [13], reported voltage instability as a main driving factor for utility network collapses, in USA, France, Belgium, Sweden and Japan. Therefore it is critical to conduct detailed analyses of grid voltage stability, with renewable DG integration onto the grid. Voltage control is also receiving great interest from power system analysts and researchers [13]. This dissertation aims to address the mentioned issues, particularly for DPVG, in radial LV DNs. Subsequent sections detail reported literature.

2.2. Distributed generation

Currently, the DG market continue to advance with increasing operational challenges for DN operators (DNOs) [11]. The market is largely dominated by solar PV small-scale systems[14]. DG can be defined as generation of electric power in small scale generation units, close to the point of consumption or to the customer side of the meter [7]. It can only be connected to a single DN [15]. Consequently, it was stated that the main technology for DG from renewable sources is solar PV [7].

2.3. Voltage stability issues

2.3.1. Voltage rise

VR phenomenon is one of the foremost concerns for DNOs [16]. A VR problem results in grid voltage fluctuation in residential homes. This section detail reported work on VR.

According to [17] - a scenario where distributed PV system injects power to the grid, a VR occurs at the electricity Customer Distribution Unit (CDU)[1] or PV node. Traditional DNs were not designed for bidirectional power flow. Hence, RPF mainly results in VR on customer load buses [16], and DN rendered as active. Consequently, bus voltage rises and fluctuate as a function of PV power and customer location (from a central MV/LV distribution transformer).

A main cause of a VR can also be framed on PV active power injection at unity power factor (PF), where connected load demand is exceeded [18]. In [19], a root cause of a VR phenomena was identified as high PV penetration, particularly, in Low and Medium Voltage (LV & MV) DNs. Demirok et al. [20] further emphasized that high PV penetration may lead to violation of grid voltage regulation limits (VR). Tonkoski [9] reported that low load and high PV generation coincidence (at noon) is more likely, than not, to result in RPF. This operating region occurs when PV power generation peaks (due to high available solar irradiance, on a sunny day), and house load consumption at minimum.

A further study in [1], detailed an analyses of impacts of solar PV active and reactive power on steady state grid voltage stability. This was achieved through a study of PV power supply effect on distribution System Loadability[2] (SL). Active power was more helpful in improvement of DN SL, than reactive power, and high PV penetration resulted in RPF; hence VR in the distribution feeder. Solar irradiance fluctuation (due to cloud movements on a semi-cloudy day) directly lead to PV system output power fluctuation and VR, which may lead to bus voltage values beyond acceptable operational limits [16].

Therefore, in this work, DG mainly refers to solar PV systems; however, it does not have to be always so. The amount of DG (wind, solar, hydropower biomass etc.), feeder configuration and DG location, determine the magnitude of VR on the customer points of service or CDU. The research work that has been conducted and reported up to this point, indicates and emphasizes importance of addressing the VR problem prior to any major DPVG project. Moreover, the basic root cause of VR on the DN can be attributed to RPF phenomena, as in [19], where it was used as a basic quantity for the research work. It is clear that the mismatch between customer load and PV generation is more likely to cause problems for customers and DNOs.

[1] SAn equivalent [11] for electricity customer service point, where PV generator and load are connected.
[2] Amount of load that can be supplied by a DN before a collapse of grid voltage magnitude bellow minimum regulation limit [1].

Impact of voltage rise

A significant volume of current literature have reported on the impacts of VR on the distribution system. This section looks at the analyses and impacts of VR due to PV generation in LV DNs. A high uptake of solar PV generation potentially leads to over-voltages and failures in a DN and customer power equipment. In the event where PV output terminal voltage exceeds set standard operational limits ($\pm\Delta V$ = maximum allowed voltage change), connected load appliances may be subjected to voltages for which they were not designed to operate under. Sensitive electrical equipment may malfunction or deteriorate in lifespan. As a result, solar PV maximum capacity which can be supported by a specific DN is largely constrained by the VR problem [10].

In [14], the VR impact was analyzed on a modified traditional 2 bus system shown in Fig. 2.1 (without shunt capacitor), where:

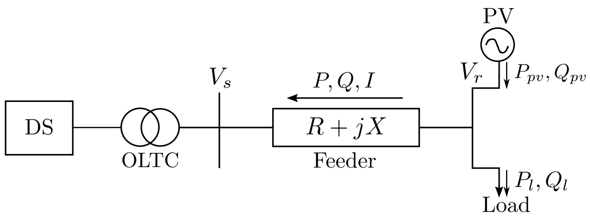


Figure 2.1: Two-bus distribution circuit used for VR analyses [14].

- DS = distribution system
- OLTC = On/Off load tap changer, substation transformer
- V_s = sending end voltage
- V_r = receiving end voltage
- P, Q, I = active and reactive power supplied by PV generation/DG and line current
- P_l, Q_l = load active and reactive power demand
- P_{pv}, Q_{pv} = PV system active and reactive power generation output
- $R + jX$ = feeder line impedance, where R and X are the resistance and reactance, respectively.

A mathematical analysis of the VR phenomenon and maximum DG capacity that can be connected without violating voltage limits was calculated along with VR mitigation techniques [14].

The VR can be defined as follows [14, 7]:

$$\Delta V = V_r - V_s \approx \frac{RP + XQ}{V_r} \tag{2.1}$$

where $P = P_{pv} - P_l$ and $Q = (\pm Q_{pv} - Q_l)$ are net active and reactive power magnitudes, respectively. From Eq. (2.1), it can be seen that the VR is affected by net customer CDU power and feeder line characteristics.

Sensitive electrical and electronic customer equipment incurs a reduction in life time span due to voltage fluctuations. Sub-transmission and transmission systems are both affected by the high penetration of renewable DGs [22]. Therefore, the VR analyses can be extended to the transmission system and studies individually or with sub-transmission system.

2.3.2. Voltage drop

Grid integration of small-scale renewable generation on a DN has an impact on the feeder voltage drop (VD). In order to understand how DG affects the VD, a study in [22], provided a mathematical relationship between line VD and DG on a modified one line diagram, similar to Fig. 2.1, shown in Fig. 2.2.

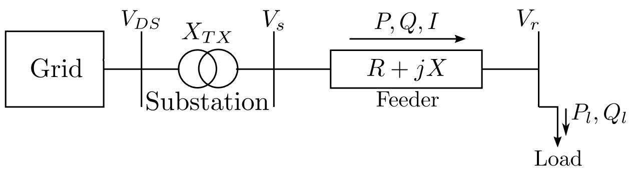


Figure 2.2: One line diagram for voltage drop analysis [22].

From Fig. 2.2, the added parameters are: the line current I, and the MV primary voltage V_{DS}. The VD derivation is undertaken below [22]: The line current I is a function of the load; $S = P_l + jQ_l$, and load terminal voltage $V_r = \frac{S}{I} = \frac{P_l + jQ_l}{I}$

$$\text{Therefore,} \quad I = \frac{S}{V_r} = \frac{P_L + jQ_L}{V_r} \tag{2.2}$$

The mathematical expression for the line voltage drop is given by:

$$V_s - V_r = I(R + jX) = \frac{(RP_l + XQ_l) - j(RQ_l - XP_l)}{V_r} \tag{2.3}$$

The imaginary part was ignored on grounds of high R/X ratio of DNs, as in [23]. The VD calculation: $\Delta V = V_s - V_r$, was simplified and approximated as follows:

$$\Delta V = \frac{RP_l + XQ_l}{V_r} \tag{2.4}$$

A second diagram with renewable DG connection on the feeder, is shown in Fig. 2.3.

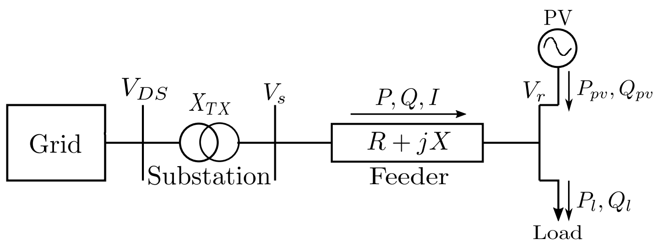


Figure 2.3: One line diagram with distributed PV generation.

The VD expression at the end of the line with respect to the beginning of the feeder line, with DPVG can be approximated as [22, 23]:

$$\Delta V = V_s - V_r = \frac{R(P_l - P_{pv}) + X(Q_l - Q_{pv})}{V_r} \tag{2.5}$$

Based on (2.5), it was concluded that DG reduces the VD. If generator power is greater than feeder or local customer load, the system will inject excess power onto the grid and a VR will emerge. Moreover, is the DG absorb/inject reactive power, it can either decrease/increase line VD [22]. Since the VD is directly related to electrical power losses, PV generation can contributed in reduction of network losses.

2.3.3. Voltage fluctuation

Additionally, a sub-portion of the broad voltage fluctuation phenomena, is a voltage dip problem, which occurs due to passing clouds under high DPVG on a distribution network. In [24], voltage dip issue was found to be significant and subsequently required more specific investigation. Naturally, solar irradiance is intermittent, and as a result, voltage fluctuation and VR are highly expected when DG is connected onto a DN. In [25], voltage fluctuation was defined as a change in voltage from a prescribed value. Movement of clouds is the primary source of induced voltage fluctuation in the grid [25].

2.3.4. Voltage unbalance

Small-scale RPVS or residential PV systems and mismatch in customer load profiles can cause voltage unbalance (VU) in the LV DN. A study in [26], addressed voltage unbalance due to RPVSs and customer loads on a more practical perspective. It was implicitly stated that VU mainly result from different load demand curves between houses, random PV locations and power ratings. As a result, the PV percentage on each phase may be unknown [26].

2.4. Voltage regulation

Current literature have reported on a number of strategies for LV DN power quality improvements through distribution feeder voltage control. This has been achieved through clustered solar PV inverters and utility side management. In 2009, Demirok [20] undertook a comprehensive study and review of grid voltage control techniques for power quality improvements, at that point in time. The study investigated problems arising due to a bilateral interaction between the distributed PV inverters and LV DN. Two major control strategies; *power curtailment and reactive power control* ; for voltage control were analyzed. Both control methods were found to be insufficient and the study stressed more research on intelligent control strategies. Power curtailment resulted in unfair PV inverter scaling among individual connected customers and reactive power method was not suitable for networks with high R/X ratio (LV DNs).

Power curtailment and reactive power control strategies were compared in PSCAD simulation tool. Power curtailment control resulted in limited 59:72% total generation capacity injected into the feeder, and reactive power control method allowed an increases of this capacity - with constrained inverter reactive power support. It was further found that these two control methods can be used together to optimize active power and the operating range can be raised efficiently on different R/X ratio networks [20]. Potential solutions for voltage regulation were identified as:

- Output power limitation
- Reactive power control capability
- Storage system
- DVR, STATCOM, SVC addition to the network [20]

Ref. [14], suggested resistance reduction voltage control approach, to mitigate VR. It was based on the direct proportional relationship between VR and feeder line resistance; $\Delta V \propto R$, where V is grid voltage and R is line resistance [14]. Therefore, to reduce the VR, the line cable size should be increased and possible reconstruct the DN. However, it is stressed that this operation can be costly, and DNOs should consider the value of increasing the cable size and for increasing DG hosting capacity (HC) and reducing voltages [14].

2.5. Active Power Curtailment

The most basic over-voltage mitigation technique is the active power curtailment (APC). This method reduces PV system power below operating point, and is mostly implemented on the PV inverter device. There have been significant work on the basic APC method and improvements, as detailed in this section of the literature.

A study in [27] reviewed the most common APC strategies for distributed renewable energy resources. The most referenced APC techniques were investigated and tested on a 2 bus and more realistic DNs, namely 27:

a) Generator trip or disconnection APC
   - Disconnects generator when overvoltage condition is reached at generator terminals
   - This basic strategy has disadvantage in terms of energy loss, since a generator is disconnected close to maximum generation point
   - An advantage is that it is simple and has potential as a solution for generators with low intermittency

b) Fixed APC
   - Limitation of maximum power fed into the grid
   - Features in most inverters for prevention of overloading
   - A power limiter controller is activated when a pre-set active power set-point is reached

- Offers more benefits compared to generator disconnection strategy

1. Active power vs voltage droop (W/V) control

   - Only active power which results in network congestion is curtailed (Fig. 2.4)

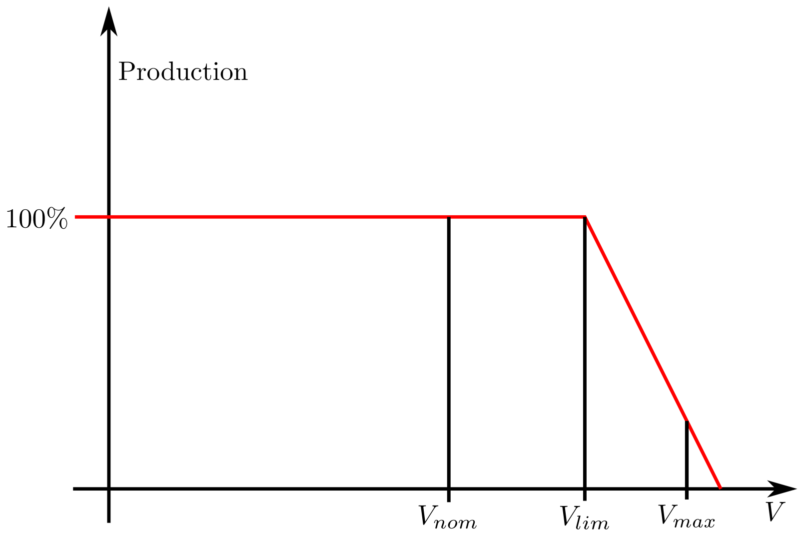


Figure 2.4: Illustration graph of the active power vs voltage droop control strategy [27].

2. Generation of fixed portion of available generation

   - Applies fixed production set-point based on available power generation
   - Large amounts of power curtailment (energy losses) compared to the other strategies
   - Can be applied seasonally, during periods of high power production [27]

The W/V control approach resulted in high hosting capacity[3] for smaller active power curtailments and recommended for PV plants [27].

2.6. Droop-based APC

A research study in [28] proposed a constant adaptive droop-based active power APC, based on adaptive dynamic programming (ADP), for mitigation of overvoltage in LV DN.The methodology was tested on a typical North American LV DN with high PV penetration. It was implemented on a one house model, and reduced energy losses (power curtailment), from traditional APC method, by 25% while maintaining voltages within standard limits. Nonetheless, there was more future work suggested to apply the method on all DN houses and verify overvoltage prevention and power curtailment minimization [28]. This strategy have not been fully applied practically and is currently work in progress.

[3] Amount of generation that can be connected in a distribution network without any problems [27].

2.7. Reactive Power Control

In order to control voltage at the PV inverter terminals, reactive power have been studied in literature to in an attempt to control the grid voltage. Research studies have focused on basic principles of reactive power control to advanced flexible approaches. Ref. [21] of 2008, studied effects of distributed high solar PV penetration on the distribution voltage control and reactive power flow on the power network on a feeder with residential and commercial characteristics. PV penetration levels (5,10,30,50)%, and RPF impacts on feeder voltage profile and network voltage control equipment, respectively, were studied. This study found that reactive power capabilities of PV inverters improve the voltage profile and coordinated control of network equipment and DG can improve overall performance. Implementation used a representative distribution feeder, with on load tap changer (OLTC) transformer, step voltage regulator (SVR) and a capacitor bank voltage regulation equipment to analyze feeder voltage profile and power flow (P & Q). Feeder primary voltage control is achieved by coordinated and uncoordinated control between distribution voltage regulation equipment and oversized (S = 110%) PV inverters. Two extreme scenarios, peak load and maximum RPF, were simulated in order to study the feeders voltage performance under different conditions [21].

In 2013, Malekpour [29] proposed a dynamic reactive power control strategy (var injection) to reduce grid voltage variations due to intermittent solar irradiance caused by fast moving clouds, in a second by second time resolution. Using the capability of smart inverter-based PVs at residential level, traditional and oversized inverter deployment were utilized to investigate the effectiveness of the proposed approach. It was found that oversized inverters reduce the voltage variations significantly and has better control over IEEE 1547 (2003) [30] and traditional inverter control approaches. Most recently [23] (2017), Malekpour proposed and presented a novel dynamic smart PV inverter reactive power control strategy, for mitigation of PV power volatility effects, increasing of PV penetration levels and efficient use of rooftop PV systems, in various weather conditions. The proposed strategy considered three PV system operational states:

- normal state associated with reactive power control in slow PV ramping period (sunny or overcast state, in which loss reduction is the main objective)
- fluctuating state accommodating fast ramp-up or ramp-down PV power, during intermittent cloudy periods, with the objective to smooth out overall feeder voltage profile
- contingency state experienced when PV terminal voltage deviates from the normal operating range (low load high generation or high load low generation) [23].

Each operational state (determined from PV active power and inverter terminal voltage variations) control goal is to eliminate or reduce over or under voltage in the LV grid [23].

PV inverter power oversizing is the main driver of grid voltage control through local reactive power injection/absorption. A diagram showing the relationship between PV inverter power variables is shown in Fig. 2.5. A study in [31] (2010) compared an optimal global and suboptimal local reactive power control strategies on a specific unique distribution circuit. PV inverter oversizing reduced network losses and improved power quality for both strategies. However, the global method was more complex (required significant communication and

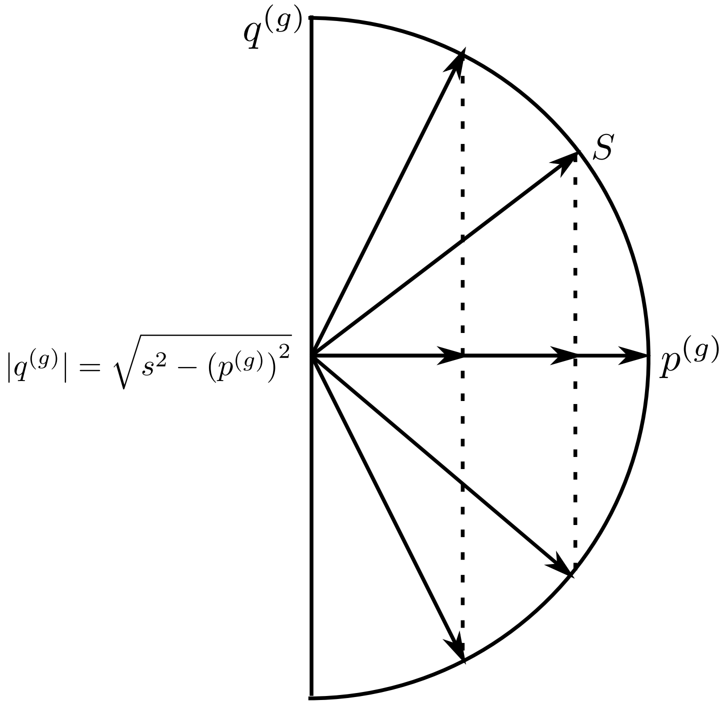


Figure 2.5: Complex power diagram for PV inverter, showing reactive power control range [31].

coordination) in contrast to the simple local algorithm [31].

