IMPACT OF LOCATION AND SIZE OF SOLAR PV PLANTS FOR INTEGRATION IN THE LUSAKA DISTRIBUTION GRID NETWORK

By

Suzyo Joe Silavwe

A dissertation submitted in partial fulfillment of the requirements for the Degree of Master of Engineering in Electrical Power Engineering

UNIVERSITY OF ZAMBIA
LUSAKA

2019

DECLARATION

I, **Suzyo Joe Silavwe**, do hereby declare that this dissertation is the result of my own research work and that it has not previously been submitted for a degree, diploma or other qualification at this or another University.

Signature…………………………………………….

Date………………………………………………….

COPYRIGHT

APPROVAL

This dissertation of Suzyo Joe Silavwe is approved as fulfilling the partial requirements for the award of the Degree of Master of Electrical Power at the University of Zambia.

Examiner 1……..…………………signature …………………………date………………

Examiner 2……..…………………signature …………………………date………………

Examiner 3……..…………………signature …………………………date………………

Chairperson……..…………………signature …………………………date………………
Board of Examiners

Supervisor……..…………………signature …………………………date………………

ABSTRACT

Energy generation mix is an important area that could potentially have a significant impact on the Distribution network to address increase in system losses at distribution level, voltage drops and load growth. The distribution lines in Lusaka area are heavy-load lines with the highest demand density in Zambia. The Lusaka distribution line network system consists of a loop formed by interconnection of bulk supply points. Integration of energy generation mix into the existing Zesco power system has substantial impact on the system, with the power system losses and voltage profiles being the key issues. The impact of renewable energy in a generation mix has been investigated in this work. The project investigates the impact of location and size of solar PV plants for integration in the 33kV Lusaka Distribution network. The impact was assessed by examining the effect of solar PV plant on real power flow, system losses and voltage regulation in the 33kV distribution network. The loads, active and reactive power injections and network parameters were defined for the 33kV Lusaka distribution network and the load flow analysis for network was simulated using DIgSILENT Power Factory software to find the system losses, bus voltages and changes in power flow. The Global Positioning System was used to estimate the identified land availability and location of 13 feasible 33kV substations i.e. Chibombo, Chisamba, Fig tree, Chongwe 88/33kV, Avondale, Chalala, Katuba, L85, Makeni, Chawama, Chilanga, Mapepe, Chalala and Katuba. Based on the scope, the following 6 substations Makeni, Avondale, Chelstone, Chilanga and Mapepe, a comparative simulations impact analysis was undertaken for the progressive increase in the penetration level. The results show that at penetration levels up to 20% there was progressive reduction in bus power losses and progressive reduction in the voltage regulation. When penetration level goes beyond 21% bus losses starts to increase and above 50% penetration level there was change or reverse in power flow direction. The integration of renewable energy on the grid network shows reduction in active power losses and progressive improvement of the voltage regulation. It has also provided power locally to the substation load demand and reduces the power flow from the source.

Keywords: *energy generation mix; heavy-load lines; global positioning; penetration level; active power*

ACKNOWLEDGEMENT

First and foremost, I wish to express my special thank you and gratitude to Jehovah the Almighty God for giving me the strength to do this work. I would like to express my deepest gratitude to my supervisors and mentors Dr Ackim Zulu and Dr Luke Ngoyi for their guidance and encouragement throughout the project work.

My sincere thanks to the utility company ZESCO limited for according me the opportunity to study the Lusaka 33kV distribution network and in particular Mr. Gyavira Malama Bwalya, Mr. Given Moonde and Mr. Jagger Hamulili Bwembelo for their support in obtaining the tools and technical information necessary for conducting my research. My gratitude also goes to my employer the Rural Electrification Authority for according me the opportunity to pursue Master in Electrical Power Engineering and for the use of time and resources.

Special thanks to my wife and children for their patience and support.

DEDICATION

To Ned Daniel Silavwe, Lydia Silavwe, my wife Vanessa Mirriam, my daughter Mukupa Vanessa, my two sons Joel Greenwell and Ned Suzyo and my parents for their love, patience and support.

TABLE OF CONTENT

ABBREVIATIONS

ZRA	Zambezi River Authority
DG	Distributed Generation
PV	Photovoltaic
PCC	Point of Common Connection
DN	Distributed Network
EPC	Engineering Procurement Construction
DIgSILENT	DIgital Simulation of Electrical NeTworks
CT	Current Transformer
VT	Voltage Transformer
EU	European Union
RES	Renewable Energy Systems
OPF	Optimal Power Flow
PSS/ E	Power System Simulation for Engineering
NR	Newton Raphson
IEEE	Institute of Electrical and Electronics Engineers
ETAP	Electrical Transient and Analysis Program
PSO	Particle Swarm Optimization
DSTATCOM	Distribution Static Compensation
THD	Total Harmonic Distortion
GA	Genetic Algorithm
CEC	Copperbelt Energy Corporation
ACSR	Aluminium Conductor Steel Reinforced
PILC	Paper Insulated Lead Cable
XLPE	Cross Linked Polyethylene

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

CHAPTER ONE

INTRODUCTION

Hydropower accounts for about 94% of Zambia's existing power source and only about 40% of the estimated 6,000MW hydropower potential has been developed. Due to the favorable economic conditions, the demand for electricity has been increasing at an annual rate of 3 – 4%. This puts a major task to develop power sources to meet the growing demand for power. It is for this reason that there is need to plan for optimal generation that are centered around renewable energy. (Ministry of Energy and Water Development, 2011). At the same time, the country has been experiencing power deficit of about 1,000MW due to the low rainfall experienced during 2014/2015 and 2015/2016 season. According to the Zambezi River Authority (ZRA), the 2016 projected water levels at Kariba hydropower station, the trends show that water levels will steadily rise until June 2016 but start declining from July until December 2016. The April 2017 trends shows that there has been a significant steady rise in the water levels compare to the 2016 levels over the same period and that the levels will start declining from July 2017 (Zambezi River Authority, 2017). This entails that Zesco will have to adjust their generation capacity to preserve the water levels in the Kariba reservoir. The reduction in in the water levels will trigger a power deficit, which will result in power cuts thus affecting the loads at 33kV on the Lusaka distribution network. Therefore, this calls for an urgent need for energy generation mix using Distributed Generation (DG) to meet the demand for power, loss minimization and maintaining minimum and maximum operating voltage limits. Climate change is real and has adversely affected the energy sector and the country's economic activities (Siliya, 2016).

The power system in Zambia is characterized by the bulk hydropower generation power stations located in the southern part of the country, supplying major load centers on the Copperbelt and North Western provinces. The transmission lines from the generating stations run from south to north through a corridor of multiple of 330kV lines. The transmission network serves as a means of transferring power from generating power stations to distribution bulk supply substations and for system interconnections.

The Lusaka transmission network is supplied at 330kV through two main supply stations i.e. Leopards Hill substation in the east of the city and Lusaka West in the west of the city. From the Lusaka West substation, the Ring transmission forms a network by going through Coventry substation in Lusaka light industrial area. From Coventry substation, the Ring cuts through to Waterworks substation then the Ring heads eastwards to Leopards Hill substation. As for the transmission line from Leopards Hill substation, the Ring moves north-west into Avondale substation, crosses Great East road then heads westwards through Chelstone substation passes along the northern boundary of Foxdale housing complex into Roma substation.

The distribution system is part of the power system that distributes power to consumers for consumption. The Lusaka distribution network is arranged in a closed loop forming a Ring network. The subject area of study under this research is the 33kV distribution network. The support structures for the 33kV distribution lines in Zambia are wooden poles, which are used because they are readily available in Zambia from Copperbelt Forestry Company (CFC) and are relatively cheap. The standard wooden pole length utilized on 33kV distribution line is 12meters. The line span distance between supporting structures is 50meters at minimum to 120meters maximum.

Energy generation mix is an important area that could potentially have a significant impact on the Distribution Network and the Zambian economy. Due to favorable economic development, the distribution lines in Lusaka area are heavy-load lines with the highest demand density in Zambia. The Lusaka distribution line network system consists of a loop formed by interconnection of Bulk Supply Points. There is need for better understanding of the impact of location and sizing of Solar PV plants for integration into the Lusaka Distribution Grid network to ensure a safe and reliable distribution network. Climate change, load growth and the low water levels have adversely affected hydropower generation, distribution network performance and the country’s economic activities. To address the low water levels, increase in system losses at distribution level, voltage drops and load growth, there is need to investigate the impact location and size of solar PV plant at 33kV distribution to reduce system losses, improve voltage profiles and meet power demand. This will also defer infrastructure investment at generation and transmission levels. Power losses reduction and improving voltage profiles are important in power systems performance.

Distributed Generation is the use of small generation units installed in strategic points of the electric power system and mainly, close to load centers. DGs can be categorized into renewable and non-renewable energy sources. The renewable DG sources are solar, wind, small hydro, biomass, geothermal whereas DG technologies based on non-renewable are combustion turbines, steam turbines etc. DGs can provide benefits for the customers as well as for the utilities (Athira & Tibin, December 2013). DGs are classified into four types based on real and reactive power generation capabilities. The classifications are as follows (Bhanu & Boora, 2016):

i. DG capable of injecting real power only;
ii. DG capable of injecting reactive power only;
iii. DG capable of injecting both real and reactive and
iv. DG capable of injecting real but consuming reactive power.

The grid connected PV system (DG capable of injecting real power only) is one of the most promising renewable energy solutions in Zambia with the available 5kWh/m^2 insolation offering many benefits to both the end user and utility network. The utility and end users of electric power are becoming concerned about meeting the growing energy demand, system losses and quality of voltage profiles. Photovoltaic technology provides an attractive method of power generation and meets the criteria of clean energy and sustainability. The technical requirements from the utility power system side need to be satisfied to ensure the safety of the PV installer and the reliability of the utility grid. Classification of the technical requirement for grid interconnection and solving the interconnection problem such as islanding detection, harmonic distortion requirements and electromagnetic interference are therefore important issues for widespread application and penetration of PV systems.

Grid connection of PV systems is accomplished through the inverter. It is important that any inverter system connected to the grid does not degrade the quality of supply at the

Point of Common Connection (PCC). The PV power quality injected into the grid is evaluated at the PCC to determine the technical parameters and their influence on the grid. Knowing the possible impact of large grid connected PV systems on Distribution Network (DN) can provide feasible solutions.

The distribution networks are designed to transfer power from transmission network lines to the customers. There are numerous approaches proposed to location and sizing of Distributed Generation (DG) units such as fuzzy Genetic Algorithm to reduce power losses of the distribution system, Analytical methods to minimize the power losses. DG units can offer an alternate planning approach to utilities to satisfy demand growth. The planning may provide benefits to distribution network operators to choose where to locate it as well as control its operating pattern through peak load operations and may defer the transmission and distribution expansion. DG sources are normally placed closer to the load centers and are modular in nature. A common strategy for sizing and location is to minimize system power loss, voltage at each bus is in acceptable limits and line power flows are within limits. The DG can be simulated at different buses to evaluate the appropriate buses for DG integration using load flow analysis. The power flow analysis will indicate the feeder power losses and it allows to obtain the best bus candidates to locate DGs.

Since 2009, solar energy has emerged as a primary resource of green energy alternative to non-renewable energy resources. The Photovoltaic (PV) system prices have dropped, which has led to remarkable growth in solar system installations. Solar energy is probably the strongest growing renewable energy electricity generation technology, demonstrating recent annual growth rates of around 23%. The worldwide production of 23-34GW in 2012 and 2013 resulted in a total exceeding 139GW consisting of both grid connected and off-grid remote power supplies (Parknison, 2013).

The European Union was aiming at a significant carbon dioxide reduction in the electricity sector in future, with a target to reduce total emissions by 20% by 2020 compared to 1990 levels. This has resulted in significant growth of Photovoltaic installation all over Europe. This increased PV capacity has influenced power system operation, planning and design. This requires developing a proper plan and design approach that integrates the technology into distribution system to ensure that solar technology is adopted by utilities and the market for the need to assure a technically sound installation and operation (Institute of Electrical and Electronics Engineers, November/ December 2015; Institute of Electrical and Electronics Engineers, March/ April 2013).

1.1. Problem statement

The distribution system is part of the power system that distributes power to consumers. The Lusaka distribution network is arranged in a closed loop forming a Ring network. The support structures for the 33kV distribution lines in Zambia are the standard 12 meters wooden poles. At the last level of the distribution network, step down transformers are used to step down the voltage from 33kV to 400V. The transformers are referred to as the distribution step down transformers. Zesco tries as much as possible to ensure that the loads remain evenly balanced among the phases. These loads are composed of industrial, commercial and residential type of loads. Due to favorable economic development, the 33kV distribution lines in the Lusaka area are heavy load lines.

The reduction in the water levels at Kariba dam will trigger a power deficit, which will affect the loads at 33kV, as generation will be reduced. The utility company Zesco limited will be required to meet the increasing power demand in Lusaka area while effectively managing operational cost, deferring transmission and distribution infrastructure investment due to high capital investment. At the same time, the utility will be required to maintain the existing power quality in terms voltage profiles and reliability power supply. The increasing power demand for electricity in Lusaka has led to the Lusaka distribution line to be heavily loaded, increase in power system losses and voltage drops. This therefore exposes the 33kV distribution network line to the risk such as low voltage and even to voltage collapse.

Integration of DGs tend to change the loading condition depending on the point of connection. The change can be in terms of change in power flow, voltage profile and power system losses, which are a function of the net power injection. The penetration level tends to impose either negative or positive impact on the grid network.

1.2. Aim

The aim of the research is to determine the impact of location and size of Solar PV plants at 33kV distribution for integration into the Lusaka Distribution Grid network.

1.3. Research objectives

The specific objectives are:

1. To determine location and size of solar PV plants for integration to 33kV Lusaka distribution grid network.
2. To investigate system losses by varying the solar PV plant penetration levels upon integration to the already heavy-load 33kV Lusaka distribution grid network.
3. To investigate system voltage by varying the solar PV plant penetration levels upon integration to the already heavy-load 33kV Lusaka distribution grid network.
4. To investigate power flow changes by varying the solar PV plant penetration levels upon integration to the already heavy-load 33kV Lusaka distribution grid network.

1.4. Research questions

The following are the research questions arising from the objectives:

1. What are the available sites for the solar PV plants?
2. What is the impact of the solar PV plant penetration on the distribution system losses?
3. What is the impact of the solar PV plant penetration on the distribution system voltage profile?
4. What is the impact of the solar PV plant site on the power flow?

1.5. Significant of study

In this research, the impact of location and size of solar PV plant penetration level on the distribution system is one of the systematic ways to determine the effects of integration on power losses, voltage profile and changes in power flow on the Power System. The problem of integration into the grid network is complex from the economical, electrical and computational point of view. First, understanding the impact of the the solar PV plant penetration levels upon integration to the already heavy-load 33kV Lusaka distribution grid network on the available generation resources, will be significant to understand the security and reliability of the system. Secondly, by planning for the impact of the solar PV plant penetration levels upon integration to the already heavy-load 33kV Lusaka distribution grid network using renewable energy technologies like wind and solar power, it is possible to maximize its penetration in the system, thereby minimizing not only the costs of electricity supply, but also deferring investment cost of the transmission and distribution network. Distributed Generation integration can contribute to the enhancement of the overall system efficiency, for example, reducing power losses in the network and meeting the load power. The main problem found in planning studies of distributed generation is that its study is tightly linked to the study of the power flow problem of power systems. Equations of the power flow problem are characterized by non-linearities that make it rather complex to solve with traditional optimization techniques. However, if DG penetration increases to acceptable levels then impact of DG with continuity of supply will be acceptable. Additionally, high penetration of renewable energy technologies will pose a challenge for the operability of the system in terms of increase in power losses and change in power flow.

1.6. Scope and limitations

The scope and limitations of this research are as follows:

1. The technology has been limited to solar PV plant generation, which are based on injecting real power. Fixed solar PV size are directly connected to the grid.
2. Only the 33kV Lusaka distribution network and substations with loading more that 10MW has been considered.

3. The solar PV penetration level considered was approximately to 100%.

1.7. Organization of the dissertation

This research contains 5 chapters, one appendix and it is organized as follows:

Chapter 1: This chapter gives a brief introduction to the concept of Distributed Generation reflecting the importance of location and size of DG systems to the utility network and customers, besides the drawbacks occurring if DG is connected to the distribution systems.

Chapter 2: The chapter describes the literature review of the power system in Zambia, solar technology sizing and typical grid connected centralized system. It also insight of the different algorithms used for location and sizing of DG, increase in penetration levels and impact of DG on power system grid and the energy policy in Zambia.

Chapter 3: This chapter describes the overall design of the research process, data collection and computational procedures for modelling of the 33kV Lusaka distribution network to investigate the impact of varying the solar PV plant penetration levels upon integration.

Chapter 4: In this chapter, simulation results for the load calculation done for all the buses to determine the impact of location and size of solar PV plant are presented. The chapter also discusses the simulation results for the six substations identified for possible integration and Google earth images identified using the GPS.

Chapter 5: The chapter highlights the identified areas for possible location and how the impact of location and size of the solar plant penetration level into the Lusaka 33kV distribution affects the distribution network grid. The results also show the recommended acceptable penetration levels and the potential to improve distribution system performance.

CHAPTER TWO

LITERATURE REVIEW

2.1. Power System in Zambia

2.1.1. Zesco network

Zesco was incorporated in 1970 as a vertically integrated monopoly responsible for Generation, Transmission, Distribution and Supply. It is a National power utility 100% owned by the Government of the Republic of Zambia.

The Zesco power system is characterized by location of power stations in the south of the country while the major load centers, the Copperbelt and Northwestern Provinces, are in the north. Power transmission to this area is via a south-north running corridor of multiple 330kV lines, collectively known as the 330kV backbone. From various 330/220kV stepdown substations, sub-transmission lines at 66kV, 88kV and 132kV are used to supply Lusaka (88kV, 132kV), Central (88kV), Eastern, Northeastern and Western parts of Zambia.

2.1.2. Generation

In Zambia, the bulk of the generation is from hydropower generation. The installed capacity of power generation facilities in Zambia totals about 2,388.3MW hydro and 438.6MW thermal. Zesco limited owns the majority of the power generation facilities of a total of 2,396.9MW, followed by Maamba Collieries Limited at 300MW, other private producers at 50MW and Copperbelt Energy Corporation (CEC) at 80MW. There are five major hydropower stations managed by Zesco, these are Kafue Gorge Upper Power Station, Kariba North Bank Power Station (KNBPS), Kariba North Bank Extension Power Station, Itezhi-tezhi 120MW hydropower plant which was commissioned 2016 and Victoria Fall Power Station (VFPS). The hydropower stations account for about 86% of Zambia's entire installed generation capacity. Table 1 shows the Hydro generation facilities in Zambia and Table 2 shows the thermal generation facilities in Zambia.

Table 1: Hydro generation facilities in Zambia

Station	Capacity (MW)	Type	Owner
Kafue Gorge Upper	990	Dam	Zesco
Kariba North Bank	720	Dam	Zesco
Kariba North Bank Extension	360 (Peak plant)	Dam	Zesco
Itezhi-Tezhi	120	Dam	Zesco
Victoria Falls	108	Run-of-river	Zesco
Lunsemfwa	50	Dam	LHPC (SN Power)
Lunzua	14	Run-of-river	Zesco
Lusiwasi	12	Run-of-river	Zesco
Chishimba Falls	6	Run-of-river	Zesco
Musonda Falls	5 (upgrading to 10MW)	Run-of-river	Zesco
Shiwangandu	1	Run-of-river	Zesco
Zengamina	0.7	Run-of-river	Zengamina

Table 2: Thermal generation facilities in Zambia

Station	Capacity (MW)	Type	Owner
Ndola Heavy Fuel O (HFO)	50	HFO	Ndola Energy Company
Zambezi	2.35 (decommissioned in 2017)	Diesel	Zesco
Kabompo	1.55 (decommissioned in 2017)	Diesel	Zesco
Mwinilunga	1.5 (decommissioned in 2016)	Diesel	Zesco
Lukulu	1.5 (decommissioned in 2017)	Diesel	Zesco

Station	Capacity (MW)	Type	Owner
Luangwa	1.5	Diesel	Zesco
Shangombo	1	Diesel	Zesco
Chavuma	1 (decommissioned in 2017)	Diesel	Zesco
Mufumbwe	0.9 (decommissioned in 2016)	Diesel	Zesco
Nakambala	40	Biomass	Zambia sugar
Copperbelt Energy Corporation	90	Diesel	CEC
Maamba	300	Coal	Maamba Collieries Limited

In addition to the major hydropower stations, Zesco also manages mini-hydropower stations in five different locations i.e. Lunzua – 14MW, Chishimba – 6MW, Musonda Falls being upgraded from 5MW to 10MW, Lusiwasi – 12MW and Shiwangandu – 1 MW. Currently the three are not sufficient to support the current growing demand and reduce system losses in Zambia. Recently, the decision was made to rehabilitate and upgrade the generating capacity of some units (Energy Regulation Board, 2017). Appendix A is the map of Zambia showing the generation stations and transmission network at different voltage levels in Zambia.

2.1.3. Transmission

The transmission network serves as a means of power electrical power from one location to another or from one network to another network. Transmission system includes terminal substations, transmission lines and intermediate substations. Transmission system in Zambia is meant for bulk power transfer from generating stations to distribution bulk supply points and for system interconnections.

The Lusaka transmission network is supplied at 330kV through two main supply sub stations; Leopards Hill in the east of the city and Lusaka West in the west of the city. These two substations supply three main Bulk Supply Points (BSPs) into Lusaka through a transmission ring connecting Coventry (132kV), Roma (132kV) and Waterworks (88kV) sub stations.

From Lusaka West 330/132/88kV substation the Ring travels approximately 9km south-east into Coventry 88kV substation in the Lusaka light industrial area. From Coventry, the Ring cuts across Mumbwa Road, through Soweto Market, past Los-Angeles Road and across Kafue Road through Kamwala South and Misisi and finally terminates after 7km at Waterworks 11kV substation in Libala South. From Waterworks substation, the Ring heads eastward to Leopards Hill 330/132/88kV substation for a distance of 22km, passing within the vicinity of Bauleni and Lusaka South Multi Facility Economic Zone (MFEZ).

From Leopards Hill substation, the Ring moves north-west into Avondale, then across Great East Road near Kenneth Kaunda International Airport round-about, crossing Airport Road. It then heads westward through Chelstone and Ng'ombe passing along the northern boundary of Foxdale residential housing complex, and crosses Zambezi Road into Roma 132/33/11kV substation. The distance between Leopards Hill and Roma substations is approximately 28km.

The Zambian transmission system has a total of 6359km of transmission lines at different voltage levels spread across the country as follows: 2,008km of 330kV lines, 548km of 220kVlines, 85km of 132kV lines, 704km of 88kV lines and 3,014km of 66kV lines. The total transformer installed capacity is about 3,000 MVA.

2.1.4. Lusaka 33kv distribution network

The distribution system is part of the power system that distributes power to consumers for utilization. This is an electrical system between the substation fed by the transmission system and the customer's meter. The subject area of study under this research is the 33kV distribution network. Zambia's Lusaka distribution network is arranged in a closed loop forming a ring main. It is feed at more than one point making the system to be flexible and reliable. In a case a fault develops, the affected section is isolated and continuity of supply is maintained for the remaining sections. Appendix B shows –

Lusaka 33kV Distribution network drawing No. LUS-GEN-DE-08-A-11746 rev 4, Lusaka Division 33kV Distribution Network Operation configuration drawing No. LUS-GEN-DE-08-G-12253 rev 8 and Lusaka 33kV Network geographical representation drawing No. LUS-GEN-DE-08-E-11829 as obtained from Zesco. Figure 1 shows the part pictorial view of part of Kwamwena substation and Figure 2 shows the tapping point of the Kwamwena substation feeder line which is managed by Zesco.

Figure 1: 31.5MVA 33/11kV Kwamwena substation

Figure 2: 33kV distribution line tapping point to Kwamwena substation

Figure 3: 11kV lines take off points feeding Kwamwena area

Figure 4: 100kVA 11/0.4kV transformer feeding households

Figures 3 and 4 show the typical distribution network configuration. Figure 3 shows the take-off point of the 11kV line from the substation and Figure 4 shows how the power is supplied to the consumers. The distribution lines in the Lusaka area are heavy load lines with one of the highest demand in Zambia. The distribution system consists of a loop formed by interconnection of Bulk Supply Power stations such as Lusaka West – 132/33kV, Roma – 132/33kV, Mapepe – 88/33kV, Waterworks – 88/33kV, Chongwe – 88/33kV, Coventry – 132/88kV, Fig Tree – 88/33kV by means of the 33/11kV substation bus and 33kV distribution lines.

33kV overhead distribution power lines in the Lusaka network is installed with different sizes of ACSR ranging from 50mm^2 to 150mm^2 in accordance with the load capacity of the line. In heavy loaded areas, large capacities of ACSR are installed ranging from 200mm^2 to 350mm^2 also in accordance with the load capacity. For the 33kV underground distribution lines the cables installed ranges in size from 70mm PILC, 120mm^2 PILC, 185mm^2 XLPE and 240mm^2 XLPE in accordance with the load capacity. In heavy load areas large capacity cables range from 300mm^2 to 500mm^2 XLPE are installed corresponding with the load capacity.

The support structures for the 33kV and 11kV distribution lines Zambia are wooden poles which are used due the fact that they are readily available in Zambia from Copperbelt Forestry Company and are relatively cheap. The standard wooden pole length utilized on 33kV and 11kV distribution line is 12meters. The line span distance between supporting structures is 50meters at minimum to 120meters maximum. Figure 5 shows the pictorial view of part of 33kV line H-structure of the Kaulu line constructed by the Rural Electrification Authority in Petauke district, Eastern province.

Figure 5: Pictorial view of part of 33kV line H-Structure

2.1.5. Demand

The load on the distribution network is never constant. It varies from time to time. Zesco's load variation during the whole day are recorded half-hourly and are plotted against time on the graph. The curves obtained are known as the daily load curve. Figure 6 shows the typical daily load curve.

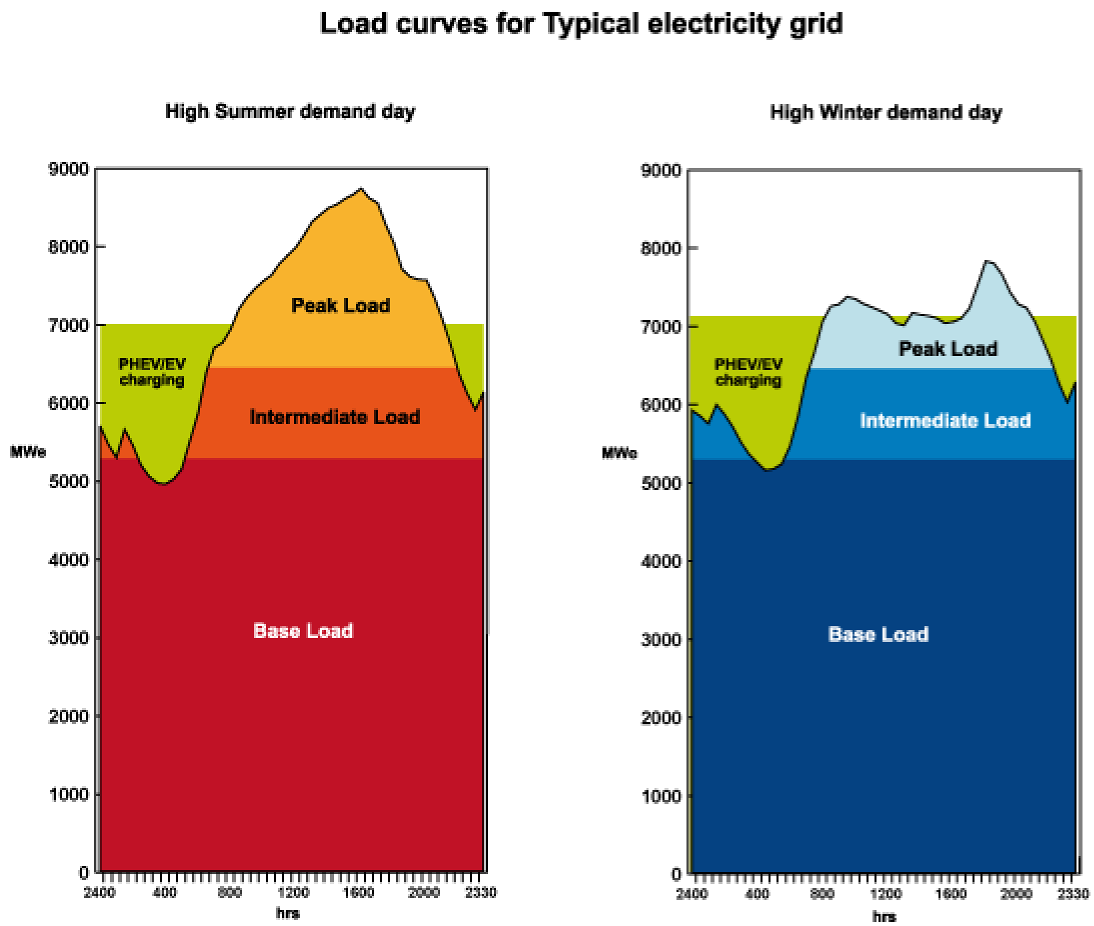

Figure 6: Typical daily load curve (World Nuclear Association , 2016)

The load curves for a winter's day (or month) would be different for the load curve for a summer's day (or month) as shown in figure 6. Load curves can vary from day to day (especially weekday to weekend), from week to week and from year to year. For Zambia, the load curves tend to show greater variations from day to day because not all days are hot whereas in winter the curves tend to be similar because the cold days are uniform. The shape of a load curve is also influenced by special events such as a World Cup football, an important English Premier League match, swearing in of a president, funeral of a famous person etc. Also, distortions can be produced by promotional activities of the power utility such as discounts or even load-shedding.

A load curve is normally made up of three parts namely:

- **Base load**: This is the unvarying load which occurs almost the whole day.

- **Intermediate load**: This load is supplied by plant operating for shorter periods of time may be one or two shifts.
- **Peak load**: This is the highest load experienced on any given day and is typically on the system for very short periods

In relation to the Solar PV integration, the maximum demand of interest is from 6AM to 10AM and 12PM to 17PM when the power from the Solar PV plant will be available. During these times, the Solar PV will be able to minimize system losses, maintaining the minimum and maximum voltage operating limits and meet power demand. The load curves help in selecting the size of Solar PV plant and in preparing the operation scheduling. Table 3 shows the demand estimates for each substation for the Lusaka area as provided by Zesco.

Table 3: Demand estimates for each substation for the Lusaka area

SN	Substation	Demand (MVA)	Power Factor
1	Mwembeshi	2.4	0.9
2	Shorthorn	3.594	0.9
3	Makeni	17.4	0.9
4	Chilanga	12.3	0.9
5	Mapepe	42	0.9
6	Barlaston	20.1	0.9
7	Liverpool	44.5	0.9
8	Coventry	27.5	0.9
9	Chawama	14.2	0.9
10	Zesco workshops	10	0.9
11	Matero	36	0.899
12	Manda hill	22	0.9
13	Dublin	14.8	0.9
14	Kafue road	49.5	0.9
15	Levy park	4.5	0.899
16	University	29.5	0.9

SN	Substation	Demand (MVA)	Power Factor
17	Birdcage walk	21	0.9
18	Chelstone	26	0.9
19	Kabulonga	23	0.9
20	Woodlands	23.8	0.9
21	Kwamwena	3	0.9
22	Chalala	5	0.9
23	Ngwerere	11.4	0.9
24	Avondale	12.2	0.95
25	Chongwe	8.9	0.95
26	Chongwe town	10	0.9
27	Bauleni	16	0.9
28	Ndipo	8.5	0.9
29	New Kanyama	7.5	0.9
30	Palabana	1	0.9
31	Penyaonse	1.5	0.899
32	Shimabala	6	0.899
33	Bonaventure	5	0.9
34	Burnet	8.4	0.9
35	Chisamba	2.5	0.9
36	Globber	1.2	0.9
37	Kabangwe	7.2	0.9
38	Kabanana	7.4	0.9
39	UTH	8.9	0.9
40	Kalubwe	2.4	0.9
41	Katuba	2.5	0.9
42	Kembe	0.7	0.9
43	L85	4.9	0.9
44	Landless Corner	4.8	0.9
45	Mikango Barracks	2.5	0.9

2.2. Solar PV Technology

2.2.1. Solar PV power system

The PV cell technology is the starting point for electricity generation by converting solar radiation into electricity using semiconductors that exhibit a photoelectric effect. A solar PV power plant can be classified based on the way it supplies power to the consumer. Their application can be split into four main categories the Solar Home System (SHS), Off-grid non-domestic, Grid connected centralised PV and Grid connected distributed PV. The project focuses on grid – connected centralised solar PV power which has four major components as follows: Solar PV module; Inverters; Step-up transformers and the grid connection interface.

A grid connection of sufficient capacity is required to enable the export of power. The viability will depend on capacity, availability and proximity. The capacity to accept power from solar PV plant will depend on the existing network infrastructure and the current use of the system. Figure 7 below shows typical grid connected centralized PV with the four major components (Alasdair & Lumby, 2012).

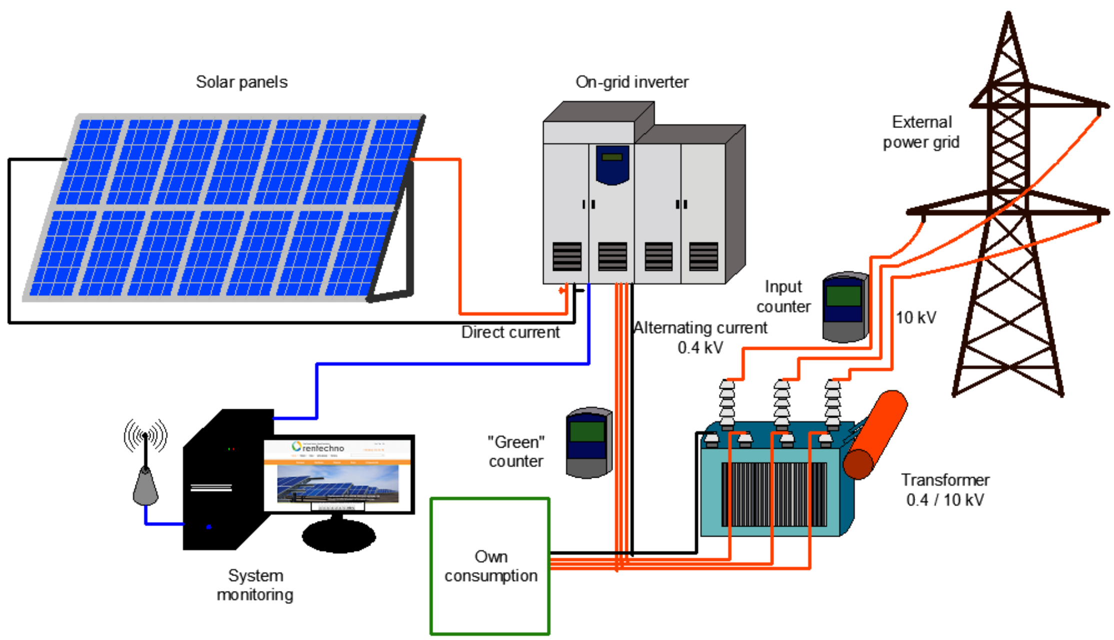

Figure 7: Typical grid connected centralized PV (Rentechno Group, 2009)

2.2.2. Solar PV sizing

Site selection take place even in unlikely areas such as Steep Mountain slopes, within farms and on waste disposal sites. The Geographical Information System (GIS) mapping tool helps in the process of site selection to visually display the limitations and determine the total land area available for development. The area required per kWp of installed capacity varies with the technology chosen. The Global Positioning System (GPS) was used to determine the location of the solar PV plant on the Lusaka distribution network substations (Alasdair & Lumby, 2012).

2.2.3. Solar PV site area

There are no clear rules on solar PV array area site selection. The process of site selection must consider the limitations and impact on the cost of the electricity to be generated. The site must be in an area where there is little risk of damage from either people or wildlife. If the land is currently used for agriculture, it will need to be re-classified as an 'industrial area'. Solar PV power plants will need to be built on low value land. The solar PV site area must have sufficient area for the required power capacity to be installed without reducing the pitch to levels that causes unacceptable yield loss. Any trees on the site area must be cut and removed (Alasdair & Lumby, 2012).

2.3. Distributed Generation

Distributed Generation (DG) are generating units of electric power connected to the distribution network at the substation, distribution feeder or at customer load. Application of DGs has many advantages, such as better economy in comparison with the development of large power plants, reduced loss in distribution systems, maintaining voltage profile limits and releasing of network capacity. Hydro and wind turbine, photovoltaic, fuel cells, biomass gasification and geothermal are the most significant technologies for DG.

Conventional electric distribution systems are radial in nature and have a simple protection system usually implemented using fuses, re-closers, and over-current relays. Presence of DGs in a network may lead to losing coordination of protection devices. This problem can drastically deteriorate the system reliability, and it is more serious and complicated when there are several DG sources in the system (Rugthaicharoencheep & Auchariyamet, 2012).

2.4. Planning consideration

There is no doubt that energy generation mix is the key to solve the energy crisis, large environmental pressures and may other critical issues. Energy generation mix planning should be based on load forecasting results in the network and the constraints of the existing network during the planning period to determine the impact of location and size of the DG to meet the load growth and supply power safely and reliably, making the cost of distribution construction and operation to the minimum. The gradual promotion of Distributed Generation technologies will have an impact on the node voltage, short circuit current, network reliability in the distribution network and its incidence is closely related to the location and size of distributed power. To reduce or avoid the disorderly construction of Distribution Generation and damage to the security and stability of distribution system, it is necessary to take effective measures to choose the reasonable location and size of distributed power (Rugthaicharoencheep & Auchariyamet, 2012).

2.5. Location and sizing algorithms

The penetration of DG depends on them providing acceptable power quality and reliability. To achieve desired performance, suitable placement and sizing is required. The identification of the bus with highest power loss was necessary because losses at that bus constitutes majority of total losses in the system. Power cost can be reduced by reducing power losses. This can be achieved with DG placement in the network (Bhanu & Boora, July 2016). The Optimal Power Flow studies in finding feasible generation impact by considering system constraints power loss in the network can be reduced with the help of injecting solar power at the receiving end to satisfy constraints. Non-optimal size and sitting may lead to high power losses, which is a function of loss coefficients. The loss coefficient changes depending on injection of power (Yogendra, et al., March 2016). The proper placement will reduce losses while improper may increase system losses. Cost savings can be expected with proper placement deferring transmission and distribution upgrades. Any new source of generation should increase the overall generation efficiency. To truly minimize losses, one should integrate over the entire load profile Therefore, placement is based on losses at peak load (Griffin, et al., 2000). Load flow analysis can be performed using DIgSILENT power Factory (Naser, et al., 2014), ETAP software (Nibedita, et al., 2012), using Power World Simulator (Sunil, et al., 2015) to determine the impact of sizing and placement. A common method to find the site for DG is to minimize the power loss of the system. The common method used is in sitting shunt capacitors in distribution systems using 2/3 rule, where it suggests installing DG of approximately 2/3 capacity of the incoming generation at approximately 2/3 of the length of the line. The procedure to determine the optimal bus for placing of DG may also need to take other factors into account, such as economic and geography. The load flow analysis helps to overcome issues to determine non-optimal location, which may lead to increased power loss and reduced voltage profile (Jegadeesan & Keerthana, 2014). There are numerous algorithms available (Niti, et al., 2015) for sizing and location of DGs such as analytical method loss reduction (Salem, et al., 2014), optimal placement of solar PV in distribution system using particle Swarm Optimization in the radial distribution systems (Athira & Tibin, 2013) and using Genetic Algorithm (Mohammed & amer, 2012).

The area required per MW of installed solar power plant capacity varies with the technology chosen. Solar power plants require significant amounts of land to generate power. The area required depends on the amount of MW to be accommodated. A simple rule of thumb to take is 1 MW solar PV power plant requires about 4 acres if it uses crystalline solar panels without trackers and 6 acres if it uses thin film solar panels without trackers also considering space for other accessories as well. The area required per MW for a thin film solar panel is higher than that for a crystalline panel because high efficiency solar panels will require less area for the same MW capacity than lower efficiency panels. The table 6 shows the available land and area size near the substations and maximum capacity of solar PV power plant derived on the available area (Mango, 2015).

2.6. Penetration level

Penetration level refers to the ratio of capacity factor, multiplied by the total DG power installed and the peak power demanded on the feeder. It was varied by increasing the generating capacities of each planned DG on the system. The penetration level was measured by the ratio of the capacity factor, multiplied by the total DG power installed and the peak power demanded in the feeder. The penetration of DG may impact the operation of a distribution network in both beneficial and detrimental ways. The penetration level is given by the equation (Sheikhi, et al., 2013):

$$\text{Penetration level} = \frac{CF * DG}{P} \tag{2.1}$$

Where CF – Capacity factor

DG – DG power installed

P – Peak Power

Advances have taken place in the development of renewable energy and the impact that it has had on the planning, design and operation of electric power system. Wind and PV generation have emerged as the mainstream energy resources that have increasing economic competitiveness in many power systems around the world. With increase in deployment, there is need for fundamental understanding of Distributed Generation's characteristics, impacts, and benefits. The more mature approach to assessing the impacts and benefits of DGs recognizes the ongoing challenges to integration at increased penetration levels. Research analysis has shown based on power losses that penetration level of DG up to 23% is acceptable level. Over 23%, curtailment is required in order to avoid unacceptable levels of power losses and changes in power flow (Dumitru, et al., 2015).

In the Zambian case, the Energy Regulation Board, Utility and Planners will discover and develop a larger set of flexibility options both in methods to operate existing grid assets and to deploy energy generation mix based on the innovative technology options.

Zambia's current hydro market might not serve the requirements of tomorrow's challenges such as loss minimization, maintaining the minimum and maximum voltage limits and demand reduction amidst the climate change. Hence, a well-functioning energy generation mix framework will ensure the smooth transition of the Zambia electricity sector to promote national grid energy generation mix.

2.7. Technical impacts

Distributed Generation has a good potential to improve distribution system performance. The introduction of Distributed Generation to distribution system can significantly impact the flow of power and voltage conditions at customers and utility equipment. The impacts may be either positive or negative depending on the distribution system operation, the Distributed Generation characteristics and optimal location. The positive impacts are generally called system support benefits and include loss reduction, improved utility system reliability, voltage support and improved power quality, transmission and distribution capacity release, deferments of new or upgrade transmission and distribution infrastructure, easy and quicker installation on account of prefabricated standardized components, lowering of cost by avoiding long distance high voltage transmission, environment friendly where renewable sources are used. The technical impacts are mainly in Distribution system planning, Power flow, Reliability, Islanding, Power quality, Power loss and Voltage regulation. To obtain the benefits from Distributed Generation, it is necessary to know both positive and negative impacts of Distributed Generation on the distribution system (Rugthaicharoencheep & Auchariyamet, 2012). Power quality in terms of voltage and power losses are the major problem that occurs between grid to end user transmission lines due to growing power demand. The variable power flow due to the fluctuation of solar irradiance and temperature affects voltage profile. The Distribution Static Compensator (DSTATCOM) helps to rectify power quality problems such as voltage sag and swell. (Murali & Manivannan, 2013). The variation in solar irradiance may cause power fluctuation, and power fluctuation may cause power swing in the lines, over and under loadings. The fluctuations may also be due to excessive real power produced by the PV unit (Masoud, et al., 2013). DG affects distribution network in several ways such as magnitude and direction of power flow, electrical losses, voltage profile, power factor and fault levels. If DG capacity becomes larger and the distance between DG and load is longer, the losses tend to increase. The capacity of DG, location of DG, location load and size of load play an important role on system losses (Surakit & Attapol, 2013). The DG may level the load curve, improve voltage profile and reduce transformer loading levels. The introduction of DG can significantly impact the flow of power and voltage conditions at customers and utility equipment. (Begovic, et al., 2001).

2.8. Protection overview

The addition of Distributed Generation changes energy flows which can flow in either direction through system protection devices. A system wide approach to protection is required when evaluating the impact related to the introduction of a Distributed Generation connection. For a fault on the grid the desired response may be to island. Speed of separation is dependent on critical loads needs. The impact of the Distributed Generation system protection should be analyzed in a structured approach. The purpose of the interconnection protection is to protect the grid from Distributed Generation unit on the grid – side during parallel operations of the Distributed Generation and the grid. The interconnection protection requirements are normally established by the utility and include (Ahmed, et al., 2013):

5. Disconnect the generator when detecting an 'islanding' condition;
6. Protect the utility from damage caused by the Distributed Generation and
7. Protect the Distributed Generation from damage caused by the utility.

Many utilities will require Distributed Generation installations to conform to the Grid and Distribution codes. The utility may provide detailed requirement (Andrew T, 2008). The Penetration of DGs in distribution system should be accompanied with changes in the protection scheme. When the DG size was increased, its contribution to fault current in the system increased. (Ahmed, et al., 2013). The protection coordination effect depends on the size, type and location of the DG. It can make system reliability better or worse. It is important to perform a detailed study before installing DG in distribution feeders to make sure that it can improve total system reliability (Seyed Ali & Maryam, 2011).

2.9. Energy Policy

The energy policy of the European Union (EU) focuses on the concrete actions required to ensure the realization of internal energy market in the context of high levels of renewable energy in the post-2020 period. The most important developments include the agreement by the European Council on energy and climate targets for 2030 and the launch of the Energy Union by the European Commission in February 2015. At the end of 2014, 610MW of solar power and 4,893MW of wind power capacity was installed in Denmark, Ireland had installed approximately 2,500MW of renewable generation, in Italy, installed capacity of wind and PVs was about 8.7GW and 18.7GW, respectively and France has installed 9.1GW wind and 5.3GW PVs (Institute of Electrical and Electronics Engineers, November/ December 2015).

Zambia's National Energy Policy adopted of 2008 (NEP 2008) provides the sector policy framework. The main thrust is on the diversification the energy mix through the use of renewable energy and creating conditions that ensure availability of adequate supply of energy from various sources which are dependable and at the lowest economic, financial, social and environmental costs consistent with the national development goals. The institutional framework at energy sector level is comprised of government agencies and energy utilities such as ZESCO and Independent Power Producers (IPPs), the Rural Electrification Authority (REA) responsible for developing electricity services in the rural areas (Ministry of Energy and Water Development, 2008).

2.10. Power flow study

Load flow sometimes known as power flow is power system expression for the steady-state solution of an electrical power network. It provides information about the line and transformer loads as well as loses throughout the system and voltages at different points in the system for evaluation and regulation of the performance of the power system. The commonly used iterative numerical procedures are the Gauss – Seidel and Newton Raphson methods. Load flow studies are performed to investigate the power system network performance in terms of Flow on MW and MWAr in the network, busbar voltages, effect or rearranging circuits and incorporating new circuits on the system, effect of temporary loss of generation and transmission on system loading, effect of injecting in – phase and quadrature boost voltages on the system loading, optimum system running conditions and load distribution, minimization of system losses, optimum rating and tap – range of transformers and improvement from change of conductor size and system voltage (Meghana, 2011).

The buses are classified as Load bus (P – Q) – any bus of the system for which the real and reactive power are specified. They cannot provide the necessary reactive power support to constrain the voltage magnitude at the specified value. P – V (Generator or voltage controlled bus) – any bus for which the voltage magnitude and the injected real power are specified. And V – Q (Swing or Slack bus) – this is a bus for which the voltage magnitude and angle are specified. The real and reactive powers are unknowns. (Gupta, 2014). Four variables linked to each bus are voltage angle (δ), voltage magnitude (V), reactive power (Q) and real power (P). Distribution load flow solution provides voltage magnitude and angle at each busbar, real and reactive power loss, power flows and MVA loadings at both ends of each branch of the distribution system and total system losses.
Voltage at any node can be represented as

$$V_n = V_{n-1} - I_b Z_b \qquad (2.2)$$

Where V_{n-1} = Voltage at $(n-1)^{th}$ node

$b = (n-1)$

I_b = current in branch b

Z_b = impedance branch b

The real and reactive power loss in the system is given by

Real power loss: $P = \sum_{b=1}^{Nb} |I_b|^2 R_b$ (2.3)

Reactive power loss: $Q = \sum_{b=1}^{Nb} |I_b|^2 X_b$ (2.4)

The bus power S_i injected into the bus can be represented as power generated minus the load at the corresponding bus. By adding power at all n buses, we can therefore obtain the total power generated minus the total load network, and then we will get the losses in the network (Bhanu & Boora, 2016).

$$P_L + jQ_L = \sum_{i=1}^{n} S_i = \sum_{i=1}^{n} S_i = \sum_{i=1}^{n} V_i\, I_i \tag{2.5}$$

Where P_L – Total real power loss

Q_L – Total reactive power loss

S_i – Bus power inserted at bus i

V_i – Bus voltage at bus i

I_i – Bus current vector of bus i

The total active power loss in a power system is given by

$$P_L = \sum_{i=1,j=1}^{n} [\alpha_{ij}(P_i P_j + Q_i Q_j) + \beta_{ij}(Q_i P_j + P_i Q_j)] \tag{2.6}$$

Where $\alpha_{ij} = \frac{rij}{ViVj} \text{Cos}\,(\delta_i - \delta_j)$

$\beta_{ij} = \frac{rij}{ViVj} \text{Sin}\,(\delta_i - \delta_j)$

i and j are the suffix values at i^{th} and j^{th} node respectively.

$$Z_{ij} = r_{ij} + Jx_{ij} \tag{2.7}$$

Where Z_{ij} is the impedance of the line between bus i and bus j

r_{ij} is the resistance of the line between bus i and bus j

x_{ij} is the reactance of the line between bus i and bus j

V_i is the voltage magnitude at bus i

V_j is the voltage magnitude at bus j

2.10.1. Constraints

2.10.1.1. Bus voltage limits

A small change in nodal voltage affects the flow of reactive power whereas the active power practically does not change. Therefore, the operating voltage range at each node must be in the range as follows:

$V_{imin} \leq V_i \leq V_{max}$

Where V_{imin} – minimum voltage limit of i^{th} node

V_{max} – maximum voltage limit of i^{th} node

V_i – voltage at i^{th} node

2.10.1.2. Feeder capacity limits

Power flow in each branch must be less than or equal to its maximum capacity as given below.

$|I_i| \leq I_{imax}$

Where I_{imax} – maximum current capacity of i^{th} branch

I_i – current in i^{th} branch

2.10.2. Power flow equations

Total active power generation must be equal to the sum of total active power losses and total load. Similarly, to total reactive power generation given by the following equations:

$$\sum P_{iGen} = P_L + P_{Lload} \tag{2.8}$$

$$\sum Q_{iGen} = Q_L + Q_{Lload} \tag{2.9}$$

Where $\sum P_{iGen}$ – total active power generation

$\sum Q_{iGen}$ – total reactive power generation

P_L – total active power loss

Q_L – total reactive power loss

P_{LLoad} – total active load

Q_{LLoad} – total reactive load

2.10.3. Bus

The nodes at which two or more devices join are called buses. These are literally a bar of metals to which all the appropriate incoming and outgoing conductors are connected. The right of way buses i.e. the bus which is not appropriate for DG allocations due to some restriction considerations are excluded (Singh, 2014).

In the case, where the voltage at generator busbar and power is known at the load busbar and the voltage is unknown at the load, the load power is

$$S_L = P_L + jQ_L = V_L I^* \tag{2.10}$$

2.10.4. Power flows and Busbar voltages

The active power at the generator busbar is equal to the active power at the load as there are no active power losses in the circuit (R=0). For a transmission line as $R \ll X$, $Z \cong X$ and $\theta \cong 90^0$

$$P_G = \frac{V_G V_L}{X} \operatorname{Sin} \delta \tag{2.11}$$

$$Q_C = \frac{V_G (V_G - V_L)}{X} \operatorname{Cos} \delta \tag{2.12}$$

The expressions (4.10) and (4.11) illustrate some aspects of transmitting active and reactive power across the network. Active power flow (P) requires a difference in phase angle between the busbar voltages while reactive power flow (Q) requires a difference in voltage magnitude and between generator and load busbars.

Power systems are operated with relatively constant voltages and the differences in voltage magnitudes between various nodes are not allowed to be large. There are no such strict constraints on differences in phase angles across a line in Sin δ but Cos δ remians close to 1. Since X ≫ R, the reactive losses are much larger than the active losses (Weedy, et al., 2012).

2.10.5. The Newton Raphson method

The DIgSILENT software utilizes the Newton Raphson (NR) method for iteration. The NR method has better convergence characteristics and for many systems it is faster than the Gauss – Seidel method. The NR method is very suitable for load flow studies on large systems.

Complex power equation as equations with real coefficients

$$S_i = V_i I_i^* \quad = V_i \left(\sum_{k=1}^{n} Y_{ik} V_k\right)^* \tag{2.13}$$

Where

$Y_{ik} = G_{ik} + jB_{ik}$

$V_i = |V_i| e^{j\theta i} = |Vi| \angle \theta_i$

$\theta_{ik} = \theta_i - \theta_k$

$e^{j\theta} = \cos\theta + j\sin\theta$

The real power balance equations

$$Si = P_i + jQ_i = V_i \sum_{k=1}^{n} Y_{ik}^* V_k^* = \sum_{k=1}^{n} |V_i||V_k| e^{j\theta ik} (G_{ik} - jB_{ik}) \tag{2.14}$$

$$= \sum_{k=1}^{n} |V_i||V_k|(\cos\theta_{ik} + j\sin\theta_{ik}) (G_{ik} - jB_{ik}) \tag{2.15}$$

Resolving into real and imaginary parts

$$P_i = \sum_{k=1}^{n} |V_i||V_k|(G_{ik}\cos\theta_{ik} + B_{ik}\sin\theta_{ik}) = P_{Gi} - P_{Di} \tag{2.16}$$

$$Q_i = \sum_{k=1}^{n} |V_i||V_k|(G_{ik}\sin\theta_{ik} - B_{ik}\cos\theta_{ik}) = Q_{Gi} - Q_{Di} \tag{2.17}$$

CHAPTER THREE

RESEARCH METHODOLOGY

Once the loads, active and reactive power injections and network parameters are defined, load flow analysis solves for system losses, bus voltages and phase, after which the branch power flow can be calculated. Power flow or load flow requires an iterative solution of system simultaneous nonlinear equations. Hence, the need to choose a reliable method of simulating the 33kV distribution network using DIgSILENT Power Factory software.

The research involved data collection and modelling of the current 33kV Lusaka distribution network from Zesco, who own more than 70% of the electrical infrastructure in Zambia. This was needed to model the entire Lusaka 33kV distribution network with all the generators, loads, distribution lines and transmission lines parameters. The collection of generators, transmission and distribution line/ cable parameters was achieved through existing 33kV Lusaka distribution network and operational configuration Zesco drawings as well as conducting oral interviews from the personnel involved.

The research involved

1. Literature Review on the impact location and sizing of solar PV plants for integration to the distribution network.
2. Translating the 33kV Lusaka distribution network using DIgSILENT PowerFactory software.
3. Base case load flow analysis of the 33kV Lusaka distribution network at substations using DIgSILENT PowerFactory software to explain the load flow simulation analysis of the Grid network without solar PV plant connected to the system to investigate power system losses and the voltage profile.
4. The Global Positioning System (GPS) marking to determine the impact on locations (in terms of land availability).
5. Load flow analysis with solar PV plant connected to the 33kV Lusaka distribution network at substations using DIgSILENT PowerFactory software to explain the

load flow simulation analysis of the Grid network on the solar PV penetration level, to investigate the impact power system losses, voltage profile and power flow.

To determine the impact of location and size of solar PV plants on the Lusaka Distribution network to minimize system losses, maintaining the minimum and maximum voltage operating limits and demand reduction, DIgSILENT was used to provide support for decision making on a load flow-based approach for the impact of location and size.

DIgSILENT is an acronym for DIgital SImulation of Electrical NeTworks, is a computer aided tool for analyzing the transmission, distribution and electrical power systems. It is an integrated and interactive software package dedicated to electrical power system and control analysis to achieve the main objectives of planning and operation optimization. The software through load flow simulation allowed identifying in the power grid the suitable bus that can carry the solar PV plant (DIgSILENT, August 2013).

A GPS mapping tool was used to assist in the site selection process in terms of location and size by assessing multiple constraints, determine the total area and suitable land available for solar PV project development. The final site selection can only be made when main constraints have been assessed such as but not limited to solar resource, local climate, topography, land use, environmental designation, geotechnical condition, accessibility, module soiling and water availability. The GPS mapping tool cannot perform such detailed technical assessment regarding the above-mentioned constraints. Under this research, the GPS and Google Earth was used to visually display the area and mark the available land.

3.1. Simulation of Lusaka 33kV distribution network in DIgSILENT

When a power system is being simulated using DIgSILENT software, concerns such as control conditions and operational requirements are taken into account. Solving an optimization problem means to get the best suitable value for an objective function which is subject to constraints. The constraints are operational or design limits.

The 33kV Lusaka distribution network is supplied through four main Bulk Supply Points (BSPs) into Lusaka through a transmission ring connecting Coventry (132kV), Roma

(132kV), Lusaka West (132kV) and Waterworks (88kV) sub stations, referred to as the Lusaka 132kV ring transmission line. These BSPs further supply the 67 identified 33kV distribution substations throughout Lusaka area, which in turn supply the existing11kV distribution networks. The detailed 33kV distribution network is shown in Appendix B, drawing title Lusaka 33kV distribution network, drawing no. LUS-GEN-DE-08-G-11746. The load flow analysis was carried out on the Lusaka 33kV distribution network to determine the load flow base case data. The following assumptions were made:

- The load was modelled as a constant power demand load;
- Power generation at full capacity and
- System design based on the current status with no consideration of future planned lines

The Lusaka 33kV distribution network single line diagram was created on DIgSILENT PowerFactory 14.1 software. This software is a computer aided engineering tool for the analysis of transmission, distribution and industrial electrical power systems. It is an interactive software package dedicated to electrical power system and control analysis to achieve the planning and operation optimization. It is a power system analysis software with an integrated graphical single-line diagram interface and can easily execute available functions such as load flow, short circuit calculation, harmonic analysis, protection coordination, stability calculation and modal analysis.

The reason for choosing DIgSILENT software compared to others is that it has a faster response even in a large power system and good to analyses big systems. It is an easy software to learn within the shortest possible time and fully windows compatible. It provides all the necessary functionality to conduct complex studies for the integration of renewable generations into the distribution network which is one of the key issues in network planning and analysis. The software combines extensive modelling capabilities with advanced solution algorithms, thereby providing tools to undertake the full range of studies required for grid connection and grid impact analysis of wind and solar PV and all other kinds of modules using renewable energy. The software was also made available by Zesco at no cost to undertake the simulation.

Information on existing overhead lines and cables was obtained from Zesco such as single line diagrams, system map and parameters. A review was made on the data provided and was used for system design and configuration in DIgSILENT. Appendix D shows the electrical parameters for overhead lines and cables provided.

A number of different conductor types have been used with various line configuration and the required parameters based on standard manufacture's data and local environment conditions prevailing on the Zesco system. The cable data collated with the typical manufacture's catalogue. The Table 4 shows the cable parameter condition, which were obtained from Zesco as, input into the software for simulation.

Table 4: Cable parameter condition

Parameter	11kV Cables	33kV Cables
Direct in ground/ in air Ducts	Direct in ground	Direct in ground
Depth of laying	0.9 meter	1.3 meter
Ground temperature	20 Degrees C	20 Degrees C
Ambient air temperature	30 Degrees C	30 Degrees C
Maximum conductor temperature	XLPE: 90^0C/ PILC: 70^0C	XLPE: 90^0C/ PILC: 65^0C
Soil thermal resistivity	1.2 ^{0}C km/ W	1.2 ^{0}C km/ W
Single core cable flat/ trefoil	Trefoil	Trefoil

The Grid Code regulates the reciprocal obligations of industry participants in the use of the Transmission System and operation of the Interconnected Power System. It ensures that investments are made within the requirements of the Code and provide access, on agreed standard terms, to all parties wishing to connect to or use the Transmission System. The Code applies the principal of non-discrimination through the provision of consistent and transparent principles, criteria and procedures. Table 5 shows the technical voltage limits as stipulated by the Grid Code (ENERGY REGULATION BOARD, 2013).

Table 5: Technical voltage limits

Voltage level (V)	Compatibility level (%)
$<$88000	$\pm$10
$\geq$88000	$\pm$5
Note – in the absence of any agreement of the contrary, the supply voltage level shall not deviate from the compatibility level for any period longer than 10 consecutive minutes.	

The data was obtained to analyze the present operation and obtain the behavior of the power system. This was to obtain the impact of location and size of the solar PV plant.
Load flow calculations were used to analyze the power system network under steady state condition. This is a state in which all the variables and parameters are assumed to be constant during the period observation. In this simulation, the load is considered to increase from early in the morning until it reaches its maximum before the sunset. After the sunset, the solar irradiance begins to increase. The load flow analysis considers the power system network to be in steady state analysis because it reflects the system conditions for a certain point in time such as the maximum demand during day time. The load flow calculation will determine the active and reactive power flows, system losses, the voltage magnitude and the phase angle for all the nodes.

The computational procedure below shows the process flow undertaken to investigate the impact of location and size of the Solar PV plant. The load flow-based simulation procedure was undertaken as follows (Naser, et al., 2014):

Step 1: Obtain the Lusaka 33kV distribution network and system parameters from Zesco limited;

Step 2: Develop the distribution network single – line diagram on DIgSILENT software;

Step 3: Run the simulation to obtain the load flow base line case;

Step 4: Identify solar PV site area near substations and determine the solar PV capacity;

Step 5: Based on step 4, identify substation with more than 10MW for solar PV integration;

Step 6: Change the size of the Solar PV in "small" step and observe the constraints by running the load flow simulation;

Step 7: Analyze and store the simulation results for power losses, power flow direction changes and the voltage limits requirements;

Step 8: Repeat Steps 6 and 7 for identified substations in steps 4 and 5 for Solar PV integration.

Step 9: Finally, obtain the impact size of the solar PV plant at each substation identified for solar PV plant integration that is contributing to the overall minimum power loss reduction, power flow direction changes and voltage profile improvement.

The proposed methodology process flow chart shown in Figure 8 was used to find the impact of location and size of solar PV plants for integration in the Lusaka distribution grid network. The proposed methodology was tested on Makeni, Avondale, Chelstone, Chawama, Chilanga and Mapepe 33kV substations. Solar PV plants was connected to the identified substations and load flow simulation was undertaken in step wise penetration levels.

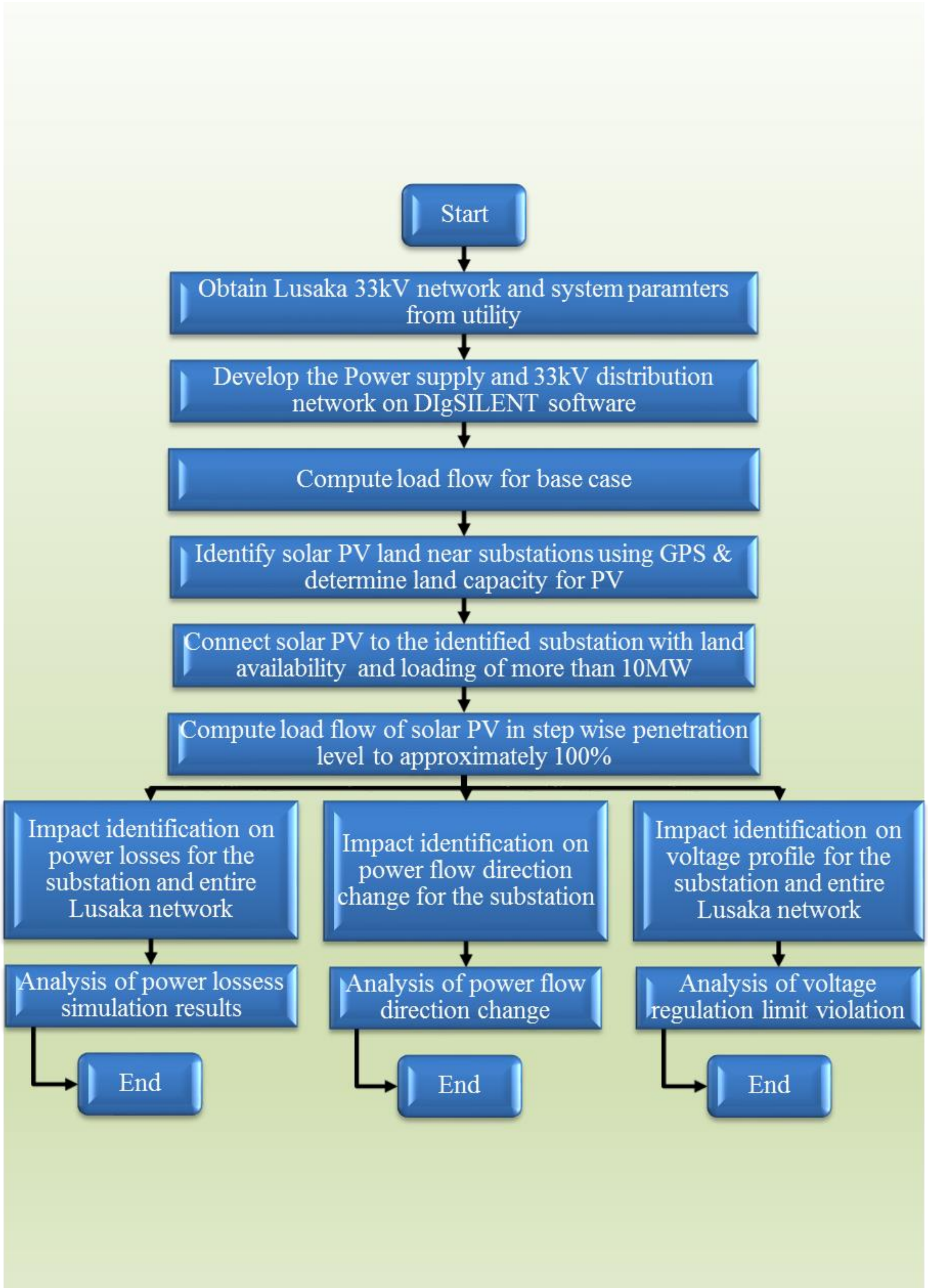

Figure 8: System methodology flow chart

CHAPTER FOUR

RESEARCH FINDINGS AND ANALYSIS

The load flow calculation was done for all the buses to determine the impact of the location and size of the solar PV plant on the distribution network with the objective of minimization of the system losses, maintaining the minimum and maximum voltage operating limits. The load flow calculation was carried out on the Lusaka 33kV distribution network to determine the steady state solution.

The areas identified were used to determine the maximum solar PV power plant capacity allowable, but the actual acceptable capacity was determined using the simulation on maintaining the minimum and maximum voltage and system losses. The table 6 below shows the area and calculated maximum solar PV power plant capacity. Land being used for agriculture can be classified for industrial use.

The impact on location and size was performed by locating sites available near the substations. A total of forty-five (45) 33kV substations out of sixty-seven (67) 330kV, 132kV, 88kV, 66kV and 33kV substations were initially identified as candidates for location of solar PV plant connection and Figure 9 shows the geographical location of the forty-five (45) 33kV substations in Lusaka. The map shows a concentration of substations especially in the Central Business District. This shows the challenge of finding land available near most of the substations and an indication that the distribution lines are heavy loaded due to demand. The Sixty-seven (67) substations are a combination of transmission and distribution substations. The forty-five (45) 33kV substations are supplied through eight Bulk Supply Points (BSPs) into Lusaka through a transmission ring connecting Coventry (132/88/33/11kV), Roma (132/33kV), Lusaka West (132kV), Mapepe (88/33kV), Chibombo (88/33kV), Lusaka West (330/132/33kV), Chongwe (88/33kV), Fig Tree (88/33kV) and Waterworks (88/33kV) sub stations, referred to as the Lusaka 132kV ring transmission line.

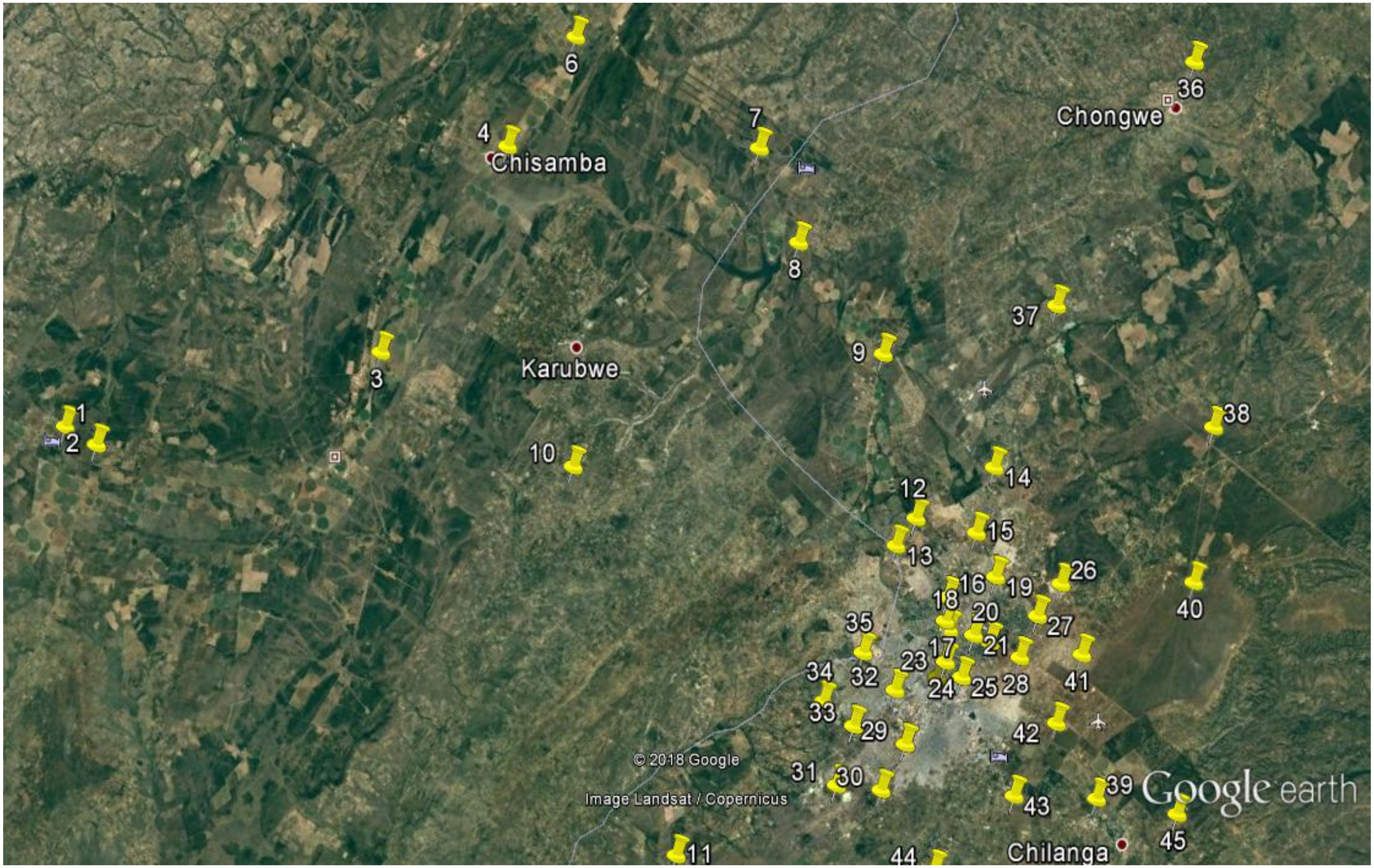

Figure 9: Geographical location of the forty-five (45) Lusaka 33kV substation

Legend of the geographical location for the forty-five (45) Lusaka 33kV substations

SN	Substation	SN	Substation	SN	Substation	SN	Substation
1	Chibombo	2	Landless	3	Burnet	4	Chisamba
5	Fig tree	6	Globber	7	Penyaonse	8	Karubwe
9	Ngwerere	10	Katuba	11	L 85	12	Kwamwena
13	Roma	14	Avondale	15	Chelstone	16	UNZA
17	Manda Hill	18	Dublin	19	Kabulonga	20	UTH
21	Birdcage	22	Coventry	23	Zesco Workshop	24	Levy
25	Kafue Road	26	Bauleni	27	Woodlands	28	Waterworks
29	Kanyama	30	Ndipo	31	Lusaka West	32	Liverpool
33	Mungwi	34	Barlastone	35	Matero	36	Chongwe
37	Chongwe 88kV	38	Leopard hill	39	Chilanga	40	MFEZ
41	Chalala	42	Chawama	43	Bonaventure	44	Makeni
45	Mapepe						

The 45 substations candidates were further reduced to thirteen (13) feasible locations by identifying the available land near the substation with the help of Google earth. Table 6 shows the 13 feasible substations and available area size near the substations. The impact on locations and size was determined through simulation to determine the power loss reduction and voltage profile improvement. The busbar and line parameter values were compared to the base case (before solar PV plant connection) and after solar PV plant connection.

The 13 feasible substations were preferred for impact on location and size of solar PV plants on the Lusaka 33kV distribution network. The 13 substations are Makeni, Chelstone, Mapepe, Chilanga, Chalala, Fig tree, Chibombo, Katuba, Chisamba, Chongwe 88/ 33kV, Avondale, L85 and Chawama.

The solar PV plant size was tested with the step size of 10MW. The power losses and voltage profiles in base case and after solar PV plant placement have been shown in the simulation system summary results, tables and figures below. Figures 10 – 22 show

Google earth images of the location for solar PV array sites and marked area identified using GPS.

Figure 10: Site and area available near Chibombo Substation

Figure 11: Site and area available near Chisamba Substation

Figure 12: Site and area available near Fig Tree Substation

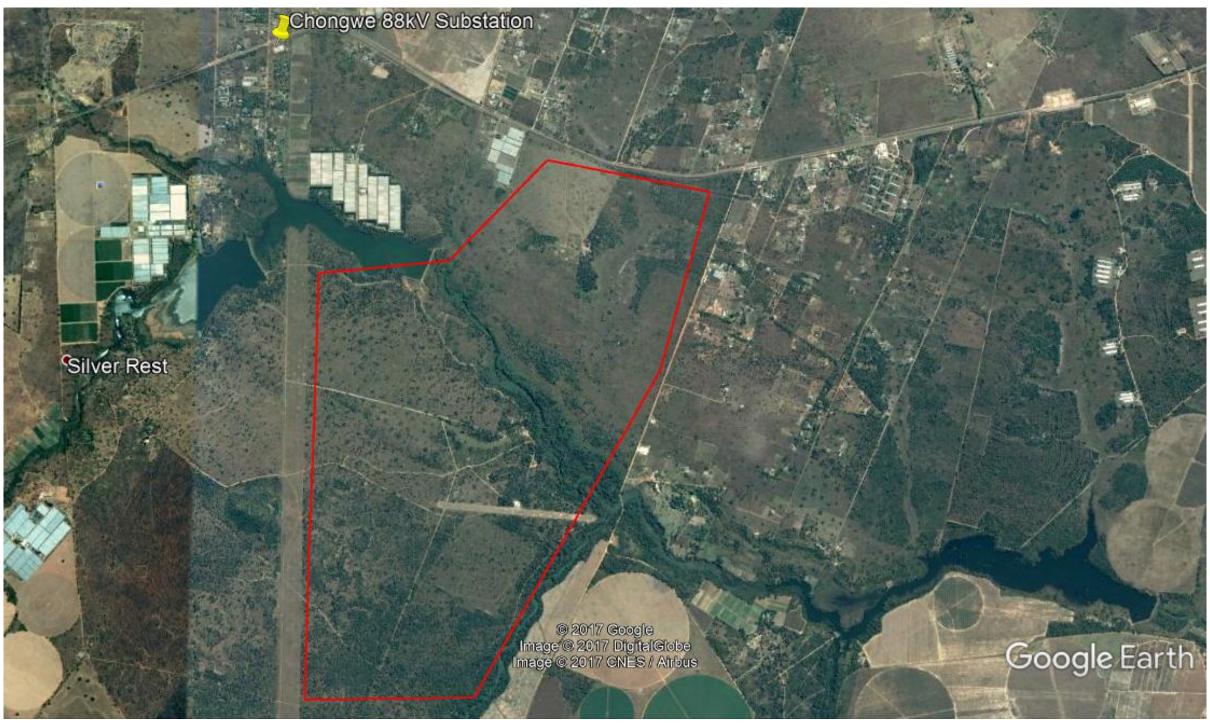

Figure 13: Site and area available near Chongwe 88/33kV Substation

Figure 14: Site and area available near Avondale Substation

Figure 15: Site and area available near Chelstone Substation

Figure 16: Site and area available near L 85 Substation

Figure 17: Site and area available near Makeni Substation

Figure 18: Site and area available near Chawama Substation

Figure 19: Site and area available near Chilanga Substation

Figure 20: Site and area available near Mapepe Substation

Figure 21: Site and area available near Chalala Substation

Figure 22: Site and area available near Katuba Substation

Table 6 shows the initial 13 substation identified location for possible solar PV integration and estimated available land size using Google Earth. The Google Earth software is capable to estimate the area of a location marked. Based on the estimated area, the capacity was calculated based on the rule of thumb that is 1 MW solar PV power plant requires about 4 acres if it uses crystalline solar panels without trackers and 6 acres if it uses thin film solar panels without trackers also considering space for other accessories as well (Mango, 2015).

Table 6: Area and calculated maximum solar PV capacity

No.	Substation	Area (m^2)	Maximum Capacity (MW AC)
1	Chibombo	5 099 073	210.00
2	Chisamba	5 670 509	233.54
3	Fig Tree	6 125 636	252.28
4	Chongwe 88/33kV	9 289 294	382.57
5	Avondale	4 930 352	203.05
6	Chelstone	944 709	38.91
7	L 85	12 227 135	503.57
8	Makeni	1 691 270	69.65
9	Chawama	1 875 990	77.26
10	Chilanga	1 813 794	74.70
11	Mapepe	5 121 676	210.93
12	Chalala	9 751 695	210.93
13	Katuba	1 716 313	70.69

4.1. Impact of Solar PV penetration level at different substations

This section discusses the simulation of the six substations i.e. Makeni, Avondale, Chelstone, Chawama, Chilanga and Mapepe substations, identified for possible solar PV integration. The six substations were identified based on available land near the substations and loading of more than 10MW. To analyse the impact of solar PV penetration on the 33kV Lusaka distribution network, DigSILENT software was used for simulation. The basic function of the simulation was to perform load flow to determine the impact of solar PV plant location and size at different penetration levels on the power losses, voltage profiles and power flow on the substations.

The simulation and analysis were first performed by varying the solar PV penetration levels at the identified substation, then observe the impact on the bus power loss, voltage profile and power flow direction on the substation.

Then second, the same simulation and analysis were performed by varying the solar PV penetration levels on the same substation to determine the impact of solar PV penetration levels on the entire Lusaka network. The impact on the entire Lusaka network was analysed on the major transmission transformers, 330kV power supply inter grid power flow, Lusaka bulk supply power grid losses, 33kV busbar voltage profiles and the total Lusaka network grid losses.