2.8. Central Transformer Voltage Regulation

The OLTC distribution transformer have been reported significantly in literature, with a focus its real-time response, in terms of tap changing, to network variations and increasing of distributed PV hosting capacity, as in [32, 33]. A comprehensive study of the Off-load tap-change (Off-LTC) distribution transformer voltage control, under distributed PV interconnections, has not been reported in the current literature. This work also addresses this gap in the literature by analyzing impacts of the Off-LTC transformer voltage control under high DPVG. Off-LTC transformers are largely used on the grid downstream from the main generating plants, where there are smaller electricity grids.

Ref. [34], suggested an over-voltage prevention strategy of adjustment of the transformer tap to reduce secondary voltage magnitude. An assumption was made that the transformer tap is not changed frequently. However a practical test of this hypothesis was and has not been conducted.

2.9. Other Dispatch Algorithms

Apart from APC and RPC voltage control strategies, there have been a number of studies recently proposing new novel solutions. As a first instance [16], proposed an efficient distributed renewable resource dispatch algorithm (based on population games), which utilizes cyber connectivity between power devices. In this way, mass integration of renewable resources is facilitated while mitigating VR. The algorithm further aims to minimize dependency of the local LV DN on the main grid for sustainable system operation [16]. However, this algorithm is more suitable for more advanced network architects, which mostly do not exist in developing economies.

Ref. [19], presented an index-based assessment method for quantifying impacts of high PV penetration on VR, with a focus on reverse power flow and VR issues. Indices which link these two phenomena and their impact on the feeder voltage profile are defined. Voltage control strategy consists of derivation of acceptable range and safe margins for the proposed indices. This strategy was then compared with basic APC with no constraint method. Application of this method is only valid for three phase balanced networks (MV/LV). This paper concluded that the IBA methodology was better than the basic APC methodology, and can be applied in large networks in combination with other VR mitigation techniques [19].

Ref. [35], detailed a coordinated control of consumer controllable load - Heat Pump Water Heater (HPWH) - to regulate grid voltage within normal operating limits, for future Japan DNs with large PV penetration levels. A central controller at the distribution substation regulates node voltages by altering HPWH power consumption. However, voltage violations were not completely suppressed at feeder end nodes, under proposed methodology. Nonetheless, this study showed that there is a high possibility of mitigating voltage violations in future DNs [33]. Coupling of LV feeders under a common or different distribution transformers, through a distribution STATCOM device, for voltage quality (VR, VD, unbalance & fluctuation) improvement, has been proposed in [26]. The distribution STATCOM voltage control was tested on the network with varying PV generation and consumer loads. A techno-cost analysis was not undertaken as these devices were not commercially available in high numbers, hence the methodology was still under development [26].

2.10. Conclusion

This chapter presented a comprehensive review of current research on DPVG integration in radial LV DNs. Potential issues identified and associated with DPVG connection on LV DNs are: RPF, VR, VU, voltage fluctuation etc. In this work, these problems will be investigated on an existing LV case study DN, and confirmation thereof. Mathematical equations and circuit diagrams were utilised for VR and VD analysis. These equations can be used for VD reduction, system loading improvement and VR reduction by changing parameters, however this is outside the scope of this dissertation. The most important issue to be investigated is VR phenomenon under high DPVG. Each network need to be investigated for the issues in question independently [19].

3. CURRENT INDUSTRY STANDARDS

3.1. International Standards

3.1.1. Grid Voltage Limits

In Canada, a study in [34], described normal and extreme grid voltage operating limits, which are adopted by most Canadian utilities. The steady-state normal and extreme voltage limits were described as 0.917 and 1.042 pu & 0.88 and 1.058 pu, respectively.

3.2. Voltage Control

In the United States of America (USA), there was an amendment of the international standard, developed by the IEEE, IEEE 1547 (2003) [30] in 2014 [34], and has resulted in more literature works on distributed PV inverter reactive power control for grid voltage support and regulation. The IEEE 1547 - 2014 Amendment I [36] details reactive power control strategies in order to maintain power quality levels or provide ancillary services to the LV DN [23].

According to [34], [37] ”specifies the electrical requirements for inverter-based micro-distributed resource systems interconnection to LV grids in Canada”. This standard does not allow small-scale distributed generator to control grid voltage through reactive power, unless in agreement with the utility. However, the inverters may operate with a power factor between ± 0.85, the standard does not provide any restrictions in the APC method [34].

3.3. South African Standards

3.3.1. Grid Voltage Limits

3.3.2. Voltage Control

In South Africa, the NRS 097 standard specifies grid requirements for interconnection of distributed generation on LV DNs. This standard consists of the following parts under the broad framework title: *Grid Interconnection of Embedded Generation*.

1. Part 1: *Distribution standard for the interconnection of embedded generation*
   - This part specifies minimum technical requirements for grid connection of embedded generation in high voltage HV and MV DNs
2. Part 2: Small-scale embedded generation
   - The specification details technical requirements for the utility interface, the distributed generator and the utility DN with respect to distributed generation, connected in LV DNs

It is to be noted that the embedded generation is equivalent to DG in the research literature. In this report, only Part 2 (NRS 097-2) is applicable for grid interconnection of distributed solar PV, and consists of two sections [38, 39] which are referenced in this work. Section 1 [38] specifies the following, for grid connection of DG:

1. the distributed generator should not control the voltage, unless agreed to by the utility
2. a distributed generator should not inject reactive onto the grid, and reactive power absorption should be limited to a power factor of 0.9. This limits apply, unless agreed otherwise with the utility
3. the embedded or distributed generator shall automatically disconnect from the grid in an event of abnormal conditions:
   - *network voltage or frequency out of bounds condition*
   - *loss-of-grid*; condition in which supply from the utility network is interrupted for whatever reason
4. the distributed generator should be equipped with a disconnection function to disconnect the distributed generator from the grid in an event of either of the above abnormal conditions
5. the distributed generator should trip when the nominal voltage is out of the continuous operating range of $85\% \leq V \leq 110\%$ [38]

From this specification requires PV systems to absorb limited reactive power (at a PF = 0:9), to support voltage regulation in the LV feeder. This can also assist in the reduction of voltage fluctuations and VR in the

LV feeder. However, this limit can be exceeded in agreement with the network utility operator. The reactive power injection functionality is available in an agreement with or of the utility. Therefore detailed and thorough network studies are needed to assess performance and impacts of PV inverter voltage regulation and reactive power injection on the grid, particularly in the SAn networks. Moreover, a protection scheme shall be integrated in the PV system connection plan to disconnect when the voltage limits are violated. This required feature is in line with widespread international practice.

Specifications in the subsequent Section 3 of NRS 097-2, with respect to distributed solar PV generation - *Simplified utility connection criteria for low-voltage connected generators*, are as follows:

- If the the connection criteria in this section is not met, it does not mean that the DG cannot be connected, but detailed network studies are required to assess if the generator can be connected
- utilities may modify or add additional criteria, to meet their specific requirements regarding their network characteristics
- DG connected to the LV network should be 25% of the MV/LV distribution transformer rating
- the total generation (i.e. shared LV generation and dedicated LV generation) supplied by a MV/LV transformer should be less than 75% of the MV/LV transformer rating
- the maximum change in LV voltage (due to voltage drop/rise in the MV/LV transformer and LV feeders) due to embedded generators is limited to 3%
- VR on LV feeders should be limited to a maximum of 1% for dedicated LV feeders
- the maximum VR due to all generators connected to an LV network should not exceed 3%
- The maximum individual generation limit in a shared LV feeder is approximately 25% of the customers NMD, up to a maximum of 20 kVA. This generation limit will typically support a penetration level (percentage of customers that install a generator) of 30% to 50%, which is considered a reasonable and acceptable compromise between restricting individual generator sizes versus restricting penetration levels [39].

This specification provided a basic Simplified Connection Criteria (SCC) for interconnection of DG in LV DNs, without a need for detailed network studies. Accordingly, it was stated that potential network issues (VR, reverse power flow etc.) can be avoided if this connection criteria is followed properly.

3.4. Discussion

In Western countries the PV systems belong to the user usually, or at least an independent third party. Hence tight regulations about voltage control. There is a current argument about voltage control in SA, and there is a highly possible future scenario of voltage control of the distributed solar PV systems, to the standard of no voltage control. At present, Eskom is looking at applications of PV systems that will suit the SAn environment, and the PV units will be part of the Eskom system. This may make voltage control possible if they are also classed as a static synchronous compensator (STATCOM) device. Therefore, the PV inverters will be in synchronization and possible interference between adjacent inverters will be avoided.

There is also the issue that as more distributed PV is deployed, there could be an occurrence where a lot of the houses have PV systems, with different manufacturers. Therefore, if there are voltage regulators on the PV systems they will contradict each other with reactive power oscillating between the systems.

SAn standards does not restrict APC . Also, limited reactive power absorption can be implemented to avoid over-voltage in the feeder, in an absence of utility agreement. NRS grid codes [38, 39] may need updates in future, because more PV inverter functionality will be added in the future [40].

4. METHODOLOGY

In this chapter, the project design process is detailed and is divided into sections. Firstly, the case study LV DN of eThekwini Electricity is brie y described with accompanying reference published sources.

4.1. LV network model

Initially, the full DN model, which includes MV & LV networks was developed in a study in [12]. This network represents an existing network layout of a housing development estate at eThekwini Municipality, SA, and is utilized in this study for distributed generation simulation. Subsequent published work from the eThekwini Electricity network can be found in [11]. The LV network section of the overall DN is also described in this section. In the implementation of the network, LV reticulation standards for South African LV DNs were used to ensure compliance with standard regulatory practice. The case study LV network is primarily fed by the existing 33/11 kV Connaught Major Substation (CMS). A one line diagram of CMS, implemented in DP, is shown in Fig. 4.1. Electrical parameters and characteristics of transformers ($T_{r1}; T_{r2}$) are included in Table A.1, in Appendix A. The two input transformers have identical characteristics and have discrete automatic OLTC for LV side voltage regulation. The voltage set-point of the OLTC transformer was set at a value of 1.03 pu, according to LV reticulation requirements. An external grid is connected to the 33 kV input busbar, shown in Fig. 4.1.

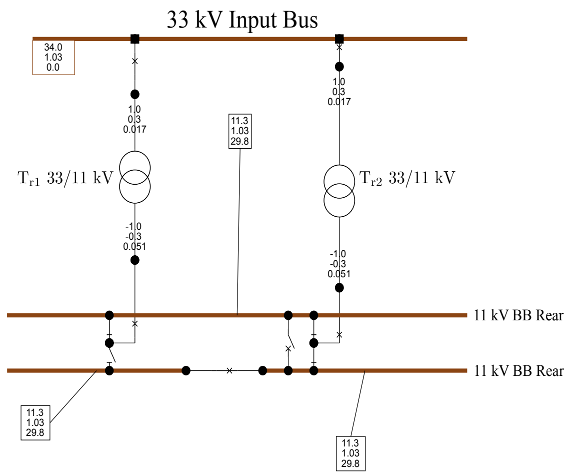


Figure 4.1: CMS one line diagram model showing the 33 kV voltage level input stage [12].

The main 11 kV stage of the substation is shown in Fig. 4.2. The 11 kV BBs are connected to the HV sides of the mini substations transformers. In turn, the 2-winding transformers step down 11 kV to 0.4 kV voltage for LV DNs. The case study electrical LV network is connected at the LV side of transformer T_{r6}.

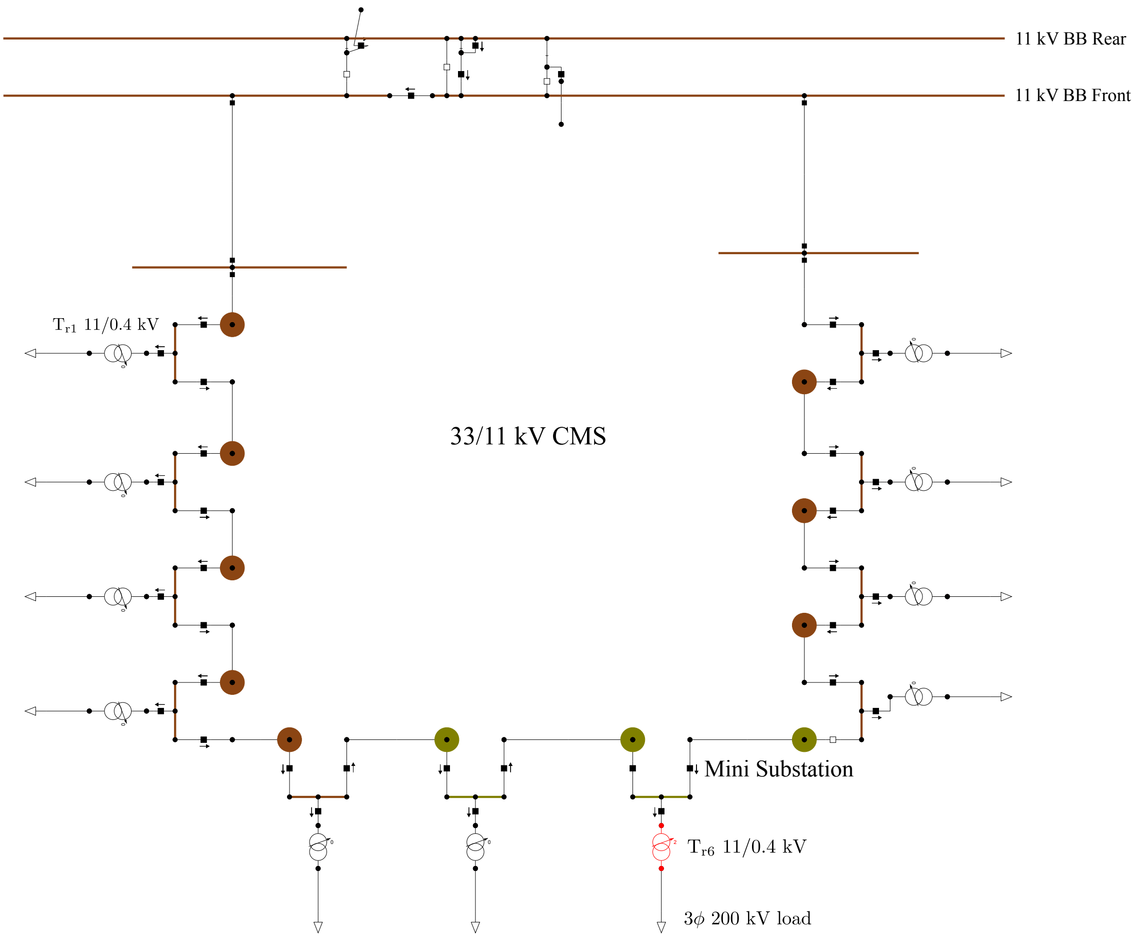


Figure 4.2: CMS 11 kV stage with the case study LV network connection point at the Mini Substation transformer T_{r6} [12].

The LV customers are connected to a grid by shared feeders of 3ϕ ground cables and grid connected customer loads, as shown in Fig. 4.3, and represents an existing housing estate at eThekwini Electricity. Customer loads connected at shared distribution feeders, are identical and single phase. The 3ϕ 200 kVA customer represents larger load (Commercial or Industrial) and has a PF of 0.95, and their balancing effect will be considered under integration of DPVG. Individual LV network feeders consists of 3ϕ ground cable lines, interconnecting the CDUs ($\Rightarrow$ Terminals - $T_1 \ldots T_9$) as shown in Fig. 4.3. Individual CDU distances from a top reference feeder terminal T0 are detailed in Table 4.1. In total length, the feeders are 0.9 km each with a CDU situated at every 0.1 km. Also, the cable length connecting the 500kVA Mini Substation to terminal T0 is 0.1 km in length.

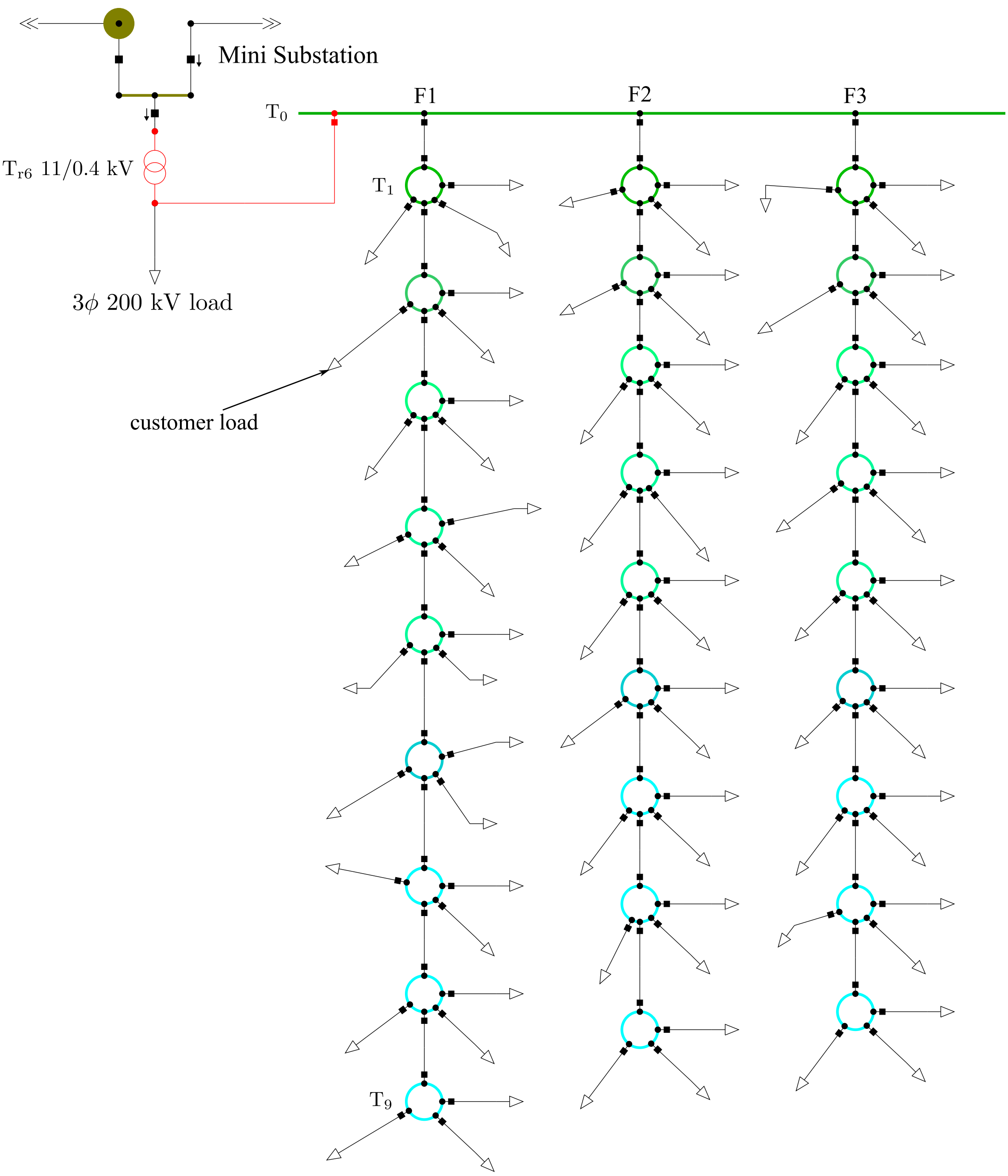


Figure 4.3: Case study 0.4 kV LV network model, with CMS connection point on LV side of transformer T_{r6}, in DIgSILENT PowerFactory [11, 12].