4.2.1. Impact of varying the size of Solar PV plant at Makeni substation

4.2.1.1. Solar PV Sizing Penetration levels

From the data obtained through load flow calculation, it was found that the voltage on the remote buses was mostly affected by varying the Solar PV size on the Makeni substation. The results of the bus voltage and the system losses are as shown in Appendix E Table E1. Using the data from Table E1 Solar PV plant penetration level, a graph of Penetration level versus Power losses and Penetration level versus Voltage profile was plotted and is shown in Figures 23 and 24 respectively.

With no solar PV plant connected (baseline case) to the system, the penetration level was considered as **zero percent**.

Sample calculation for a solar PV plant generation at **10MW**:

$$\text{Penetration level} = \frac{capacity\ factor \times DG\ power\ installed}{peak\ power\ demand}$$

Considering available 5kWh/m^2 insolation in Zambia, annual generation = 18,250 MWh approximate

$$\text{Capacity factor} = \frac{18{,}250MWh / 10MW}{8760h / Year} = \mathbf{0.21}$$

$$\text{Penetration level} = \frac{0.21 * 10MW}{15.66} \times 100\% = \mathbf{13.41\%}$$

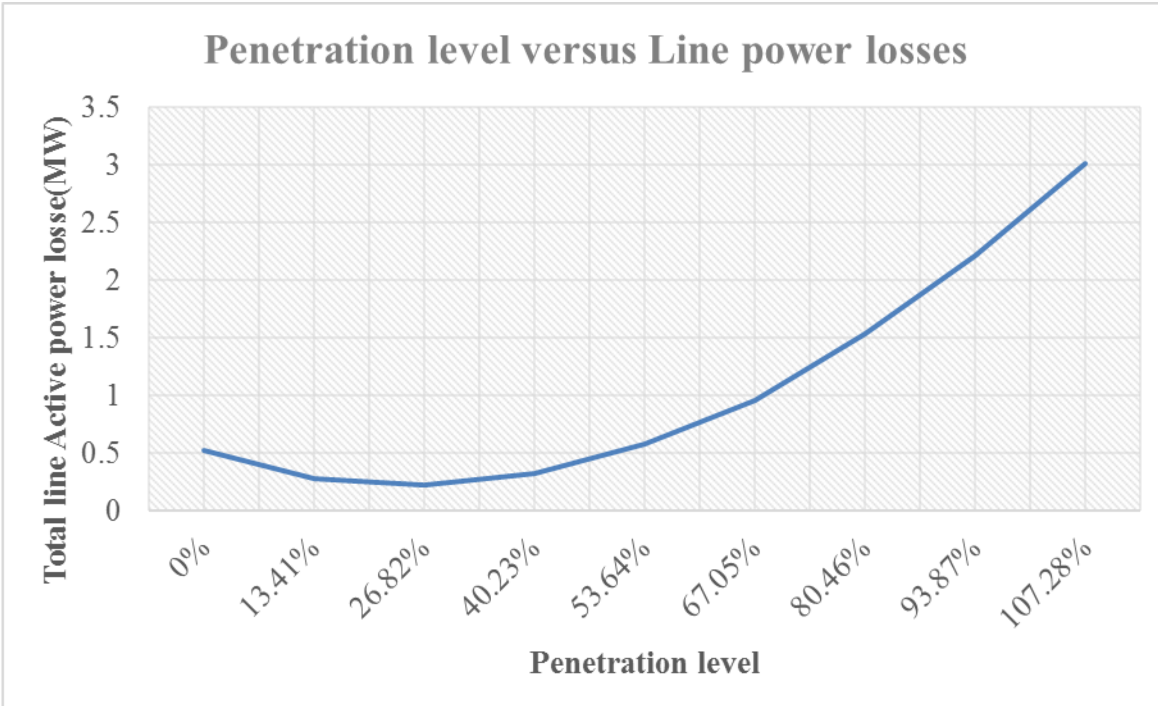

Figure 23: Penetration level versus Power losses at Makeni substation

As can be seen from the graph in Figure 23, the effect of solar PV size on the line losses forms a 'Nike mark' curve shape. As the size increases, the line losses begin to decrease up to penetration level 26.82% (20MW) where again line losses start to increase as the penetration level increases. The most probable cause for such an outcome could be that the voltage initially begins to normalize up to a certain level where it starts going into over-voltage which then contributes to the increased active losses.

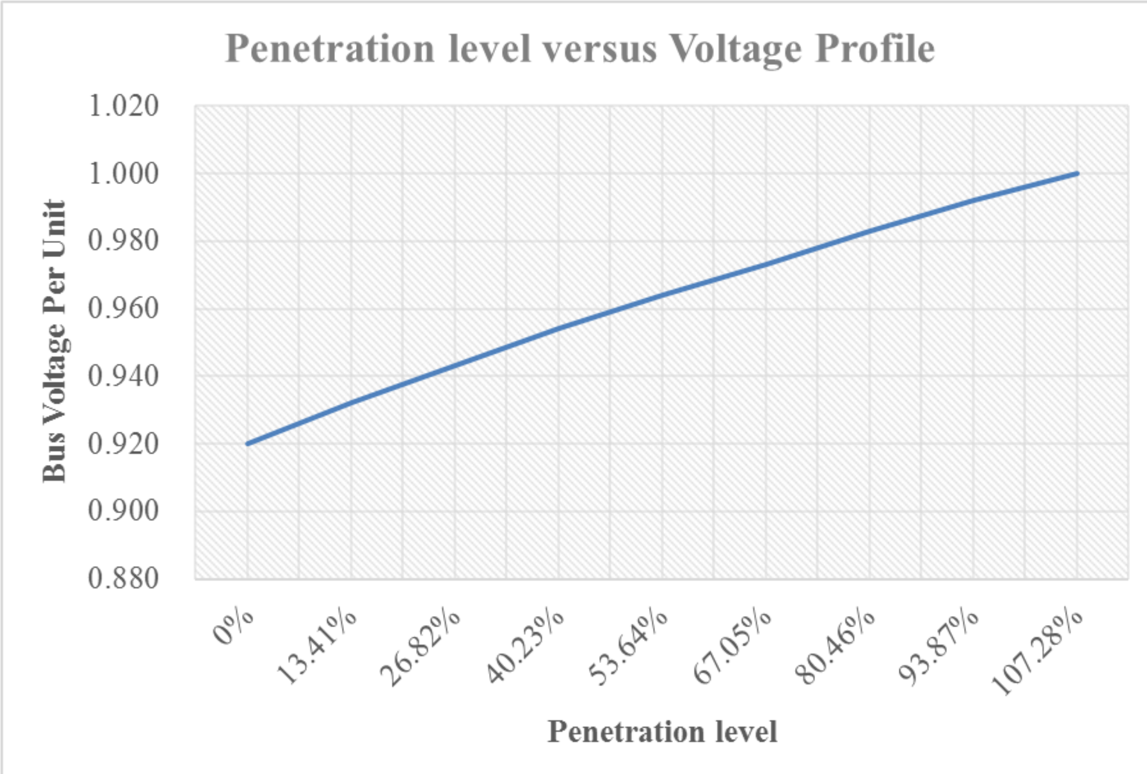

Figure 24: Penetration level versus Voltage profile at Makeni substation

The effect of solar PV size on the voltage profile is shown in graph in Figure 24. As the size increases, the voltage also increases and continues for as long as the solar PV size increases. The increase as can be seen to be equivalent to linear line.

4.2.1.2. Power Flow

The integration of solar PV plant decreases the line losses for the line in the grid to the Makeni substation. The increase in solar PV penetration resulted in subsequent reduction in the line loading. This is because the integration of solar PV provided power locally to the substation and reduced the power flow from the source. Figure 25 shows the power flow of the line towards the substation before the solar PV was connected to the substation. When the penetration level reached 26.82% (20MW), there was initial power flow direction change in one of the feeders as shown in Figure 26. When the penetration level reached 40.23% (30MW), the power flow direction totally changed by flowing outwards, i.e. away from Makeni substation as shown in Figure 27. This is because the load demand from the substation was met by the solar PV power supply. This forced the power needs to be transmitted to the other substations in the Lusaka distribution network.

When the penetration level reached 40.23% it also resulted in the increase in the losses as can be seen in Appendix E Table E4 and Figure 23.

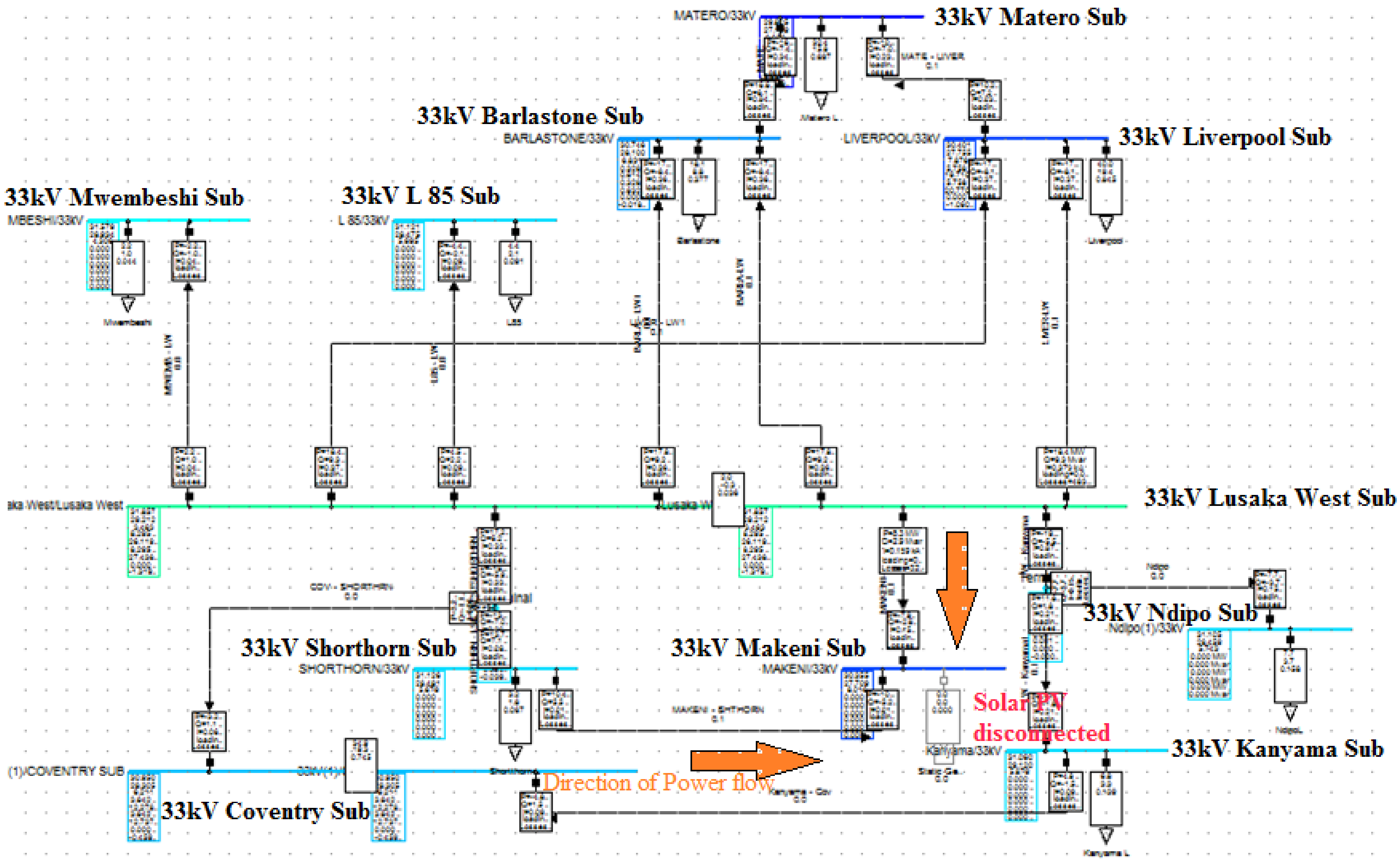

Figure 25: Power flow direction before solar PV plant connection at Makeni substation

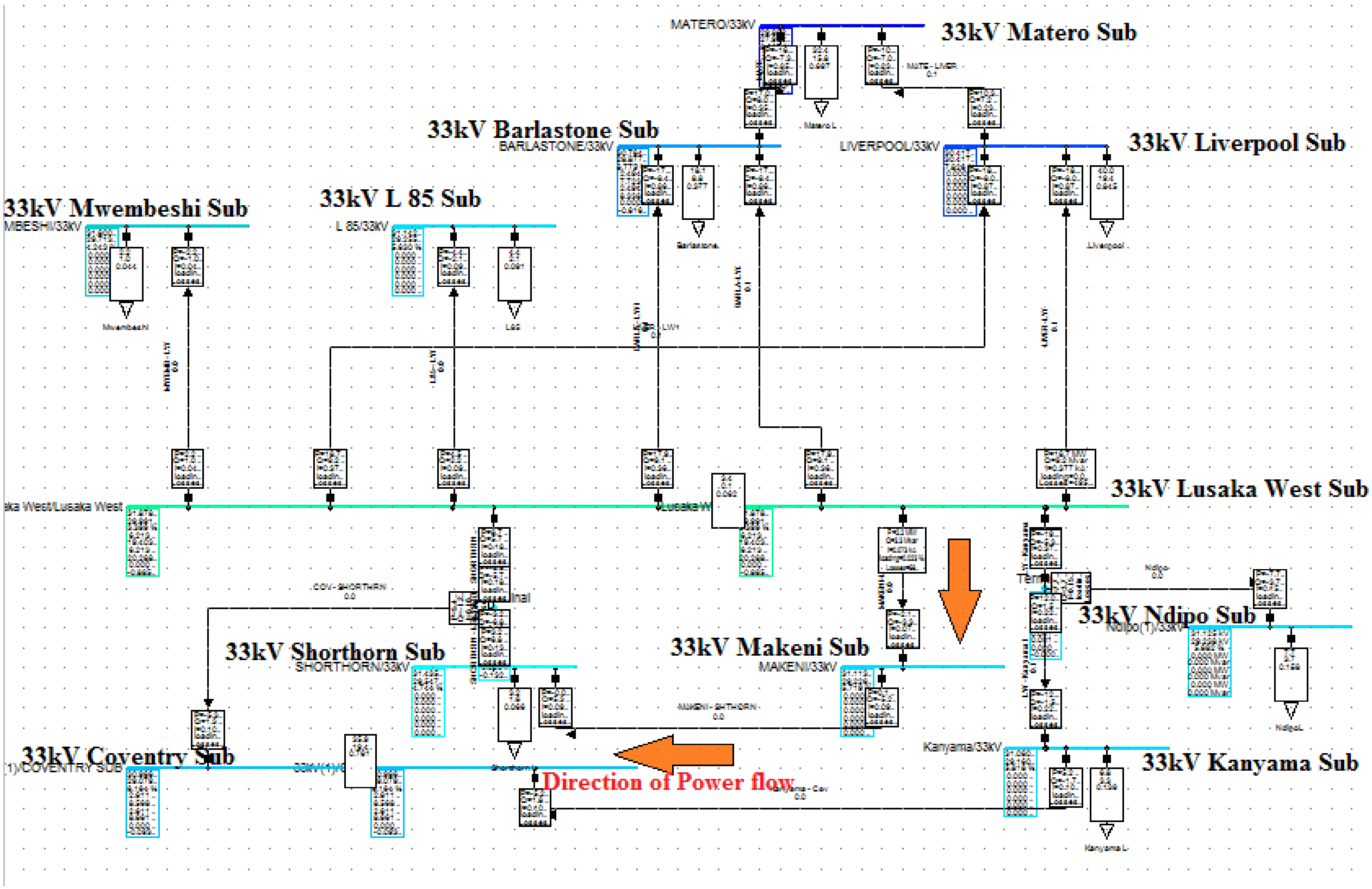

Figure 26 Initial Power flow direction change after a 26.82% (20MW) solar PV plant connection at Makeni substation

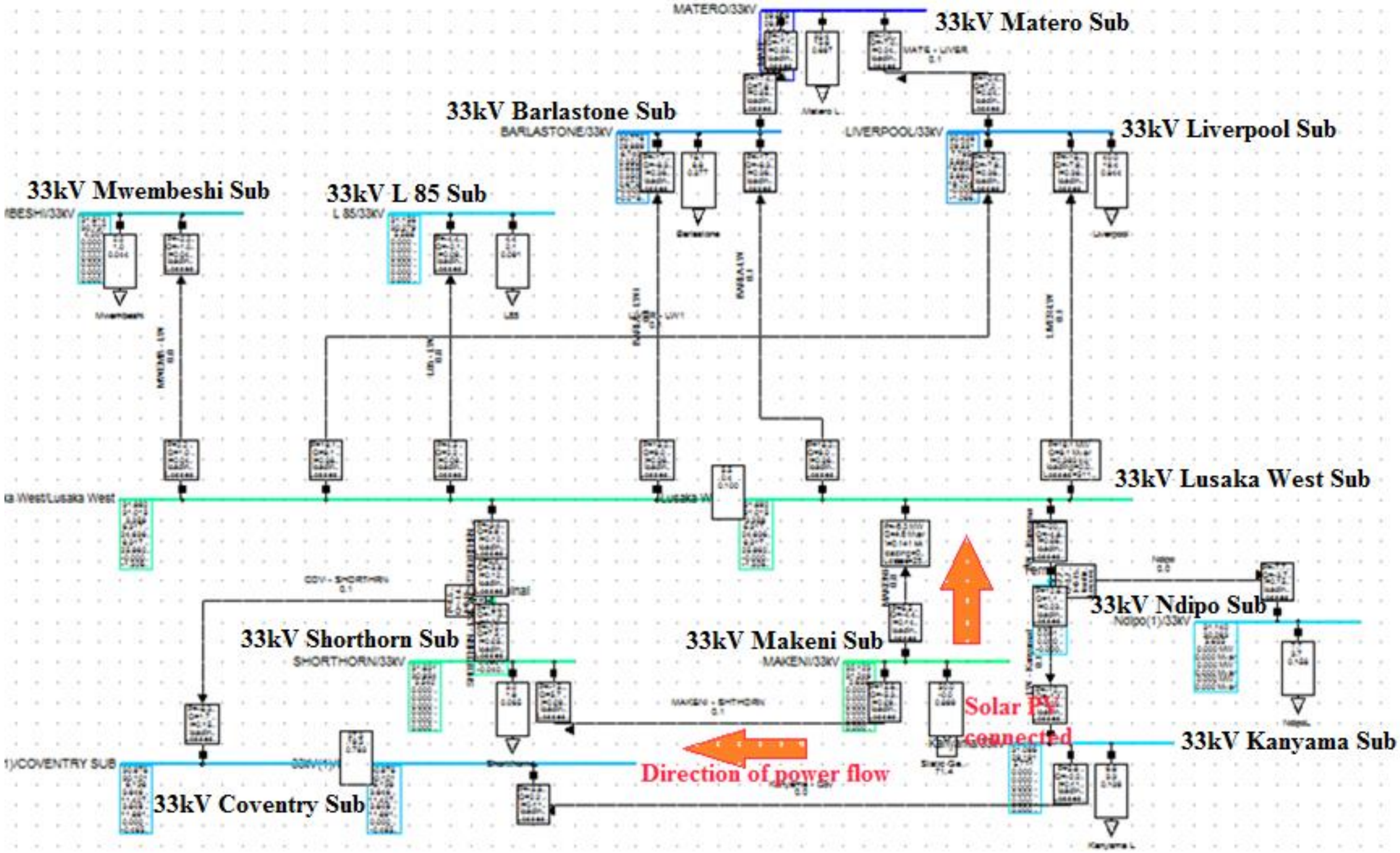

Figure 27: Overall Power flow direction change after a 67.05% (50MW) solar PV plant connection at Makeni substation

4.2.1.3. Impact of solar PV plant integration at Makeni substation on the entire Lusaka network

The results for the Inter grid power flow for the 330kV power supply for the Lusaka distribution network are shown in Appendix E Table E3. The integration of solar PV plant decreased the power from the source. The increase in penetration resulted in subsequent reduction in the transformer loadings as shown in Appendix E Table E2. This is because the integration of solar PV plant provided power at Makeni substation and reduced the power flow for power from the source. Using the data in Appendix E Table E2 and Table E3, a graph of major transformer capacity relief and 330kV supply inter grid power flow was plotted and is shown in Figures 28 and 29 respectively.

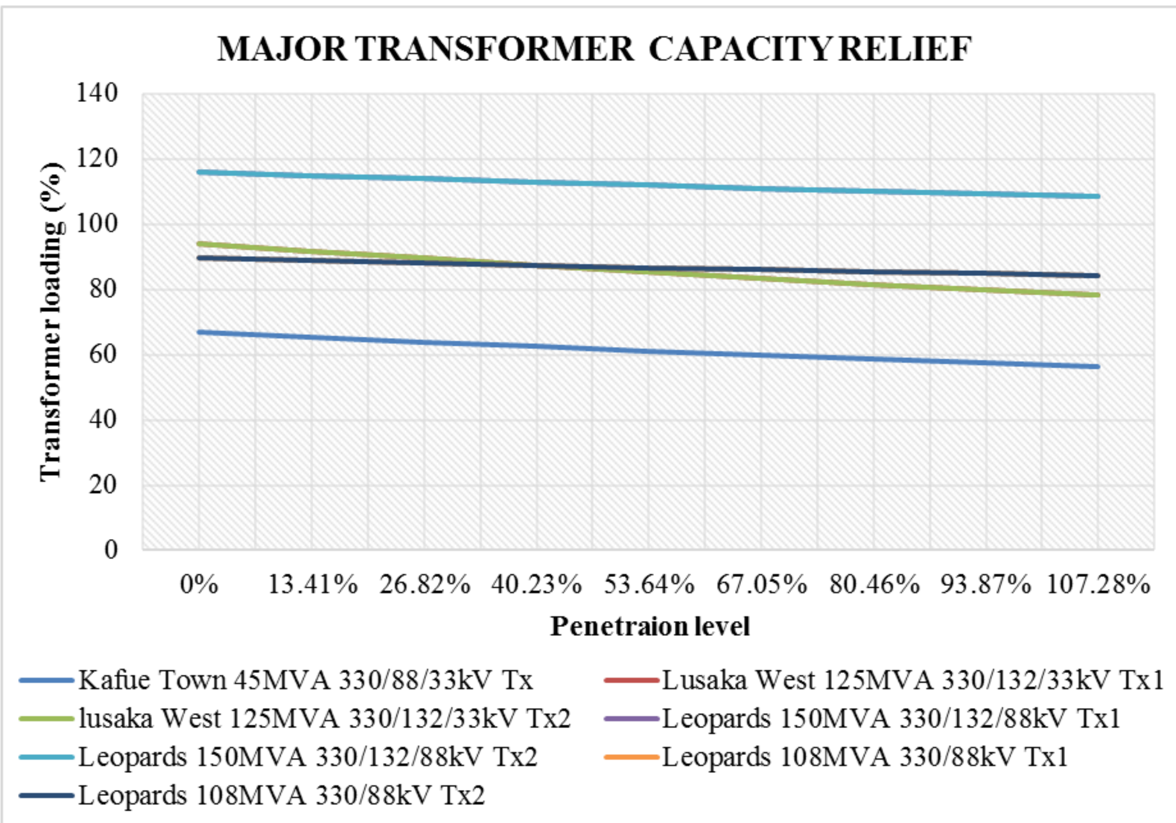

Figure 28: Major transformer capacity relief due integration at Makeni substation

The impact of solar PV penetration level due to integration at the Makeni substation on the 330kV power supply is shown in Figure 27. As the solar PV plant size increases, the power from the source is reduced and continues to reduce for as long as the solar PV size increases. The decrease as can be seen to be equivalent to linear line.

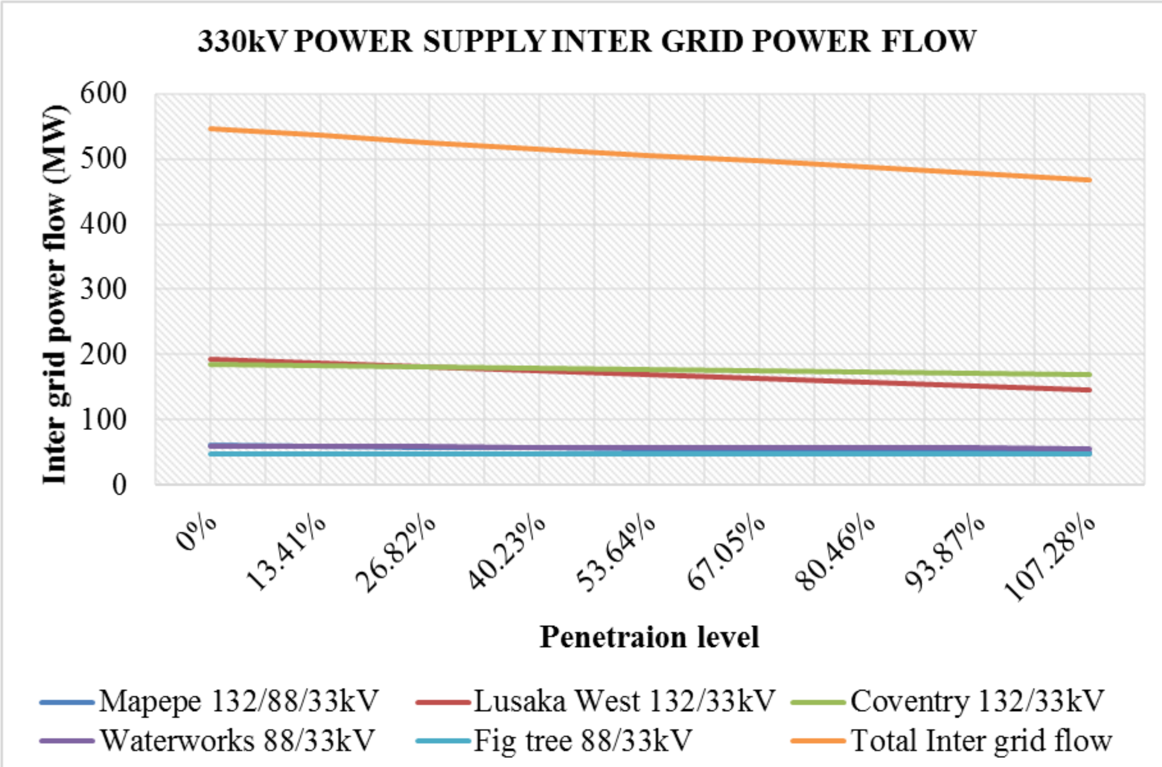

Figure 29: 330kV supply inter grid power flow impact due to integration at Makeni substation

Using the data in Appendix E Table E4 Lusaka Distribution Grid summary power losses at bulk supply substations, a graph of Lusaka bulk supply point grid losses and Total Lusaka network grid losses was plotted and is shown in Figures 30 and 31 respectively. As can be seen from the graph in Figure 31, the effect of solar PV size on the Lusaka network grid losses forms a 'bathtub' curve shape. As the size increases, the line losses begin to decrease up to penetration level 26.82% (20MW) where again line losses start to increase as the penetration level increases. The most probable cause for such an outcome could be that the voltage initially begins to normalize up to a certain level where it starts going into over-voltage which then contributes to the increased active losses.

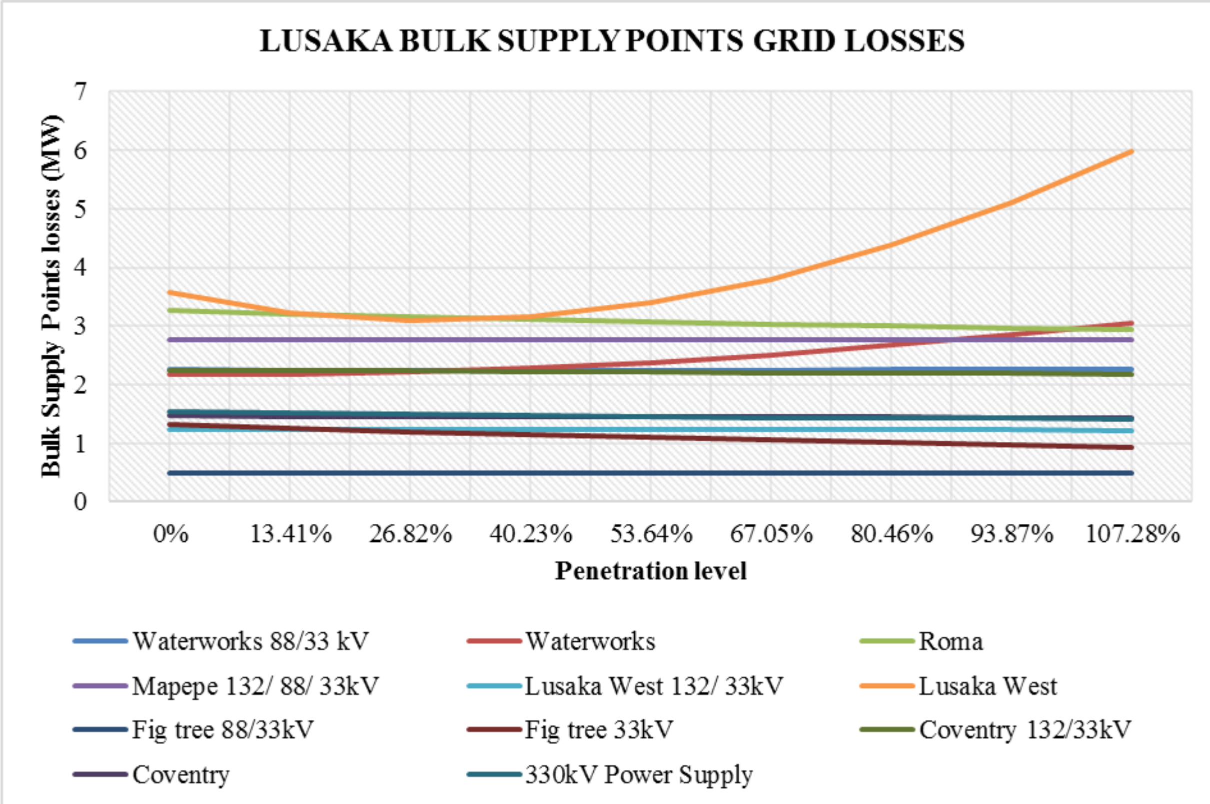

Figure 30: Lusaka bulk supply points grid losses impact due to integration at Makeni substation

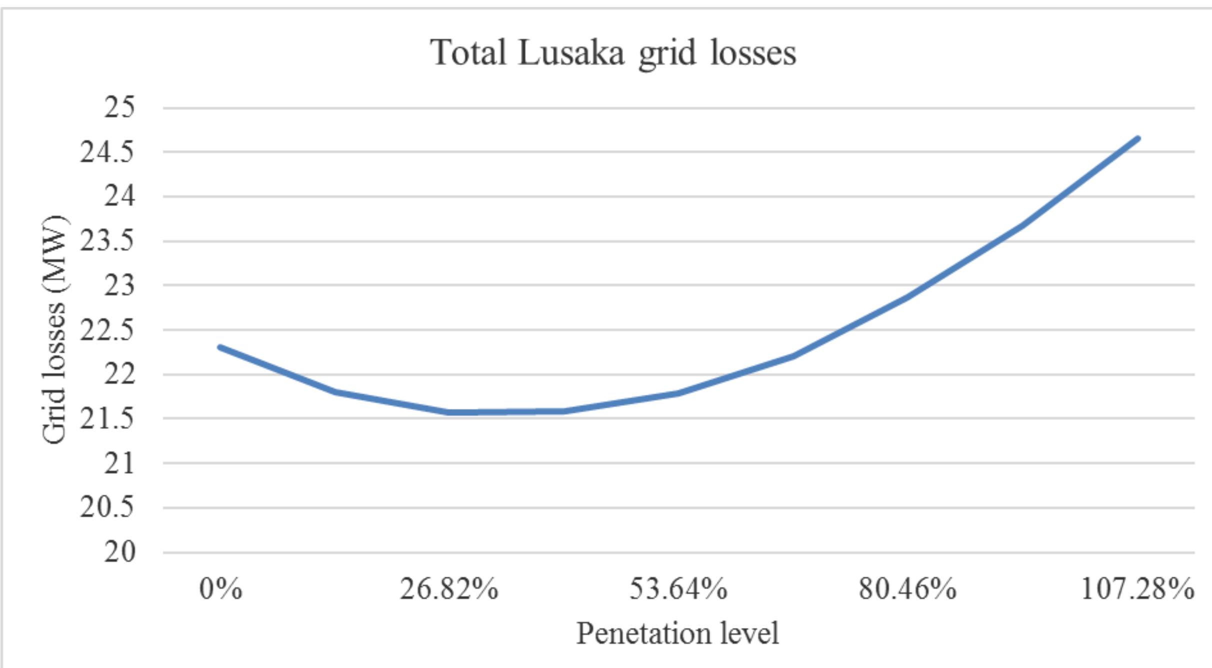

Figure 31: Total Lusaka network grid losses impact due to integration at Makeni substation

The solar PV power plants in the steps of 10MW of different capacity was integrated and simulated at the Makeni substation. The impact on the voltage level were studied and results were obtained as show in Table 7 below. It can be seen that there is voltage profile increase in the 33kV Lusaka distribution network. The comparison was done with the use of penetration levels of 0% for base case with different penetration levels up to 107.28% (80MW).

Table 7: 33kV Busbar Voltage before and after solar PV plant penetration levels impact due to integration at Makeni substation

SN	SUBSTATIONS	0%	13.41%	26.82%	40.23%	53.64%	67.05%	80.46%	93.87%	107.28%
1	Coventry sub	0.938	0.938	0.938	0.939	0.939	0.939	0.939	0.939	0.939
2	Mapepe	0.933	0.934	0.935	0.936	0.937	0.937	0.938	0.939	0.939
3	Birdcage	0.927	0.927	0.927	0.928	0.928	0.928	0.928	0.928	0.928
4	Bonaventure	0.912	0.917	0.922	0.926	0.931	0.935	0.938	0.942	0.945
5	Chawama	0.915	0.916	0.917	0.918	0.919	0.920	0.920	0.921	0.922
6	Chilanga	0.919	0.921	0.923	0.924	0.926	0.927	0.928	0.929	0.930
7	Dublin	0.932	0.932	0.932	0.932	0.933	0.933	0.933	0.933	0.933
8	Kafue Rd	0.924	0.925	0.925	0.925	0.925	0.925	0.925	0.925	0.925
9	Manda Hill	0.917	0.917	0.917	0.918	0.918	0.918	0.918	0.918	0918
10	Shimabala	0.907	0.909	0.910	0.912	0.913	0.914	0.915	0.916	0.917
11	Zesco Workshop	0.925	0.925	0.925	0.926	0.926	0.926	0.926	0.926	0.926
12	Penyaonse	0.893	0.893	0.893	0.893	0.893	0.893	0.893	0.892	0.892
13	Mt Meru	0.877	0.877	0.877	0.878	0.878	0.878	0.878	0.877	0.877
14	Kabangwe	0.898	0.898	0.898	0.898	0.898	0.898	0.898	0.898	0.898
15	Globber	0.878	0.878	0.878	0.878	0.878	0.878	0.878	0.878	0.878
16	Chisamba	0.832	0.832	0.832	0.832	0.832	0.832	0.832	0.832	0.832
17	Burnet	0.770	0.770	0.770	0.770	0.770	0.770	0.770	0.770	0.770

SN	SUBSTATIONS	0%	13.41%	26.82%	40.23%	53.64%	67.05%	80.46%	93.87%	107.28%
18	Landless	0.691	0.691	0.691	0.691	0.691	0.691	0.691	0.691	0.691
19	Kembe	0.679	0.679	0.679	0.679	0.679	0.679	0.679	0.679	0.679
20	Chisamba ranch	0.679	0.679	0.679	0.680	0.680	0.680	0.679	0.679	0.679
21	Chibombo	0.679	0.679	0.679	0.679	0.679	0.679	0.679	0.679	0.679
22	Katuba	0.834	0.835	0.835	0.835	0.835	0.835	0.835	0.835	0.834
23	Karubwe	0.893	0.893	0.893	0.893	0.893	0.893	0.893	0.892	0.892
24	Fig tree	0.893	0.893	0.893	0.893	0.893	0.893	0.893	0.892	0.892
25	Barlastone	0.932	0.932	0.932	0.932	0.932	0.933	0.933	0.933	0.932
26	Kanyama	0.941	0.942	0.942	0.942	0.942	0.942	0.942	0.942	0.942
27	L85	0.943	0.943	0.944	0.944	0.944	0.944	0.944	0.944	0.944
28	Liverpool	0.921	0.922	0.922	0.922	0.922	0.922	0.922	0.922	0.922
29	Lusaka West	0.965	0.966	0.966	0.966	0.966	0.966	0.966	0.966	0.966
30	Makeni	0.920	0.932	0.943	0.953	0.964	0.973	0.983	0.992	1.000
31	Matero	0.903	0.903	0.904	0.904	0.904	0.904	0.904	0.904	0.904
32	Mwembeshi	0.957	0.957	0.958	0.958	0.958	0.958	0.954	0.958	0.958
33	Ndipo	0.943	0.943	0.943	0.943	0.944	0.944	0.944	0.944	0.944
34	Shorthorn	0.943	0.948	0.953	0.957	0.961	0.965	0.968	0.971	0.975
35	Roma	0.931	0.931	0.931	0.931	0.931	0.931	0.931	0.931	0.931

SN	SUBSTATIONS	0%	13.41%	26.82%	40.23%	53.64%	67.05%	80.46%	93.87%	107.28%
36	Avondale	0.905	0.905	0.905	0.905	0.905	0.905	0.905	0.905	0.905
37	Bauleni	0.886	0.886	0.887	0.887	0.887	0.887	0.887	0.887	0.887
38	Chelstone	0.904	0.904	0.904	0.904	0.904	0.904	0.904	0.904	0.904
39	Chongwe town	0.934	0.934	0.934	0.934	0.934	0.934	0.934	0.934	0.934
40	Chongwe	0.941	0.941	0.941	0.941	0.940	0.940	0.940	0.940	0.940
41	Kabulonga	0.885	0.885	0.885	0.885	0.885	0.885	0.885	0.885	0.885
42	Kwamwena	0.913	0.913	0.913	0.913	0.913	0.913	0.913	0.913	0.913
43	Mikango	0.901	0.901	0.901	0.901	0.901	0.901	0.901	0.901	0.901
44	Ngwerere	0.893	0.893	0.893	0.893	0.893	0.893	0.893	0.892	0.892
45	New Kabanana	0.902	0.902	0.902	0.903	0.903	0.903	0.903	0.903	0.903
46	Palabana	0.903	0.903	0.903	0.903	0.902	0.902	0.902	0.902	0.902
47	UNZA	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912
48	Chalala	0.923	0.924	0.924	0.924	0.924	0.924	0.924	0.924	0.924
49	Levy	0.920	0.920	0.920	0.921	0.921	0.921	0.921	0.921	0.921
50	UTH	0.911	0.911	0.911	0.912	0.912	0.912	0.912	0.912	0.912
51	Waterworks	0.936	0.936	0.936	0.936	0.936	0.936	0.936	0.936	0.936
52	Woodlands	0.904	0.904	0.904	0.904	0.904	0.904	0.904	0.904	0.904

4.2.2. Impact of varying the size of Solar PV plant at Avondale substation

4.2.2.1. Solar PV sizing penetration levels

From the data obtained through load flow calculation, it was found that the voltage on the remote buses was mostly affected by varying the Solar PV size on the Avondale substation. The results of the bus voltage and the system losses are as shown in Appendix E Table E5. Using the data from Appendix E Table E5 Solar PV plant penetration level, a graph of Penetration level versus Power losses and Penetration level versus Voltage profile was plotted and is shown in Figures 32 and 33 respectively.