A new housing development in Durban was utilized for this case study. The development consisted of 81 new medium/high income homes with requests and potential for PV installations based on the energy efficiency requirements for this ecological estate. The site was fed from a 500 kVA MS which was dedicated solely for the development. The electrical layout of the development can be seen in Fig. 4.3. For the purpose of this case study, the development was modelled to consist of three feeders with 27 consumers per a feeder and 3 consumers per a CDU. The site was fed from two existing DSS, namely; 192 Underwood Road DSS and 10 Robin Road DSS. These DSS are fed from the Underwood Road Major Substation and Northdene Major Substation. Table 4.1 shows the estate internal reticulation which was designed to ensure that all phases were balanced for the purpose of this study.

CDU Number	F1	F2	F3
	Distance (km)	Distance (km)	Distance (km)
1	0.1	0.1	0.1
2	0.2	0.2	0.2
3	0.3	0.3	0.3
4	0.4	0.4	0.4
5	0.5	0.5	0.5
6	0.6	0.6	0.6
7	0.7	0.7	0.7
8	0.8	0.8	0.8
9	0.9	0.9	0.9

Table 4.1: Customer CDU distances from transformer bus terminal (T).

4.2. Residential Load Model

Residential electricity customers were modeled using data from eThekwini Electricity LV reticulation standard. In this standard customer load values and power factor (PF) are considered fixed. Basic parameters are as follows:

a) Apparent power: 4.6 kVA

b) PF: 0.95 inductive

c) Phase connection: 1ϕ

DPF load flow entry parameters, in a Graphical User Interface (GUI) for LV loads are attached in Fig. A.4 of Appendix A.

4.3. PV System Model

DPF provides a default graphic and software model for a solar PV system. This model consists of pre-built solar panels and inverter (controllers) models, which are explained in detail in the User Manual. Initial basic parameters of PV system for this study are:

- Power rating (minimum) = 1.15 kVA (based on NRS 097-2-3 [39])
- PF = 1
- Phase connection = 1ϕ phase to earth
- Model = active power input

PV system DSP GUI graphic showing entry parameters is shown in Fig. A.5, of Appendix A.

4.4. Line Data Model

Distribution feeder lines were modeled using standard LV cables - 95, 150 & 240 mm2 cables. These cable sizes are used in LV network reticulation in SA. GUI graphics showing input data for line parameters and type are shown in Fig. A.6, of Appendix A. Basic line data is as follows:

- Number of customers = 0
- Maximum & Average load = 0
- PF = 1

4.5. Customer Distribution Unit Model

A CDU[1] unit distributes power supply among three interconnected 1ϕ customers using premise service lines. DSP software represents a real CDU point using a terminal (T) graphics element and data. In this work, service line length were assumed small in comparison to feeder distribution line length, and hence negligible for simplification purposes. A DPF GUI dialog is attached in Fig. A.7, of Appendix A.

4.6. Off-LTC Transformer Models

This section details study design models for the central distribution Off-LTC transformer and overall system connection on the case study LV DN (Figure 4.3). The 11 kV/0.4 kV mini substation LV transformer (Off-LTC) feeds the whole network, and has the following parameters:

- Off load tap changer: 5 taps, 2.5% per a tap with nominal tap at third tap
- Apparent power: 500 kVA
- Voltage ratio: 11/0.4 kV
- Nominal Frequency: 50 Hz
- Core windings: 2 windings
- Feeder configuration: 3ϕ 4 wire (Y-connection)

An equivalent circuit used in DIgSILENT PowerFactory simulation is shown with the basic parameters. The p.u. parameter values used in this study are as follows:

$r_{Cu,\text{HV}} = 0$ p.u., resistance on HV side

[1]Concept for LV distribution network shared feeder power supply point, used in SA.

$r_{Cu,\text{LV}} = 0$ p.u., resistance on LV side
$X_{\sigma,\text{HV}} = 0.023$ p.u., Leakage reactance on HV side
$X_{\sigma,\text{LV}} = 0.023$ p.u., Leakage reactance on LV side
$X_M = \infty$ p.u., Magnetizing reactance
$r_{Fe} = \infty$ p.u., Shunt resistance
u_{HV} = HV side voltage
u_{LV} = LV side voltage

The circuit diagram was obtained from DIgSILENT PowerFactory 2016 user manual under a 2-winding transformer model. The basic transformer subsystem in Figure 4.4 is incorporated in the overall distribution system shown in Fig. 4.5. This is for a per-phase circuit since the loads and PV sources are assumed balanced across the phases, and all feeders identical. More detailed DIgSILENT PowerFactory parameters of the transformer can be found in the Appendix A. Feeder 2 and 3 denote three phase feeders - F2 and F3, respectively, of Figure 4.3.

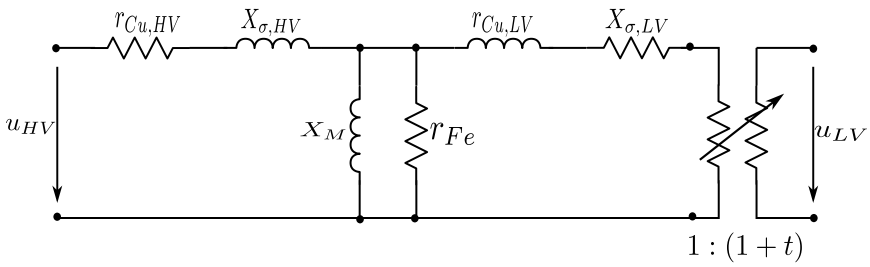


Figure 4.4: Off-LTC transformer basic circuit model with tap changer modeled on the LV side.

Table 4.2 shows the map between tap positions (TPs) and corresponding transformer LV side voltage magnitude.

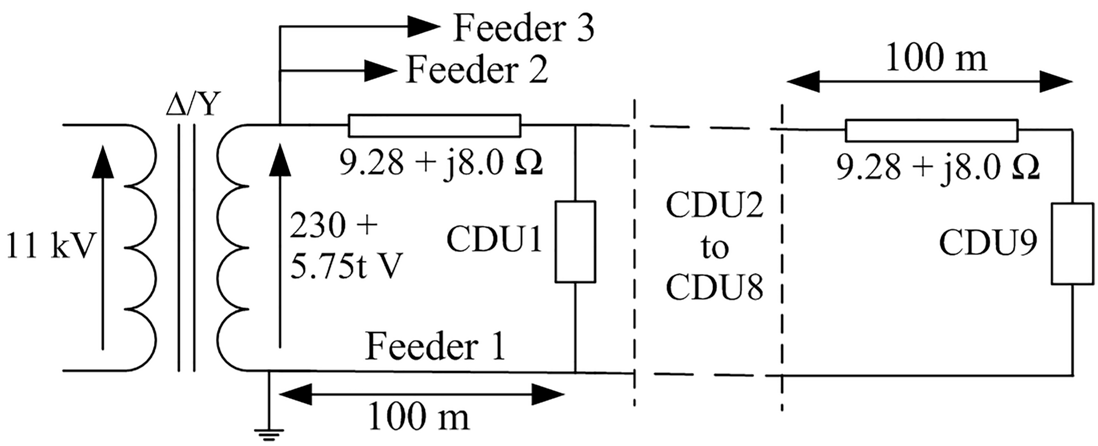


Figure 4.5: Off-LTC transformer per phase feeder 1 (F1) connection system diagram and overall case study LV DN.

Tap position	Voltage (kV)	U_k	Add. Rat. Factor
1	0.38	4.5	1
2	0.39	4.5	1
3	0.4	4.5	1
4	0.41	4.5	1
5	0.42	4.5	1

Table 4.2: Table map of Off-LTC Transformer TPs and LV side voltage magnitude.

4.7. NRS 097-2-3 Simplified Connection Criteria

In an attempt to simplify network utility connection of distributed generators in LV DNs, the NRS 097 standard [39] was developed and is used by DNO in SA. More details in regards to the description of the standard can be found in chapter 3. This section details an application of this connection specification criteria on the case study network for DPVG. A summary of constraints obtained from the NRS SCC are shown in Table 4.3.

Parameter	Value
Max. Generation	125 kVA
Max. Customer Generation	4.6 kVA
Voltage rise limit	6.9 V
Penetration Level	24 to 41 Houses

Table 4.3: NRS 097-2-3 SCC parameters for the case study DN.

4.8. Design Process

The following design process was undertaken in this study.

- Load modeling using ADMD approach
- PV system modeling using static generator concept
- Linear distribution of PV units
- DNO have explicit control of DG location

4.9. Conclusion

In this chapter, the case study LV DN was presented, along with the accompanying MV DN. Network models for all equipment used in this study were described, including a detailed diagram of the Off-LTC transformer. The NRS Simplified connection criteria was reviewed and is applied on the next chapter on the case study DN.

5. RESULTS

In this chapter, simulation results of practical scenarios with residential solar PV integration in case study LV distribution networks are detailed and analyzed. Residential solar PV units can be configured in a number of ways including rooftop or ground mounted PV system setting. More practical scenarios were obtained from an existing network model of eThekwini Electricity and using technical standards for network characteristics and PV installations. Consequently, a simulation study was conducted in DSP latest version and provides more accurate results and practical expectations. This chapter is therefore structured as follows; Firstly, residential load and PV generation profiles are presented with their practical modeling. Thereafter, more broad study assumptions are described in Section 5.2. Thereafter, assessment of VR and feeder line cable mitigation is detailed in Section 5.4. Section 5.5, presents results for network voltage control using a central MV/LV distribution transformer (Off-LTC transformer). Full papers containing more detailed descriptions of the results can be found in Appendix C.

5.1. Typical PV generation and residential load profile

To accurately understand challenges introduced by high DG, correlation between solar PV generation and residential load consumption curves need to be studied. The solar energy and residential load profiles are shown in Figure 5.1. Residential load profile is characterized by morning (6 am) and evening (9 pm) demand peaks, as shown in Figure 5.1. Residential load profile is characterized by morning (6 am) and evening (9 pm) demand peaks, as shown in Figure 5.1.

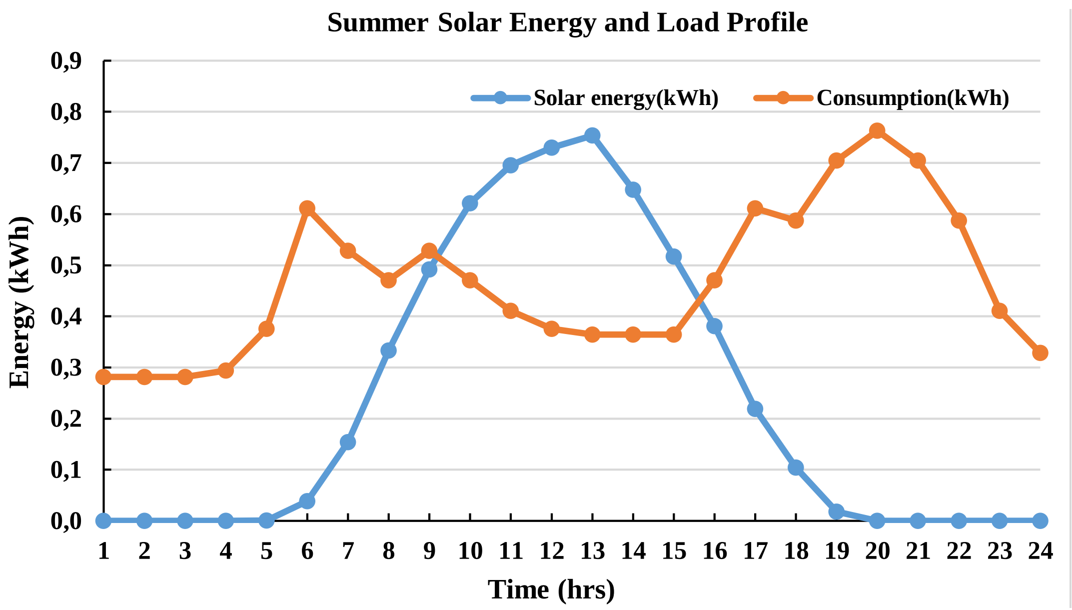


Figure 5.1: Typical LV residential load profile vs real solar energy generation profile in Summer (December): Westville, Durban.

In contrast, PV generation profile is characterized by start of power generation from sunrise (5 am) to the sunset (8 pm), with peak generation around 1 pm. The worst case solar irradiance intensity is shown in Figure 5.2. A reverse power flow scenario is more likely to occur in summer then winter, and would result in technical and power quality problems for DNOs. In winter, there may be increased network losses due to insufficient solar PV power and higher load consumption. The solar data [41] was selected for the months of December and June 2016, and represents the latest solar patterns and most representative. Residential customer data was obtained in [39], with a total day consumption of 11.17 kWh. In this paper, the standard ADMD load modeling method was used in contrast to the resistive method used to obtain the load curve in Figure 5.1.

The actual PV power generation can be computed using the solar irradiance profiles in Figure 5.1 and 5.2; however, this computation is beyond the scope of this work. The solar generation profile used is for Westville in Durban, which is the location of the study. Figure 5.1 plots clearly show that there is a mismatch between solar PV generation and individual customer load demand profile per day, and hence there is more likely a disturbance on normal grid operation.

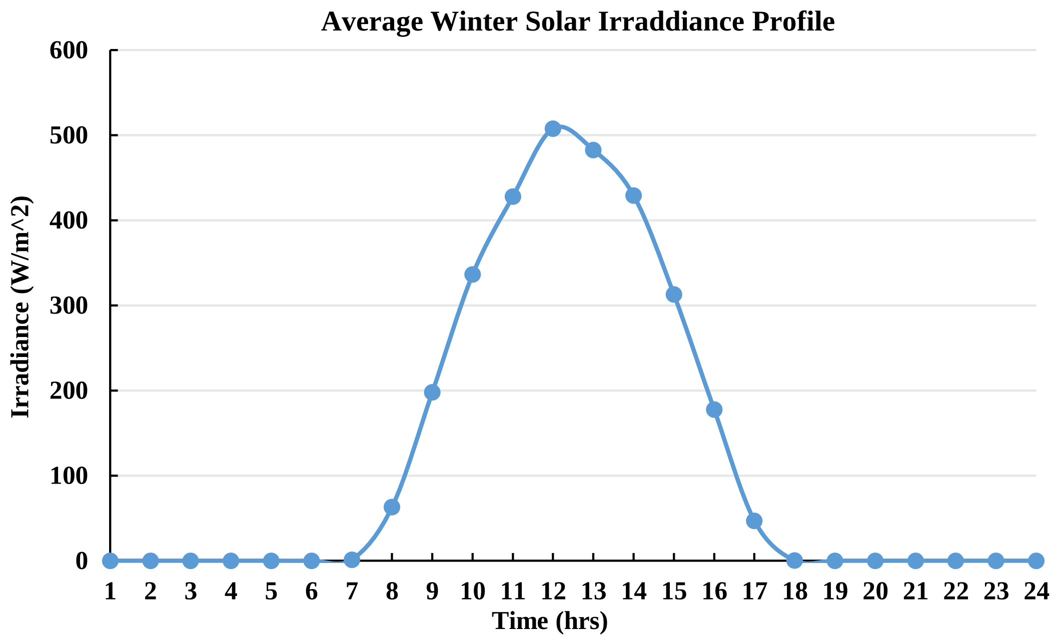


Figure 5.2: Actual average day solar irradiance (GHI) profile in winter (June); Durban - Westville.

5.2. Case study assumptions

The assumptions used for this case study are discussed below:

- All residential customers are single phase customers
- Three phase customer is grid connected
- Individual home NMD = 4.6 kVA
- All PV installations are single phase 4.6 kW systems (maximum PV installation size as per the requirements of NRS 097-2-3 [39])
- PV systems operate at standard solar irradiance (1000 W/m^2)
- LV customers are balanced across three phases
- Customer share the same load profiles and maximum power demand
- Cable length (< 5 m) between the CDU and the customer meter box can be neglected to simplify this study
- Electricity consumption of street lighting is assumed negligible
- The NRS 034 Standard [43], is widely used in SA by utilities and consultants for determination of loads and DG for new developments. This data is used to correctly size the DN components, such as cables/lines, embedded generation and transformers. Table 5.1 is an extract from the standard (Table 2) and gives the kilovolt-ampere zoning ADMD for urban areas at the transformer LV bus. Since the dwellings fell under ”Domestic normal”, an ADMD of 4.6 kVA was selected [11, 3].

	Type of Development	kVA/stand (individual)
1	Domestic electrification	0.2-1
2	Domestic low income	1-3
3	Domestic normal	3-6
4	Domestic upmarket	6-8
5	Domestic luxury single phase	8-12
6	Domestic luxury three phase	¿ 12

Table 5.1: ADMD standard for different urban categories.