With no solar PV plant connected (baseline case) to the system, the penetration level was considered as **zero percent**.

Sample calculation for a solar PV plant generation at **10MW**:

$$\text{Penetration level} = \frac{capacity\ factor \times DG\ power\ installed}{peak\ power\ demand}$$

Considering available 5kWh/m^2 insolation in Zambia, annual generation = 18,250 MWh approximate

$$\text{Capacity factor} = \frac{18{,}250MWh/_{10MW}}{8760h/_{Year}} = \mathbf{0.21}$$

$$\text{Penetration level} = \frac{0.21 * 10MW}{11.59} \times 100\% = \mathbf{18.12\%}$$

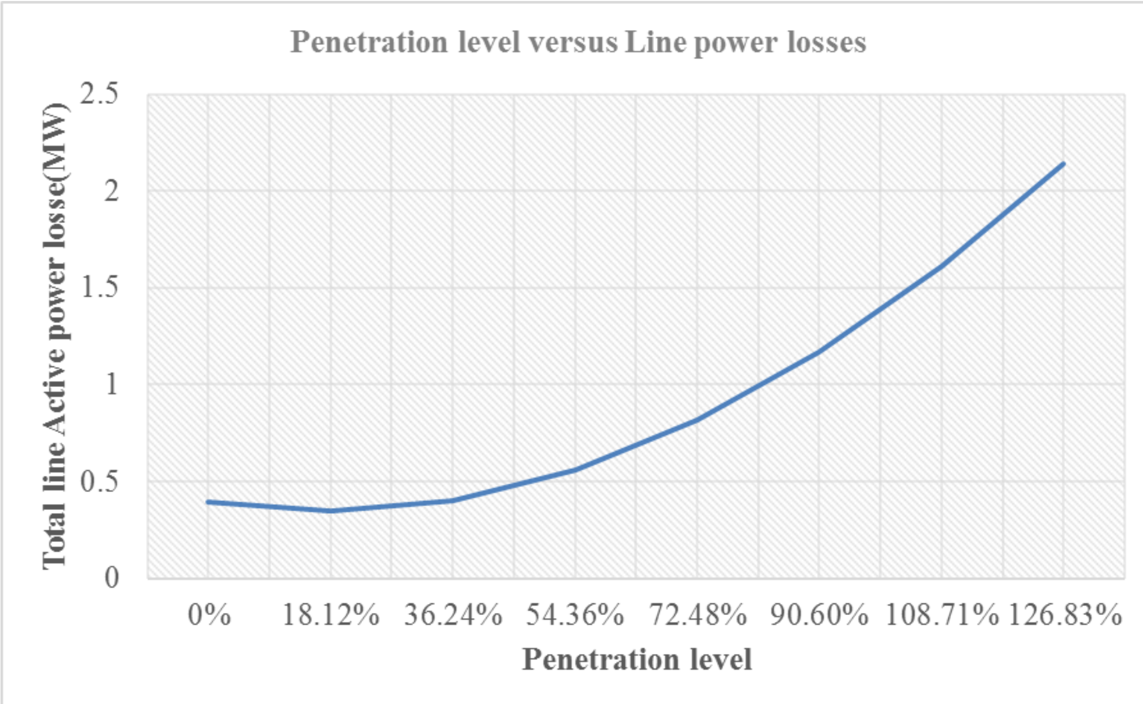

Figure 32: Penetration level versus Power losses impact at Avondale substation

As can be seen from the graph in Figure 32, the effect of solar PV size on the line losses forms a 'Nike mark' curve shape. As the size increases, the line losses begin to decrease up to penetration level 18.12% (10MW) where again line losses start to increase as the penetration level increases. The most probable cause for such an outcome could be that the voltage initially begins to normalize up to a certain level where it starts going into over-voltage which then contributes to the increased active losses.

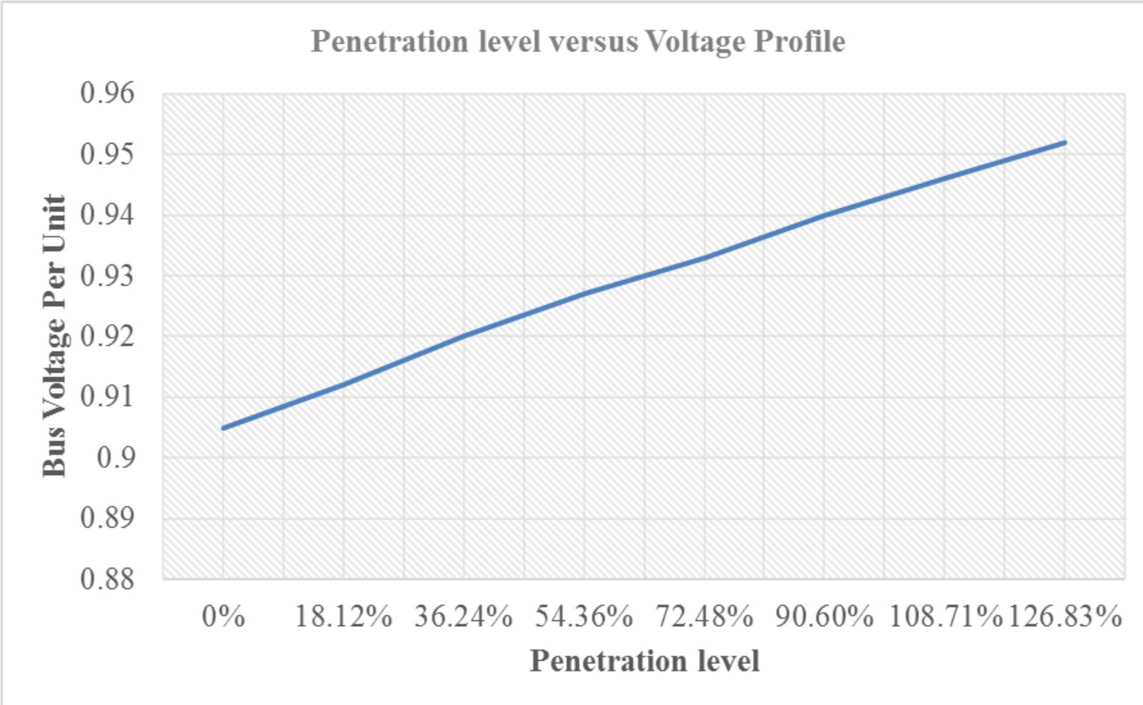

Figure 33: Penetration level versus Voltage profile impact at Avondale substation

The effect of solar PV size on the voltage profile is shown in graph in Figure 33. As the size increases, the voltage also increases and continues for as long as the solar PV size increases. The increase as can be seen to be equivalent to linear line.

4.2.2.2. Power flow

The integration of solar PV plant decreases the line losses for the line in the grid to the Avondale substation. The increase in solar PV penetration resulted in subsequent reduction in the line loading. This is because the integration of solar PV provided power locally to the substation and reduced the power flow from the source. Figure 34 shows the power flow of the line towards the substation before the solar PV was connected to the substation. When the penetration level reached 54.36% (30MW), there was initial power flow direction change in one of the feeders as shown in Figure 35. When the penetration level reached 90.60% (50MW), the power flow direction totally changed by flowing outwards, i.e. away from Avondale substation as shown in Figure 36. This is because the load demand at the Avondale substation was met by the solar PV power supply. This forced the power needs to be transmitted to the other substations in the

Lusaka distribution network. When the penetration level reached 90.60% (50MW) it also resulted in the increase in the losses as can be seen in Appendix E Table E8.

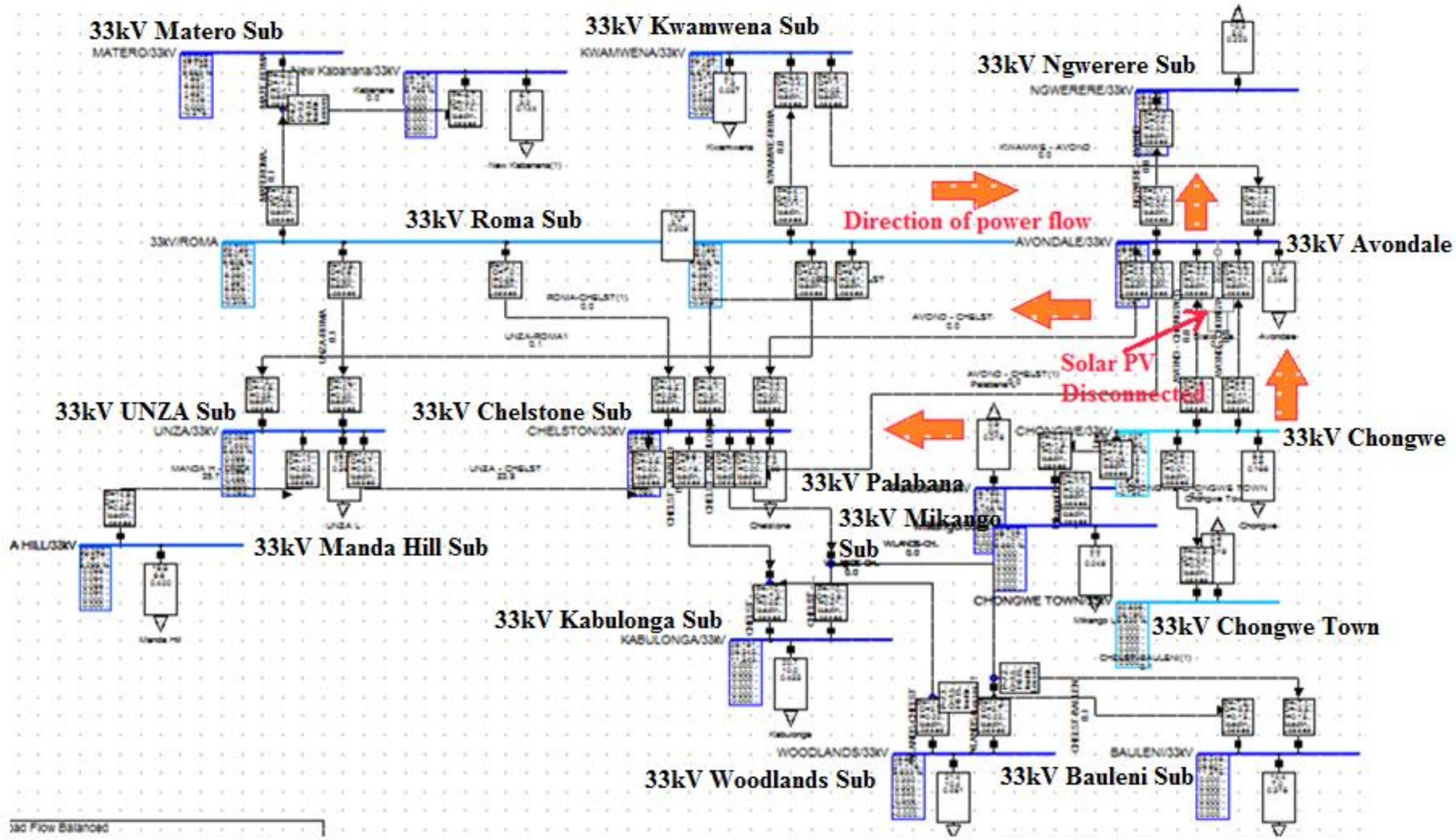

Figure 34: Power flow direction before solar PV plant connection at Avondale substation

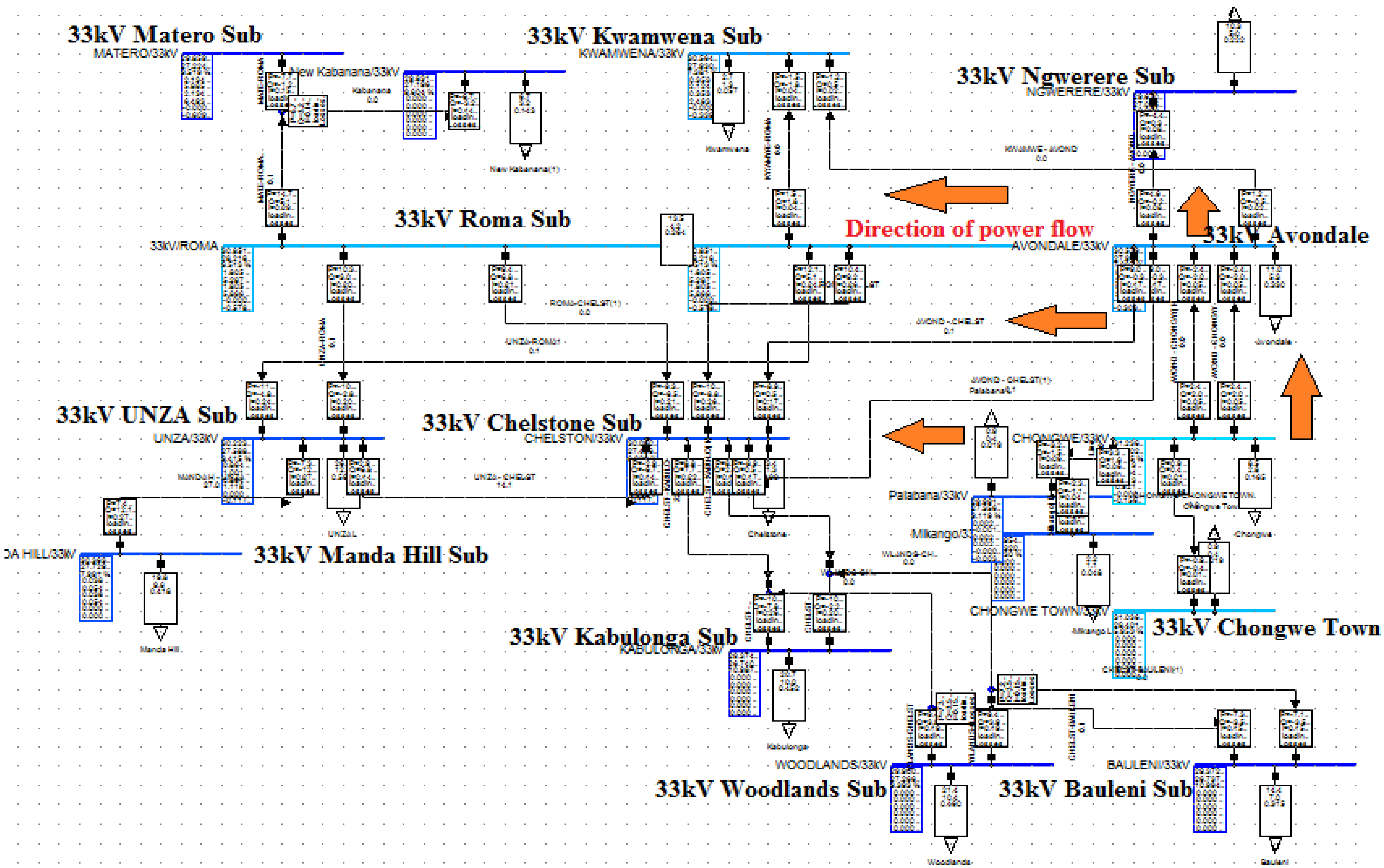

Figure 35: Initial Power flow direction change after a 54.36% (30MW) solar PV plant connection at Avondale substation

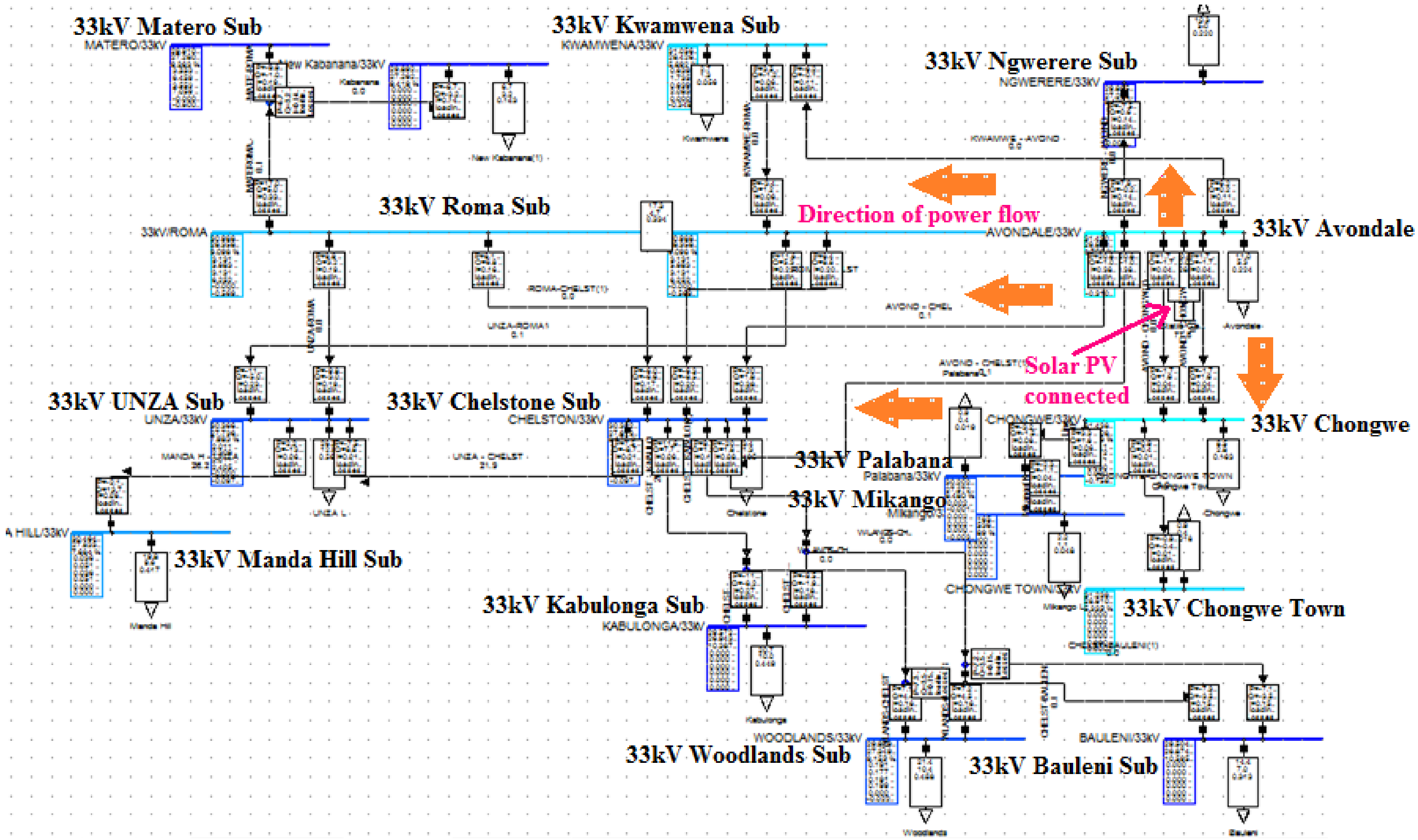

Figure 36: Overall Power flow direction change after a 90.60% (50MW) solar PV plant connection at Avondale substation

4.2.2.3. Impact of solar PV plant integration at Avondale substation on the entire Lusaka network

The results for the Inter grid power flow for the 330kV power supply for the Lusaka distribution network are shown in Appendix E Table E7. The integration of solar PV plant decreased the power from the source. The increase in penetration resulted in subsequent reduction in the transformer loadings as shown in Appendix Table E6. This is because the integration of solar PV plant provided power at Avondale substation and reduced the power flow for power from the source. Using the data from Appendix – E Table E6 and Table E7, a graph of major transformer capacity relief and 330kV supply inter grid power flow was plotted and is shown in Figures 37 and 38 respectively.

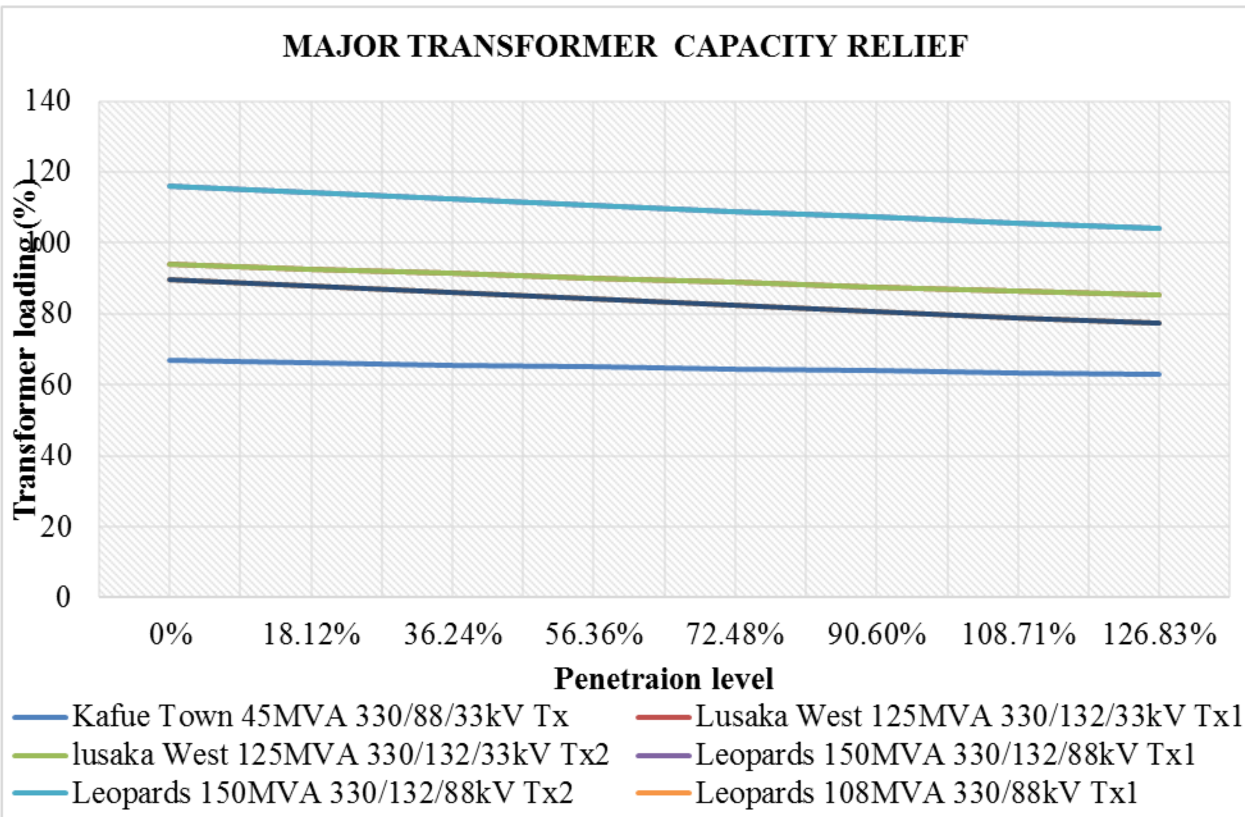

Figure 37: Major transformer capacity relief impact due to integration at Avondale substation

The effect of solar PV penetration level effect at the Avondale substation on the 330kV power supply is shown in Figure 38. As the solar PV plant size increases, the power from the source is reduced and continues to reduce for as long as the solar PV size increases. The decrease as can be seen to be equivalent to linear line.

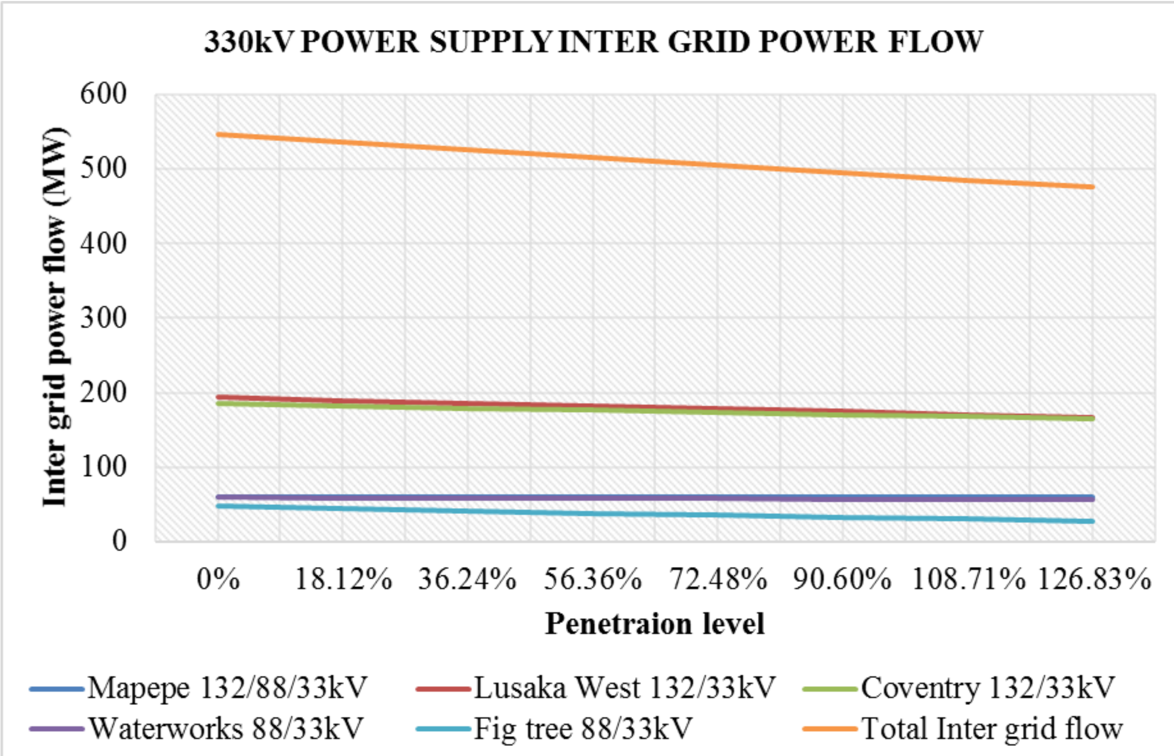

Figure 38: 330kV supply inter grid power flow impact due to integration at Avondale substation

Using the data from Appendix E Table E8 Lusaka Distribution Grid summary power losses at bulk supply substations, a graph of Lusaka bulk supply point grid losses and Total Lusaka network grid losses was plotted and is shown in Figures 39 and 40 respectively. As can be seen from the graph in Figure 40, the effect of solar PV size on the Lusaka network grid losses forms a 'bathtub' curve shape. As the size increases, the line losses begin to decrease up to penetration level 72.48% (40MW) where again line losses start to increase as the penetration level increases. The most probable cause for such an outcome could be that the voltage initially begins to normalize up to a certain level where it starts going into over-voltage which then contributes to the increased active losses.

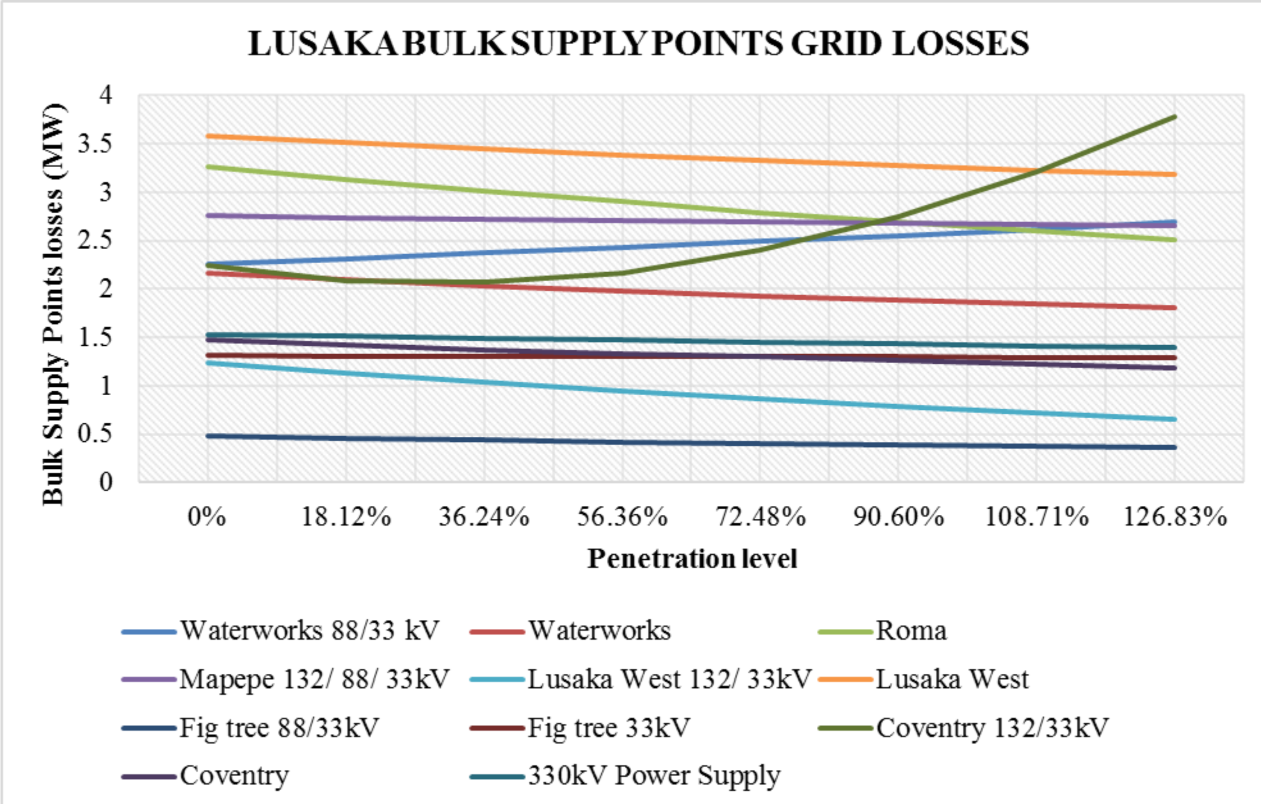

Figure 39: Lusaka bulk supply points grid losses impact due to integration at Avondale substation

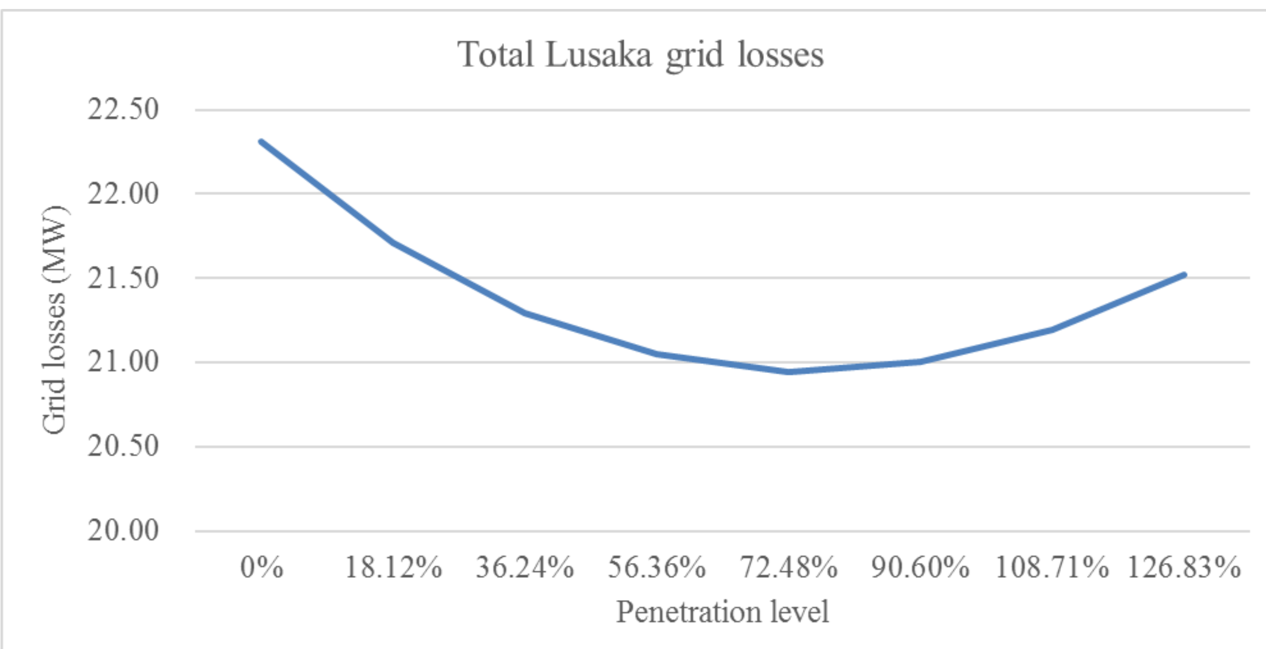

Figure 40: Total Lusaka network grid losses impact due to integration at Avondale substation

The solar PV power plants in the steps of 10MW of different capacity was integrated and simulated at the Avondale substation. The impact on the voltage level were studied and results were obtained as show in Table 8 below. It can be seen that there is voltage profile increase in the 33kV Lusaka distribution network. The comparison was done with the use of penetration levels of 0% for base case with different penetration levels up to 126.83% (70MW).

Table 8: 33kV Busbar Voltage before and after solar PV plant penetration levels impact due to integration at Avondale substation

SN	SUBSTATIONS	0%	18.12%	36.24%	56.36%	72.48%	90.60%	108.71%	126.83%
1	Coventry sub	0.938	0.938	0.939	0.939	0.939	0.939	0.939	0.939
2	Mapepe	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933
3	Birdcage	0.927	0.927	0.928	0.928	0.928	0.929	0.929	0.929
4	Bonaventure	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912
5	Chawama	0.915	0.915	0.915	0.915	0.915	0.915	0.916	0.916
6	Chilanga	0.919	0.920	0.920	0.920	0.920	0.920	0.920	0.920
7	Dublin	0.932	0.932	0.932	0.933	0.933	0.933	0.933	0.933
8	Kafue Rd	0.924	0.925	0.925	0.925	0.926	0.926	0.926	0.926
9	Manda Hill	0.917	0.918	0.919	0.920	0.921	0.922	0.922	0.923
10	Shimabala	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907
11	Zesco Workshop	0.925	0.925	0.926	0.926	0.927	0.927	0.927	0.927
12	Penyaonse	0.893	0.895	0.897	0.899	0.901	0.903	0.904	0.906
13	Mt Meru	0.877	0.879	0.881	0.882	0.883	0.885	0.886	0.887
14	Kabangwe	0.898	0.899	0.901	0.902	0.903	0.905	0.906	0.907
15	Globber	0.878	0.881	0.883	0.885	0.887	0.888	0.890	0.892
16	Chisamba	0.832	0.834	0.837	0.839	0.840	0.842	0.844	0.845
17	Burnet	0.770	0.772	0.774	0.776	0.778	0.780	0.782	0.783

SN	SUBSTATIONS	0%	18.12%	36.24%	56.36%	72.48%	90.60%	108.71%	126.83%
18	Landless	0.691	0.693	0.696	0.698	0.700	0.702	0.704	0.705
19	Kembe	0.679	0.682	0.684	0.686	0.688	0.690	0.692	0.694
20	Chisamba ranch	0.679	0.682	0.684	0.687	0.689	0.691	0.693	0.694
21	Chibombo	0.679	0.682	0.684	0.686	0.689	0.691	0.692	0.694
22	Katuba	0.834	0.836	0.838	0.840	0.841	0.843	0.844	0.845
23	Karubwe	0.893	0.895	0.897	0.899	0901	0.903	0.904	0.906
24	Fig tree	0.893	0.895	0.897	0.899	0.901	0.903	0.904	0.906
25	Barlastone	0.932	0.932	0.932	0.932	0.933	0.933	0.933	0.933
26	Kanyama	0.941	0.941	0.942	0.942	0.942	0.942	0.942	0.942
27	L85	0.943	0.943	0.943	0.943	0.943	0.943	0.943	0.943
28	Liverpool	0.921	0.922	0.922	0.922	0.922	0.923	0.923	0.923
29	Lusaka West	0.965	0.965	0.966	0.966	0.966	0.966	0.966	0.966
30	Makeni	0.920	0.920	0.920	0.920	0.920	0.920	0.920	0.920
31	Matero	0.903	0.904	0.904	0.905	0.905	0.906	0.906	0.906
32	Mwembeshi	0.957	0.957	0.957	0.957	0.957	0.957	0.957	0.957
33	Ndipo	0.943	0.943	0.943	0.943	0.943	0.943	0.943	0.943
34	Shorthorn	0.943	0.943	0.943	0.944	0.944	0.944	0.944	0.944
35	Roma	0.931	0.932	0.934	0.935	0.936	0.937	0.938	0.939

SN	SUBSTATIONS	0%	18.12%	36.24%	56.36%	72.48%	90.60%	108.71%	126.83%
36	Avondale	0.905	0.912	0.920	0.927	0.933	0.940	0.946	0.952
37	Bauleni	0.886	0.888	0.889	0.890	0.891	0.892	0.893	0.894
38	Chelstone	0.904	0.907	0.909	0.911	0.913	0.915	0.917	0.918
39	Chongwe town	0.934	0.937	0.939	0.940	0.942	0.944	0.945	0.947
40	Chongwe	0.941	0.943	0.945	0.947	0.948	0.950	0.951	0.953
41	Kabulonga	0.885	0.887	0.888	0.890	0.892	0.893	0.895	0.896
42	Kwamwena	0.913	0.918	0.922	0.926	0.930	0.934	0.938	0.941
43	Mikango	0.901	0.904	0.906	0.908	0.910	0.911	0.913	0.914
44	Ngwerere	0.893	0.895	0.897	0.899	0.901	0.903	0.904	0.906
45	New Kabanana	0.902	0.903	0.903	0.904	0.904	0.905	0.905	0.906
46	Palabana	0.903	0.905	0.907	0.909	0.911	0.912	0.914	0.915
47	UNZA	0.912	0.913	0.915	0.916	0.917	0.918	0.919	0.920
48	Chalala	0.923	0.924	0.924	0.925	0.925	0.926	0.926	0.926
49	Levy	0.920	0.921	0.921	0.922	0.922	0.922	0.923	0.923
50	UTH	0.911	0.912	0.912	0.913	0.914	0.914	0.914	0.915
51	Waterworks	0.936	0.936	0.936	0.937	0.937	0.937	0.937	0.938
52	Woodlands	0.904	0.905	0.905	0.906	0.907	0.907	0.908	0.908

4.2.3. Impact of location and size of Solar PV plant at Chelstone substation

4.2.3.1. Solar PV size penetration levels

From the data obtained through load flow calculation, it was found that the voltage on the remote buses was mostly affected by varying the Solar PV size on the Chelstone substation. The results of the bus voltage and the system losses are as shown in Appendix E Table E9. Using the data from Appendix E Table E9 Solar PV plant penetration level, a graph of Penetration level versus Power losses and Penetration level versus Voltage profile was plotted and is shown in Figures 41 and 42 respectively.

With no solar PV plant connected (baseline case) to the system, the penetration level was considered as **zero percent**.

Sample calculation for a solar PV plant generation at **10MW**:

$$\text{Penetration level} = \frac{capacity\ factor \times DG\ power\ installed}{peak\ power\ demand}$$

Considering available 5kWh/m^2 insolation in Zambia, annual generation = 18,250 MWh approximate

$$\text{Capacity factor} = \frac{18{,}250MWh/_{10MW}}{8760h/_{Year}} = \mathbf{0.21}$$

$$\text{Penetration level} = \frac{0.21 * 10MW}{23.4} \times 100\% = \mathbf{8.97\%}$$

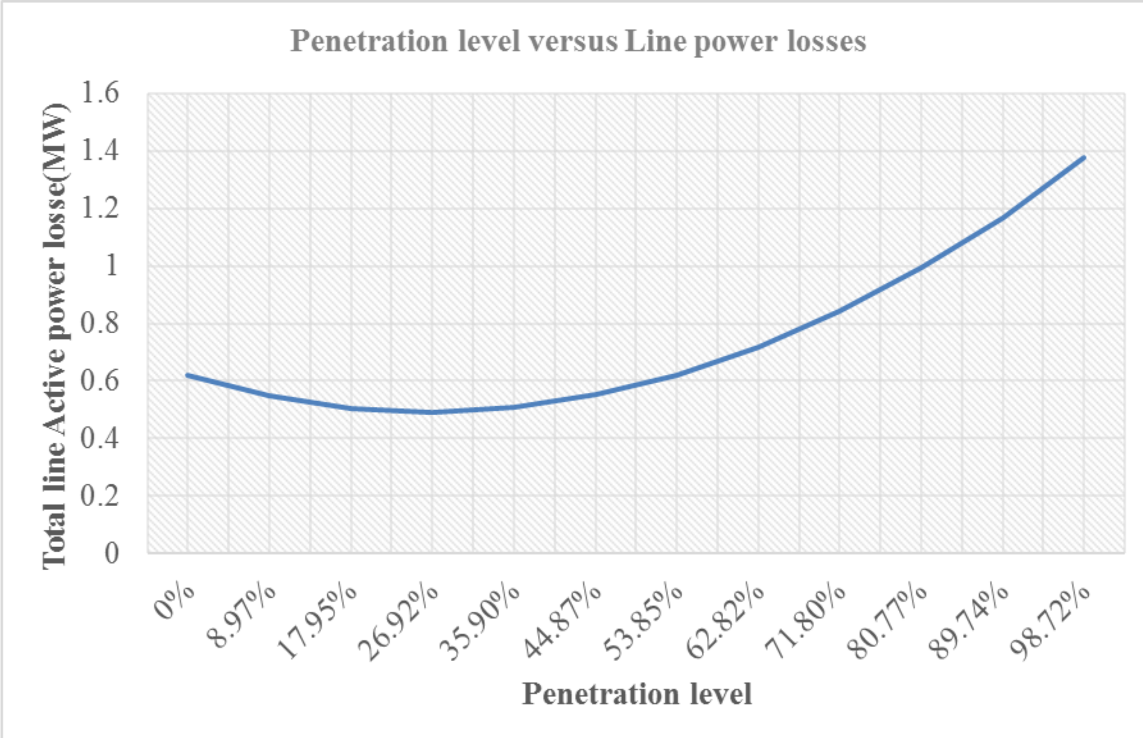

Figure 41: Penetration level versus Power losses at Chelstone substation

As can be seen from the graph in Figure 41, the effect of solar PV size on the line losses forms a ‘bathtub’ curve shape. As the size increases, the line losses begin to decrease up to penetration level 26.92% (30MW) where again line losses start to increase as the penetration level increases. The most probable cause for such an outcome could be that the voltage initially begins to normalize up to a certain level where it starts going into over-voltage which then contributes to the increased active losses.

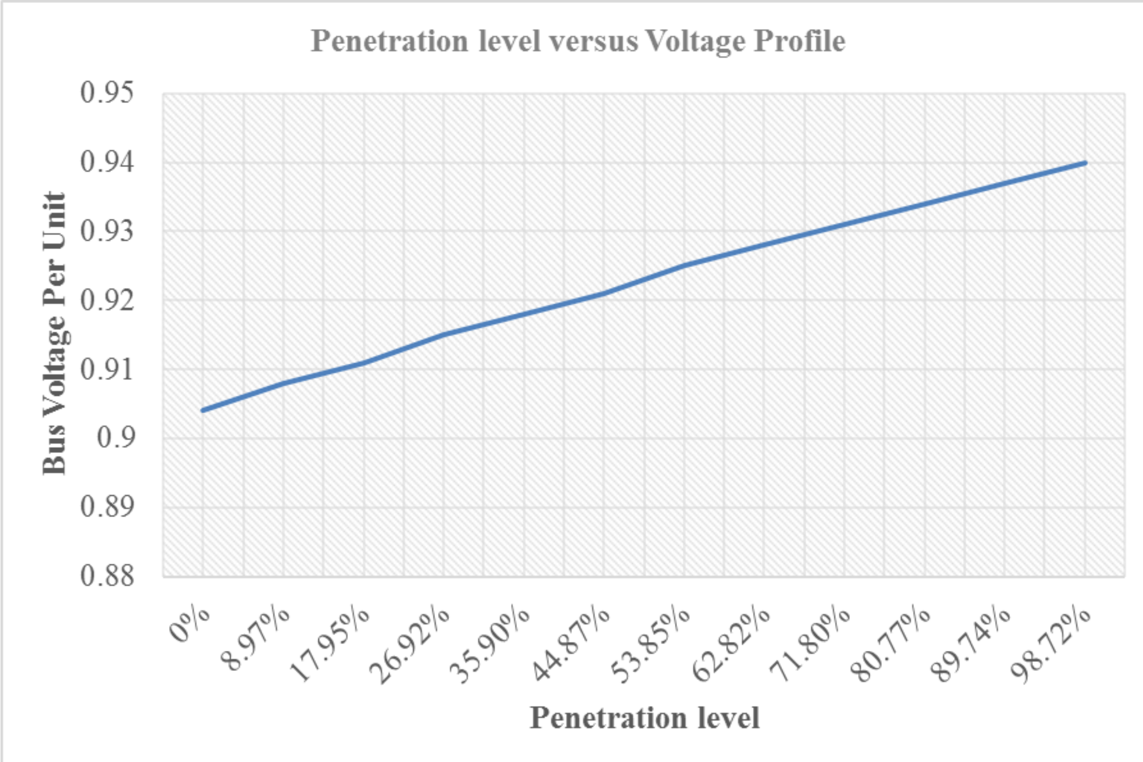

Figure 42: Penetration level versus Voltage profile at Chelstone substation

The effect of solar PV size on the voltage profile is shown in graph in Figure 42. As the size increases, the voltage also increases and continues for as long as the solar PV size increases. The increase as can be seen to be equivalent to linear line.

4.2.3.2. Power flow

The integration of solar PV plant decreases the line losses for the line in the grid to the Chelstone substation. The increase in solar PV penetration resulted in subsequent reduction in the line loading. This is because the integration of solar PV provided power locally to the substation and reduced the power flow from the source. Figure 43 shows the power flow of the line towards the substation before the solar PV was connected to the substation. When the penetration level reached 4.485% (5MW), there was initial power flow direction change in two of the feeders as shown in Figure 44. When the penetration level reached 80.77% (90MW), the power flow direction totally changed by flowing outwards, i.e. away from Chelstone substation as shown in Figure 45. This is because the load demand at the substation was met by the solar PV power supply. This forced the power needs to be transmitted to the other substations in the Lusaka

distribution network. When the penetration level reached 80.77% it also resulted in the increase in the losses as can be seen in Appendix E Table E12.

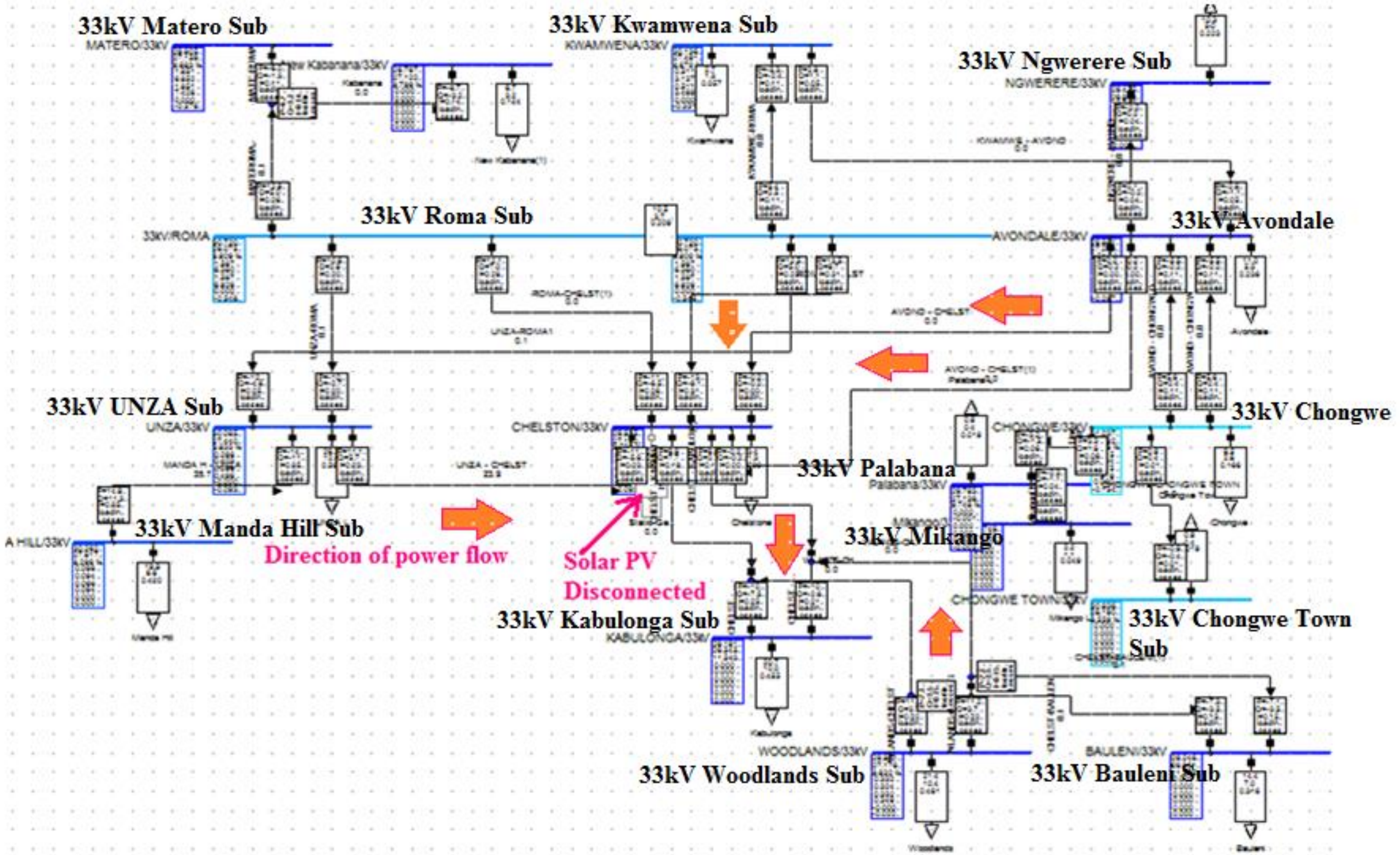

Figure 43: Power flow direction before solar PV plant connection at Chelstone substation

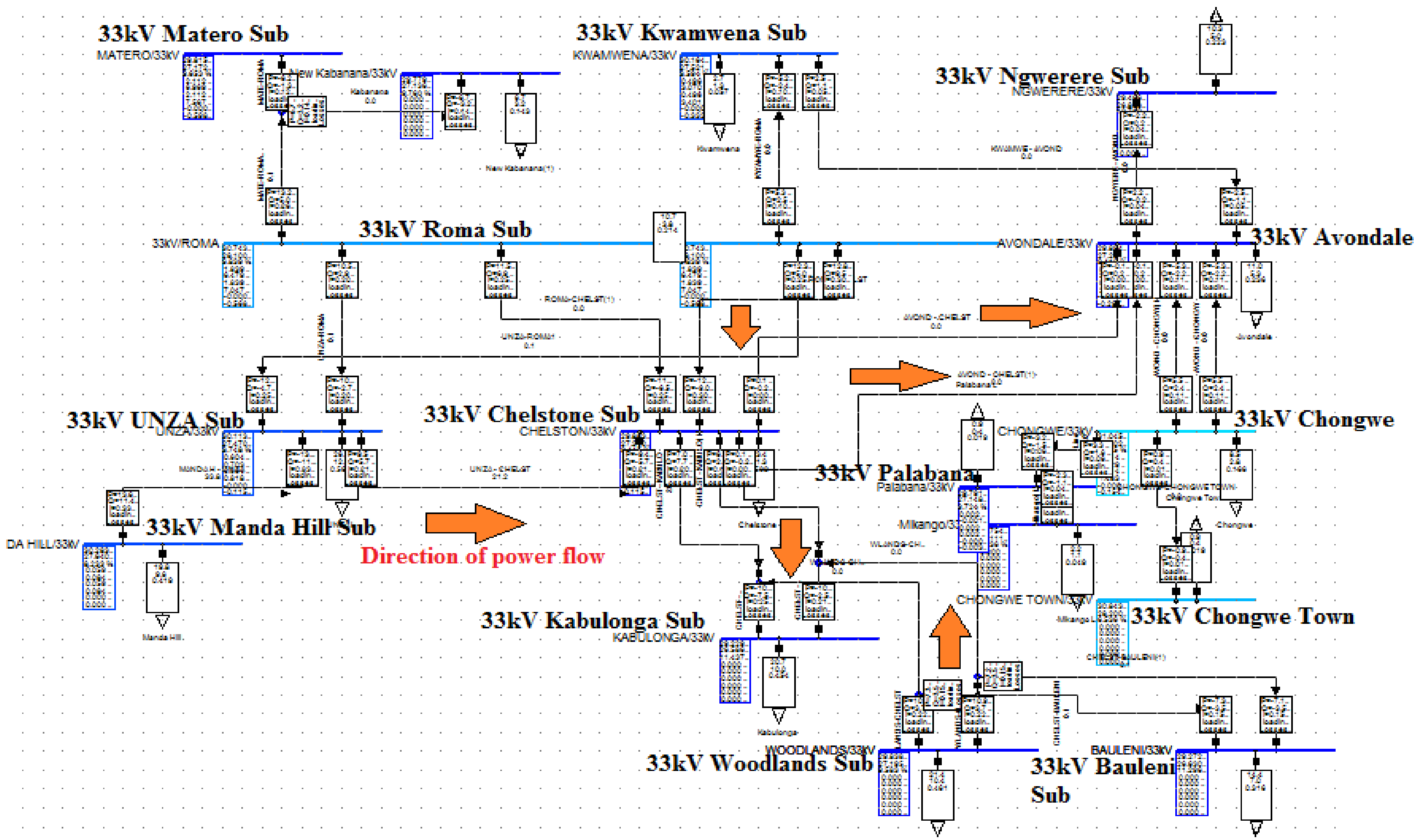

Figure 44: Initial Power flow direction change after a 4.485% (5MW) solar PV plant connection at Chelstone substation

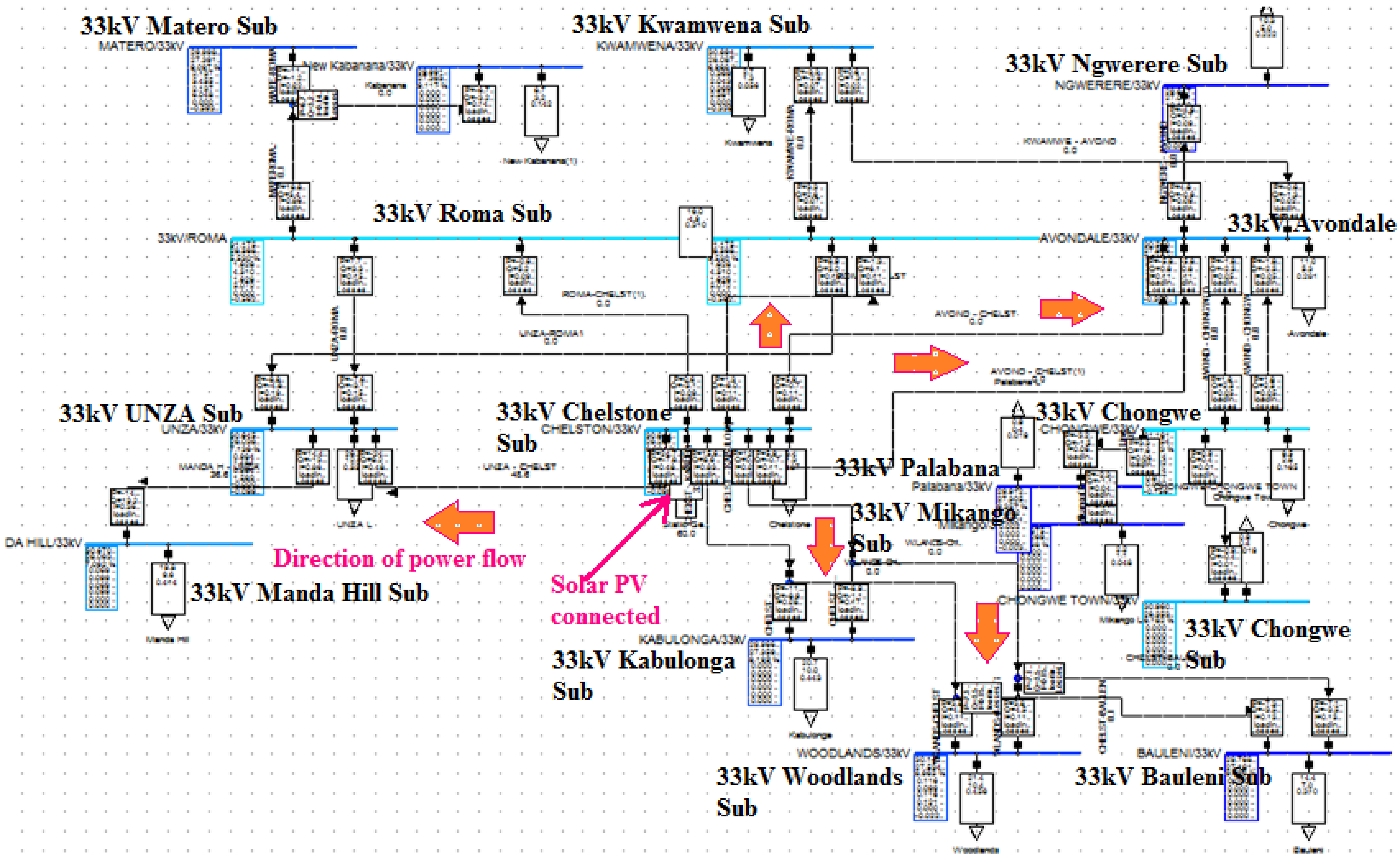

Figure 45: Overall Power flow direction change after a 80.77% (90MW) solar PV plant connection at Chelstone substation

4.2.3.3. Impact of solar PV plant integration at Chelstone substation on the entire Lusaka network

The results for the Inter grid power flow for the 330kV power supply for the Lusaka distribution network are shown in Appendix E Table E11. The integration of solar PV plant decreased the power from the source. The increase in penetration resulted in subsequent reduction in the transformer loadings as shown in Appendix E Table E10. This is because the integration of solar PV plant provided power at Chelstone substation and it reduced the power flow for power from the source. Using the data from Appendix E Table E10 and Table E11, a graph of major transformer capacity relief and 330kV supply inter grid power flow was plotted and is shown in Figures 46 and 47 respectively.

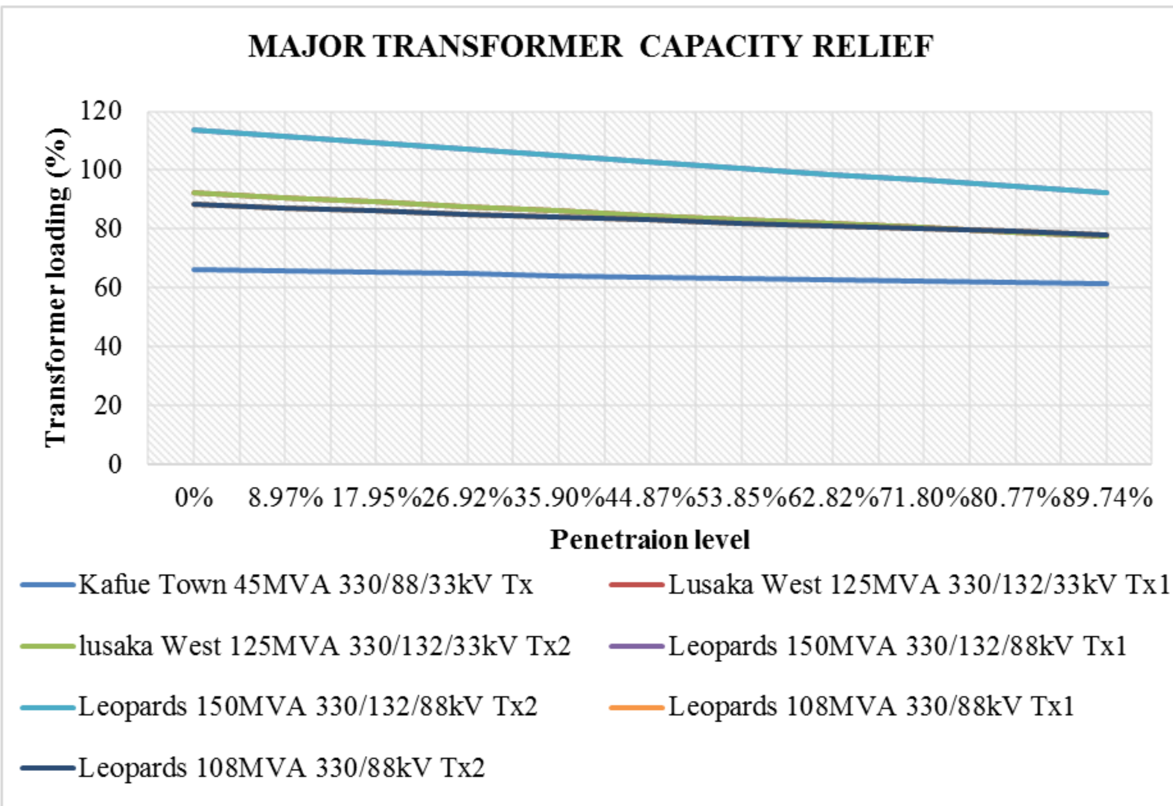

Figure 46: Major transformer capacity relief impact due to integration at Chelstone substation

The effect of solar PV penetration level effect at the Chelstone substation on the 330kV power supply is shown in Figure 47. As the solar PV plant size increases, the power from the source is reduced and continues to reduce for as long as the solar PV size increases. The decrease as can be seen to be equivalent to linear line.

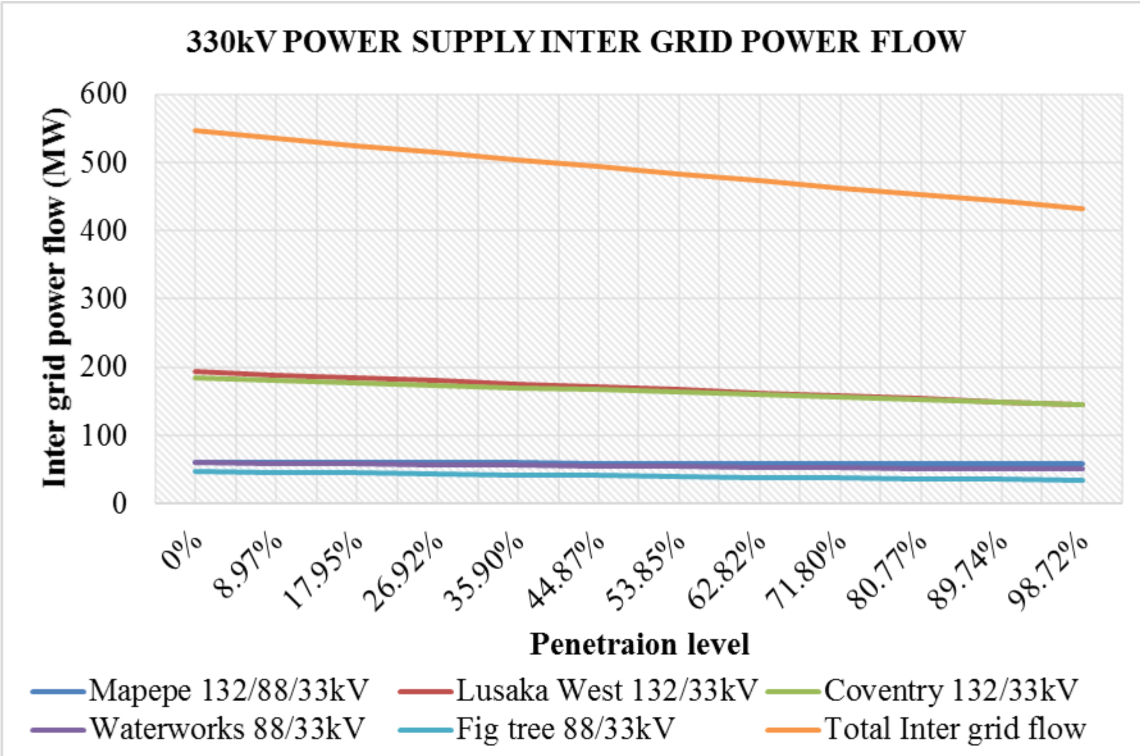

Figure 47: 330kV supply inter grid power flow impact due to integration at Chelstone substation

Using the data from Appendix E Table E12 Lusaka Distribution Grid summary power losses at bulk supply substations, a graph of Lusaka bulk supply point grid losses and Total Lusaka network grid losses was plotted and is shown in Figures 48 and 49 respectively. As can be seen from the graph in Figure 49, the effect of solar PV size on the Lusaka network grid losses forms a 'bathtub' curve shape. As the size increases, the line losses begin to decrease up to penetration level 89.74% (100MW) where again line losses start to increase as the penetration level increases. The most probable cause for such an outcome could be that the voltage initially begins to normalize up to a certain level where it starts going into over-voltage which then contributes to the increased active losses.

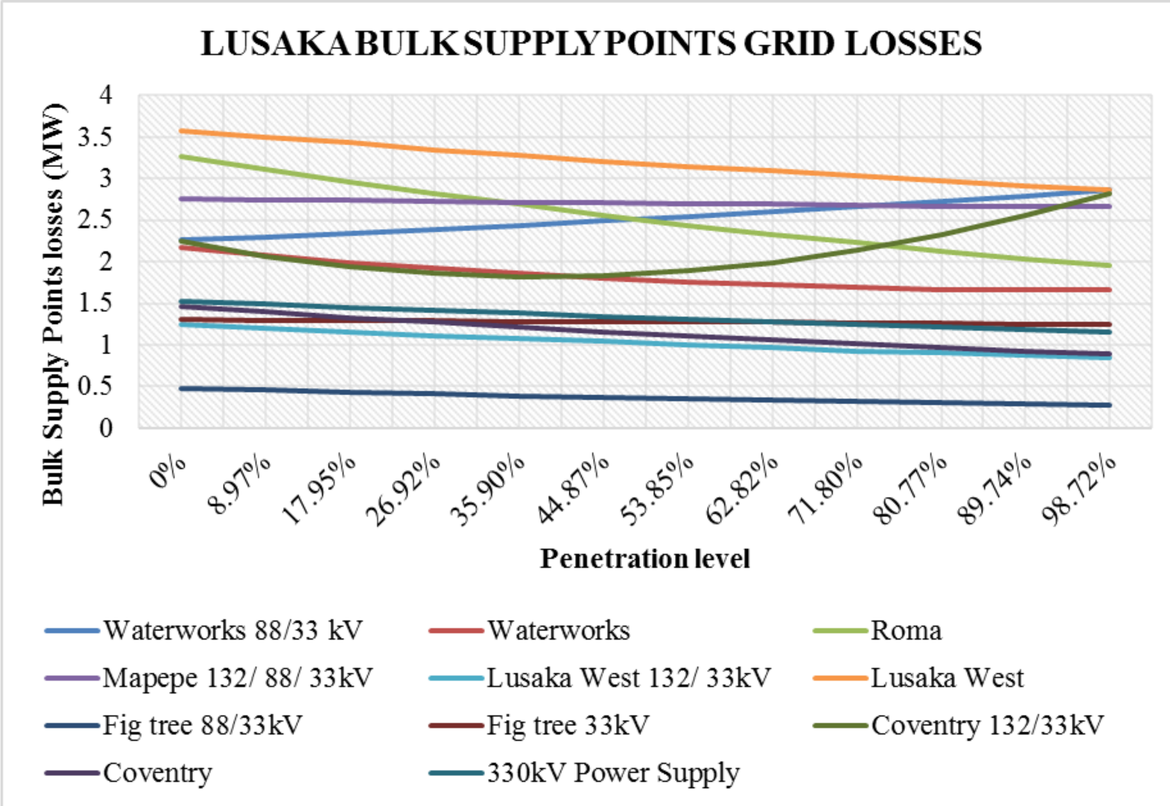

Figure 48: Lusaka bulk supply points grid losses impact due to integration at Chelstone substation

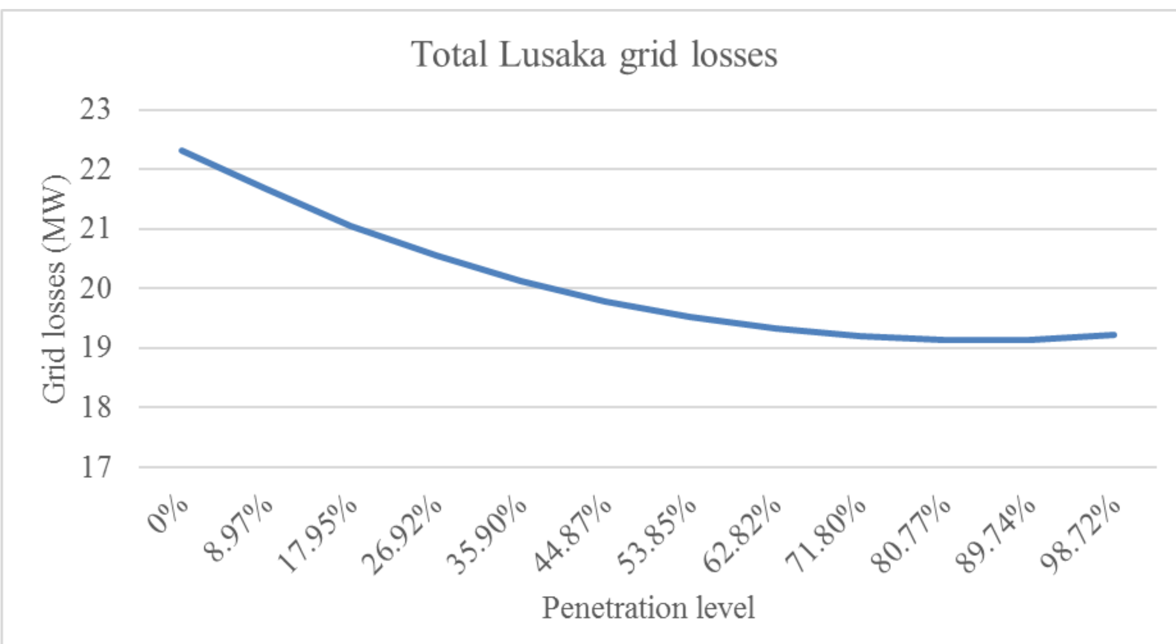

Figure 49: Lusaka network grid losses impact due to integration at Chelstone substation

The solar PV power plants in the steps of 10MW of different capacity was integrated and simulated at the Chelstone substation. The impact on the voltage level were studied and results were obtained as show in Table 9 below. It can be seen that there is voltage profile increase in the 33kV Lusaka distribution network. The comparison was done with the use of penetration levels of 0% for base case with different penetration levels up to 98.72% (110MW).

Table 9: Busbar Voltage before and after solar PV plant penetration levels impact due to integration at Chelstone substation

SN	SUBSTATIONS	0%	8.97%	17.95 %	26.92 %	35.90 %	44.87 %	53.85 %	62.82 %	71.80 %	80.77 %	89.74 %	98.72 %
1	Coventry sub	0.938	0.938	0.939	0.939	0.940	0.940	0.941	0.941	0.941	0.941	0.942	0.942
2	Mapepe	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933
3	Birdcage	0.927	0.928	0.928	0.929	0.929	0.930	0.930	0.930	0.930	0.931	0.931	0.931
4	Bonaventure	0.912	0.912	0.912	0.912	0.912	0.912	0.913	0.913	0.913	0.913	0.913	0.913
5	Chawama	0.915	0.915	0.915	0.916	0.916	0.916	0.916	0.916	0.916	0.916	0.917	0.917
6	Chilanga	0.919	0.920	0.920	0.920	0.920	0.920	0.920	0.920	0.920	0.920	0.920	0.920
7	Dublin	0.932	0.932	0.933	0.933	0.934	0.934	0.934	0.935	0.935	0.935	0.936	0.936
8	Kafue Rd	0.924	0.925	0.925	0.926	0.926	0.927	0.927	0.927	0.928	0.928	0.928	0.929
9	Manda Hill	0.917	0.919	0.920	0.922	0.923	0.924	0.926	0.927	0.928	0.929	0.931	0.932
10	Shimabala	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907
11	Zesco Workshop	0.925	0.926	0.926	0.927	0.928	0.928	0.929	0.929	0.930	0.930	0.931	0.931
12	Penyaonse	0.893	0.893	0.894	0.895	0.896	0.896	0.897	0.897	0.898	0.898	0.899	0.899
13	Mt Meru	0.877	0.879	0.881	0.882	0.884	0.885	0.887	0.888	0.890	0.891	0.892	0.893
14	Kabangwe	0.898	0.900	0.901	0.903	0.904	0.906	0.907	0.909	0.910	0.912	0.913	0.914
15	Globber	0.878	0.879	0.880	0.881	0.881	0.882	0.887	0.884	0.884	0.885	0.885	0.886
16	Chisamba	0.832	0.833	0.834	0.835	0.836	0.837	0.838	0.839	0.840	0.841	0.841	0.842

SN	SUBSTATIONS	0%	8.97%	17.95 %	26.92 %	35.90 %	44.87 %	53.85 %	62.82 %	71.80 %	80.77 %	89.74 %	98.72 %
17	Burnet	0.770	0.772	0.773	0.775	0.776	0.777	0.779	0.780	0.781	0.782	0.783	0.784
18	Landless	0.691	0.692	0.694	0.696	0.697	0.699	0.700	0.702	0.703	0.704	0.706	0.707
19	Kembe	0.679	0.681	0.683	0.684	0.686	0.687	0.689	0.690	0.692	0.693	0.694	0.696
20	Chisamba ranch	0.679	0.681	0.683	0.685	0.686	0.688	0.689	0.691	0.692	0.693	0.695	0.696
21	Chibombo	0.679	0.681	0.683	0.684	0.686	0.688	0.689	0.691	0.692	0.693	0.694	0.696
22	Katuba	0.834	0.836	0.838	0.839	0.841	0.842	0.844	0.845	0.846	0.848	0.849	0.850
23	Karubwe	0.893	0.893	0.894	0.895	0.896	0.896	0.897	0.897	0.898	0.898	0.899	0.899
24	Fig tree	0.893	0.893	0.894	0.895	0.896	0.896	0.897	0.897	0.898	0.898	0.899	0.899
25	Barlastone	0.932	0.932	0.932	0.933	0.933	0.933	0.934	0.934	0.934	0.935	0.935	0.935
26	Kanyama	0.941	0.942	0.942	0.942	0.942	0.943	0.943	0.943	0.943	0.943	0.943	0.943
27	L85	0.943	0.943	0.943	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944
28	Liverpool	0.921	0.922	0.922	0.923	0.923	0.923	0.924	0.924	0.924	0.925	0.925	0.925
29	Lusaka West	0.965	0.966	0.966	0.966	0.966	0.966	0.966	0.966	0.966	0.966	0.966	0.966
30	Makeni	0.920	0.920	0.920	0.920	0.921	0.921	0.921	0.921	0.921	0.921	0.921	0.921
31	Matero	0.903	0.904	0.905	0.905	0.906	0.907	0.907	0.908	0.908	0.909	0.910	0.910
32	Mwembeshi	0.957	0.957	0.957	0.957	0.958	0.958	0.958	0.958	0.958	0.958	0.958	0.958
33	Ndipo	0.943	0.943	0.943	0.943	0.944	0.944	0.944	0.944	0.944	0.945	0.945	0.945
34	Shorthorn	0.943	0.943	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.945	0.945	0.945

SN	SUBSTATIONS	0%	8.97%	17.95%	26.92%	35.90%	44.87%	53.85%	62.82%	71.80%	80.77%	89.74%	98.72%
35	Roma	0.931	0.933	0.934	0.936	0.938	0.939	0.941	0.942	0.943	0.945	0.946	0.947
36	Avondale	0.905	0.907	0.910	0.912	0.914	0.916	0.919	0.921	0.923	0.925	0.927	0.928
37	Bauleni	0.886	0.888	0.890	0.892	0.894	0.896	0.897	0.899	0.900	0.902	0.904	0.905
38	Chelstone	0.904	0.908	0.911	0.915	0.918	0.921	0.925	0.928	0.931	0.934	0.937	0.940
39	Chongwe town	0.934	0.935	0.936	0.936	0.936	0.937	0.937	0.938	0.938	0.938	0.938	0.939
40	Chongwe	0.941	0.941	0.942	0.942	0.943	0.943	0.943	0.944	0.944	0.944	0.945	0.945
41	Kabulonga	0.885	0.887	0.890	0.893	0.896	0.898	0.901	0.903	0.906	0.908	0.910	0.913
42	Kwamwena	0.913	0.915	0.917	0.919	0.912	0.923	0.925	0.927	0.928	0.930	0.932	0.933
43	Mikango	0.901	0.902	0.903	0.903	0.904	0.904	0.904	0.905	0.905	0.905	0.906	0.906
44	Ngwerere	0.893	0.893	0.894	0.895	0.896	0.896	0.897	0.897	0.898	0.898	0.899	0.899
45	New Kabanana	0.902	0.903	0.904	0.905	0.905	0.906	0.907	0.908	0.908	0.909	0.909	0.910
46	Palabana	0.903	0.903	0.904	0.904	0.905	0.905	0.905	0.906	0.906	0.906	0.907	0.907
47	UNZA	0.912	0.914	0.916	0.918	0.920	0.922	0.923	0.925	0.927	0.929	0.930	0.932
48	Chalala	0.923	0.924	0.925	0.926	0.926	0.927	0.927	0.928	0.928	0.929	0.929	0.930
49	Levy	0.920	0.921	0.922	0.923	0.923	0.924	0.924	0.925	0.926	0.926	0.927	0.927
50	UTH	0.911	0.912	0.913	0.915	0.915	0.916	0.917	0.917	0.918	0.919	0.920	0.920
51	Waterworks	0.936	0.936	0.937	0.938	0.938	0.938	0.938	0.939	0.939	0.939	0.940	0.940
52	Woodlands	0.904	0.905	0.906	0.908	0.908	0.909	0.910	0.911	0.912	0.913	0.914	0.915

4.2.4. Impact of location and size of Solar PV plant at Chawama substation

4.2.4.1. Solar PV size penetration levels

From the data obtained through load flow calculation, it was found that the voltage on the remote buses was mostly affected by varying the Solar PV size on the Chawama substation. The results of the bus voltage and the system losses are as shown in Appendix E Table E13. Using the data from Appendix E Table E13 Solar PV plant penetration level, a graph of Penetration level versus Power losses and Penetration level versus Voltage profile was plotted and is shown in Figures 50 and 51 respectively.

With no solar PV plant connected (baseline case) to the system, the penetration level was considered as **zero percent**.