5.3. Normal operational results

A primary base case network operation condition, from Fig. 4.3, without PV system connections on T_9, is used as primary study case. During the network design, LV network reticulation standards used by eThekwini Electricity were implemented on the DP model. Accordingly, additional assumptions for the primary base case are as follows:

- House loads are balanced across all feeders
- T_{r6} TP is set at nominal tap (V_{rms})
- All feeders utilize the 240 mm^2 4C PVC underground cable

It should be noted that in the primary base case, cable line $L_{3\phi}$, between T_{r6} 11/0.4 kV and terminal T0, in Fig. 4.3, experienced an overload of 168.92% rated current. Moreover, Mini Substation transformer T_{r6} was loaded at 86.61%, slightly above a standard recommendation of maximum 75% loading. Table **??** shows simulation results in DPF with no solar PV connections on the LV network. Current overloading in line $L_{3\phi}$, between the transformer and T_0, occurred at simultaneous load consumption above 50% ADMD, as indicated in Table 5.2. It is highly unlikely that the LV loads will coincide 100%, as some loads may be pure resistive. However, it is critical to plan in advance for such occurrence. Next section details a first

LSF	V_{T_0} (p.u.)	V_{T_9} (p.u.)
0.25	1.01	0.99
0.50	1.00	0.97
0.75	0.99	0.95
1.00	0.98	0.93

Table 5.2: Beginning and end of feeder voltages (V_{T_0} and V_{T_9}) with discrete variable loads.

step in the grid integration of DPVG using different cables sizes and NRS 097-2-3 [39] SCC specification, on the case study LV network. NRS 097-2-3 standard strictly states that this simplified approach can be followed in order to avoid network problems and further detailed network studies, due to grid connection of embedded generation.

5.4. Performance of feeder cables

Firstly, this study investigated the most optimal feeder cable size for residential PV intake in a typical SAn or similar LV networks. A research paper [11], focusing on this section, was published online and is referenced to acknowledge the published results. Determination of impacts of DPVG and feeder line cable performance were both assessed from a modified typical SAn LV network, developed by eThekwini Electricity, and shown in chapter 4.1: Fig. 4.3. A base case network configuration (with no residential solar PV connections) was compared with step levels of different DPVG Penetration Level(s)[1]. Three standard different cable sizes used for each shared distribution feeder (used for LV reticulation at eThekwini Electricity), and are shown in Table 5.3. Central transformer tap was

fixed at the nominal TP 3 (chapter 4 - Table 4.2), for simulation studies in this Section. LV feeders F_1, F_2 and F_3 were modeled using 95 mm^2, 150 mm^2 and 240 mm^2 cable sizes, respectively. Individual cable current ratings, in amperes, are indicated in Table 5.3. Due to homogeneous properties between the three feeders, each cable performance represents the other two feeders.

Feeder	Cable size (mm^2)	Cable rating (A)
F_1	95	172
F_2	150	249
F_3	240	370

Table 5.3: LV cable ratings utilized in this study.

5.4.1. Method

The following steps were followed in this case study:

- Network assessment at PV penetration levels of [0, 50, 100]%
- Variation of maximum individual consumer loads (4.6 kVA) at [25, 50, 75,100]% variation steps, for each PV penetration level
- Evaluate performance of the 95 mm^2, 150 mm^2 and 240 mm^2 LV feeder cables, on each feeder
- Investigate load variation effects for each PV penetration level

5.4.2. Results for Feeder Cables and VR

Rooftop PV case study 1: base case: No PV generation

In this study case, LV customers were assumed to have no PV installations in their homes. Table 5.4 shows the beginning (T_0, chapter 4 - Fig. 4.3) and end of feeder (T_9 or CDU_9) voltages (V_{T_0}&V_{T_9}), respectively.

[1]Percentage of residential customers with rooftop solar PV system installations.

All three feeders share a common voltage value (V_{T_0}) at the begging of the feeder (Terminal T_0), for all load variations. From Table 5.4, it can be seen that feeders (F_1&F_2) experience VD (below acceptable limits) around peak load periods when large current flows through the transformer. Hence, for normal operation (with no connected PV systems), the optimal operational cable is the larger 240 mm^2 cable size. In this way, all feeder voltages will remain within the acceptable SAn regulatory statutory limits (±10% [42] of nominal 0.23 kV phase voltage [43]). In this particular case, the cable implementation technical costs will be minimal, and energy costs reduced, since the Housing Development[2], at eThekwini Municipality, is currently under a planning phase. Alternatively, procurement cost can be reduced by consideration of the smaller cable sizes and increasing the transformer tap position to offset the VD. It can be assumed that similar results will be obtained on other local SAn or similar networks.

LSF	V_{T_0}	95 mm^2	150 mm^2	240 mm^2
0.25	1.02	0.98	1.00	1.01
0.50	1.00	0.94	0.96	0.99
0.75	0.99	0.89	0.92	0.96
1.00	0.97	0.84	0.89	0.93

Table 5.4: Beginning and end of feeder voltages (V_{T_0}&V_{T_9}, nominal tap) with no solar PV generation [11].

Case study 2: 50% PV penetration

A second operational state, includes a PV penetration level of 50% in residential homes. Feeder voltages remained within acceptable ±10% limits [42], as shown in Table 5.5. In this case, when the high impedance feeder cables (95 mm^2 and 150 mm^2) are utilized, there is no violation of voltage regulatory limits, as shown in Table 5.5. The Voltage Profile[3] improvement is mainly due to total load reduction and local customer demand offset by residential PV units. At peak load (100% ADMD) (8 pm) there is a significant VD on the smallest cable size (95 mm^2) as expected, due to large grid currents. The VR issue only arises for the smaller (95 mm^2 and 150 mm^2) cables, as can be seen in Table 5.5. In this scenario, the bigger 240 mm^2 cable (as recommended in chapter 5.4.2 for normal operation) demonstrated good performance, and suppressed the VR problem. Moreover, smaller cables usage still has valid performance with an adjustment of the transformer tap position. NRS 097 guidelines [39] states that with a limit of 25% of the circuit breaker rating (80 A single phase), a PV penetration level of (30 - 50)% can be supported by the LV network with no technical problems.

LSF	V_{T_0}	95 mm^2	150 mm^2	240 mm^2
0.25	1.03	1.04	1.00	1.01
0.50	1.01	1.06	0.96	0.99
0.75	1.00	0.96	0.97	0.98
1.00	0.98	0.92	0.94	0.96

Table 5.5: Beginning and end of feeder voltages (V_{T_0}&V_{T_9}, nominal tap) at 50% PV penetration [11].

[2]New housing estate development at eThekwini Municipality, Durban, SA.
[3]A voltage vs. distance (km) graph showing voltage variation against CDU distance from a reference terminal (T_0), in this context.

Case study 3: 100% PV generation

A third case study includes a 100% rooftop PV penetration level, with all houses having a PV unit. The feeder voltages all remained within the required statutory limits of ±10% [42], similar to previous case. More so, with use of smaller size feeder cables (95 mm^2 and 150 mm^2) no voltage violations were experienced as shown in Table 5.12. As for this instance, the 240 mm^2 cable demonstrated acceptable performance, when the transformer tap is fixed at nominal or neutral tap position. Therefore, to reduce tap change costs, the 240 mm^2 can be installed and its financial cost recovered from the reduced energy losses and increase in revenue.

LSF	V_{T_0}	95 mm^2	150 mm^2	240 mm^2
0.25	1.03	1.10	1.07	1.05
0.50	1.02	1.06	1.04	1.02
0.75	1.00	1.02	1.01	1.00
1.00	0.99	0.98	0.98	0.98

Table 5.6: Beginning and end of feeder voltages (V_{T_0}&V_{T_9}, nominal tap) at 100% PV penetration [11].

5.4.3. Power losses

Feeder losses: base case: No PV generation

Table 5.7 shows feeder power losses experienced on the LV feeders for different loading conditions with no rooftop PV connections onto the distribution network. From Table 5.7, it is clear that the network losses increase in proportion with the load demand, as expected. The 95 mm^2 and 150 mm^2 cables yield 373% and 185% losses, respectively, compared to the 240 mm^2 cable losses, at 100% ADMD load demand time.

LSF	95 mm^2 (kW)	150 mm^2 (kW)	240 mm^2 (kW)
0.25	0.34	0.21	0.08
0.50	1.06	0.66	0.24
0.75	2.30	1.42	0.50
1.00	4.21	2.54	0.89

Table 5.7: Feeder active power losses (nominal tap) at 0% PV penetration [11].

Feeder losses: 50% PV penetration

Table 5.8 shows results for a PV penetration level of 50%. There exist significant increase in network losses at minimum 25% ADMD load, particularly for the smallest cable size 95 mm^2, as shown in Table 5.8. This is a result of excess power generation on the network, VR and RPF, as indicated in Table 5.8. However, there is a drastic reduction in losses, on all three feeders, when the load is at least 50% ADMD. This reduction is due a decrease in exported PV power and increase in load. Network losses increase at minimum LSF = 0.25, for the 95 mm^2 and 150 mm^2 LV cables, are 342% and 177%, respectively, compared to the 240 mm^2

LV cable. NRS 097-2-3 Standard [37] guidelines states that with a limit of 25% of the circuit breaker rating (80A single phase), a PV penetration level of 30 - 50% can be supported by an LV network with no technical problems.

LSF	95 mm^2 (kW)	150 mm^2 (kW)	240 mm^2 (kW)
0.25	1.37	0.86	0.31
0.50	0.54	0.34	0.13
0.75	0.15	0.09	0.04
1.00	0.12	0.08	0.03

Table 5.8: Feeder active power losses (nominal tap) at 50% PV penetration [11].

Feeder losses: 100% PV generation

Table 5.9 shows that there is an increase in the losses on the network in the study case of 100% PV generation on the distribution network. This can be attributed to the fact that there is significant excess generation on the network in comparison with load demand. However, losses are much less in comparison to the base case, in Table 5.7 with no PV generation. The reduction in losses for the case of 100% of ADMD load are 12.12%, 12.99% and 13.48% for 95 mm^2, 150 mm^2 and 240 mm^2 LV cable sizes, in comparison to base case network losses (Table 5.7). The subsequent Section describes simulation study of the central transformer with 100% of customers having PV system installations, and all LV feeders equipped with the 240 mm^2 4C PVC copper cable.

LSF	95 mm^2 (kW)	150 mm^2 (kW)	240 mm^2 (kW)
0.25	1.11	0.74	0.28
0.50	0.62	0.41	0.16
0.75	0.40	0.26	0.10
1.00	0.51	0.33	0.12

Table 5.9: Feeder active power losses (nominal tap) at 100% PV penetration [11].

5.5. Off-LTC Transformer voltage control

In this Section, all LV feeders utilized the 240 mm^2 cable, and only results from feeder F1 were recorded, since all feeders are homogeneous. Existing research publication from this Section can be found in [3], and is acknowledged and referenced. It is important to note that the tap positions (TPs) 1 & 5 results, from [3], were swapped to ensure consistency with the voltage magnitude.

5.5.1. Method

This work proposed Off-LTC transformer voltage control method, under high PV generation, was tested in the case study LV network, with more details in [3]. This section assesses performance of this specific transformer with an expansion stage of residential PV systems. The following process was undertaken:

- Assessment at PV penetration levels ((5.1)) of [0, 50, 100]% of local active load, or PV system APC at the penetration levels
- Assessment of network electrical parameters under [25, 50, 75, 100]% load demand $\leq$ ADMD, or LSF = 0.25, 0.5, 0.75, 1.0$\times$ ADMD, for each PV penetration level
- Evaluation of impacts and performance of discrete Off-LTC transformer TPs 1,3,5, for each PV penetration level
- Quantify impacts of bus voltage variations and power losses on the network under different network loading, transformer taps and PV penetration levels [3].

5.5.2. Evaluation of voltage rise

For all subsequent results, the primary voltage at the point of common coupling of the transformer remained regulated at 1.03 pu (11.3 kV) for all considered operational scenarios before and after PV connections. The voltage was regulated by the automatic OLTC transformers at the CMS substation. The transformer LV side voltage magnitude follows and controlled by off-load tap changes on the primary transformer winding (chapter 4.6 - Table 4.2). In this Section, the PV system penetration level was de

ned as a percentage of the local maximum active customer load [19] as follows:

$$\text{PV penetration level} = k \times \text{ADMD} \times \text{PF[kW]} \tag{5.1}$$

Index k represents the ratio of maximum PV capacity (kWp) to maximum customer active load, and is called the maximum PV penetration level [19]. The values of k index have a range of 0 to 1 [3].

PV case study 1: base case: No PV generation

Table 5.10 shows V_{T_0} and V_{T_9} CDU voltage magnitudes on the LV network. From Table 5.10, statutory voltage limits of $\pm$10% [42] were violated at the feeder end, for load ¿ 75% (LSF = 0.75). This VD results from the transformer minimum TP. This is largely due to high grid current and low transformer secondary voltage. Thus, for standard operation, with no PV systems, operation at low TPs may be avoided to ensure maintenance of feeder line voltages within the regulatory limits, for a nominal 0.23 kV [43]) bus voltage. Operation at TP 5 may results in over-voltages, in rarer circumstances, where load is less than 25%. It is clear that the VP is a function of TP, and hence TPs can be tuned in simulation to obtained optimal operating point. As evidenced in Table 5.10, feeder VP is directly and inversely proportional to transformer tap changes and LSC, respectively. Thus in normal operation, the best TP was identified at neutral TP to avoid under or over voltage [3].

LSF	TP 1		TP 2		TP 3	
	V_{T_1} (p.u.)	V_{T_9} (p.u.)	V_{T_1} (p.u.)	V_{T_9} (p.u.)	V_{T_1} (p.u.)	V_{T_9} (p.u.)
0.25	0.96	0.95	1.01	1.00	1.07	1.05
0.50	0.94	0.92	1.00	0.97	1.05	1.03
0.75	0.93	0.88	0.98	0.95	1.04	1.01
1.00	0.92	0.87	0.97	0.93	1.03	0.99

Table 5.10: T_1 and T_9 voltages at 0% PV penetration [3].

Case study 2: 50% PV penetration level

At k = 0.5, all feeder voltages remain within regulatory limits [42], for all TPs, as shown in Table 5.11. In this case, operation at the minimum tap regulates voltages within statutory limits. However, increasing tap changes can result in a volatile voltage change and instability. Feeder VP was improved by PV power generation at customer houses, and reduction in grid power demand. Maximum TP can be avoided to mitigate instances where load is less than 25%, and voltage upper limit violated. In incorporating the unconsidered region, load ¡ 25% ADMD, the nominal tap still results in appropriate voltages within range. Moreover, VR limit (6.9 V, see Table 4.3 in chapter 4.7) [39] is exceeded for a load step change from 50% down to 25%, in TP 1. In practice, this event is more likely to occur during sunny days, PV generation constant, and customer loads changing rapidly.

LSF	TP 1		TP 2		TP 3	
	V_{T_1} (p.u.)	V_{T_9} (p.u.)	V_{T_1} (p.u.)	V_{T_9} (p.u.)	V_{T_1} (p.u.)	V_{T_9} (p.u.)
0.25	1.02	1.02	1.02	1.02	1.08	1.07
0.50	0.96	0.95	1.01	1.00	1.07	1.06
0.75	0.95	0.93	1.00	0.98	1.05	1.04
1.00	0.93	0.91	0.99	0.96	1.04	1.02

Table 5.11: T_1 and T_9 voltages at 50% PV penetration [3].

Case study 3: 100% PV penetration level

At k = 1.0, i.e. 100% PV penetration (APC = 0), all voltages consistently remained regulated within statutory limits [42], as more load is supplied from local PV systems, as shown in Table 5.12. In a case of low load periods, there are no significant changes in voltage levels for all considered k values, i.e. k = 0, 0.5 & 1. Load increase from low to peak demand, results in VD as more reactive current ows on the feeder line. Ideally, in this scenario, total load seen by the central transformer is pure reactive load. The VR phenomena occurred at operation of TPs 1 and 3. Maximum tap mitigated VR, however, may result in overvoltage for load less than 25%. Neutral tap regulated voltages within acceptable range, with a VR value less then the maximum limit of 3%[37]. Hence, for all PV penetration level, operation at nominal tap yields best performance, in comparison with other TPs.

LSF	TP 1		TP 2		TP 3	
	V_{T_1} (p.u.)	V_{T_9} (p.u.)	V_{T_1} (p.u.)	V_{T_9} (p.u.)	V_{T_1} (p.u.)	V_{T_9} (p.u.)
0.25	0.98	1.00	1.03	1.05	1.09	1.01
0.50	0.97	0.98	1.02	1.03	1.08	1.08
0.75	0.96	0.96	1.01	1.01	1.07	1.07
1.00	0.95	0.94	1.00	0.99	1.06	1.05

Table 5.12: T_1 and T_9 voltages at 100% PV penetration [3].

5.5.3. Feeder power losses

The next phase of simulation, assess TP performance in terms of network power losses, in three PV case studies. Energy losses investigated, is the electrical energy dissipated on the feeder line resistance. This energy loss results in less power delivered to the houses, and revenue losses for the DNOs.

Feeder losses: base case: No PV generation

Table 5.13 shows network power losses per a feeder, for different load demands, with no PV installations. Feeder losses increased with load demand, for all Off-LTC transformer TPs, as expected. TPs 3 & 5 resulted in equal and lower losses compared to TP 1, where losses increased by 25%. For normal operation, the distribution transformer can still be operated at neutral tap to avoid unnecessary power losses and under/over voltages beyond acceptable limits.

LSF	95 mm^2 (kW)	150 mm^2 (kW)	240 mm^2 (kW)
0.25	0	0	0
0.50	1	1	1
0.75	3	2	2
1.00	5	4	4

Table 5.13: Feeder power losses with no PV penetration (Rounded to the nearest kilowatt) [3].

Feeder losses: 50% PV penetration

In this scenario, the PV penetration level k ((5.1)) is set at 0.5 (APC = 50%), and results are tabulated in Table 5.14. It can be seen from Table 5.14 that network power losses decreases with the increase in PV penetration. For load range [0 - 50]%, there are no energy losses, because of load balance by PV system generation, and high R/X characteristic ratio of DNs [17]. High R/X ratio for radial DN [22, 23] means that PV active power effects on loadability are very high, as discussed in [1]. In practice, there will be small, but negligible reactive power losses on the feeder line. Consequently, DN operational expenditures [44] are reduced and revenue increased. Power losses emerge after LSF = 0.5, where there is a net load and customers draw active and reactive currents from the transformer. Similar to no SPVG case, TPs 3 & 5 have lower and equal losses, compared to TP 1 with 100% power loss increase.

LSF	95 mm^2 (kW)	150 mm^2 (kW)	240 mm^2 (kW)
0.25	0	0	0
0.50	0	0	0
0.75	1	1	1
1.00	2	1	1

Table 5.14: Feeder power losses at 50% PV penetration (Rounded to the nearest kilowatt) [3].