Sample calculation for a solar PV plant generation at **10MW**:

$$\text{Penetration level} = \frac{capacity\ factor \times DG\ power\ installed}{peak\ power\ demand}$$

Considering available 5kWh/m^2 insolation in Zambia, annual generation = 18,250 MWh approximate

$$\text{Capacity factor} = \frac{18{,}250MWh/_{10MW}}{8760h/_{Year}} = \mathbf{0.21}$$

$$\text{Penetration level} = \frac{0.21 * 10MW}{12.78} \times 100\% = \mathbf{16.43\%}$$

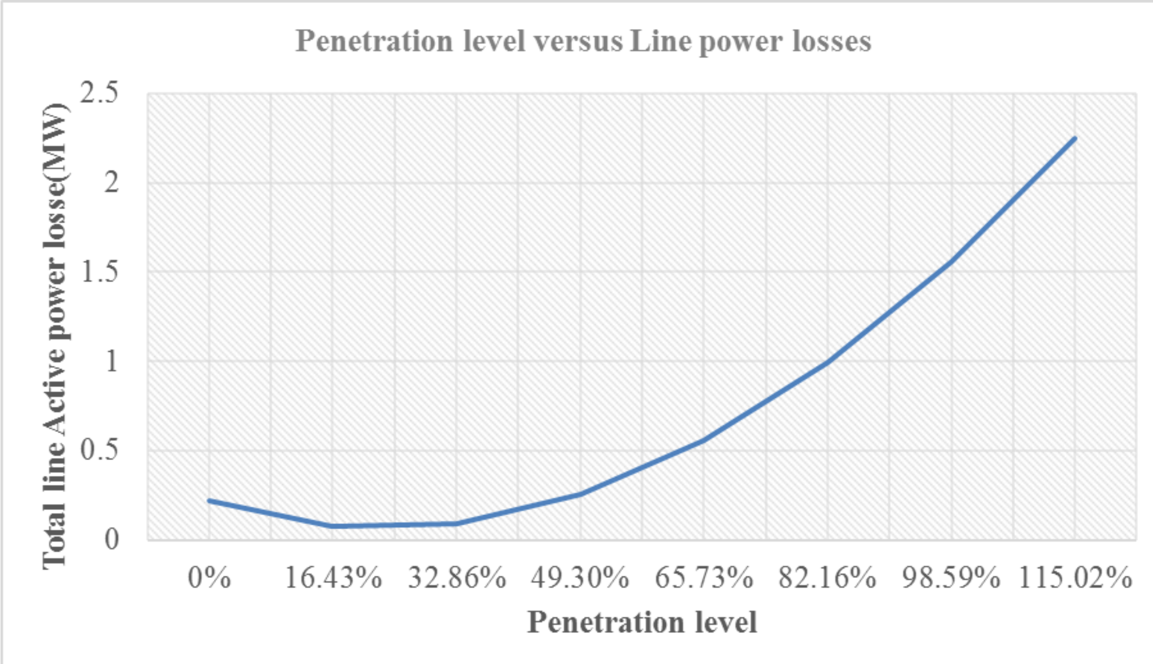

Figure 50: Penetration level versus Power losses at Chawama substation

As can be seen from the graph in Figure 50, the effect of solar PV size on the line losses forms a 'Nike mark' curve shape. As the size increases, the line losses begin to decrease up to penetration level 32.86% (20MW) where again line losses start to increase as the penetration level increases. The most probable cause for such an outcome could be that the voltage initially begins to normalize up to a certain level where it starts going into over-voltage which then contributes to the increased active losses.

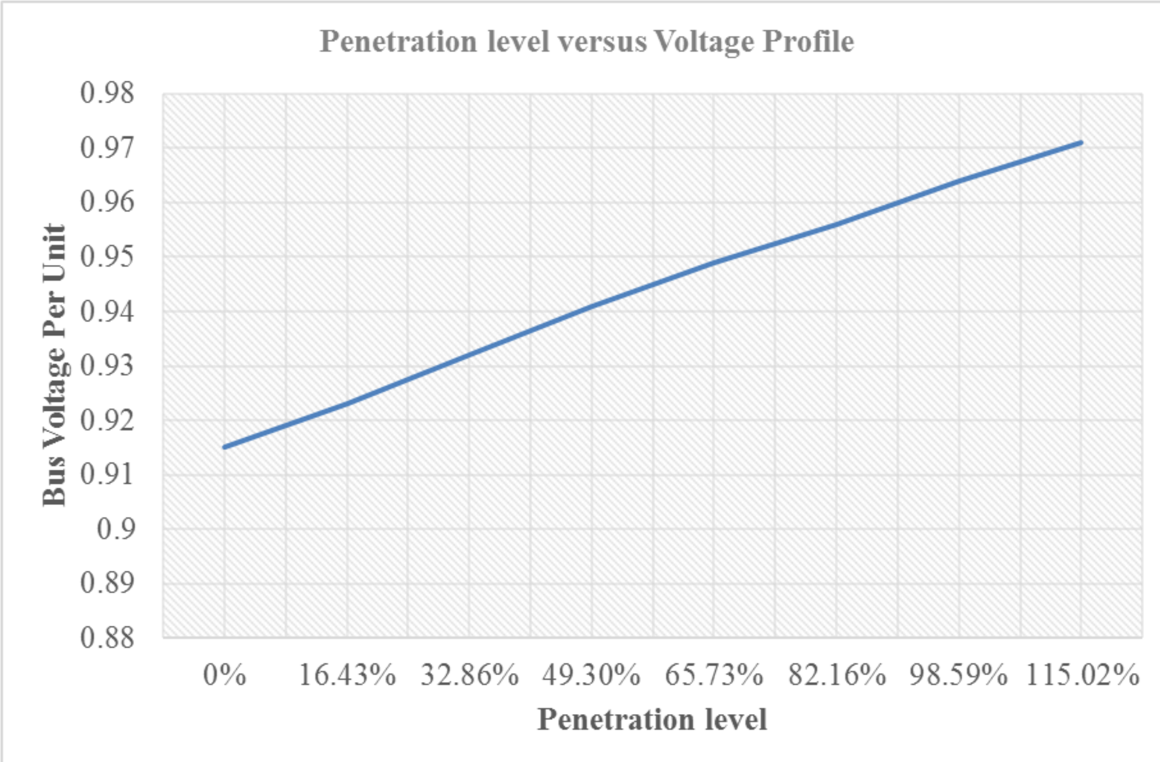

Figure 51: Penetration level versus Voltage profile at Chawama substation

The effect of solar PV size on the voltage profile is shown in graph in Figure 51. As the size increases, the voltage also increases and continues for as long as the solar PV size increases. The increase as can be seen to be equivalent to linear line.

4.2.4.2. Power flow

The integration of solar PV plant decreases the line losses for the line in the grid to the Chawama substation. The increase in solar PV penetration resulted in subsequent reduction in the line loading. This is because the integration of solar PV provided power locally to the substation and reduced the power flow from the source. Figure 52 shows the power flow of the line towards the substation before the solar PV was connected to the substation. When the penetration level reached 16.43% (10MW), there was initial power flow direction change in two of the feeders as shown in Figure 53. When the penetration level reached 32.86% (20MW), the power flow direction totally changed by flowing outwards, i.e. away from Chawama substation as shown in Figure 54. This is because the load demand at the substation was met by the solar PV power supply. This forced the power needs to be transmitted to the other substations in the Lusaka

distribution network. When the penetration level reached 32.86% it also resulted in the increase in the losses as can be seen in Appendix E Table E16.

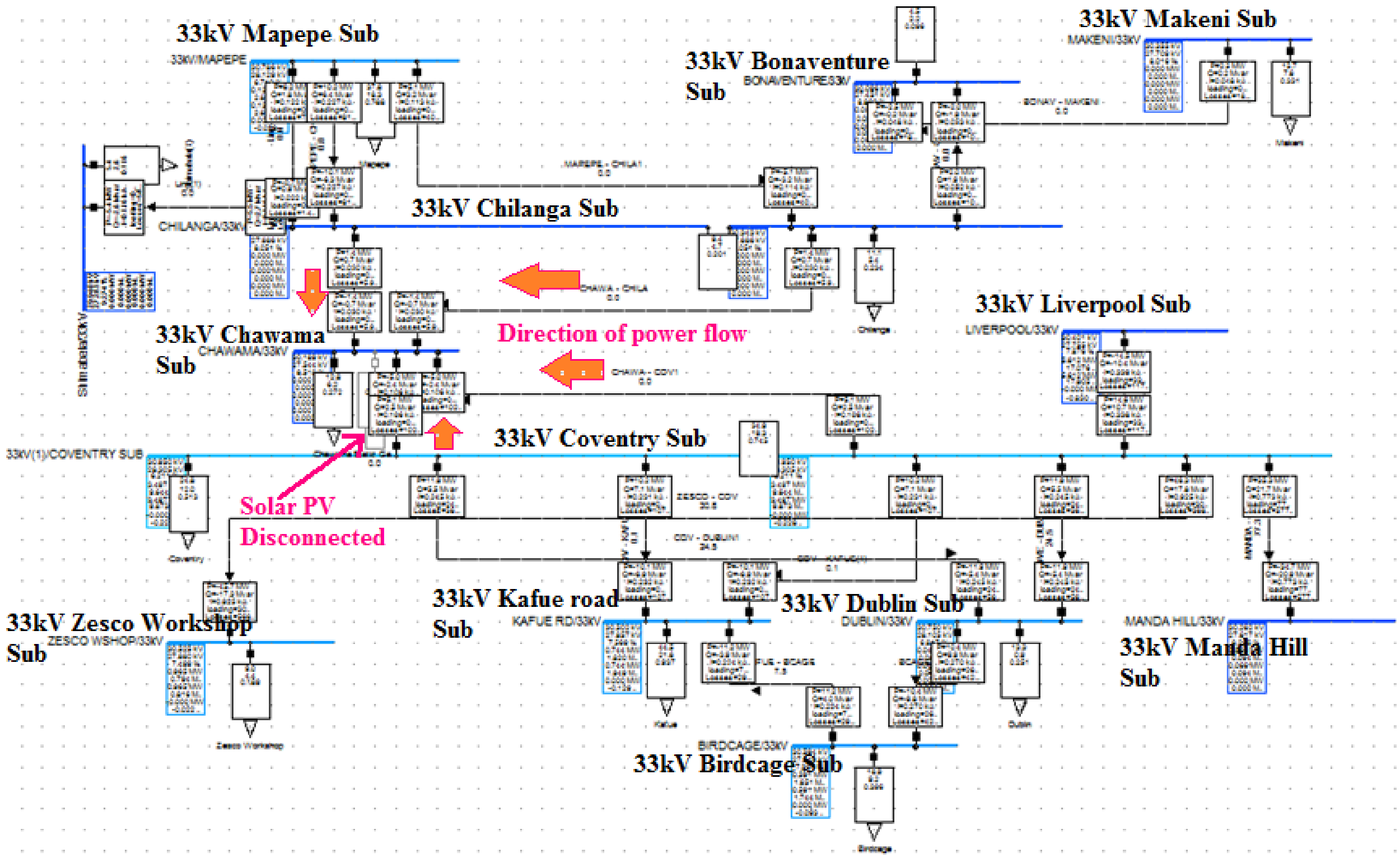

Figure 52: Power flow direction before solar PV plant connection at Chawama substation

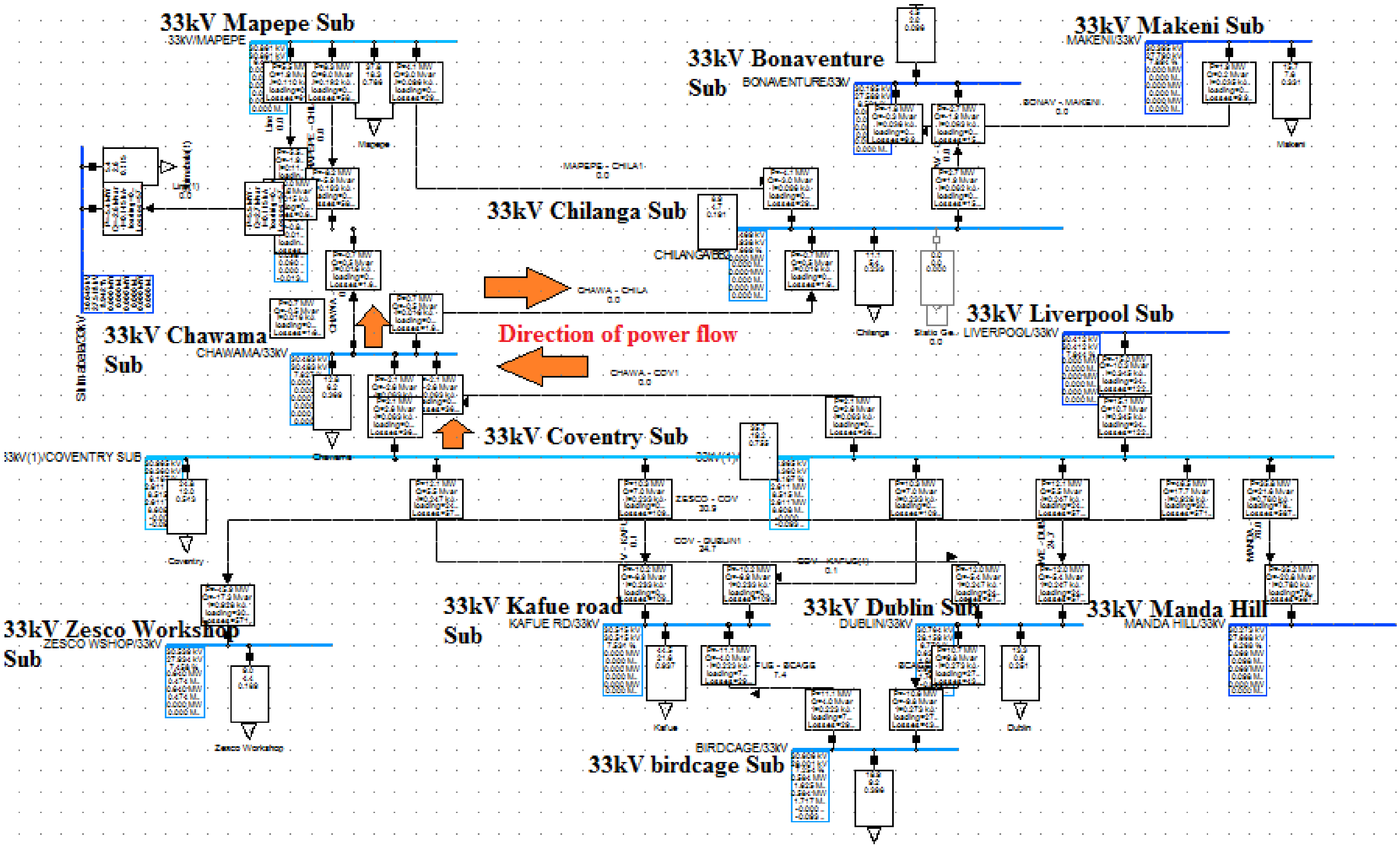

Figure 53: Intial Power flow direction change after a 16.43% (10MW) solar PV plant connection at Chawama substation

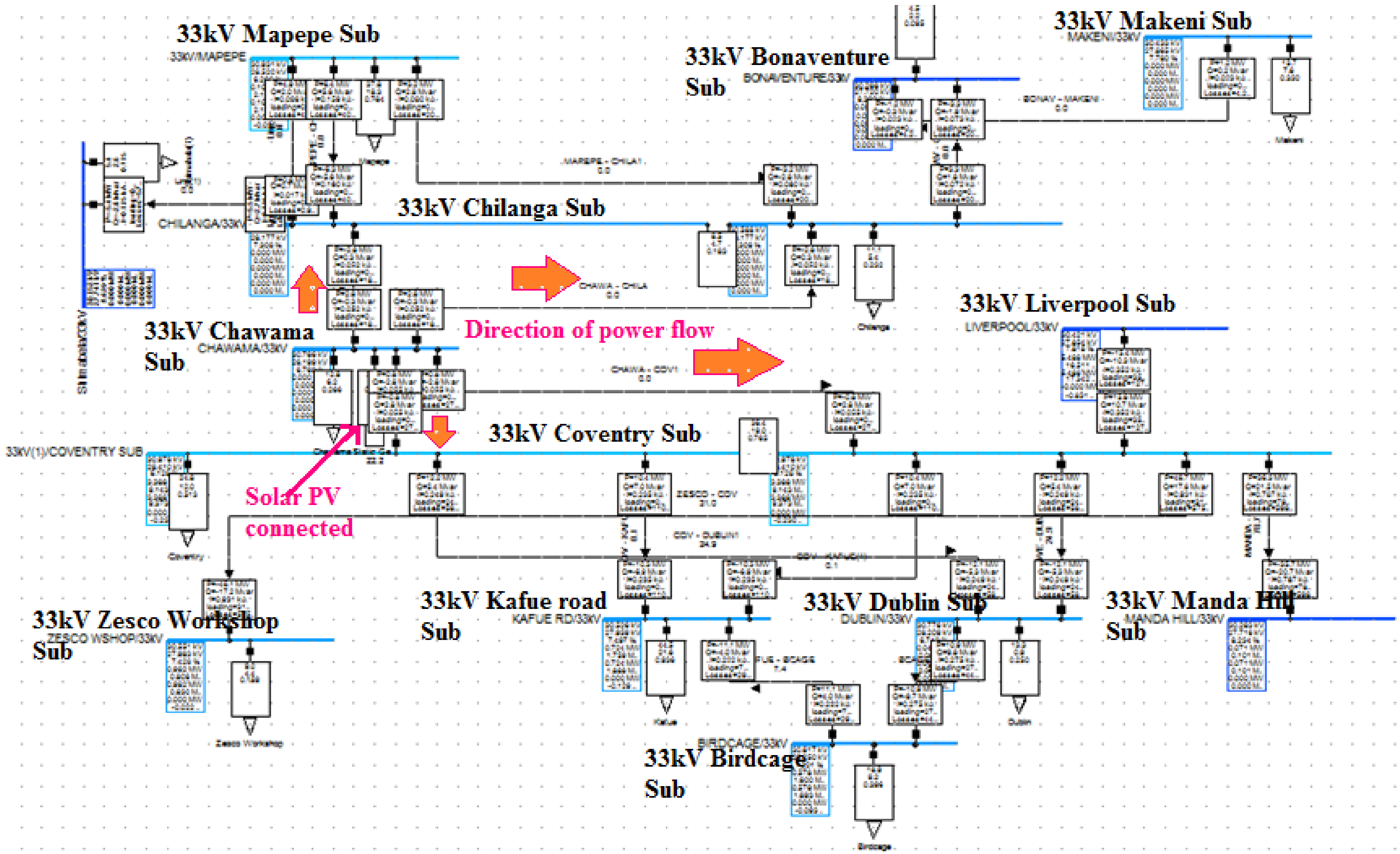

Figure 54: Overall Power flow direction change after a 32.86% (20MW) solar PV plant connection at Chawama substation

4.2.4.3. Impact of solar PV plant integration at Chawama substation on the entire Lusaka network

The results for the Inter grid power flow for the 330kV power supply for the Lusaka distribution network are shown in Appendix E Table E15. The integration of solar PV plant decreased the power from the source. The increase in penetration resulted in subsequent reduction in the transformer loadings as shown in Appendix E Table E14. This is because the integration of solar PV plant provided power at Chawama substation and reduced the power flow for power from the source. Using the data from Appendix E Table E14 and Table E15, a graph of major transformer capacity relief and 330kV supply inter grid power flow was plotted and is shown in Figures 55 and 56 respectively.

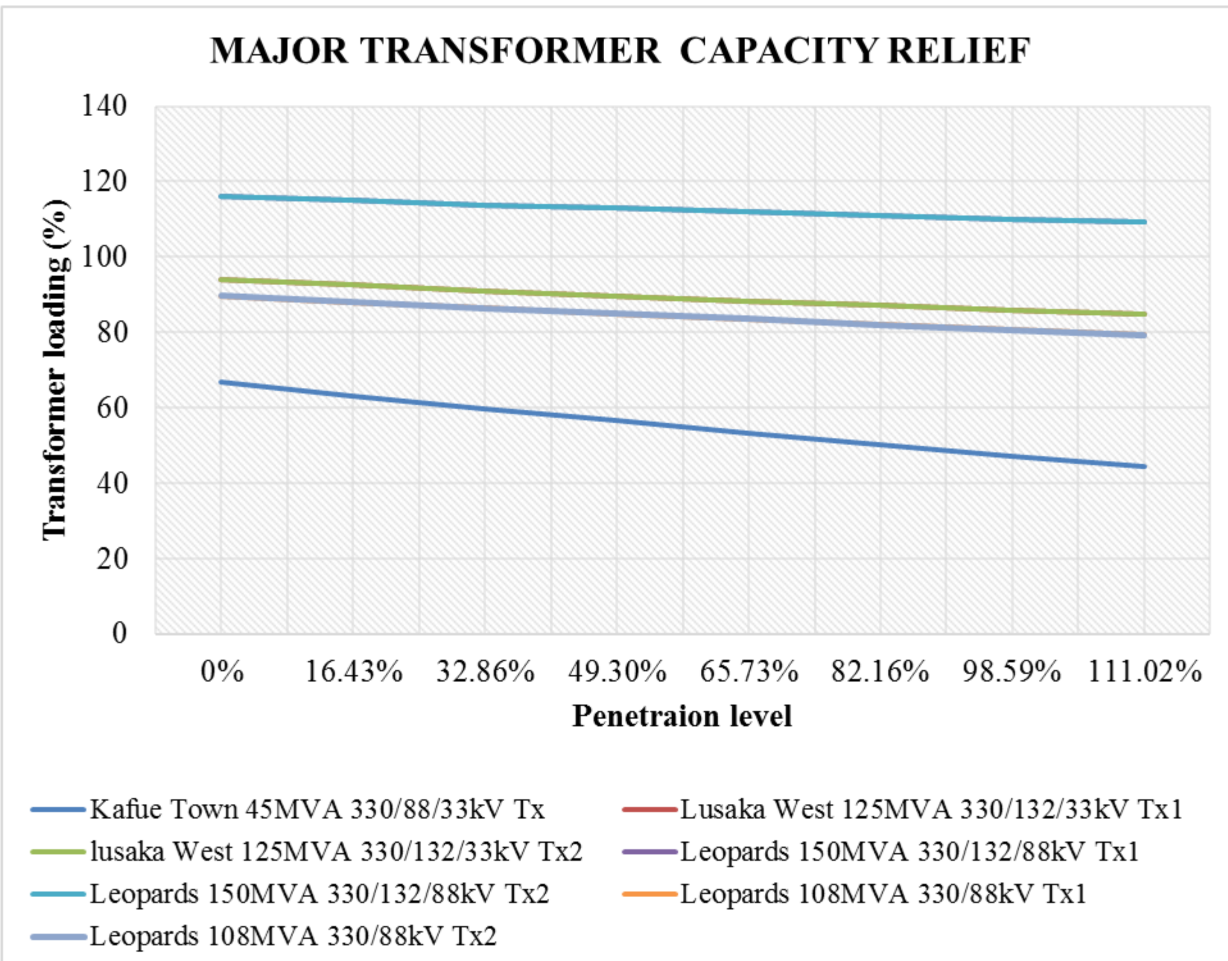

Figure 55: Major transformer capacity relief impact due to integration at Chawama substation

The effect of solar PV penetration level effect at the Chawama substation on the 330kV power supply is shown in Figure 56. As the solar PV plant size increases, the power from the source is reduced and continues to reduce for as long as the solar PV size increases. The decrease as can be seen to be equivalent to linear line.

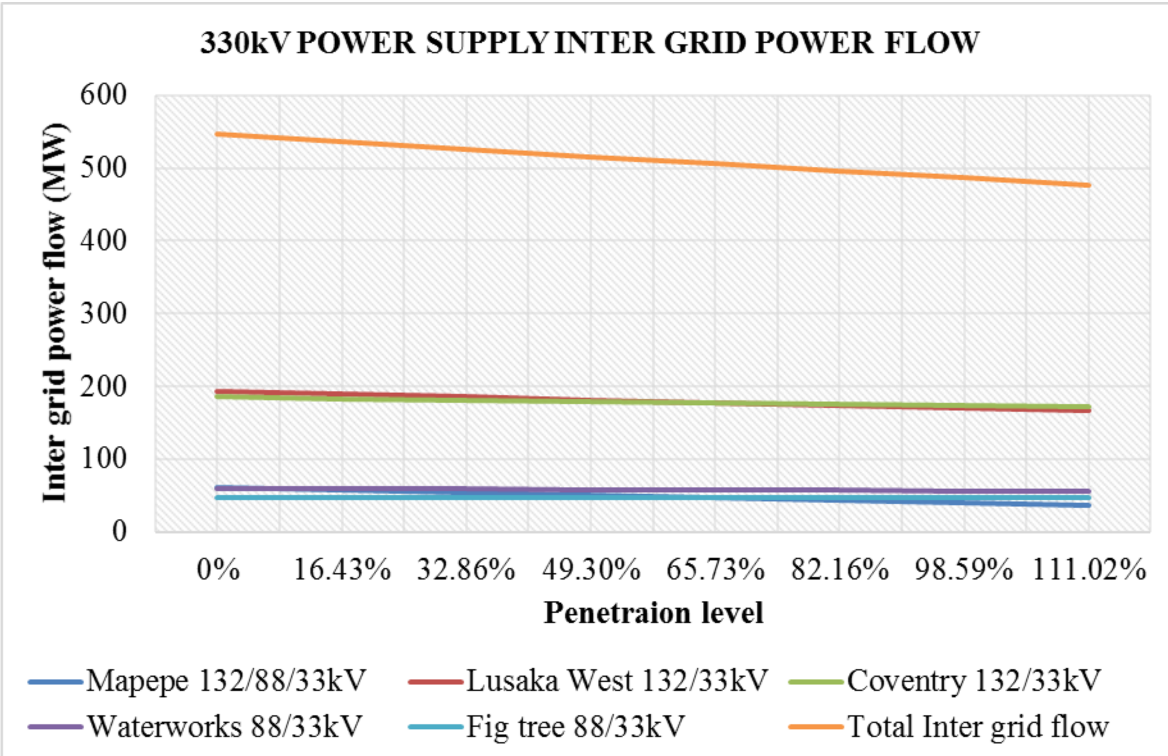

Figure 56: 330kV supply inter grid power flow impact due to integration at Chawama substation

Using the data from Appendix E Table E16 Lusaka Distribution Grid summary power losses at bulk supply substations, a graph of Lusaka bulk supply point grid losses and Total Lusaka network grid losses was plotted and is shown in Figures 57 and 58 respectively. As can be seen from the graph in Figure 58, the effect of solar PV size on the Lusaka network grid losses forms a 'bathtub' curve shape. As the size increases, the line losses begin to decrease up to penetration level 49.30% (30MW) where again line losses start to increase as the penetration level increases. The most probable cause for such an outcome could be that the voltage initially begins to normalize up to a certain level where it starts going into over-voltage which then contributes to the increased active losses.

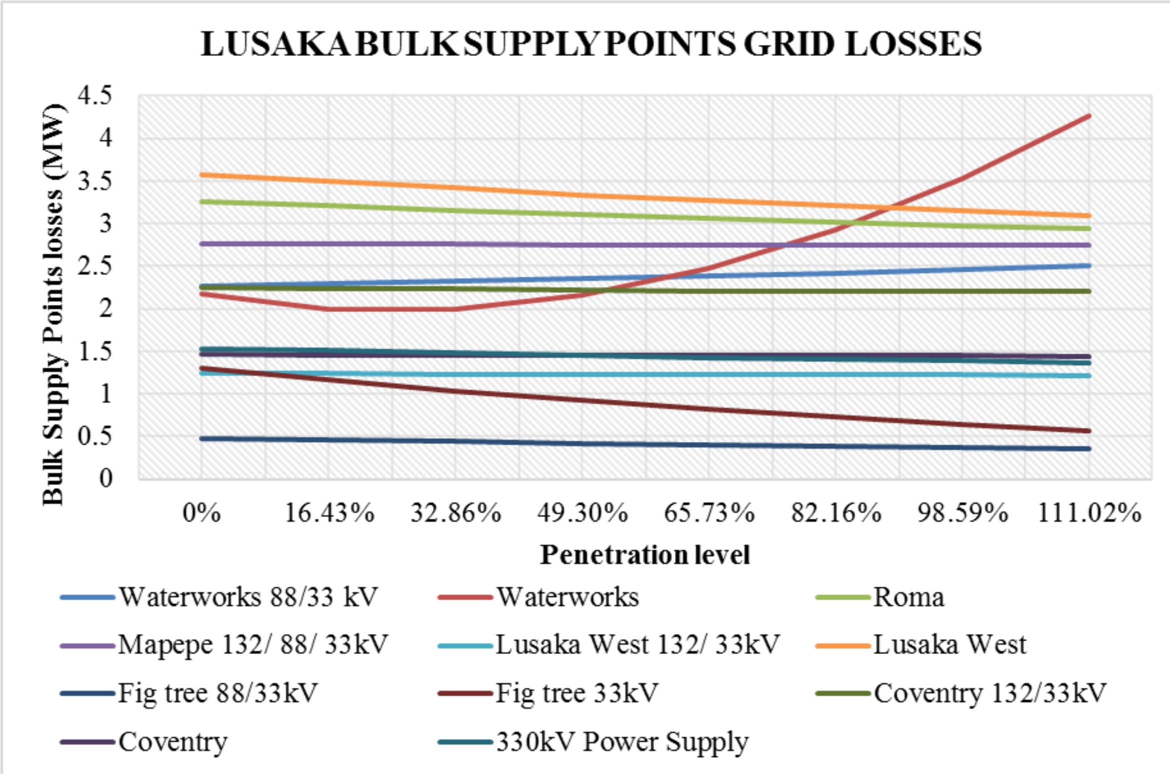

Figure 57: Lusaka bulk supply points grid losses impact due to integration at Chawama substation

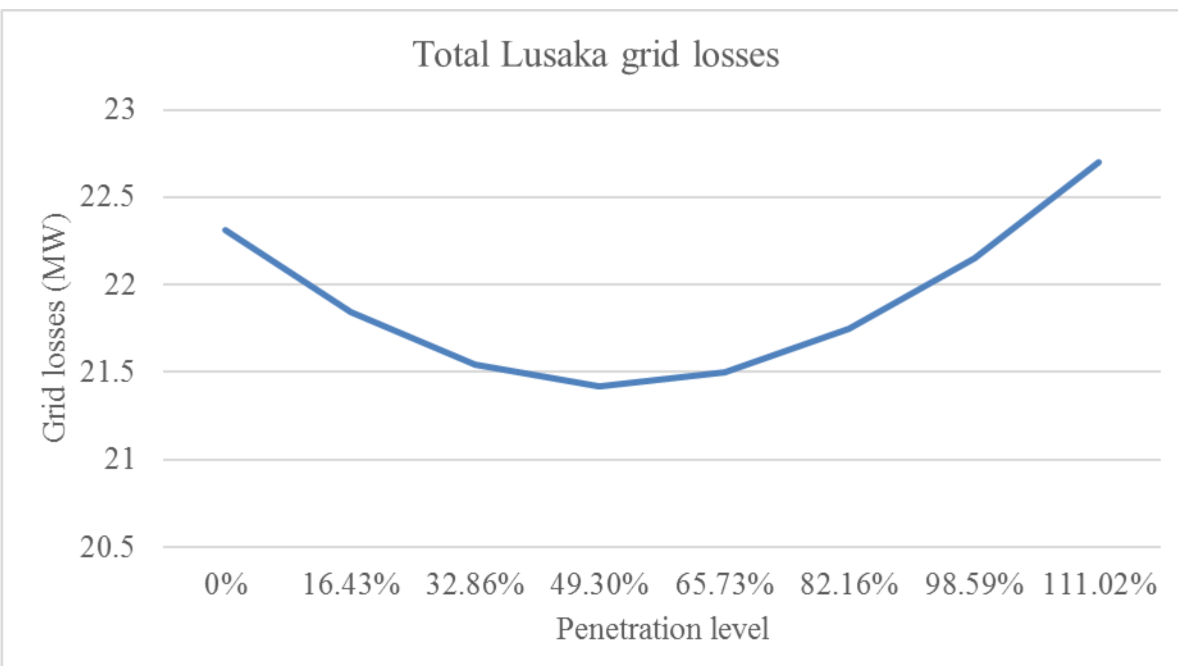

Figure 58: Lusaka network grid losses impact due to integration at Chawama substation

The solar PV power plants in the steps of 10MW of different capacity was integrated and simulated at the Chawama substation. The impact on the voltage level were studied and results were obtained as show in Table 10 below. It can be seen that there is voltage profile increase in the 33kV Lusaka distribution network. The comparison was done with the use of penetration levels of 0% for base case with different penetration levels up to 111.02% (70MW).

Table 10: 33kV Busbar Voltage before and after solar PV plant penetration levels impact due to integration at Chawama substation

SN	SUBSTATIONS	0%	16.43%	32.86%	49.30%	65.73%	82.16%	98.59%	111.02%
1	Coventry sub	0.938	0.938	0.939	0.939	0.939	0.940	0.940	0.940
2	Mapepe	0.933	0.935	0.937	0.939	0.941	0.943	0.945	0.946
3	Birdcage	0.927	0.927	0.928	0.928	0.928	0.928	0.929	0.929
4	Bonaventure	0.912	0.915	0.918	0.920	0.923	0.925	0.928	0.930
5	Chawama	0.915	0.924	0.932	0.941	0.949	0.956	0.964	0.971
6	Chilanga	0.919	0.923	0.927	0.930	0.934	0.937	0.940	0.942
7	Dublin	0.932	0.932	0.933	0.933	0.933	0.933	0.934	0.934
8	Kafue Rd	0.924	0.925	0.925	0.925	0.926	0.926	0.926	0.926
9	Manda Hill	0.917	0.917	0.918	0.918	0.918	0.918	0.918	0.919
10	Shimabala	0.907	0.911	0.914	0.917	0.919	0.922	0.925	0.927
11	Zesco Workshop	0.925	0.925	0.926	0.926	0.926	0.927	0.927	0.927
12	Penyaonse	0.893	0.893	0.893	0.893	0.893	0.893	0.893	0.893
13	Mt Meru	0.877	0.877	0.878	0.878	0.878	0.878	0.878	0.878
14	Kabangwe	0.898	0.898	0.898	0.898	0.898	0.898	0.898	0.898
15	Globber	0.878	0.878	0.878	0.879	0.879	0.879	0.879	0.879
16	Chisamba	0.832	0.832	0.832	0.832	0.832	0.833	0.833	0.833
17	Burnet	0.770	0.770	0.770	0.771	0.771	0.771	0.771	0.771

SN	SUBSTATIONS	0%	16.43%	32.86%	49.30%	65.73%	82.16%	98.59%	111.02%
18	Landless	0.691	0.691	0.691	0.691	0.691	0.691	0.691	0.691
19	Kembe	0.679	0.679	0.679	0.680	0.680	0.680	0.680	0.680
20	Chisamba ranch	0.679	0.680	0.680	0.680	0.680	0.680	0.680	0.680
21	Chibombo	0.679	0.679	0.679	0.680	0.680	0.680	0.680	0.680
22	Katuba	0.834	0.835	0.835	0.835	0.835	0.835	0.835	0.835
23	Karubwe	0.893	0.893	0.893	0.893	0.893	0.893	0.893	0.893
24	Fig tree	0.893	0.893	0.893	0.893	0.893	0.893	0.893	0.893
25	Barlastone	0.932	0.932	0.932	0.932	0.932	0.932	0.932	0.932
26	Kanyama	0.941	0.941	0.942	0.942	0.942	0.942	0.942	0.942
27	L85	0.943	0.943	0.943	0.943	0.943	0.943	0.944	0.944
28	Liverpool	0.921	0.922	0.922	0.922	0.922	0.922	0.923	0.923
29	Lusaka West	0.965	0.966	0.966	0.966	0.966	0.966	0.966	0.966
30	Makeni	0.920	0.921	0.922	0.923	0.924	0.925	0.926	0.927
31	Matero	0.903	0.903	0.904	0.904	0.904	0.904	0.904	0.904
32	Mwembeshi	0.957	0.957	0.957	0.957	0.957	0.957	0.957	0.957
33	Ndipo	0.943	0.943	0.943	0.943	0.943	0.943	0.944	0.944
34	Shorthorn	0.943	0.944	0.944	0.945	0.945	0.946	0.946	0.946
35	Roma	0.931	0.931	0.931	0.931	0.931	0.931	0.932	0.932

SN	SUBSTATIONS	0%	16.43%	32.86%	49.30%	65.73%	82.16%	98.59%	111.02%
36	Avondale	0.905	0.905	0.905	0.905	0.905	0.905	0.906	0.906
37	Bauleni	0.886	0.887	0.887	0.887	0.887	0.887	0.887	0.887
38	Chelstone	0.904	0.904	0.905	0.905	0.905	0.905	0.905	0.905
39	Chongwe town	0.934	0.935	0.935	0.935	0.935	0.935	0.935	0.935
40	Chongwe	0.941	0.941	0.941	0.941	0.941	0.941	0.941	0.941
41	Kabulonga	0.885	0.885	0.885	0.885	0.885	0.885	0.886	0.886
42	Kwamwena	0.913	0.913	0.914	0.914	0.914	0.914	0.914	0.914
43	Mikango	0.901	0.901	0.902	0.902	0.902	0.902	0.902	0.902
44	Ngwerere	0.893	0.893	0.893	0.893	0.893	0.893	0.893	0.893
45	New Kabanana	0.902	0.902	0.902	0.903	0.903	0.903	0.903	0.903
46	Palabana	0.903	0.903	0.903	0.903	0.903	0.903	0.903	0.903
47	UNZA	0.912	0.912	0.912	0.912	0.913	0.913	0.913	0.913
48	Chalala	0.923	0.924	0.924	0.924	0.924	0.924	0.925	0.925
49	Levy	0.920	0.920	0.921	0.921	0.921	0.922	0.922	0.922
50	UTH	0.911	0.911	0.912	0.912	0.912	0.912	0.913	0.913
51	Waterworks	0.936	0.936	0.936	0.936	0.937	0.937	0.937	0.937
52	Woodlands	0.904	0.904	0.905	0.905	0.905	0.905	0.905	0.905

4.2.5. Impact of location and size of Solar PV plant Chilanga substation

4.2.5.1. Solar PV size penetration levels

From the data obtained through load flow calculation, it was found that the voltage on the remote buses was mostly affected by varying the Solar PV size on the Chilanga substation. The results of the bus voltage and the system losses are as shown in Appendix E Table E17. Using the data from Appendix E Table E17 Solar PV plant penetration level, a graph of Penetration level versus Power losses and Penetration level versus Voltage profile was plotted and is shown in Figures 59 and 60 respectively.

With no solar PV plant connected (baseline case) to the system, the penetration level was considered as **zero percent**.