5.6. Summary of results

This chapter presented results of an analysis of DPVG integration on a LV DN representing network characteristics in SA. Firstly, typical residential customer load and PV generation profiles were analyzed to identify the source of potential network problems. Indeed, potential issues of VR and RPF, on the DN, were identifiable from the graphs in Fig. 5.1 (chapter 5.1). In order to begin network analysis, a comprehensive study was done on the case stuty network without PV generation and results recorded (chapter 5.3). A line current overload was detected at $L_{3\phi}$ for simultaneous high load demand above 50% of individual customer ADMD (Table 5.4). It was shown that this current overload is reduced by connection of PV units onto the grid. Consequently, NRS 097-2-3 [39] standard was evaluated and applied on the LV network by scaling individual solar PV systems rating, connected at customer CDUs.

The NRS 097-2-3 standard clearly states that the SCC, for interconnection of embedded generation in LV DN, can be used to avoid network issues and further detailed network studies. However, for this particular case study LV network (Fig. 4.3), it does not address adequately the need for a reduction in current loading of line $L_{3\phi}$ of transformer LV side. Furthermore, there is an unfair generation distribution between customers. Local customers with PV systems reduce their dependency on the grid and load, and can generate financial income from exported PV electricity. This means even if there were a power outage, these customers can still have a power supply locally without islanding. The local generation capacity limitation to 25% of customer NMD also has disadvantages. It limits customer load offset and potential financial income, that can be gained by a customer through PV power export, by a large margin. As a result, it is more than necessary to perform further detailed studies on the specific case study network to address these shortcomings.

In terms of feeder cable performance, a larger cable (more expensive, 240 mm^2) resulted in grid voltages within regulatory limits of $\pm 10\%$ [42], for all considered number of homes owning and operating PV units at a time (PV penetration[4]), and lesser VR (see chapter 5.4). In contrast, smaller cables (cheaper, 150 mm^2 and 95 mm^2) showed poorer performance resulting in VR (above $\pm 10\%$ for loads ¡ 25% ADMD) and VD below regulatory limits of $\pm 10\%$ in normal network operation (Table 5.4). Moreover, electrical power losses were the least for the 240 mm^2 cable, for all PV penetration levels. Therefore, weighting of prize, technical performance and revenue increase for the 240 mm^2 cable should be undertaken in practice by DNO and planning engineers.

Under an assumption that all customers own PV units and using the 240 mm^2 cable on all feeders, central transformer demonstrated adequate voltage control, for all considered local PV penetration levels[5]. Nominal

[4]Percentage of residential customers with PV units.
[5]Percentage generation of local maximum active load at customer premises.

tap (TP 3) operation resulted in bus voltages within regulatory limits, for all PV penetration levels and simultaneous load variations (chapter 5.5).

5.7. Conclusion

In this chapter, simulation results of practical scenarios with residential solar PV integration in case study LV distribution networks were detailed and analyzed. Residential solar PV units can be configured in a number of ways including rooftop or ground mounted PV system setting. More practical scenarios were obtained from an existing network model of eThekwini Electricity and using technical standards for network characteristics and PV installations. There were new findings pertaining to power losses that exist when PV is feeding in the network, and these are discussed in the next section.

6. EVALUATION AND DISCUSSION OF RESULTS

This chapter details a discussion of relevance and relation, of this study, to existing literature in the area of DPVG. In this project, a high uptake of DPVG was assessed on a sub-urban LV DN, located in eThekwini Municipality, Durban - SA. The case study network represents typical characteristics for SAn networks, which can be similar to other emerging economy countries. The network site is currently under development for future modification and reinforcements in the city of eThekwini.

Firstly, this chapter discusses the results in the context of the four research questions (RQs) RQ1-RQ4 (chapter 6.1), followed by a broader discussion of the observed results (chapter 6.2), and a discussion of the results in relation to state of the art (chapter 6.3). Finally, a general reflection on the research context and the overall results is detailed (chapter 6.4).

6.1. Discussion of results in the context of research questions

This section contains an evaluation of results in the context of RQs. A more thorough discussion of the results can be found within papers P1-P2 in Appendix C.

6.1.1. RQ1: Do challenges exist once DPVG is connected on the case study DN?

Well known challenges of RPF, VR, VD, voltage fluctuation and power losses; were identified on the case study network through DP simulations. Research papers P1 and P2, investigated challenges associated with grid connection of DPVG on the case study radial LV network.

Moreover, research results (chapter 5) confirmed the existence of these technical issues in high solar PV penetration instances. RPF was the main event for VR at the feeder end, and upstream power losses (PV generation losses). Am additional severe problem was the line current overload in the Off-LTC transformer secondary connection line $L_{3\phi}$, as shown in Table 5.2 (chapter 5.3). An unexpected finding in this research is: existence of power losses, on the distribution feeder line, during RPF operational scenario. As power flows upstream to the MV/LV transformer during RPF, these losses can be characterized as PV generation power losses (active power losses).

6.1.2. RQ2: What is the degree of these problems?

Upon grid integration of DPVG in LV network, challenges would exist due to this change in the network. A VD, beyond regulatory limits (±10% [42]) was prevalent in usage of small cable sizes (95 mm^2 and 150 mm^2 with higher losses), in absence of solar PV generation.

6.1.3. RQ3: What are suitable mitigation measures for the case study network?

Publications P1 and P2 of Appendix C, partly addressed mitigation of technical issues associated with grid connection of distributed solar PV systems. Feeder cable sizing proved to be a valuable tool to mitigate power losses and reduce RPF and VR. Paper P2 contributed significantly in the current literature by proposing an innovative standard Off-LTC transformer voltage control approach, under high DPVG connections on the grid.

6.1.4. RQ4: Is the high uptake of DPVG realizable in SA, and KZN?

Research question RQ4 was answered in the overall dissertation results and findings. A high uptake of renewable DPVG is feasible with additional network modifications (cables, transformer, loads . . . etc.) and reinforcements (PV inverters, battery storage. . . etc.).

6.2. Discussion of observed results

Firstly, in chapter 3, international and local standards were evaluated and discussed for purposes of application and future improvements. Currently, SAn standards have fixed LV grid voltage operational limits of ±10% [42]. In contrast, international standards [37] have flexible voltage regulatory limits where the voltage range is partitioned into different states. This can be helpful in practice since network equipment and customer appliances have difference voltage operational limits and sensitivity. Local standards can be further improved in this area to prevent network failures and ensure reliability in normal operation and DG integration.

In chapter 5.3, initial network state with no solar PV was analyzed in DP software. Subsequently, current overload and V occurred at high load demand scenarios. Feeder VD increased proportionally to customer load (P_l and Q_l) as in Eq. ((2.4)) in chapter 2, for fixed line resistance R and reactance X. Similarly, terminal T_0 voltage dropped proportionally to grid current increase, with respect to Off-LTC transformer secondary voltage. A low impedance (lower grid losses) cable 240 mm^2 was utilized as a base case and compared with other standard size cables, in an event of DPVG connection onto the grid.

Chapter 5 investigated a feeder line cable suitable for the application of high DPVG. Three standard cables, 95 mm^2, 150 mm^2 and 240 mm^2 (chapter 5 - Table 5.3), were considered and are utilized for LV DN reticulation in SA and eThekwini Municipality.

6.3. Discussion of results in relation to state of the art

In this research study, a standard procedure to identify important issues in power system modification [13], was undertaken. Chapter 2.1, stated issues identified and discussed for the case study LV DN. The network experienced line overloading in the absence of DPVG. However, integration of PV generation helped reduce the current drawn from the central transformer.

A VR phenomenon as explained in [17, 16], was identified through simulations, for different solar PV penetration levels and variable loads. Connection of solar PV generation caused a VR at the customer CDUs, in terms of line and phase voltages, where local load demand was exceeded and PV systems operating at unity PF [18]. In consideration of network architecture and characteristics, phase voltage remained regulated within standards statutory limits.

A VD was apparent when distribution load increases, with no solar PV connections. However, with addition of solar PV generation on the case study DN, the line VD reduced significantly, similar to findings in [22]. This was due to reduction in current drawn from the central transformer by customer loads.

6.4. Research summary

In this study, discrete variable PV penetration and distribution loads were used to quantify well known technical problems. A VR existed with increasing PV penetration level. A VD was significant when loads operate at 100% capacity, as line current was at a maximum value. Integration of PV generation contributed in alleviation of VD, and prevent malfunction of sensitive distribution equipment and customer appliances.

Voltage control was achieved through network modifications and central Off-LTC transformer tap changes. A largest cable 240mm^2 showed better performance, with or without PV generation. In terms of the central transformer, a nominal tap position maintained voltage within NRS regulatory limits.

7. CONCLUSIONS AND FUTURE WORK

This chapter summarizes the conclusions provided in the published papers and overall dissertation. The chapter contains an overview of the main conclusions based on the results presented throughout the dissertation (Chapter 7.1) and it provides directions for future work (Chapter 7.2).

7.1. Conclusions

Papers P1-P2 in Appendix C provided main conclusions from the results obtained in this work. Therefore in this chapter, an overview of the most important

findings are provided. As previously described, the main research goal for the dissertation was:

Comprehensive assessment of RPF, VR, VD, voltage fluctuation and power losses issues. Thereafter, evaluation of suitable mitigation solutions to address the mentioned issues (chapter 1.2) for the typical radial DN found in SA. Applicable of this work is valid for other networks of similar architecture and characteristics, mostly in emerging economies.

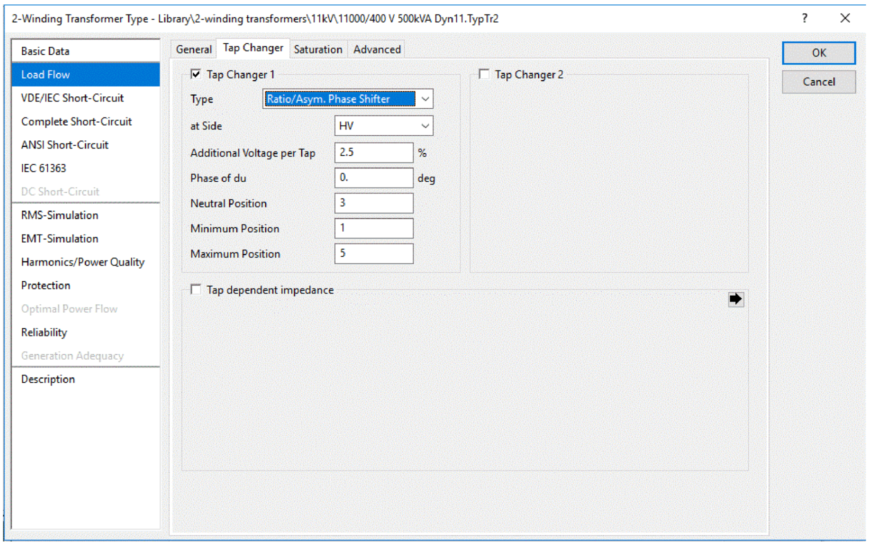
It was found and confirmed that these challenges exists and can course technical problems for DNOs (national utilities and municipalities). Mitigation of these issues can be realized using appropriate feeder cable and central transformer settings. It was further found that a bigger cable size results in less RPF. Furthermore, a nominal tap setting in the manual Off-LTC transformer avoided problems of RPF and VR, and minimized power losses.

7.2. Future work

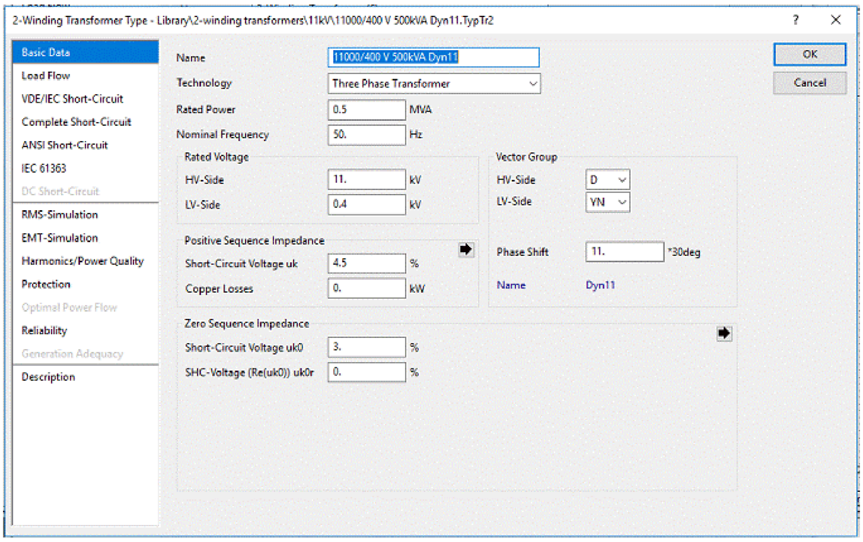
In this work, a subset of solutions associated with DPVG were investigated and applied in practical simulation of the case study DN. More solutions can be investigated in future to minimize losses and increase HC of the LV DN.

A. ADDITIONAL FILES AND SCHEMATICS

A.1. Tabular Data



(a) DigSILENT dialog for transformer tap change data entry.



(b) DigSILENT dialog for transformer model data entry.

Figure A.1: Off-LTC transformer data entry dialogs in DIgSILENT PowerFactory 2016, and used in this work

Fig.A.1 and Fig. shows the DIgSILENT PowerFactory (2016 SP5) data entry dialog for the Off-LTC distribution transformer.

A.2. Graphics and Diagrams

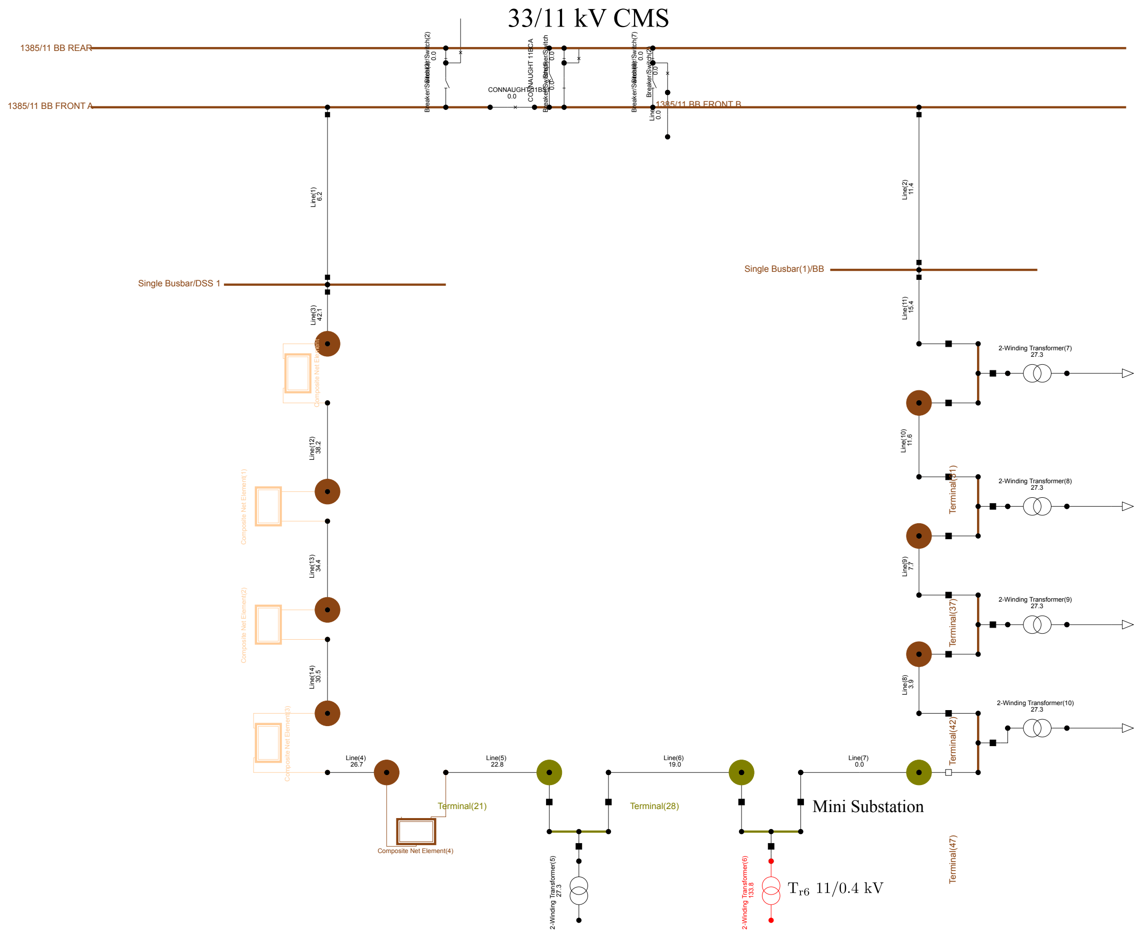


Figure A.2: A detailed diagram of the CMS 11 kV stage with the case study LV network connection point at the Mini Substation transformer T_{r2}.

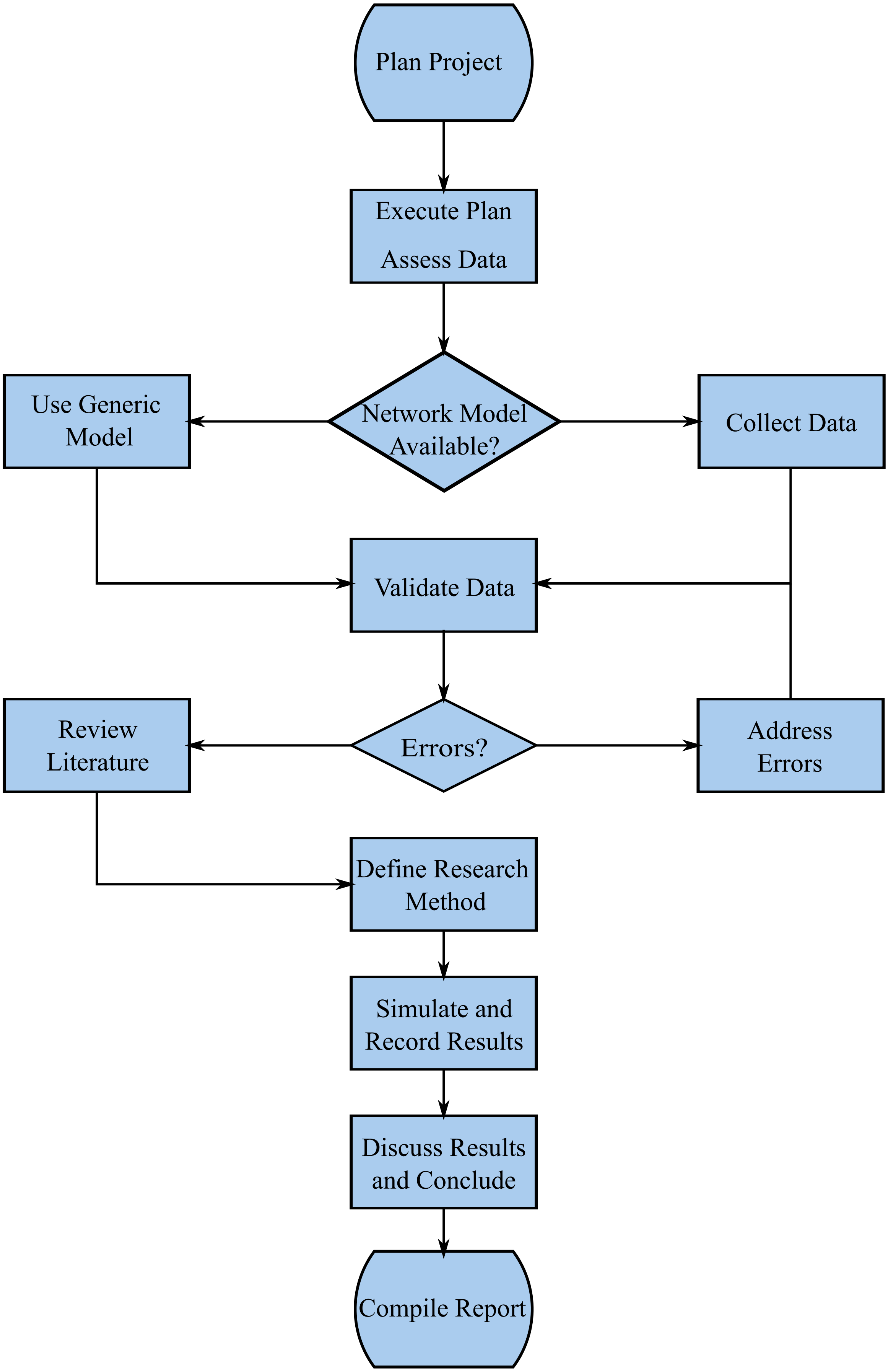


Figure A.3: Dissertation project flow chart showing major phases, tasks and activities.