Sample calculation for a solar PV plant generation at **10MW**:

$$\text{Penetration level} = \frac{capacity\ factor \times DG\ power\ installed}{peak\ power\ demand}$$

Considering available 5kWh/m^2 insolation in Zambia, annual generation = 18,250 MWh approximate

$$\text{Capacity factor} = \frac{18{,}250MWh/_{10MW}}{8760h/_{Year}} = \mathbf{0.21}$$

$$\text{Penetration level} = \frac{0.21 * 10MW}{11.07} \times 100\% = \mathbf{18.97\%}$$

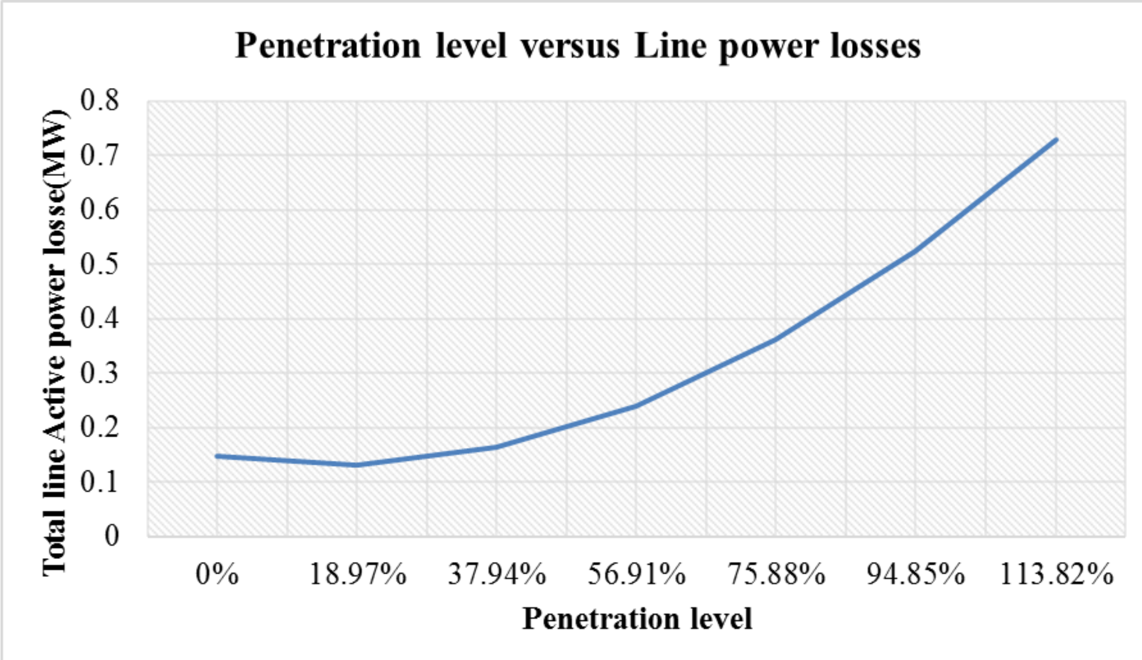

Figure 59: Penetration level versus Power losses at Chilanga substation

As can be seen from the graph in Figure 59, the effect of solar PV size on the line losses forms a ‘Nike mark’ curve shape. As the size increases, the line losses begin to decrease up to penetration level 18.97% (10MW) where again line losses start to increase as the penetration level increases. The most probable cause for such an outcome could be that the voltage initially begins to normalize up to a certain level where it starts going into over-voltage which then contributes to the increased active losses.

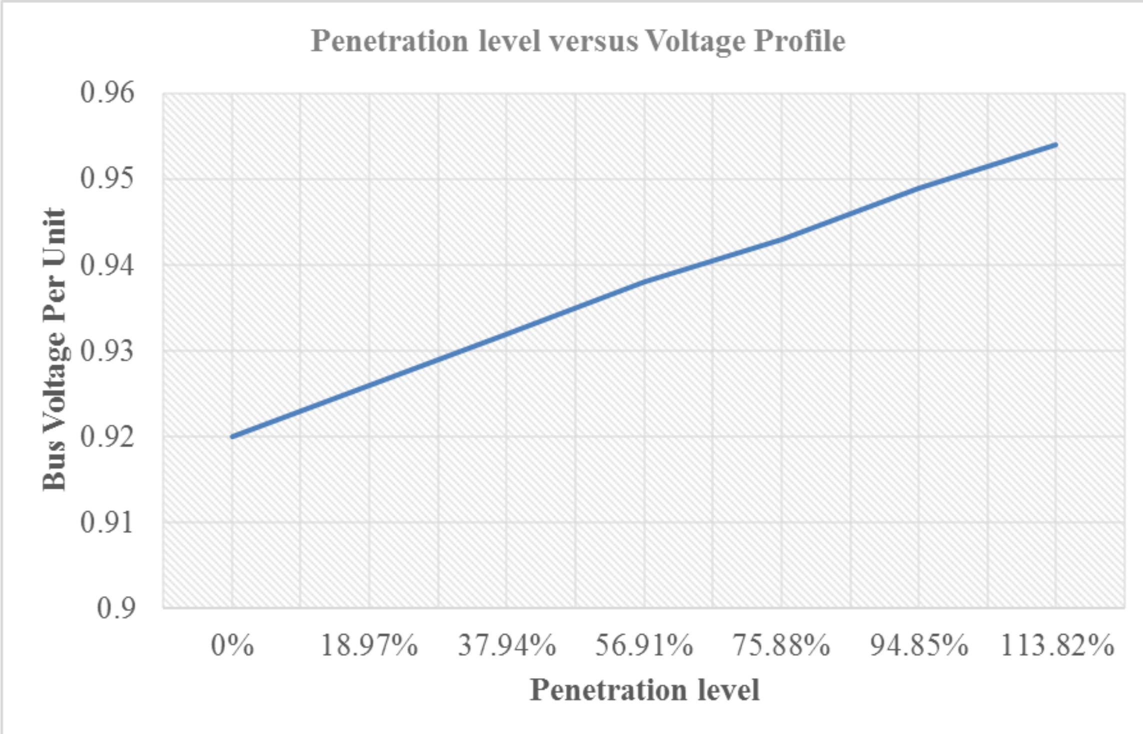

Figure 60: Penetration level versus Voltage profile at Chilanga substation

The effect of solar PV size on the voltage profile is shown in graph in Figure 60. As the size increases, the voltage also increases and continues for as long as the solar PV size increases. The increase as can be seen to be equivalent to linear line.

4.2.5.2. Power flow

The integration of solar PV plant decreases the line losses for the line in the grid to the Chilanga substation. The increase in solar PV penetration resulted in subsequent reduction in the line loading. This is because the integration of solar PV provided power locally to the substation and reduced the power flow from the source. Figure 61 shows the power flow of the line towards the substation before the solar PV was connected to the substation. When the penetration level reached 47.335% (25MW), there was initial power flow direction change in one of the feeders as shown in Figure 62. When the penetration level reached 75.88% (40MW), the power flow direction totally changed by flowing outwards, i.e. away from Chilanga substation as shown in Figure 63. This is because the load demand at the substation was met by the solar PV power supply. This forced the power needs to be transmitted to the other substations in the Lusaka

distribution network. When the penetration level reached 75.88% it also resulted in the increase in the losses as can be seen in Appendix E Table E20.

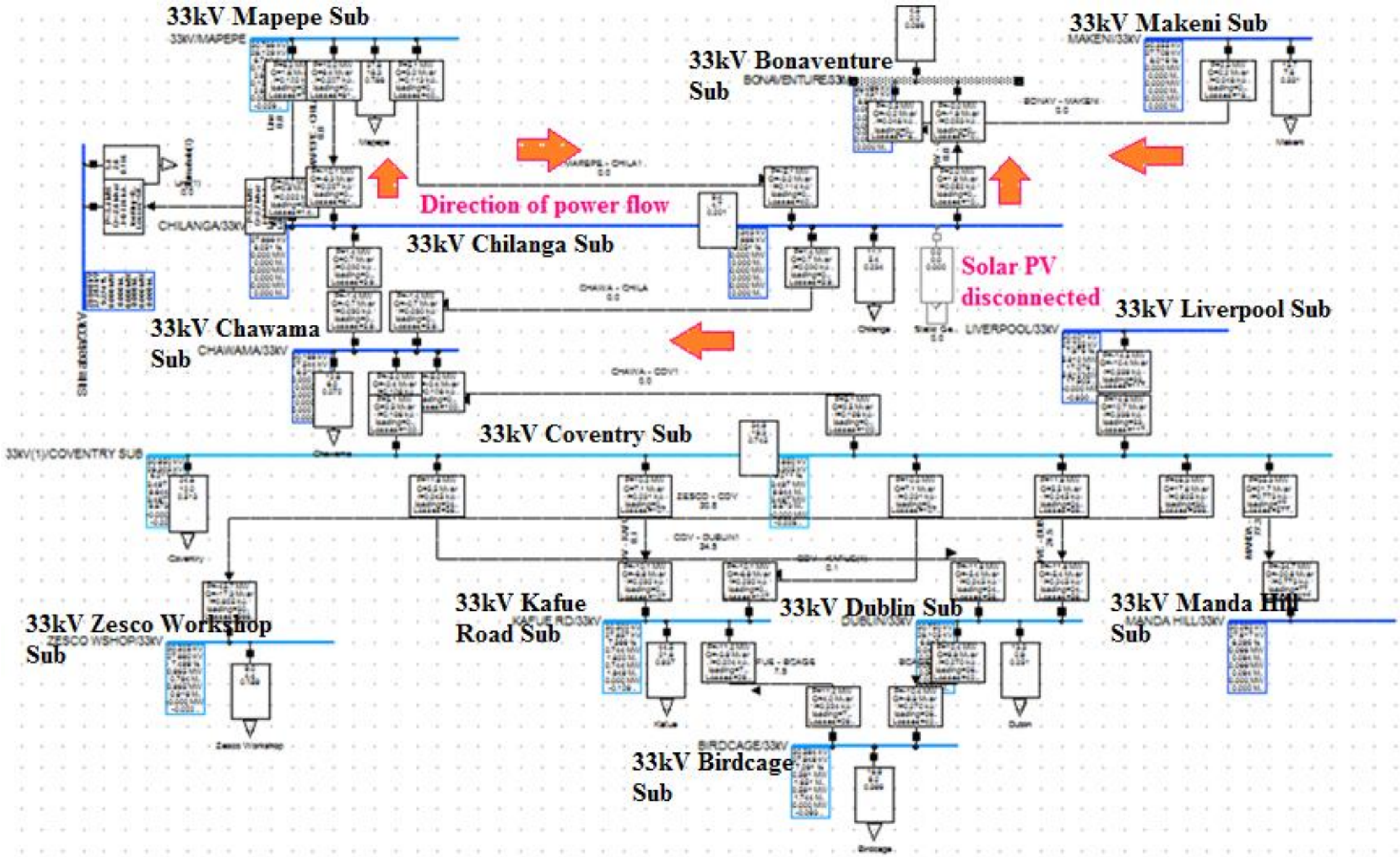

Figure 61: Power flow direction before solar PV plant connection at Chilanga substation

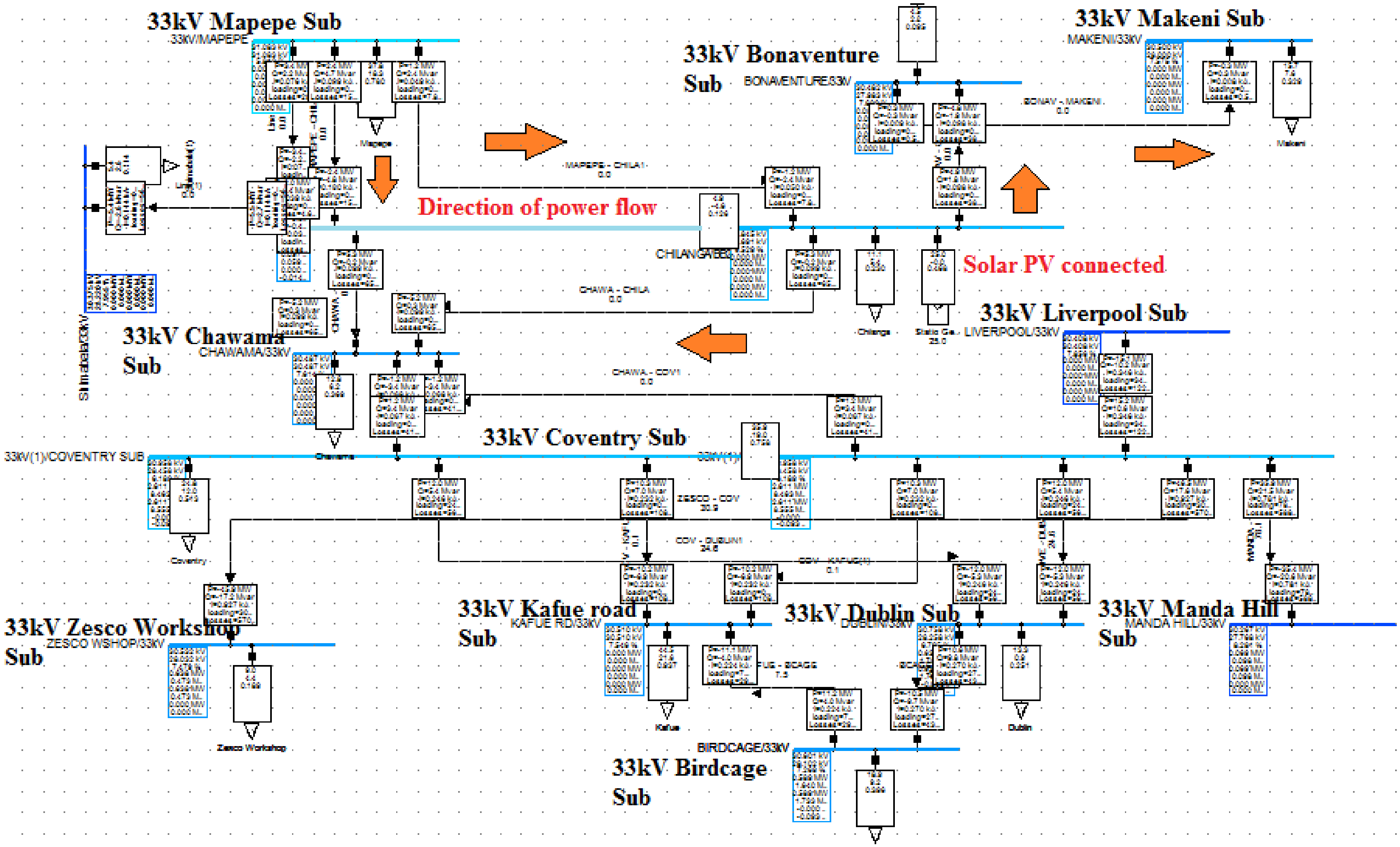

Figure 62: Initial Power flow change direction after a 47.335% (25MW) solar PV plant connection at Chilanga substation

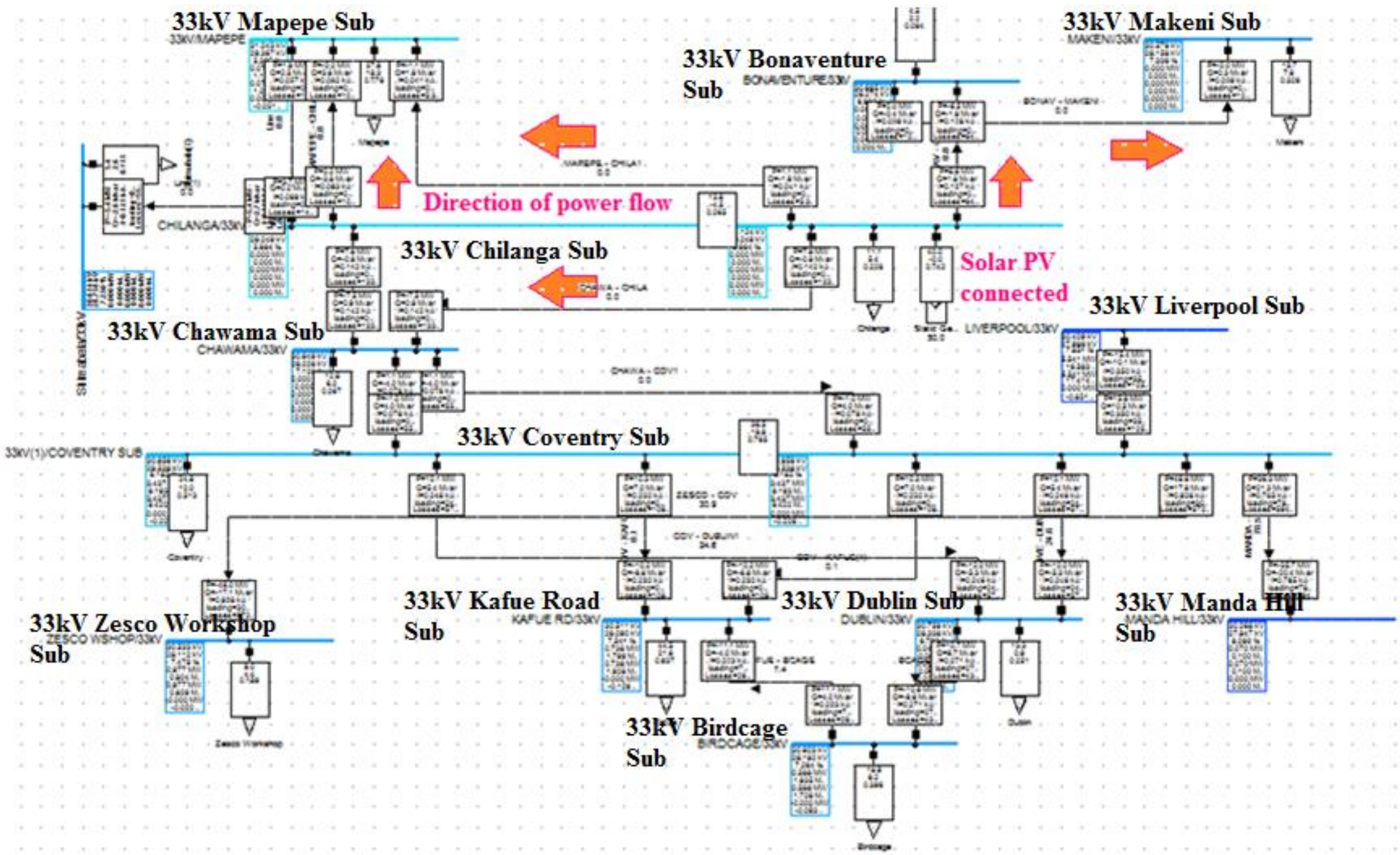

Figure 63: Overall Power flow change direction after a 75.88% (40MW) solar PV plant connection at Chilanga substation

4.2.5.3. Impact of solar PV plant integration at Chilanga substation on the entire Lusaka network

The results for the Inter grid power flow for the 330kV power supply for the Lusaka distribution network are shown in Appendix E Table E19. The integration of solar PV plant decreased the power from the source. The increase in penetration resulted in subsequent reduction in the transformer loadings as shown in Appendix E Table E18. This is because the integration of solar PV plant provided power at Chilanga substation and reduced the power flow for power from the source. Using the data from Appendix E Table E18 and Table E19, a graph of major transformer capacity relief and 330kV supply inter grid power flow was plotted and is shown in Figures 64 and 65 respectively.

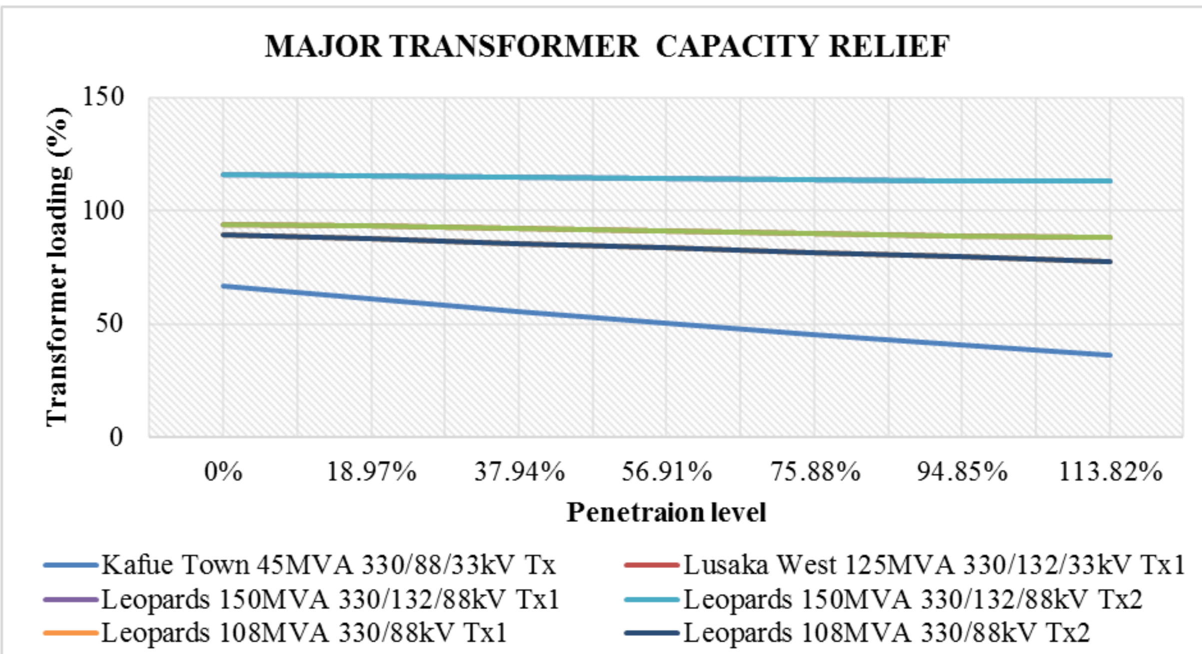

Figure 64: Major transformer capacity relief impact due to integration a Chilanga substation

The effect of solar PV penetration level effect at the Chilanga substation on the 330kV power supply is shown in Figure 65. As the solar PV plant size increases, the power from the source is reduced and continues to reduce for as long as the solar PV size increases. The decrease as can be seen to be equivalent to linear line.

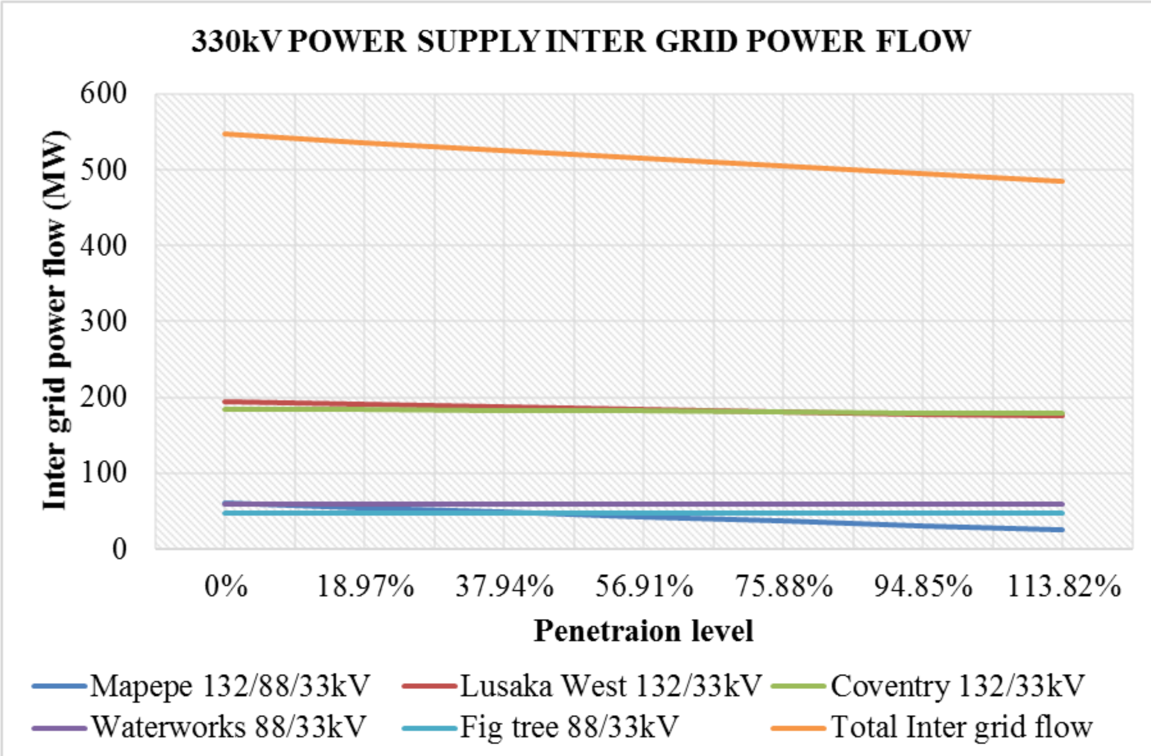

Figure 65: 330kV supply inter grid power flow impact due to integration a Chilanga substation

Using the data from Appendix E Table E20 Lusaka Distribution Grid summary power losses at bulk supply substations, a graph of Lusaka bulk supply point grid losses and Total Lusaka network grid losses was plotted and is shown in Figures 66 and 67 respectively. As can be seen from the graph in Figure 67, the effect of solar PV size on the Lusaka network grid losses forms a 'bathtub' curve shape. As the size increases, the line losses begin to decrease up to penetration level 75.88% (40MW) where again line losses start to increase as the penetration level increases. The most probable cause for such an outcome could be that the voltage initially begins to normalize up to a certain level where it starts going into over-voltage which then contributes to the increased active losses.

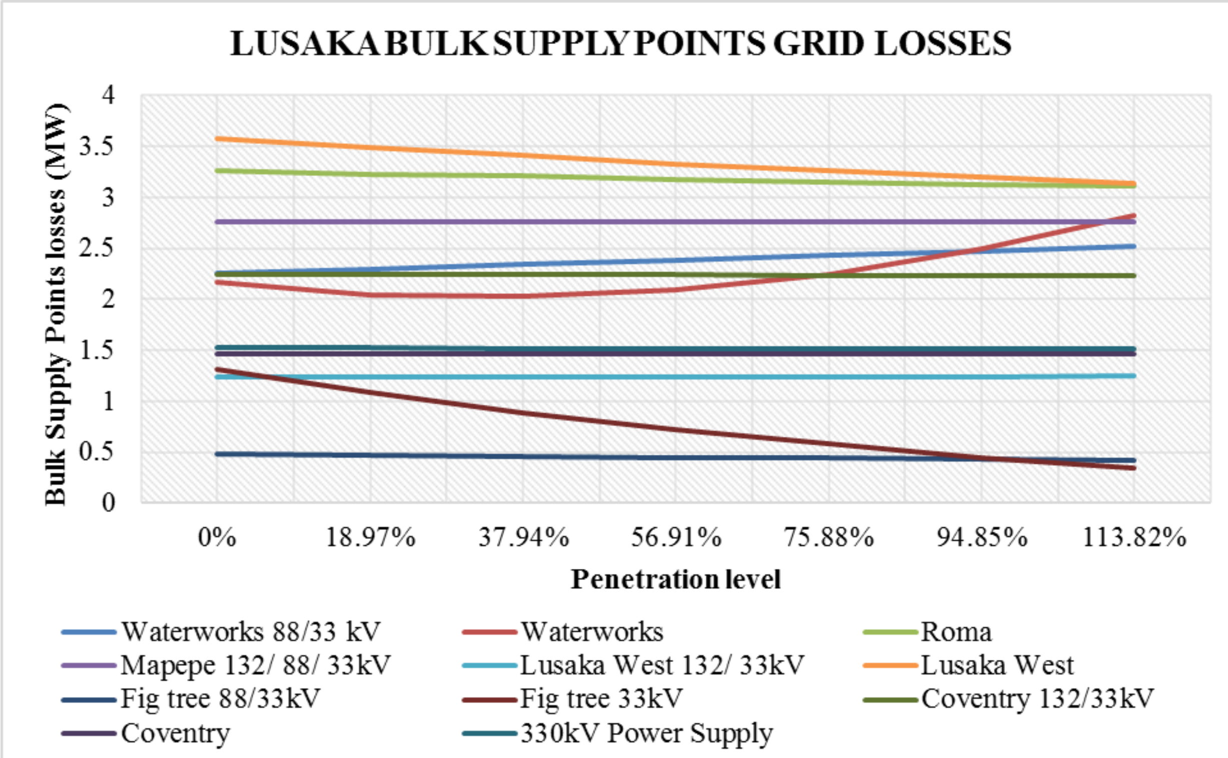

Figure 66: Lusaka bulk supply points grid losses impact due to integration a Chilanga substation

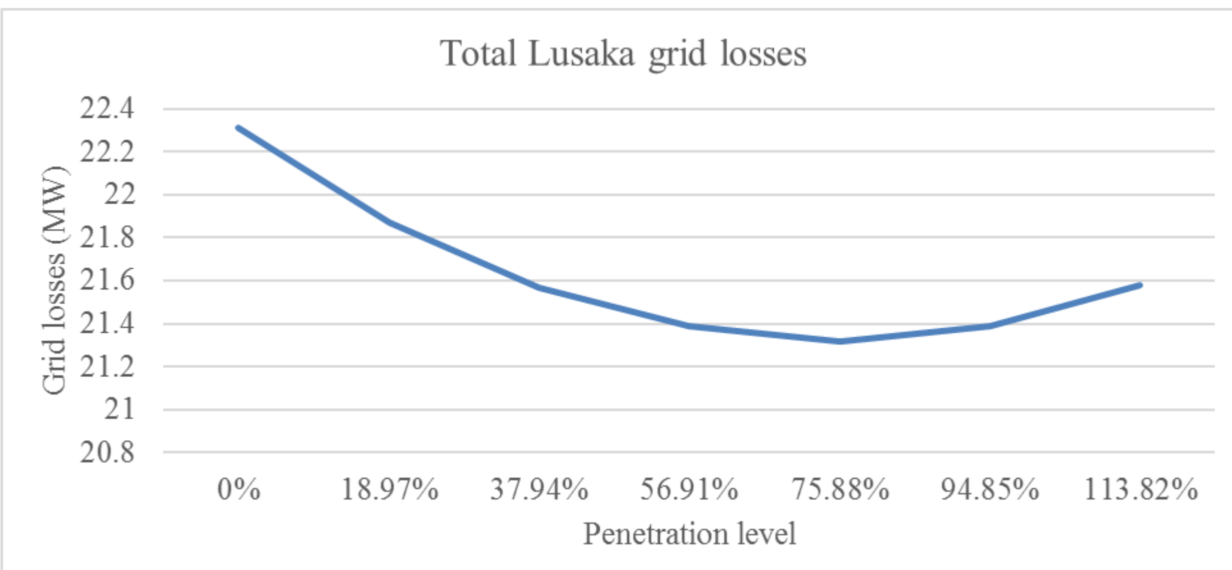

Figure 67: Lusaka network grid losses impact due to integration a Chilanga substation

The solar PV power plants in the steps of 10MW of different capacity was integrated and simulated at the Chilanga substation. The impact on the voltage level were studied and results were obtained as show in Table 11 below. It can be seen that there is voltage profile increase in the 33kV Lusaka distribution network. The comparison was done with the use of penetration levels of 0% for base case with different penetration levels up to 113.82% (60MW).

Table 11: 33kV Busbar Voltage before and after solar PV plant penetration levels impact due to integration a Chilanga substation

SN	SUBSTATIONS	0%	18.97%	37.94%	56.91%	75.88%	94.85%	113.82%
1	Coventry sub	0.938	0.938	0.938	0.938	0.938	0.938	0.938
2	Mapepe	0.933	0.937	0.940	0.944	0.947	0.950	0.953
3	Birdcage	0.927	0.927	0.927	0.927	0.927	0.927	0.927
4	Bonaventure	0.912	0.917	0.921	0.926	0.930	0.934	0.938
5	Chawama	0.915	0.919	0.922	0.926	0.929	0.932	0.938
6	Chilanga	0.919	0.926	0.932	0.938	0.943	0.949	0.954
7	Dublin	0.932	0.932	0.932	0.932	0.932	0.932	0.932
8	Kafue Rd	0.924	0.924	0.925	0.925	0.925	0.925	0.925
9	Manda Hill	0.917	0.917	0.917	0.917	0.917	0.917	0.917
10	Shimabala	0.907	0.913	0.918	0.923	0.928	0.932	0.937
11	Zesco Workshop	0.925	0.925	0.925	0.925	0.925	0.925	0.925
12	Penyaonse	0.893	0.893	0.893	0.893	0.893	0.893	0.893
13	Mt Meru	0.877	0.877	0.877	0.877	0.877	0.877	0.877
14	Kabangwe	0.898	0.898	0.898	0.898	0.898	0.898	0.898
15	Globber	0.878	0.878	0.878	0.878	0.878	0.878	0.878
16	Chisamba	0.832	0.832	0.832	0.832	0.832	0.832	0.832
17	Burnet	0.770	0.770	0.770	0.770	0.770	0.770	0.770

SN	SUBSTATIONS	0%	18.97%	37.94%	56.91%	75.88%	94.85%	113.82%
18	Landless	0.691	0.691	0.691	0.691	0.691	0.691	0.691
19	Kembe	0.679	0.679	0.679	0.679	0.679	0.679	0.679
20	Chisamba ranch	0.679	0.679	0.679	0.679	0.679	0.679	0.679
21	Chibombo	0.679	0.679	0.679	0.679	0.679	0.679	0.679
22	Katuba	0.834	0.834	0.834	0.834	0.834	0.834	0.834
23	Karubwe	0.893	0.893	0.893	0.893	0.893	0.893	0.893
24	Fig tree	0.893	0.893	0.893	0.893	0.893	0.893	0.893
25	Barlastone	0.932	0.932	0.932	0.932	0.932	0.932	0.932
26	Kanyama	0.941	0.941	0.941	0.941	0.941	0.941	0.941
27	L85	0.943	0.943	0.943	0.943	0.943	0.943	0.943
28	Liverpool	0.921	0.921	0.921	0.921	0.921	0.921	0.921
29	Lusaka West	0.965	0.965	0.965	0.965	0.965	0.965	0.965
30	Makeni	0.920	0.922	0.923	0.925	0.927	0.928	0.930
31	Matero	0.903	0.903	0.903	0.903	0.903	0.903	0.903
32	Mwembeshi	0.957	0.957	0.957	0.957	0.957	0.957	0.957
33	Ndipo	0.943	0.943	0.943	0.943	0.943	0.943	0.943
34	Shorthorn	0.943	0.944	0.945	0.945	0.946	0.947	0.947
35	Roma	0.931	0.931	0.931	0.931	0.931	0.931	0.931

SN	SUBSTATIONS	0%	18.97%	37.94%	56.91%	75.88%	94.85%	113.82%
36	Avondale	0.905	0.905	0.905	0.905	0.905	0.905	0.905
37	Bauleni	0.886	0.886	0.886	0.886	0.886	0.886	0.886
38	Chelstone	0.904	0.904	0.904	0.904	0.904	0.904	0.904
39	Chongwe town	0.934	0.934	0.934	0.934	0.934	0.934	0.934
40	Chongwe	0.941	0.941	0.941	0.941	0.941	0.941	0.941
41	Kabulonga	0.885	0.885	0.885	0.885	0.885	0.885	0.885
42	Kwamwena	0.913	0.913	0.913	0.913	0.913	0.913	0.913
43	Mikango	0.901	0.902	0.902	0.902	0.902	0.902	0.902
44	Ngwerere	0.893	0.893	0.893	0.893	0.893	0.893	0.893
45	New Kabanana	0.902	0.902	0.902	0.902	0.902	0.902	0.902
46	Palabana	0.903	0.903	0.903	0.903	0.903	0.903	0.903
47	UNZA	0.912	0.912	0.912	0.912	0.912	0.912	0.912
48	Chalala	0.923	0.923	0.923	0.923	0.923	0.923	0.923
49	Levy	0.920	0.920	0.920	0.920	0.920	0.920	0.920
50	UTH	0.911	0.911	0.911	0.911	0.911	0.911	0.911
51	Waterworks	0.936	0.936	0.936	0.936	0.936	0.936	0.936
52	Woodlands	0.904	0.904	0.904	0.904	0.904	0.904	0.904

4.2.6. Impact of location and size of Solar PV plant at Mapepe substation

4.2.6.1. Solar PV size penetration levels

From the data obtained through load flow calculation, it was found that the voltage on the remote buses was mostly affected by varying the Solar PV size on the Mapepe substation. The results of the bus voltage and the system losses are as shown in Appendix E Table E21. Using the data from Appendix E Table E21 Solar PV plant penetration level, a graph of Penetration level versus Power losses and Penetration level versus Voltage profile was plotted and is shown in Figures 68 and 69 respectively.

With no solar PV plant connected (baseline case) to the system, the penetration level was considered as **zero percent**.

Sample calculation for a solar PV plant generation at **10MW**:

$$\text{Penetration level} = \frac{capacity\ factor \times DG\ power\ installed}{peak\ power\ demand}$$

Considering available 5kWh/m^2 insolation in Zambia, annual generation = 18,250 MWh approximate

$$\text{Capacity factor} = \frac{18{,}250MWh/_{10MW}}{8760h/_{Year}} = \mathbf{0.21}$$

$$\text{Penetration level} = \frac{0.21 * 10MW}{37.80} \times 100\% = \mathbf{5.56\%}$$

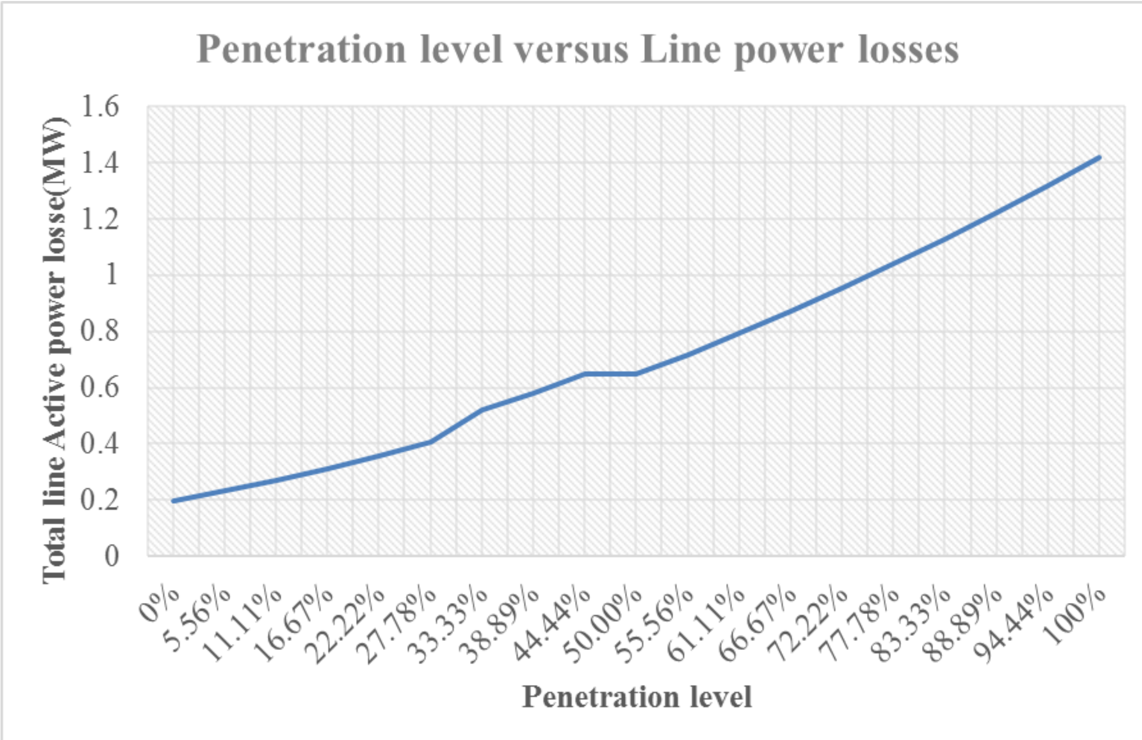

Figure 68: Penetration level versus Power losses at Mapepe substation

As can be seen from the graph in Figure 68, the effect of solar PV size on the line losses forms a 'linear' shape. As the size increases, the line losses begin to increase and continues to increase linearly as the penetration level increases. The most probable cause for such an outcome could be that the voltage initially begins to normalize up to a certain level where it starts going into over-voltage which then contributes to the increased active losses.