A.3. DPF Model Files

A.3.1. Residential Load Model

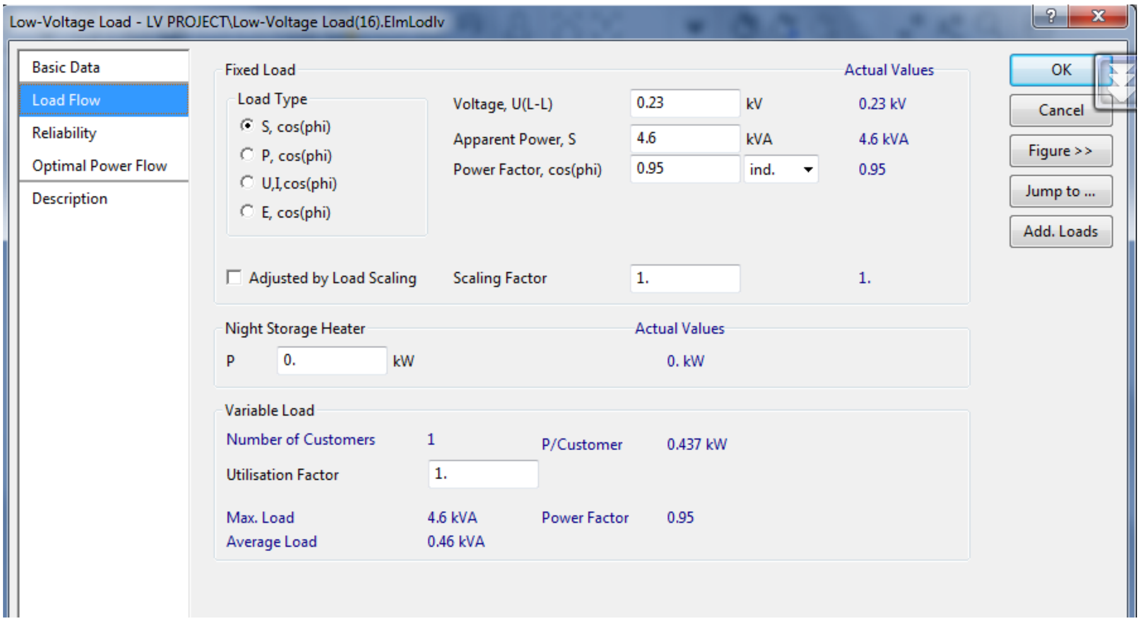


Figure A.4: Load flow parameters for LV residential customers in DSP SP5 2016.

A.3.2. Solar PV System Data

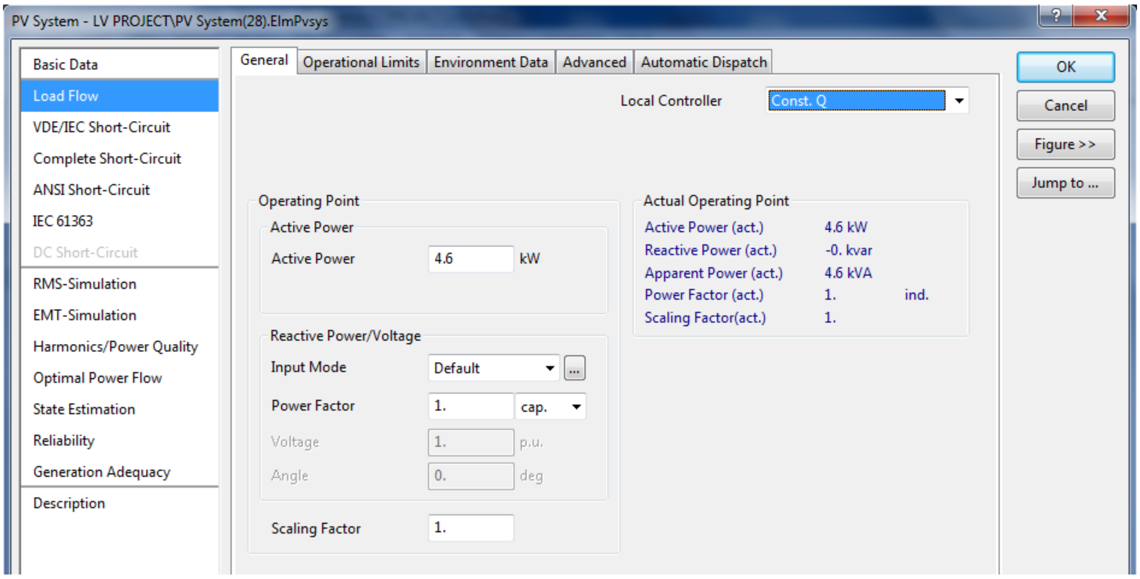
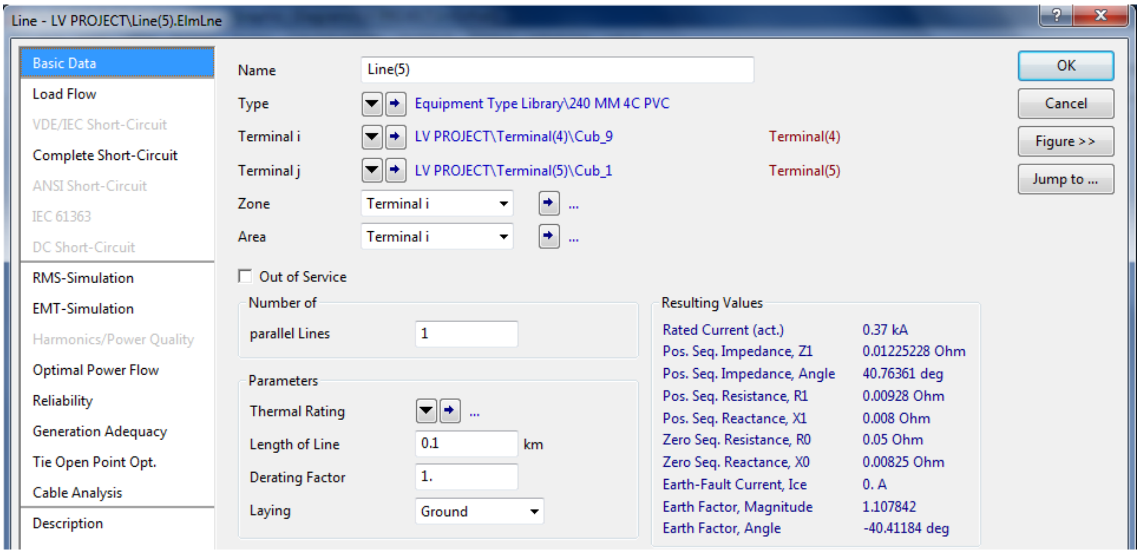
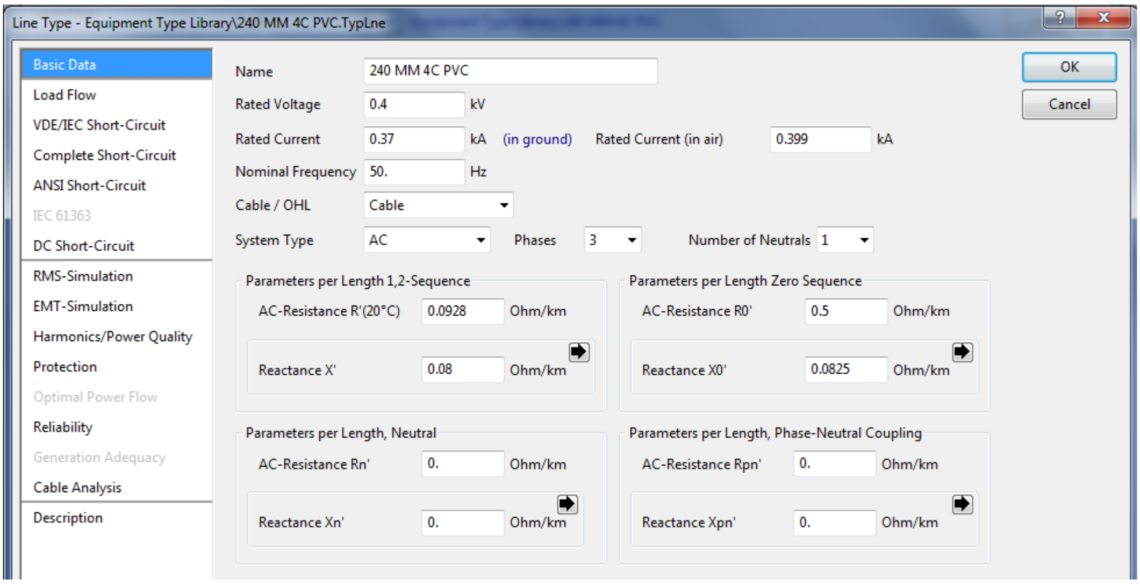


Figure A.5: Load flow parameters for a solar PV system in DSP SP5 2016.

A.3.3. Line Data



(a) Load flow parameters for all LV feeder distribution lines in DPF.



(b) Basic data of LV feeder line type for the 240mm^2 line type.

Figure A.6: Line data entry dialogs in DSP SP5 2016.

A.3.4. CDU Data

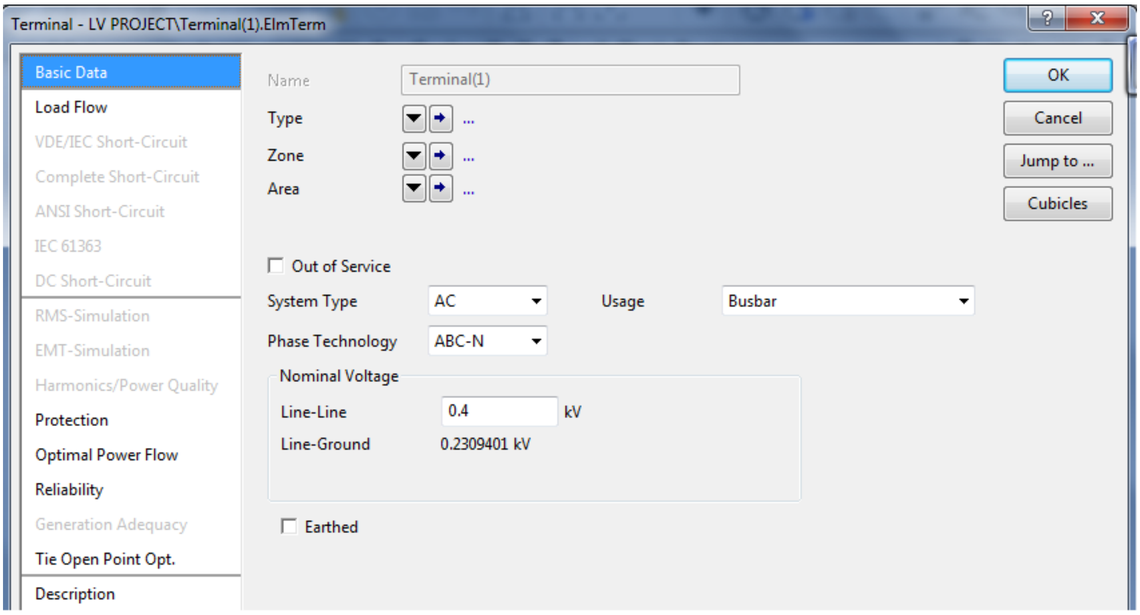


Figure A.7: Terminal (CDU) data in DPF.

B. ADDITIONAL RESULTS

Time (hrs)	% Consumption
1	0,0252
2	0,0252
3	0,0252
4	0,0263
5	0,0336
6	0,0547
7	0,0473
8	0,0421
9	0,0473
10	0,0421
11	0,0368
12	0,0336
13	0,0326
14	0,0326
15	0,0326
16	0,0421
17	0,0547
18	0,0526
19	0,0631
20	0,0683
21	0,0631
22	0,0526
23	0,0368
24	0,0294

(a) Summer load consumption data.

Time (hrs)	%Consumtion
1	0,0197
2	0,0197
3	0,0197
4	0,0217
5	0,0316
6	0,0513
7	0,0473
8	0,0454
9	0,0493
10	0,0473
11	0,0434
12	0,0394
13	0,0355
14	0,0355
15	0,0355
16	0,0394
17	0,0631
18	0,0552
19	0,0631
20	0,071
21	0,0631
22	0,0473
23	0,0316
24	0,0237

(b) Winter load cunsumption data

Figure B.1: Data for LV loads, at eThekwini Municipality distribution network, in winter and summer seasons.

Time (hrs)	% Consumption
1	0,000
2	0,000
3	0,000
4	0,000
5	0,000
6	0,000
7	1,247
8	62,947
9	197,919
10	336,185
11	427,884
12	507,724
13	482,698
14	429,155
15	312,914
16	177,742
17	47,033
18	0,197
19	0,000
20	0,000
21	0,000
22	0,000
23	0,000
24	0,000

Figure B.2: GHI profile data in summer.

C. PUBLICATIONS

In this Appendix the two research papers which contain results presented in this dissertation are included and attached. These papers are:

- **P1:** An Assessment of Voltage Rise Phenomenon on Existing eThekwini Electricity Low-Voltage Distribution Network
- **P2:** Off-load Tap-change Transformer Impact under High Distributed PV Generation

The research papers are presented in the form they were published.

Off-load Tap-change Transformer Impact under High Distributed PV Generation

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***Abstract*—Distributed solar photovoltaic (PV) generation market continues to grow with increasing operational challenges for distribution network operators. In South Africa, residential solar PV system projects have also been implemented in low voltage distribution networks, and there are plans for future projects at municipal level. Residential solar PV growth introduces more technical and economic concerns in municipalities and electricity utility network operators. This paper focusses on a technical investigation of a more practical low voltage (LV) distribution transformer performance under high distributed solar PV connections on eThekwini Electricity distribution network. The main network parameters of interest investigated in this paper include LV network power flow, line voltage dynamics and distribution feeder power losses in steady state. Customer day load demand effects on network parameters are also analyzed, at discrete levels, with discrete off-load tap-changer positions and different solar PV penetration levels. A case study residential LV distribution network of eThekwini Electricity is used in this paper to assess central transformer performance.**

***Keywords*—distribution network; feeder losses; transformer; PV**

I. Introduction

Global interest in distributed photovoltaic (PV) generation has created a need for additional robust and strict network regulations for network operators in order to ensure safe and reliable operation of electricity distribution networks. Large-scale grid integration of residential solar PV systems introduces challenging power quality issues including, but not limited to, power losses, voltage instability and changes in power flow, for distribution network operators (DNOs) [1].

There are well researched technical challenges associated with connection of distributed generation (DG) on to an electricity grid. These have been reported and need to be assessed thoroughly and independently on existing electricity distribution networks [2]. In [3], DG is defined as generation of electric power in small scale generation units close to the point of consumption or to the customer side of the meter. Consequently, the main technology for distributed generation from renewable sources is described as solar PV [3]. Therefore, in this paper the prominent DG is PV; however, it does not have to be necessarily so.

This paper details an investigation of a typical central distribution off-load tap-change (Off-LTC) transformer performance on a low voltage (LV) distribution network with high DG from solar PV systems. Off-LTC transformers are largely used on the grid downstream from the main generating plants, where there are smaller electricity grids, as this study case. A three-phase case study LV distribution network of eThekwini Electricity, South Africa (SA), [4] is used in this paper; however, further analysis is carried in with a shift of emphasis towards quantifying effects of the tap settings of the Off-LTC transformer. This has not been reported in the literature to any extent, as opposed to the on-load tap change (OLTC) distribution transformer - there have been significant work focusing on this specific transformer's real-time response, in terms of tap changing, to network variations and increasing of distributed PV hosting capacity, as in [5-6].

This study evaluates impacts of customer load variations on the case study LV network feeder power losses and distribution transformer performance under high penetration of small-scale distributed PV systems. It is couched in terms of a system in the KwaZulu-Natal region of SA to give a specific application. Other systems have been studied around the world were conditions and loads will be different; for example, in the North-West of England [14], Germany [15], and Queensland, Australia [16]. Several different aspects of LV systems with PV are investigated in these studies.

II. Simulation Models

In this paper, a standard LV reticulation cable (240 mm^2 4C PVC), was utilized on all distribution feeders, and is used for reticulation at eThekwini Electricity [4]. By utilization of an actual system in this study, more practical results were obtained from simulations. A case study network was simulated in DIgSILENT PowerFactory software and is illustrated in [4], and [17] for the full network. To summarize, the LV side has three parallel 3-phase feeders with single-

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phase 230 V, 4.5 kVA, 0.95 p.f. loads placed at equidistant locations every 100 m. These single phase loads are connected through a customer distribution unit (CDU) to the feeder, with the CDUs having a rating of 400 V (line) and 370A. The interconnecting lines have an impedance of (0.0928 + j0.08) Ω/km. Further details are given in [4]. It is also assumed that the single phase loads are balanced as well as the PV power sources. The main focus of this work is on the transformer; Fig. 1 shows the transformer equivalent circuit used in DIgSILENT PowerFactory simulation. The p.u. parameter values are:

$r_{Cu,HV}$ = 0 p.u., resistance on HV side
$r_{Cu,LV}$ = 0 p.u., resistance on LV side
$X_{\sigma,HV}$ = 0.023 p.u., Leakage reactance on HV side
$X_{\sigma,LV}$ = 0.023 p.u., Leakage reactance on LV side
X_M = ∞ p.u. Magnetizing reactance
r_{Fe} = ∞ p.u., Shunt resistance
U_{HV} = HV side voltage
U_{LV} = LV side voltage

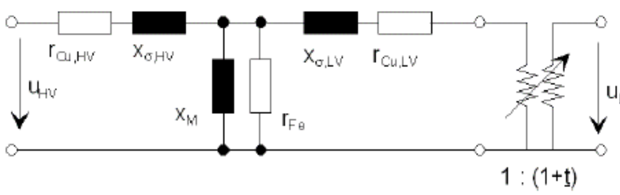

Fig. 1. Case study Off-LTC transformer circuit model with tap changer on the LV side.

The basic subsystem discussed above is incorporated in the overall system shown in Fig. 2. This is for a per-phase curcuit since the loads and PV sources are assumed balanced across the phases, and all feeders identical. More detailed DIgSILENT PowerFactory parameters of the transformer can be found in the Appendix.

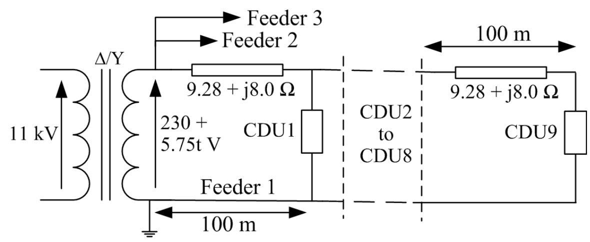

Fig. 2. Per-phase system diagram of the Off-LTC transformer connection and case study LV distribution network

III. Methodology

A. Typical PV Generation and Residential Load Profile

To accurately understand challenges introduced by high DG, correlation between solar PV generation and residential load consumption curves need to be studied. The solar energy and residential load profiles are shown in Fig. 3. Residential load profile is characterized by morning (6 am) and evening (9 pm) demand peaks, as shown in Fig. 3. In contrast, PV generation profile is characterized by start of power generation from sunrise (5 am) to the sunset (8 pm), with peak generation around 1 pm.

The worst case solar irradiance intensity is shown in Fig. 4. A reverse power flow scenario is more likely to occur in summer then winter, and would result in technical and power quality problems for DNOs. In winter, there may be increased network losses due to insufficient solar PV power and higher load consumption. The solar data [7] was selected for the months of December and June 2016, and represents the latest solar patterns and most representative. Residential customer data was obtained in [8], with a total day consumption of 11.17 kWh. In this paper, the standard After Diversity Maximum Demand (ADMD) load modeling method was used in contrast to the resistive method used to obtain the load curve in Fig. 3.

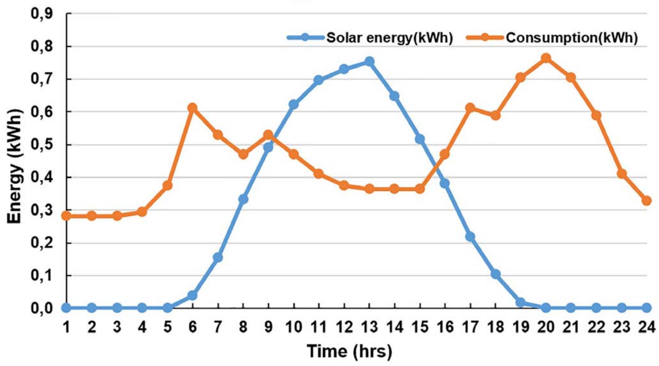

Fig. 3. Typical LV residential load profile vs real solar energy generation profile in Summer (December): Westville, Durban.

The actual PV power generation can be computed using the solar irradiance profiles in Figs. 3 and 4; however, this computation is beyond the scope of this work. The solar generation profile used is for Westville in Durban, which is the location of the study.

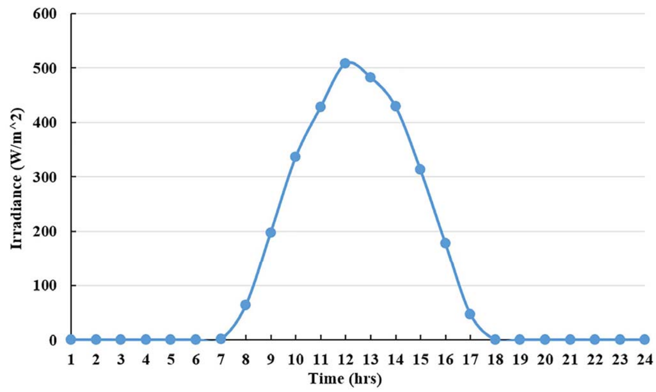

Fig. 4. Actual average day solar irradiance profile in winter (June) for Westville.

Fig. 3 plots clearly show that there is a mismatch between solar PV generation and individual customer load demand profile per day, and hence there is more likely a disturbance on normal grid operation.

B. Case Study Assumptions

Assumptions made based on the grid network in [4] are as follows:

- LV loads are single phase – phase to earth connection
- All customers own single PV units and connected such that are balanced in all three phases
- Distributed PV systems are single phase 4.3 kWp systems, operating at unity power factor (PF)
- Customer loads are balanced on all three phases and distribution feeders
- Cable length (< 5 m) between the CDU and the customer meter box can be neglected to simplify this study
- Electricity consumption of street lighting is assumed negligible
- Customers are 4.5 kVA loads (ADMD) - from Table I, (Table II in [9])

TABLE I. DOMESTIC DENSITY CLASSIFICATION [10]

Domestic Density Classification	Stand Size [m^2]	Average Load Density [kW/km^2]
Urban		(AMD min = 0.5 kVA AMD max = 4.5 kVA)
High Density (HD)	< 1000	500 to 30000
Medium Density (MD)	1000 to 4000	300 to 5000
Low Density (LD)	4000 to 20000	100 to 1500
Rural	> 20 000	0.5 to 250

C. Method

In order to assess performance of the Off-LTC transformer and the LV distribution network with expansion stage of residential PV systems, the following process was undertaken:

- Assessment at PV penetration levels (1) of 0 %, 50 % and 100 % of local active load
- Assessment of LV network electrical parameters under 25 %, 50 %, 75 % and 100 % load <= ADMD, or load scaling factor (LSF) = {0.25, 0.5, 0.75, 1.0} × ADMD, for each PV generation level
- Evaluation of impacts and performance of discrete Off-LTC transformer tap positions {1, 3, 5}
- Quantify impacts of line voltage variations and power losses on the network under different network loading, transformer taps and PV penetration levels

IV. RESULTS AND DISCUSSION

For all the simulations reported in this paper, the primary voltage at the point of common coupling of the transformer remained regulated at 1.03 p.u (11.3 kV) for all considered operational scenarios before and after PV connections. The transformer LV side voltage magnitude follows and is controlled by off load tap changes on the primary winding.

In this paper, the PV system penetration level is defined as a percentage of the maximum active individual customer load [11] as follows:

$$\text{PV penetration level} = k \times \text{ADMD} \times \text{PF [kW]} \quad (1)$$

k represents the ratio of maximum PV capacity to customer active load, and is called the maximum PV penetration level [11]. The values of k index have a range from 0 to 1.

A. PV Case Study 1: Base Case: No PV Generation

Table II shows the beginning-of-feeder and end-of-feeder voltages on the LV distribution network, with no residential PV system installations. The beginning-of-feeder and end-of-feeder voltage magnitudes are computed at the N11 and N91 nodes, respectively. From Table II, statutory voltage limits of ±10 % [10] were violated for load > 75 % (LSF > 0.75), when the transformer is operated at the maximum tap position. This is largely due to high transformer current and low secondary voltage. Thus, for standard operation, with no grid connected PV systems, operation at maximum tap may be avoided to ensure maintenance of feeder line voltages within the acceptable regulatory statutory limits, for a nominal 0.23 kV [12] phase voltage. The voltage profile is dependent on the transformer tap position, and hence in this case, power quality issues may be avoided by decreasing tap positions on the transformer winding. As evidenced in Table II, network voltage profile is inversely proportional to transformer tap changes. In normal operation, the best tap position was identified at neutral tap position to avoid under or over voltage.

B. Case Study 2: 50 % PV Penetration Level

At k = 0.5, all feeder voltages on the customer connection points remain within the regulatory limits [10], as shown in Table III. In this case, operation at the maximum tap regulates voltages within statutory limits. However, increasing tap changes can result in volatile voltage variations and instability at high LV load levels. Voltage profile improvement is primarily due to a portion of local load supplied by local PV systems. At low load demand, the voltage values at N11 and N91 are almost equal with decreasing grid current.

TABLE II. FEEDER VOLTAGES WITH NO PV UNITS, USING THE 240 MM[2] 4C PVC LV RETICULATION CABLE

LSF	Tap Position 1		Tap Position 3		Tap Position 5	
	N11 Voltage [p.u]	N91 Voltage [p.u]	N11 Voltage [p.u]	N91 Voltage [p.u]	N11 Voltage [p.u]	N91 Voltage [p.u]
0.25	1.07	1.05	1.01	1.00	0.96	0.95
0.50	1.05	1.03	1.00	0.97	0.94	0.92
0.75	1.04	1.01	0.98	0.95	0.93	0.88
1.00	1.03	0.99	0.97	0.93	0.92	0.87

C. Case Study 3: 100 % PV Penetration Level

At k = 1.0, i.e., 100 % PV penetration, all voltages consistently remained regulated within statutory limits [10], as more load is supplied from local PV systems, as shown in Table IV. For low load demand periods, there are no significant changes in voltage levels for all considered k values, i.e., k = 0, 0.5 and 1. As the load demand rises from low to peak demand, voltage levels and profile fall with increasing tap positions. Statutory limits were violated for the operating point of tap position 5 at maximum ADMD. This is a result of high reactive power current and low transformer voltage. A reverse power flow phenomenon can be characterized by an instance where the voltage at node N91 > N11 voltage, from the results tables.

TABLE III. FEEDER VOLTAGES AT 50 % PV PENETRATION LEVEL

LSF	Tap Position 1		Tap Position 3		Tap Position 5	
	N11 Voltage [p.u]	N91 Voltage [p.u]	N11 Voltage [p.u]	N91 Voltage [p.u]	N11 Voltage [p.u]	N91 Voltage [p.u]
0.25	1.08	1.07	1.02	1.02	1.02	1.02
0.50	1.07	1.06	1.01	1.00	0.96	0.95
0.75	1.05	1.04	1.00	0.98	0.95	0.93
1.00	1.04	1.02	0.99	0.96	0.93	0.91

TABLE IV. FEEDER VOLTAGES AT 100 % PV PENETRATION LEVEL

LSF	Tap Position 1		Tap Position 3		Tap Position 5	
	N11 Voltage [p.u]	N91 Voltage [p.u]	N11 Voltage [p.u]	N91 Voltage [p.u]	N11 Voltage [p.u]	N91 Voltage [p.u]
0.25	1.09	1.01	1.03	1.05	0.98	1.00
0.50	1.08	1.08	1.02	1.03	0.97	0.98
0.75	1.07	1.07	1.01	1.01	0.96	0.96
1.00	1.06	1.05	1.00	0.99	0.95	0.94

D. Feeder Losses: Base Case: No PV Generation

Table V shows network power losses experienced per feeder, for different LSFs with no PV connections on the grid. Feeder losses increase with the load demand for all transformer tap positions, as evidenced in Table V. For normal operation, the distribution transformer can be operated at lower tap points to avoid unnecessary power losses and voltage drops beyond regulatory limits. A transformer setting at the third tap yields acceptable performance as the base case.

TABLE V. FEEDER LOSSES WITH NO SOLAR PV CONNECTIONS (ROUNDED TO THE NEAREST KW)

LSF	Tap Position 1 [kW]	Tap Position 3 [kW]	Tap Position 5 [kW]
0.25	0	0	0
0.50	1	1	1
0.75	2	2	3
1.00	4	4	5

E. Feeder Losses: 50 % PV Penetration

In this scenario, the PV penetration level k (1) was set at 0.5, and simulation results are tabulated in Table VI. It can be seen from Table VI that at low LSF there are minimum power losses. Power losses emerge after LSF of 0.5, where loads begin to draw active and reactive currents from the transformer, in comparison with the no PV connections base case. Reactive power current is negligible for low load and has visible effects at high load demand. For this case, there is a 60 % reduction in peak load network power losses for transformer tap position 5, 75 % for tap positions 1-3. NRS 097 guidelines [13] states that with a limit of 25 % of the circuit breaker rating (80 A single phase), a PV penetration level of 30–50 % can be supported by the LV network with no technical problems.

TABLE VI. FEEDER LOSSES WITH 50 % SOLAR PV PENETRATION (ROUNDED TO THE NEAREST KW)

LSF	Tap Position 1 [kW]	Tap Position 3 [kW]	Tap Position 5 [kW]
0.25	0	0	0
0.50	0	0	0
0.75	1	1	1
1.00	1	1	2

F. Feeder Losses: 100 % PV Generation

Table VII shows a case of 100 % PV generation, i.e. k = 1.0. Transformer pre-set tap position changes have no effect on network power losses for LSF >= 0.75. Reverse power flow may occur due to surplus PV generation and loads fully supplied locally. In this case, the high excess power lead to power losses on the feeder at LSF = 0.25 for all transformer tap positions. For tap position 5, the losses are visible at LSF = 0.5 due to low transformer secondary voltage and high grid currents supplied by the transformer. Since the customer load is operated at a fixed PF of 0.95, and PV systems designed to cover a worst-case scenario of active power demand at k = 1, there is a mismatch in total PV system power and load ADMD size. A relationship between PV power generation, reverse power flow and feeder losses may be investigated in future studies. Moreover, dynamic and more practical customer load models and variable solar PV generation (continuous) can be comprehensively integrated in simulation and studied.

TABLE VII. FEEDER LOSSES WITH 100 % SOLAR PV PENETRATION (ROUNDED TO THE NEAREST KW)

LSF	Tap Position 1 [kW]	Tap Position 3 [kW]	Tap Position 5 [kW]
0.25	1	1	1
0.50	0	1	1
0.75	0	0	0
1.00	0	0	0

V. CONCLUSION

Low correlation between a solar PV system power generation, resulting from intermittent solar irradiance, and LV load consumption profile, results in surplus PV generation which may contribute in reduction of network power losses, on other hand increase network operational challenges. In this study, a voltage rise phenomenon was identified at the feeder end node due to excess PV power. This phenomenon may be reduced by encouraging customers to shift electric-intensive activities and heavy appliances to high solar PV generation periods specified in this paper. This entails load shifting of appliances such as electric water and air conditioning, to achieve efficient harvesting of PV power. Traditional standards allow avoidance of power quality issues. However, to increase distributed PV load contribution, more detailed and accurate studies are needed, hence this paper as reported on an actual system. This study also showed that Off-LTC transformer operation affects the feeder voltage profile, power losses and can maintain feeder voltages within regulatory limits. Increased PV penetration, with correct transformer setting, reduces the LV distribution network power losses by feeding customer loads from local PV systems and less grid current. Off-LTC operation at maximum tap resulted in undesirable effects hence the neutral tap was identified as the best setting for standard operation. Future studies can evaluate OLTC technology on the specific network considered in this paper.

VI. APPENDIX – TRANSFORMER AND DIGSILENT POWERFACTORY DETAILS

Table VIII shows the basic transformer details with Figs. 5 and 6 showing DIgSILENT dialog entries for the transformer.

TABLE VIII. BASIC TRANSFORMER PARAMETERS

Characteristic/Parameter	Value/Description
Power rating	500 kVA
Voltage ratio	11 kV/400 V
Frequency	50 Hz
Phase configuration	3 phase
HV side connection	Delta Δ
LV side connection	YN
Number of windings	2

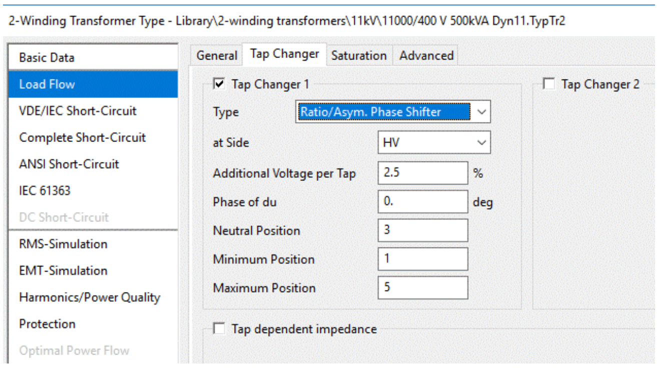

Fig. 5. DigSILENT dialog for transformer tap change data entry.

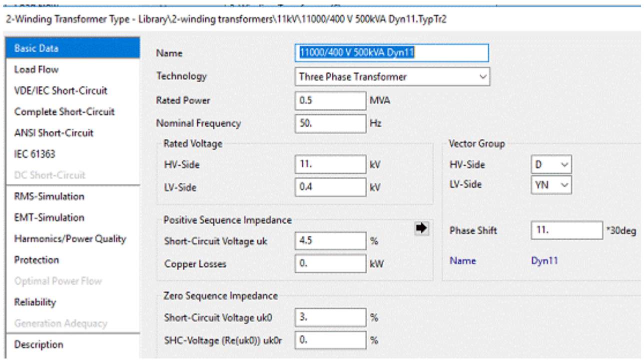

Fig. 6. Transformer data entry dialog.

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An Assessment of Voltage Rise Phenomenon on Existing eThekwini Electricity Low-Voltage Distribution Network

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***Abstract*—Rising energy costs, growing public concern about environmental impacts of fossil fuel energy generating resources and energy constraints of utilities across the globe have increased the relevance and need for alternative renewable energy resources at the customers point of use. In South Africa, there is a strong interest from electricity suppliers and customers in rooftop photovoltaic systems connection onto the electricity grid, in contrast to utilization of expensive conventional energy storage devices. Specifically, small scale projects are being planned for the near future at municipal level. However, there are known technical issues associated with large-scale connection of rooftop PV systems in low voltage distribution networks and need to be studied in detail and addressed prior commission. This paper presents results of a technical investigation of interconnection of residential rooftop PV systems on an existing low voltage distribution network, implemented in DIgSILENT PowerFactory, representing a housing estate development at eThekwini Electricity.**

***Index Terms*--eThekwini Electricity; low-voltage distribution network; rooftop PV; voltage rise**

I. Introduction

The world currently experiences high amount of electric power production from photovoltaic (PV) systems and will see more in the coming years [1]. In recent years, the solar PV sector growth has been showing signs of stagnation in its most mature markets and more growth and opportunities in emerging markets [2]. In particular, South Africa, as one of the emerging solar PV markets, is currently experiencing challenges in the electricity sector of providing adequate supply of electricity to meet a rapidly increasing and unpredictable electricity demand, partly fueled by economic growth, and this has often led to frequent load shedding to prevent a collapse of the national grid [3].

This challenge of producing additional power, in line with environmental compliance to clean energy to reduce CO2 emissions and minimize reliance on fossil fuels, led to the South African major power supplier, Eskom, to establish a Renewable Energy Independent Power Producers Procurement Programme (REIPPPP) for the installation and connection of renewable energy technologies onto the electricity grid [3-5]. However, the scope of the REIPPPP is limited to utility-scale renewable energy installations and does not include small-scale projects. As a result, Eskom and most municipalities have planned small-scale renewable energy projects, and have been inundated with applications to connect distributed energy generation sources (largely solar PV in the residential sector) to low and medium voltage distribution networks.

There are known technical challenges associated with the connection of distributed generators onto the electricity grid, and need to be assessed thoroughly and independently on existing electricity distribution networks [6]. Electricity utilities, including Eskom and municipalities, have concerns regarding distributed generators (DG) interconnection, partially because of the lack of intensive published studies, and therefore do not feel able to guarantee reliability and quality to customers once they allow connection of DG without strict requirements. An important limiting issue is over and under voltage in low voltage (LV) distribution networks in the presence of DG [7].

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Local traditional distribution systems in South Africa were designed such that electric power flows from the transmission to the distribution network and to the end consumers, with electricity flow fixed in downward direction to the consumer. When there is connection of rooftop PV, and other DG, into a distribution network, there is a possibility of a change in direction of power flow and thus a change on the complexity of the network. The problem arises when there is more generation capacity on the distribution network from DG compared to local load consumption on the network. This results in net power flow back onto the distribution network, for which existing power networks are not designed to manage and may raise voltage levels beyond acceptable operational limits [8]. Consequently, a voltage rise phenomenon may occur and lead to distribution network failure.

Several large municipalities have procedures in place to facilitate connection of small-scale DG (including PV systems) to their LV networks, mainly: City of Cape Town, eThekwini, City of Johannesburg and Ekurhuleni. Connection requirements of DG resources and tariffs offered vary widely among these municipalities [9].

Most customers require financial compensation for excess electricity exported to the local grid and in an effort to address this, eThekwini Municipality is exploring a pilot net-metering (NM) program to motivate consumers to invest in PV systems [3]. Distributed generation schemes (landfill gas, wind, solar) integration in distribution networks considering energy loss and voltage stability (including voltage rise) has attracted attention in local electricity suppliers and is an issue to be investigated [8]. The main objective of this paper is to investigate a voltage rise phenomenon and network losses, under different PV penetration levels, on an existing LV distribution network by performing load flow studies in DIgSILENT PowerFactory software. An existing eThekwini Electricity LV distribution network is utilized for this case study.

This research study further investigates the impacts of increased penetration of residential rooftop PV on existing LV distribution network in eThekwini Municipality. The key focus of this study is on the impacts of voltage and network power losses with increasing residential solar PV penetration.

II. DISTRIBUTION NETWORK MODEL AND CASE STUDY

The LV distribution network model utilized for this case study consisted of a mini substation with an associated distribution transformer, shared feeders with ground cables and grid connected customer loads, as shown in Fig. 1, and represents an existing housing estate at eThekwini Electricity. The 11 kV/0.415 kV mini substation LV transformer feeds the whole network, and has the following parameters:

a) Off load tap changer: 5 taps, 2.5% per a tap with nominal tap at third tap

b) Apparent power: 500 kVA

c) Voltage: 415 V

d) Nominal Frequency: 50 Hz

e) Phase configuration: Three phase 4 wire system

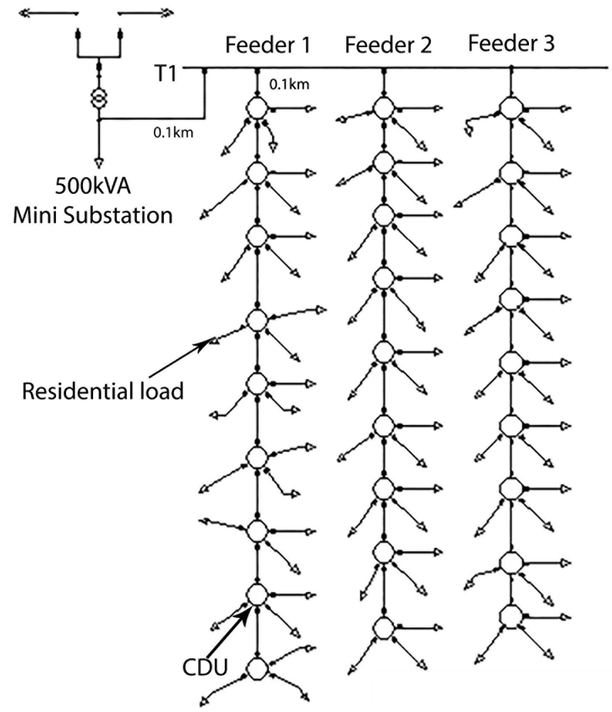

Figure 1. Existing eThekwini Electricity LV distribution network model in DIgSILENT PowerFactory software [11].

Customer loads connected at shared distribution feeders, are identical and single phase and their parameters are as follows:

a) Apparent power: 5 kVA, at 0.95 power factor lagging

b) Real power: 4.75 kW

Each of the shared feeders consist of nine ground cable lines, of same length, interconnecting the customer distribution units (CDU's) as shown in Fig. 1. Individual CDU distances from a top reference feeder terminal (T1) are detailed in Table I. In total length, the feeders are 0.9 km each with a CDU situated at every 0.1 km of distance down the line. Also, the cable length connecting the 500kVA Mini Substation to terminal T1 is 0.1 km in length.

TABLE I. DISTRIBUTION FEEDER LINE DISTANCES OF THE HOUSING ESTATE USED FOR THE SIMULATIONS

CDU NUMBER	FEEDER 1	FEEDER 2	FEEDER 3
	Distance from T1 (km)	Distance from T1 (km)	Distance from T1 (km)
1	0.1	0.1	0.1
2	0.2	0.2	0.2
3	0.3	0.3	0.3
4	0.4	0.4	0.4
5	0.5	0.5	0.5
6	0.6	0.6	0.6
7	0.7	0.7	0.7
8	0.8	0.8	0.8
9	0.9	0.9	0.9

In order to determine the impact of residential solar PV on the LV distribution network, a case study was carried out utilizing the eThekwini Electricity LV distribution grid represented in Fig. 1. A new housing development in Durban was utilized for this case study. The development consisted of 81 new medium/high income homes with requests and potential for PV installations based on the energy efficiency requirements for this ecological estate. The site was fed from a 500 kVA miniature substation which was dedicated solely for the development. The electrical layout of the development can be seen in Fig. 1. For the purpose of this case study, the development was modelled to consist of three feeders with 27 consumers per a feeder and 3 consumers per a CDU.

The site was fed from two existing distributor substations (DSS), namely; 192 Underwood Road DSS and 10 Robin Road DSS. These DSS are fed from the Underwood Road Major Substation and Northdene Major Substation. Table II shows the estate internal reticulation which was designed to ensure that all phases were balanced for the purpose of this study. The case study compared the base case network (with no residential solar PV connections) to that of different levels of solar PV penetration on the network in order to ascertain the potential impacts of residential rooftop solar PV in case of an increase in penetration levels.

TABLE II. DISTRIBUTION FEEDER LAYOUT OF THE HOUSING ESTATE USED IN SIMULATION [11]

CDU NUMBER	FEEDER 1	FEEDER 2	FEEDER 3
	Number of Customers	Number of Customers	Number of Customers
1	3	3	3
2	3	3	3
3	3	3	3
4	3	3	3
5	3	3	3
6	3	3	3
7	3	3	3
8	3	3	3
9	3	3	3

To study impacts of cable sizes on the simulation, three standard different cable sizes were utilized and are used for LV reticulation at eThekwini Electricity, and are shown in Table III. The first feeder of the LV housing estate, Feeder 1, was modelled using a 95 mm2 cable, Feeder 2 using a 150 mm2 cable, and Feeder 3 was modelled using a 240 mm2 cable size. Individual cable current ratings are also indicated in Table III.

TABLE III. LV CABLE RATINGS UTILISED BY ETHEKWINI ELECTRICITY [11]

Feeder Number	Cable Size (mm2)	Cable Rating (A)
1	95	172
2	150	249
3	240	399

A. *Case Study Assumptions*

The assumptions used for this case study are discussed below:

a) All customers are single phase customers.

b) All PV installations are single phase 4.6 kW systems (maximum PV installation size as per the requirements of NRS 097 Part 3 [13]).

c) Existing LV loads are balanced.

d) Due to the short cable length (< 5 meters) between the CD and customer meter box, which was on the boundary, the cable was neglected to simplify the simulation.

e) Electricity consumption of street lighting was not considered.

f) The National Rationalization Standards 069, is a widely used South African standard by utilities and consultants for determination of loads and DG for new developments. This data is used to correctly size the distribution network components, such as cables/lines, embedded generation and transformers. Table IV is an extract from the standard and gives the kilovolt-ampere zoning After Diversity Maximum Demand (ADMD) for urban areas at the transformer LV bus. Since the dwellings fell under "Domestic normal", an ADMD of 4.6 kVA was selected. [12]

TABLE IV. ADMD STANDARD FOR DIFFERENT URBAN CATEGORIES [11]

	Type of Development	kVA/stand (individual)
1	Domestic Electrification	0.2 - 1
2	Domestic low income	1- 3
3	Domestic normal	3 – 6
4	Domestic upmarket	6 – 8
5	Domestic luxury single phase	8 – 12
6	Domestic luxury three phase	> 12

B. *Typical PV Generation Profile Vs Typical Residential Load Profile*

A typical residential load profile is characterized by the morning and evening peaks as shown in Fig. 2. Whilst a typical PV generation profile is characterized by the start of generation from sunrise to sunset with peak generation occurring around noon as shown in Fig. 2. In a residential distribution network, there is a mismatch between the PV generation and load demand which results in export of excess PV generated electricity to the electricity grid, as evidenced in Fig. 2.

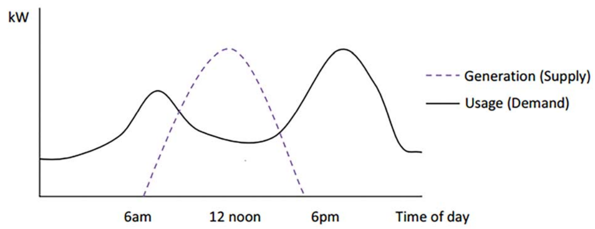

Figure 2. Typical residential load profile vs PV generation profile [11], [14]

C. *Case Study*

The following were taken into consideration during the case study:

a) Study of network parameters under 25%, 50%, 75% and 100% of maximum individual consumer load (4.6 kVA) [12].

b) Assessment at PV penetration levels of 0, 50% and 100%.

c) Evaluate impacts of utilization of 95 mm^2, 150 mm^2 and 240 mm^2 low voltage feeder cables.

d) Study the impacts of voltage rise and power losses on the network under different network loading and PV penetration levels.

e) Investigate load variation effects under different PV penetration levels

III. SIMULATION RESULTS

A. *Rooftop PV Case Study 1: Base Case: No PV Generation*

Table V shows the beginning and end of feeder voltage drop on the LV network with no rooftop PV installations. From Table V, it can be seen that Feeder 1 and Feeder 2 experience voltage drop problems during the peak loading periods where there is significant increase in the current drawn from the LV transformer. Hence for normal operation with no connected PV systems, the feeder may be designed and implemented using the low impedance 240 mm^2 cable to maintain all feeder voltages within the acceptable South African regulatory statutory limits (±10%) [15], of nominal 230V phase voltage.

TABLE V. END OF FEEDER VOLTAGE DROP (NOMINAL TAP) [11]

Load (%)	Start Feeder Voltage (PU)	95 mm^2 (Feeder 1) End of Feeder Voltage (PU)	150 mm^2 (Feeder 2) End of Feeder Voltage (PU)	240 mm^2 (Feeder 3) End of Feeder Voltage (PU)
25	1.019	0.984	0.995	1.009
50	1.002	0.940	0.961	0.985
75	0.985	0.892	0.924	0.959
100	0.966	0.840	0.885	0.931

B. *Case Study 2: 50% PV Penetration*

With 50% residential rooftop solar PV penetration on the LV network, all PV consumer voltage levels, on the point of common coupling, remain within acceptable ±10% statutory limits [15], as shown in Table VI. In this case, when the high impedance feeder cables (95 mm^2 and 150 mm^2) are utilized, there is no violation of voltage regulatory limits, as shown in Table VI. The voltage profile improvement is due to additional power generated from residential PV systems. When the operating point of customer loads is at 100% ADMD, there is a significant voltage drop on the smaller size cable (95 mm^2), due to large current drawn from the grid and large line resistance. In this scenario, the bigger 240 mm^2 cable has lesser voltage drops and good performance.

TABLE VI. END OF THE FEEDER VOLTAGE WITH 50% PV [9]

Load (%)	Start Feeder Voltage	95 mm^2 (Feeder 1) (PU)	150 mm^2 (Feeder 2) (PU)	240 mm^2 (Feeder 3) (PU)
25	1.026	1.044	1.037	1.028
50	1.011	1.055	1.006	1.006
75	0.995	0.963	0.972	0.982
100	0.977	0.918	0.936	0.957

C. *Case Study 3: 100% PV Generation*

With a 100% rooftop PV penetration, the feeder voltages all remain within the required statutory limits of ±10% [15], same as in the previous case. More so, with use of smaller size feeder cables (95 mm^2 and 150 mm^2) no voltage violations are experienced as shown in Table VII.

TABLE VII. END OF THE FEEDER VOLTAGE WITH 100% PV [11]

Load (%)	Start Feeder Voltage (PU)	95 mm^2 (Feeder 1) (PU)	150 mm^2 (Feeder 2) (PU)	240 mm^2 (Feeder 3) (PU)
25	1.032	1.091	1.070	1.045
50	1.018	1.055	1.040	1.023
75	1.003	1.017	1.009	1.001
100	0.986	0.975	0.976	0.977

D. *Feeder Losses: Base Case: No PV Generation*

Table VIII shows the kW power losses experienced on the LV feeder for different percentage loading with no rooftop PV connection into the distribution network. From Table VIII, it is clear that the network losses increase in proportion with the load demand. The 95 mm^2 cable yields 373% more loss, (compared to the losses experienced on the 240 mm^2 cable) whilst the losses on the 150 mm^2 cable yields a 185% loss (compared to the losses experienced on the 240 mm^2 cable) under 100% of ADMD load demand scenario.

TABLE VIII. FEEDER LOSSES (KW) WITH NO ROOFTOP PV CONNECTION [11]

Load (%)	95 mm^2 (Feeder 1) (kW)	150 mm^2 (Feeder 2) (kW)	240 mm^2 (Feeder 3) (kW)
25	0.34	0.21	0.08
50	1.06	0.66	0.24
75	2.3	1.42	0.5
100	4.21	2.54	0.89

E. *Feeder Losses: 50% PV Penetration*

Table IX shows that there is an increase in network losses for a case of 50% PV generation and 25% of the ADMD load demand on the network. This is a result of excess power generation on the network. However, there is a drastic reduction in losses on the network when the percentage load to ADMD is at least 50%, and a drastic reduction in network losses on all three feeders can be seen. This is due to the local load purely supplied and matched by local PV generation and no power drawn from the utility grid. The reduction in losses for 100% ADMD load with 50% PV generation and with the use of a 95 mm^2 LV cable is 2.85%, whilst 3.15% for the 150 mm^2 LV cable and 3.37% with the use of a 240 mm^2 LV cable, in comparison with base case network losses shown in Table IX. NRS 097 guidelines states that with a limit of 25% of the circuit breaker rating (80A single phase), a PV penetration level of 30–50% can be supported by LV network with no technical problems [13].

TABLE IX. FEEDER LOADING WITH 50% ROOFTOP SOLAR PV [11]

Load (%)	95 mm^2 (Feeder 1)	150 mm^2 (Feeder 2)	240 mm^2 (Feeder 3)
25	1.37	0.86	0.31
50	0.54	0.34	0.13
75	0.15	0.09	0.04
100	0.12	0.08	0.03

F. Feeder Losses: 100% PV Generation

Table X shows that there is an increase in the losses on the network in the case of 25% of ADMD loading with 100% PV generation on the distribution network. This can be attributed to the fact that there is significant excess generation on the network in comparison with load demand on the local network. The losses reduce when compared to the base case, in Table VIII with no PV generation, once the percentage load is greater than 50% of ADMD. The reduction in losses for the case of 100% of ADMD load with 100% PV generation on the network with the use of a 95 mm^2 LV cable is 12.12%, whilst for 150 mm^2 LV cable is 12.99%, and 13.48% for 240 mm^2 LV cable in comparison to base case network losses.

TABLE X. FEEDER LOADING WITH 100% ROOFTOP PV PENETRATION [11]

Load (%)	95 mm^2 (Feeder 1)	150 mm^2 (Feeder 2)	240 mm^2 (Feeder 3)
25	1.11	0.74	0.28
50	0.62	0.41	0.16
75	0.4	0.26	0.1
100	0.51	0.33	0.12

IV. CONCLUSION

The mismatch between the PV generation profile and residential load profile (Fig. 2) affects the amount of excess energy exported to the distribution network. However, it is possible by performing load shifting to utilize electricity household equipment during rooftop solar PV power generating period. Consequently, this means operation of items such as pool pumps, dish washers, washing machines, etc. during the day to allow efficient utilization of the generated electricity from solar PV systems. South African utilities applying the NRS 097 standard [12], will ensure that power quality problems such as voltage rise can be avoided. However, for a higher penetration level of solar PV, more detail and accurate software simulation studies need to be carried out as was done in this study. This case study also showed that cable size affects the network and by increasing the LV cable size it is possible to avoid voltage rise problems. Increased PV penetration also reduces the LV distribution network losses by feeding loads from the local PV systems as opposed to drawing power from the grid, thereby contributing to the reduction of network power losses.

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