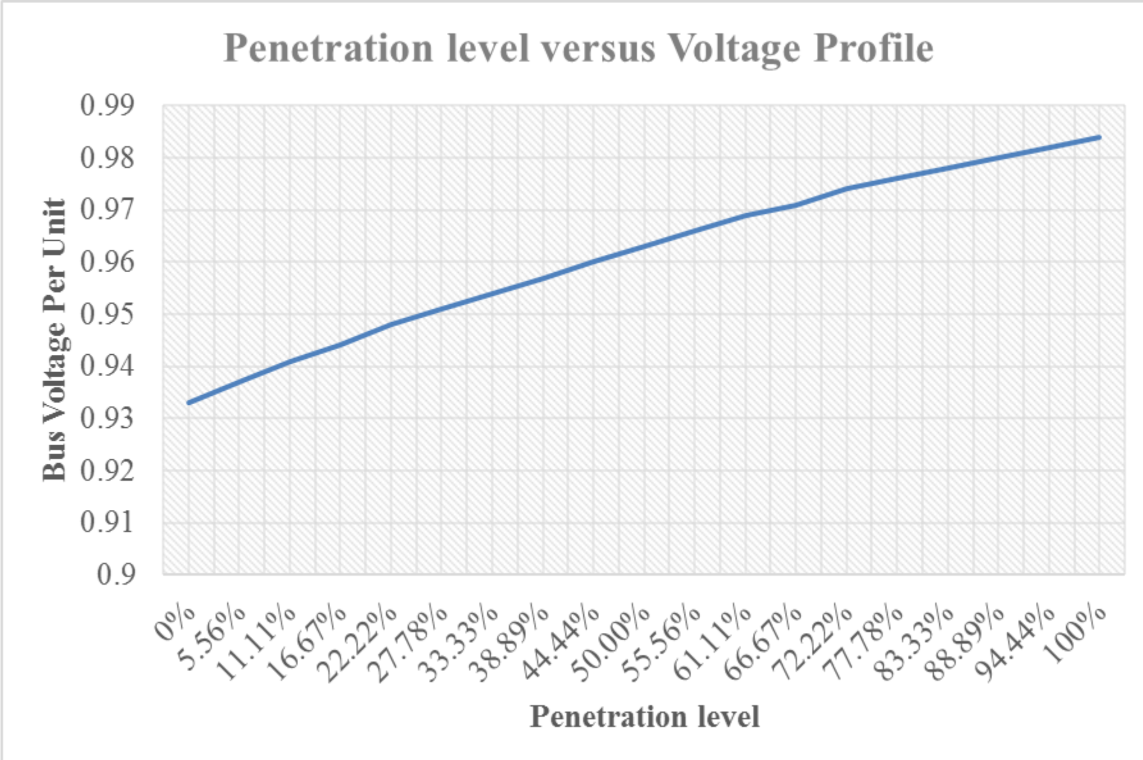

Figure 69: Penetration level versus Voltage profile at Mapepe substation

The effect of solar PV size on the voltage profile is shown in graph in Figure 69. As the size increases, the voltage also increases and continues for as long as the solar PV size increases. The increase as can be seen to be equivalent to linear line.

4.2.6.2. Power flow

The integration of solar PV plant decreases the line losses for the line in the grid to the Mapepe substation. The increase in solar PV penetration resulted in subsequent reduction in the line loading. This is because the integration of solar PV provided power locally to the substation and reduced the power flow from the source. Figure 70 shows the power flow of the line towards the substation before the solar PV was connected to the substation. When the penetration level reached 50.00% (90MW), there was an immediate total complete power flow direction changed by flowing outwards, i.e. away from Mapepe substation as shown in Figure 71. This is because the load demand from the Mapepe substation was met by the solar PV power supply. This forced the power needs to be transmitted to the other substations in the Lusaka distribution network. When the penetration level reached 50.00% (90MW) it also resulted in the increase in the losses as can be seen in Appendix E Table E24.

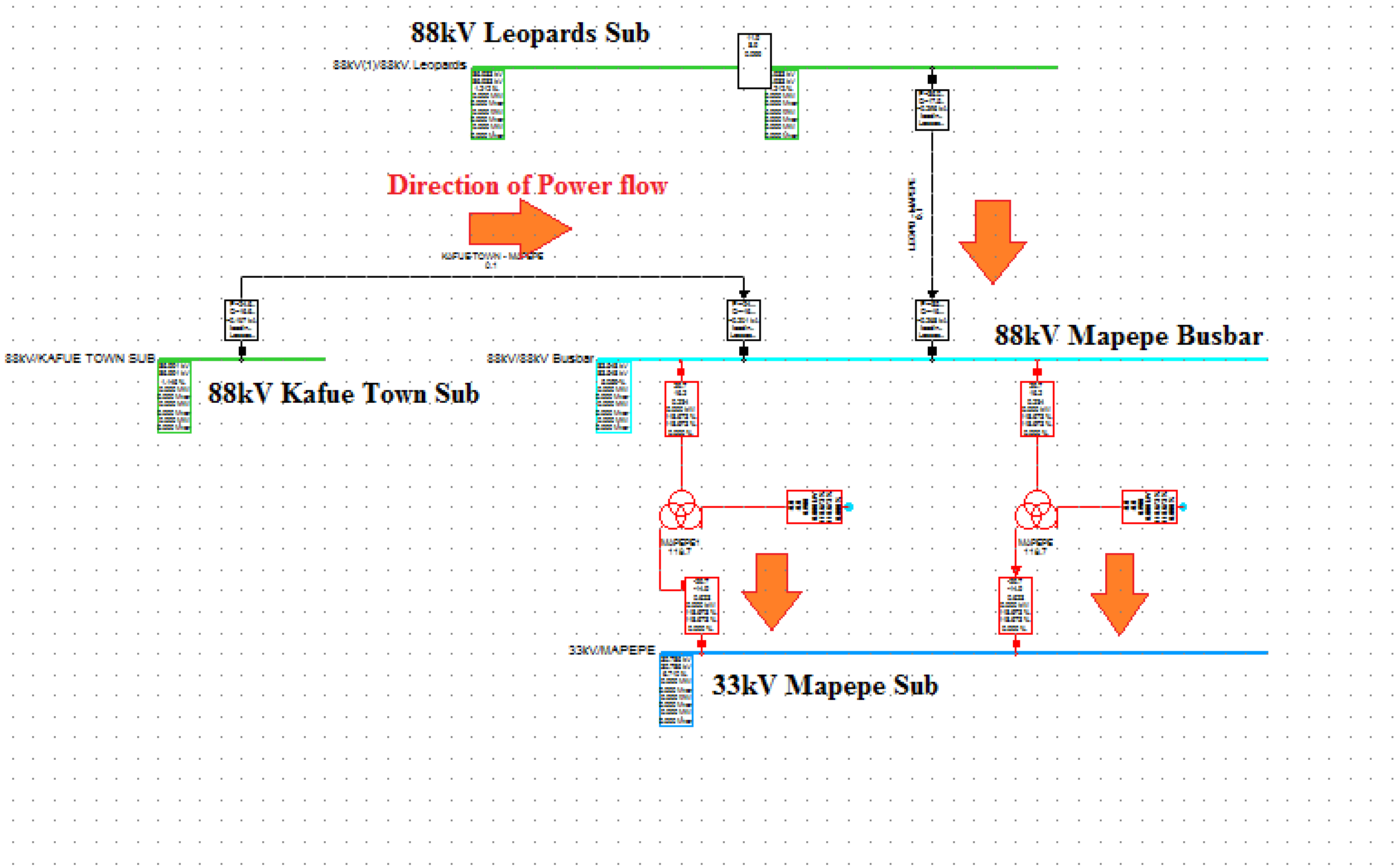

Figure 70: Power flow direction before solar PV plant connection at Mapepe substation

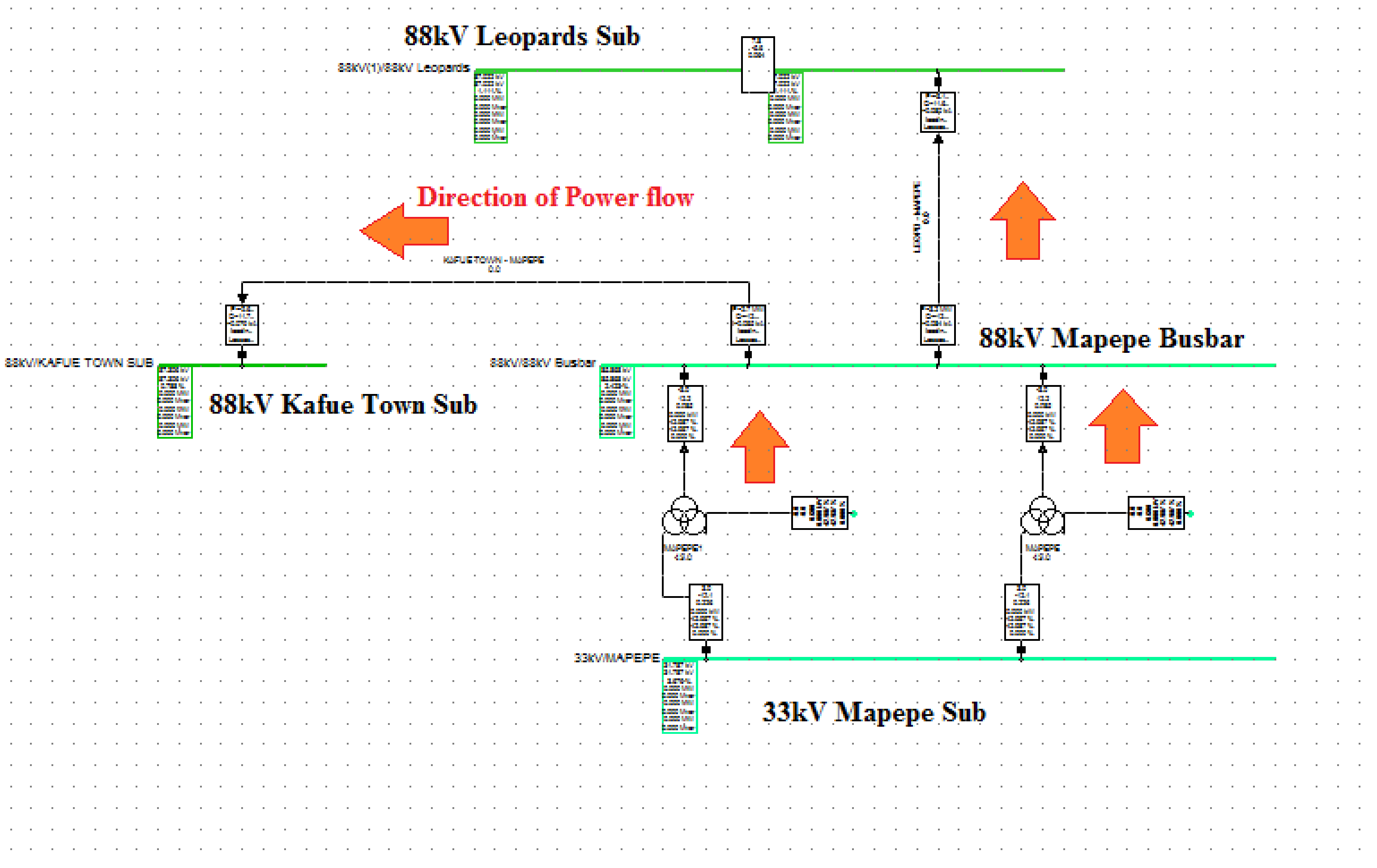

Figure 71: Initial and overall Power flow direction change after a 50.00% (90MW) solar PV plant connection at Mapepe substation

4.2.6.3. Impact of solar PV plant integration at Mapepe substation on the entire Lusaka network

The results for the Inter grid power flow for the 330kV power supply for the Lusaka distribution network are shown in Appendix E Table E23. The integration of solar PV plant decreased the power from the source. The increase in penetration resulted in subsequent reduction in the transformer loadings as shown in Appendix E Table E22. This is because the integration of solar PV plant provided power at Mapepe substation and reduced the power flow from the source. Using the data from Appendix E Table E22 and Table E23, a graph of major transformer capacity relief and 330kV supply inter grid power flow was plotted and is shown in Figures 72 and 73 respectively.

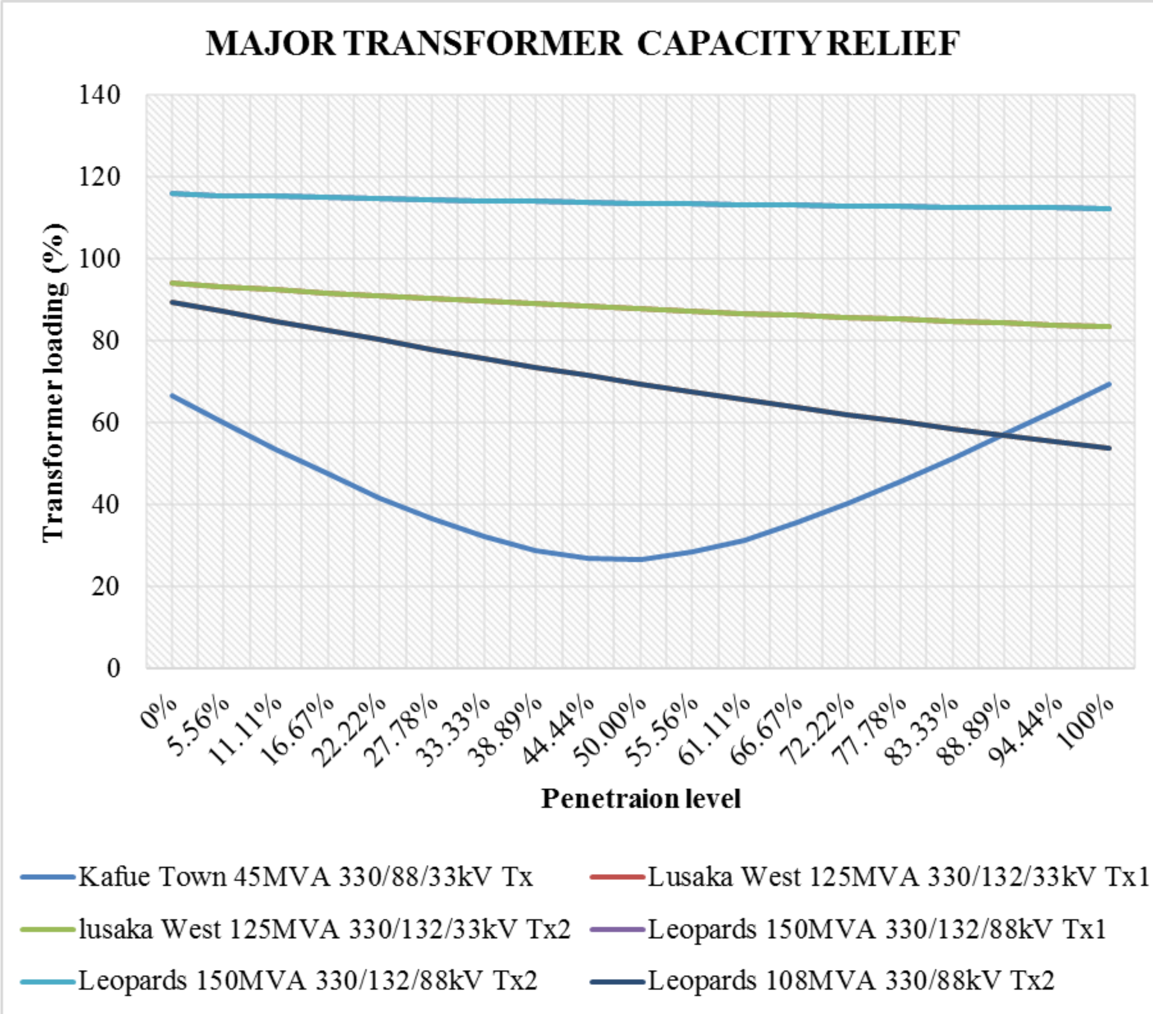

Figure 72: Major transformer capacity relief impact due to integration at Mapepe substation

The effect of solar PV penetration level effect at the Mapepe substation on the 330kV power supply is shown in Figure 73. As the solar PV plant size increases, the power from the source is reduced and continues to reduce for as long as the solar PV size increases. The decrease as can be seen to be equivalent to linear line.

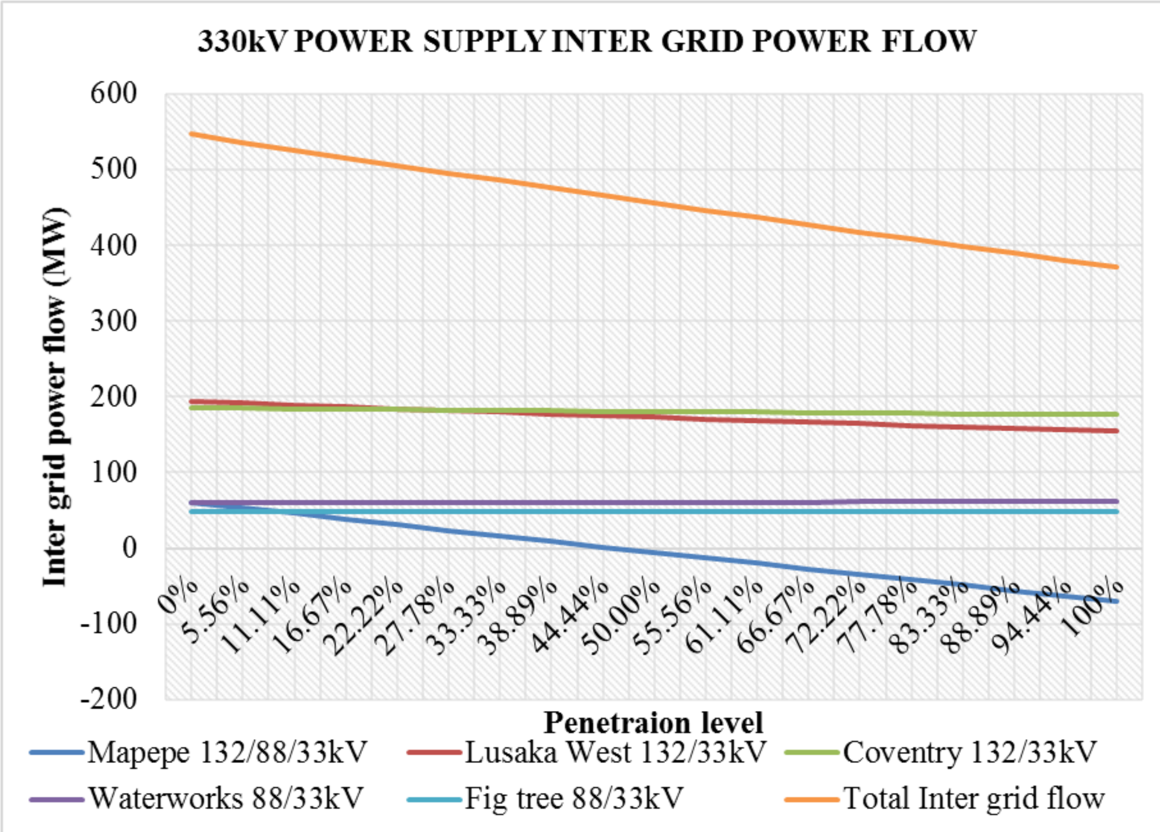

Figure 73: 330kV supply inter grid power flow impact due to integration at Mapepe substation

Using the data from Appendix E Table E24 Lusaka Distribution Grid summary power losses at bulk supply substations, a graph of Lusaka bulk supply point grid losses and Total Lusaka network grid losses was plotted and is shown in Figures 74 and 75 respectively. As can be seen from the graph in Figure 75, the effect of solar PV size on the Lusaka network grid losses forms a 'bathtub' curve shape. As the size increases, the line losses begin to decrease up to penetration level 5.56% (10MW) where again line losses start to increase as the penetration level increases. The most probable cause for such an outcome could be that the voltage initially begins to normalize up to a certain level where it starts going into over-voltage which then contributes to the increased active losses.

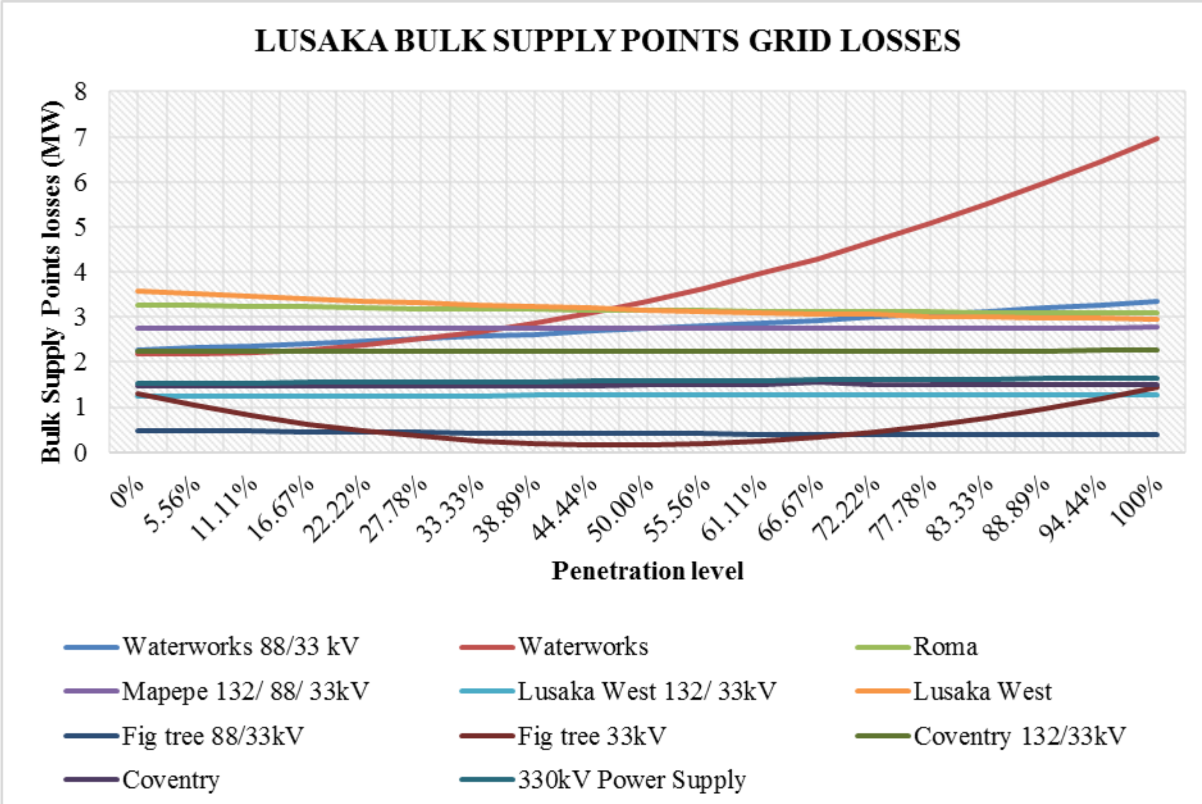

Figure 74: Lusaka bulk supply points grid losses impact due to integration at Mapepe substation

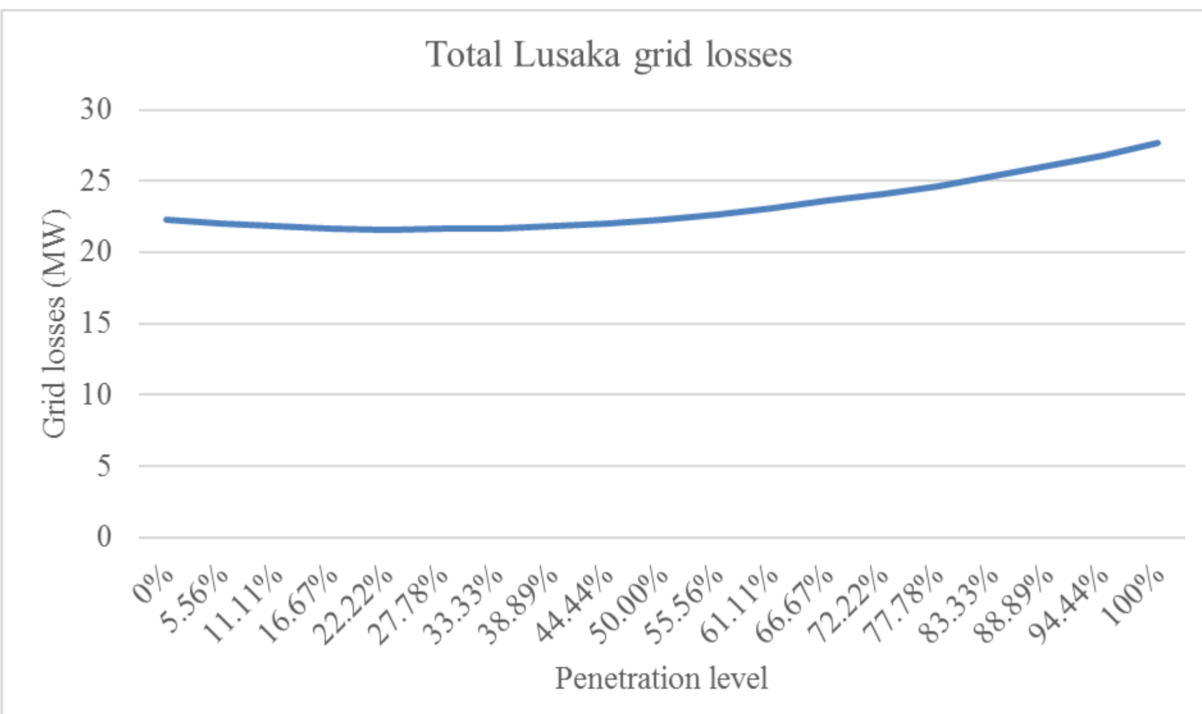

Figure 75: Lusaka network grid losses impact due to integration at Mapepe substation

The solar PV power plants in the steps of 10MW of different capacity was integrated and simulated at the Makeni substation. The impact on the voltage level were studied and results were obtained as show in Table 12 below. It can be seen that there is voltage profile increase in the Lusaka distribution network. The comparison was done with the use of penetration levels of 0% for base case with different penetration levels up to 100% (180MW).

Table 12: 33kV Busbar Voltage before and after solar PV plant penetration levels impact due to integration at Mapepe substation

SN	SUBSTATIONS	0%	5.56%	11.11%	16.67%	22.22%	27.78%	33.33%	38.89%	44.44%
1	Coventry sub	0.938	0.938	0.938	0.938	0.938	0.938	0.938	0.938	0.938
2	Mapepe	0.933	0.937	0.941	0.944	0.948	0.951	0.954	0.957	0.960
3	Birdcage	0.927	0.927	0.927	0.927	0.927	0.927	0.927	0.927	0.927
4	Bonaventure	0.912	0.915	0.917	0.920	0.922	0.924	0.927	0.929	0.931
5	Chawama	0.915	0.917	0.919	0.921	0.923	0.924	0.926	0.927	0.929
6	Chilanga	0.919	0.923	0.926	0.930	0.933	0.936	0.938	0.941	0.944
7	Dublin	0.932	0.932	0.932	0.932	0.932	0.932	0.932	0.932	0.932
8	Kafue Rd	0.924	0.924	0.924	0.924	0.924	0.924	0.924	0.924	0.924
9	Manda Hill	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917
10	Shimabala	0.907	0.911	0.915	0.918	0.921	0.924	0.927	0.930	0.933
11	Zesco Workshop	0.925	0.925	0.925	0.925	0.925	0.925	0.925	0.925	0.925
12	Penyaonse	0.893	0.893	0.893	0.893	0.893	0.893	0.893	0.893	0.893
13	Mt Meru	0.877	0.877	0.877	0.877	0.877	0.877	0.877	0.877	0.877
14	Kabangwe	0.898	0.898	0.898	0.898	0.898	0.898	0.898	0.898	0.898
15	Globber	0.878	0.878	0.878	0.879	0.879	0.879	0.879	0.879	0.879
16	Chisamba	0.832	0.832	0.832	0.832	0.832	0.832	0.833	0.833	0.833
17	Burnet	0.770	0.770	0.770	0.770	0.770	0.770	0.770	0.770	0.770

SN	SUBSTATIONS	0%	5.56%	11.11%	16.67%	22.22%	27.78%	33.33%	38.89%	44.44%
18	Landless	0.691	0.691	0.691	0.691	0.691	0.691	0.691	0.691	0.691
19	Kembe	0.679	0.679	0.679	0.679	0.679	0.679	0.679	0.679	0.679
20	Chisamba ranch	0.679	0.679	0.679	0.680	0.680	0.680	0.680	0.680	0.680
21	Chibombo	0.679	0.679	0.679	0.679	0.679	0.679	0.679	0.679	0.679
22	Katuba	0.834	0.834	0.835	0.835	0.835	0.835	0.835	0.835	0.835
23	Karubwe	0.893	0.893	0.893	0.893	0.893	0.893	0.893	0.893	0.893
24	Fig tree	0.893	0.893	0.893	0.893	0.893	0.893	0.893	0.893	0.893
25	Barlastone	0.932	0.932	0.932	0.932	0.932	0.932	0.931	0.931	0.931
26	Kanyama	0.941	0.941	0.941	0.941	0.941	0.941	0.941	0.941	0.941
27	L85	0.943	0.943	0.943	0.943	0.943	0.943	0.943	0.943	0.943
28	Liverpool	0.921	0.921	0.921	0.921	0.921	0.921	0.921	0.921	0.921
29	Lusaka West	0.965	0.965	0.965	0.965	0.965	0.965	0.965	0.965	0.965
30	Makeni	0.920	0.921	0.922	0.923	0.924	0.925	0.925	0.926	0.927
31	Matero	0.903	0.903	0.903	0.903	0.903	0.903	0.903	0.903	0.903
32	Mwembeshi	0.957	0.957	0.957	0.957	0.957	0.957	0.957	0.957	0.957
33	Ndipo	0.943	0.943	0.943	0.942	0.942	0.942	0.942	0.942	0.942
34	Shorthorn	0.943	0.944	0.944	0.944	0.945	0.945	0.945	0.946	0.946
35	Roma	0.931	0.931	0.931	0.931	0.931	0.931	0.931	0.931	0.931

SN	SUBSTATIONS	0%	5.56%	11.11%	16.67%	22.22%	27.78%	33.33%	38.89%	44.44%
36	Avondale	0.905	0.905	0.905	0.905	0.905	0.905	0.905	0.905	0.905
37	Bauleni	0.886	0.886	0.886	0.886	0.886	0.886	0.886	0.886	0.886
38	Chelstone	0.904	0.904	0.904	0.904	0.904	0.904	0.904	0.904	0.904
39	Chongwe town	0.934	0.935	0.935	0.935	0.935	0.935	0.935	0.935	0.935
40	Chongwe	0.941	0.941	0.941	0.941	0.941	0.941	0.941	0.941	0.941
41	Kabulonga	0.885	0.885	0.885	0.885	0.884	0.884	0.884	0.884	0.884
42	Kwamwena	0.913	0.913	0.913	0.913	0.913	0.913	0.913	0.913	0.913
43	Mikango	0.901	0.902	0.902	0.902	0.902	0.902	0.902	0.902	0.902
44	Ngwerere	0.893	0.893	0.893	0.893	0.893	0.893	0.893	0.893	0.893
45	New Kabanana	0.902	0.902	0.902	0.902	0.902	0.902	0.902	0.902	0.902
46	Palabana	0.903	0.903	0.903	0.903	0.903	0.903	0.903	0.903	0.903
47	UNZA	0.912	0.912	0.912	0.912	0.912	0.912	0.911	0.911	0.911
48	Chalala	0.923	0.923	0.923	0.923	0.923	0.923	0.923	0.923	0.923
49	Levy	0.920	0.920	0.920	0.920	0.920	0.920	0.920	0.920	0.920
50	UTH	0.911	0.911	0.911	0.911	0.911	0.911	0.911	0.911	0.911
51	Waterworks	0.936	0.936	0.936	0.936	0.936	0.936	0.936	0.936	0.936
52	Woodlands	0.904	0.904	0.904	0.904	0.904	0.904	0.904	0.903	0.903

SN	SUBSTATIONS	50.00%	55.56%	61.11%	66.67%	72.22%	77.78%	83.33%	88.89%	94.44%	100%
1	Coventry sub	0.937	0.937	0.937	0.937	0.937	0.937	0.936	0.936	0.936	0.936
2	Mapepe	0.963	0.966	0.969	0.971	0.974	0.976	0.978	0.980	0.982	0.984
3	Birdcage	0.927	0.927	0.927	0.926	0.926	0.926	0.926	0.926	0.925	0.925
4	Bonaventure	0.932	0.934	0.936	0.937	0.939	0.940	0.942	0.943	0.944	0.945
5	Chawama	0.930	0.931	0.932	0.934	0.935	0.935	0.936	0.937	0.938	0.938
6	Chilanga	0.946	0.949	0.951	0.953	0.955	0.957	0.959	0.961	0.962	0.964
7	Dublin	0.931	0.931	0.931	0.931	0.931	0.931	0.930	0.930	0.930	0.930
8	Kafue Rd	0.924	0.924	0.924	0.924	0.923	0.923	0.923	0.923	0.923	0.922
9	Manda Hill	0.917	0.916	0.916	0.916	0.916	0.916	0.916	0.915	0.915	0.915
10	Shimabala	0.936	0.938	0.941	0.943	0.945	0.947	0.949	0.951	0.953	0.955
11	Zesco Workshop	0.925	0.924	0.924	0.924	0.924	0.924	0.923	0.923	0.923	0.923
12	Penyaonse	0.893	0.893	0.893	0.893	0.893	0.893	0.893	0.893	0.893	0.893
13	Mt Meru	0.877	0.877	0.877	0.877	0.877	0.877	0.876	0.876	0.876	0.876
14	Kabangwe	0.897	0.897	0.897	0.897	0.897	0.897	0.897	0.897	0.896	0.896
15	Globber	0.879	0.879	0.879	0.879	0.879	0.879	0.879	0.879	0.878	0.878
16	Chisamba	0.833	0.832	0.832	0.832	0.832	0.832	0.832	0.832	0.832	0.832
17	Burnet	0.770	0.770	0.770	0.770	0.770	0.770	0.770	0.769	0.769	0.769
18	Landless	0.691	0.691	0.691	0.690	0.690	0.690	0.690	0.690	0.690	0.690

SN	SUBSTATIONS	50.00%	55.56%	61.11%	66.67%	72.22%	77.78%	83.33%	88.89%	94.44%	100%
19	Kembe	0.679	0.679	0.679	0.679	0.679	0.679	0.678	0.678	0.678	0.678
20	Chisamba ranch	0.679	0.679	0.679	0.679	0.679	0.679	0.679	0.679	0.678	0.678
21	Chibombo	0.679	0.679	0.679	0.679	0.679	0.679	0.679	0.678	0.678	0.678
22	Katuba	0.834	0.834	0.834	0.834	0.834	0.834	0.834	0.834	0.833	0.833
23	Karubwe	0.893	0.893	0.893	0.893	0.893	0.893	0.893	0.893	0.893	0.893
24	Fig tree	0.893	0.893	0.893	0.893	0.893	0.893	0.893	0.893	0.893	0.893
25	Barlastone	0.931	0.931	0.931	0.931	0.931	0.931	0.930	0.930	0.930	0.930
26	Kanyama	0.941	0.940	0.940	0.940	0.940	0.940	0.940	0.939	0.939	0.939
27	L85	0.943	0.942	0.942	0.942	0.942	0.942	0.942	0.942	0.941	0.941
28	Liverpool	0.921	0.921	0.921	0.921	0.920	0.920	0.920	0.920	0.920	0.919
29	Lusaka West	0.965	0.965	0.965	0.965	0.964	0.964	0.964	0.964	0.964	0.964
30	Makeni	0.928	0.928	0.929	0.929	0.930	0.930	0.931	0.931	0.932	0.932
31	Matero	0.903	0.903	0.903	0.902	0.902	0.902	0.902	0.902	0.902	0.901
32	Mwembeshi	0.957	0.956	0.956	0.956	0.956	0.956	0.956	0.956	0.955	0.955
33	Ndipo	0.942	0.942	0.942	0.942	0.941	0.941	0.941	0.941	0.941	0.940
34	Shorthorn	0.946	0.946	0.946	0.947	0.947	0.947	0.947	0.947	0.947	0.947
35	Roma	0.931	0.930	0.930	0.930	0.930	0.930	0.930	0.930	0.930	0.929
36	Avondale	0.905	0.905	0.905	0.905	0.904	0.904	0.904	0.904	0.904	0.904

SN	SUBSTATIONS	50.00%	55.56%	61.11%	66.67%	72.22%	77.78%	83.33%	88.89%	94.44%	100%
37	Bauleni	0.886	0.886	0.886	0.885	0.885	0.885	0.885	0.885	0.884	0.884
38	Chelstone	0.904	0.904	0.903	0.903	0.903	0.903	0.903	0.903	0.902	0.902
39	Chongwe town	0.935	0.935	0.935	0.935	0.935	0.935	0.935	0.935	0.935	0.935
40	Chongwe	0.941	0.941	0.941	0.941	0.941	0.941	0.941	0.941	0.941	0.941
41	Kabulonga	0.884	0.884	0.884	0.884	0.883	0.883	0.883	0.883	0.883	0.882
42	Kwamwena	0.913	0.913	0.913	0.913	0.913	0.912	0.912	0.912	0.912	0.912
43	Mikango	0.902	0.902	0.902	0.902	0.902	0.902	0.902	0.902	0.902	0.902
44	Ngwerere	0.893	0.893	0.893	0.893	0.893	0.893	0.893	0.893	0.893	0.893
45	New Kabanana	0.902	0.902	0.901	0.901	0.901	0.901	0.901	0.901	0.900	0.900
46	Palabana	0.903	0.903	0.903	0.903	0.903	0.903	0.903	0.903	0.903	0.903
47	UNZA	0.911	0.911	0.911	0.911	0.911	0.910	0.910	0.910	0.910	0.910
48	Chalala	0.923	0.923	0.923	0.923	0.923	0.923	0.922	0.922	0.922	0.922
49	Levy	0.920	0.919	0.919	0.919	0.919	0.919	0.919	0.918	0.918	0.918
50	UTH	0.911	0.911	0.910	0.910	0.910	0.910	0.910	0.909	0.909	0.909
51	Waterworks	0.936	0.936	0.935	0.935	0.935	0.935	0.935	0.935	0.935	0.934
52	Woodlands	0.903	0.903	0.903	0.903	0.903	0.903	0.902	0.902	0.902	0.902

CHAPTER FIVE

DISCUSSION, CONCLUSION AND RECOMMENDATION

As was highlighted in Chapter 3, the closer the solar PV Plant is to the substation, the easier it is for a plant to be integrated to the grid network. GPS mapping tool is usually used in the process of site selection to visually display the limitations and determine the total area available. The literature review highlighted the rule of thumb principle for determining the solar PV power plant size required based on the estimated area available. The rule of thumb takes into consideration the limitation, type of technology whether it uses crystalline solar panels without tracker and the efficiency of the panels.

Chapter 3 also highlighted the issue related to penetration levels. According to research, the recommended penetration level ranges between 0 to 30%. The impact of penetration levels is used to help in the reduction of power losses, improve voltage profile and investigate the change in the power flow. This does help in determine the solar PV plant size for integration to the grid network. In turn, the size will help determine the actual size of land required for the solar PV plant.

Chapter 4 identified the initial 13 33kV distribution substations location for possible solar PV power plant integration to the network. The 13 33kV substations are Makeni, Chelstone, Mapepe, Chilanga, Chalala, Fig tree, Chibombo, Katuba, Chisamba, Chongwe 88/33kV, Avondale, L85 and Chawama. The identification of the substation was done by physically marking the substations using the GPS and the Google Earth was used to visually display the area and mark the approximate available land near the substation to determine the size and relate it to the capacity of the solar PV plant generation. Base on the scope limitation, six substations were considered for investigation of the impact of penetration level of solar PV plant on the 33kV distribution system power losses, voltage profile and power flow. The six 33kV substations are Makeni, Avondale, Chelstone, Chawama, Chilanga and Mapepe.

The overall analysis of penetration levels of solar PV plant for power losses for the six substations i.e. Makeni, Avondale, Chelstone, Chawama, Chilanga and Mapepe substations is shown in Figure 76.

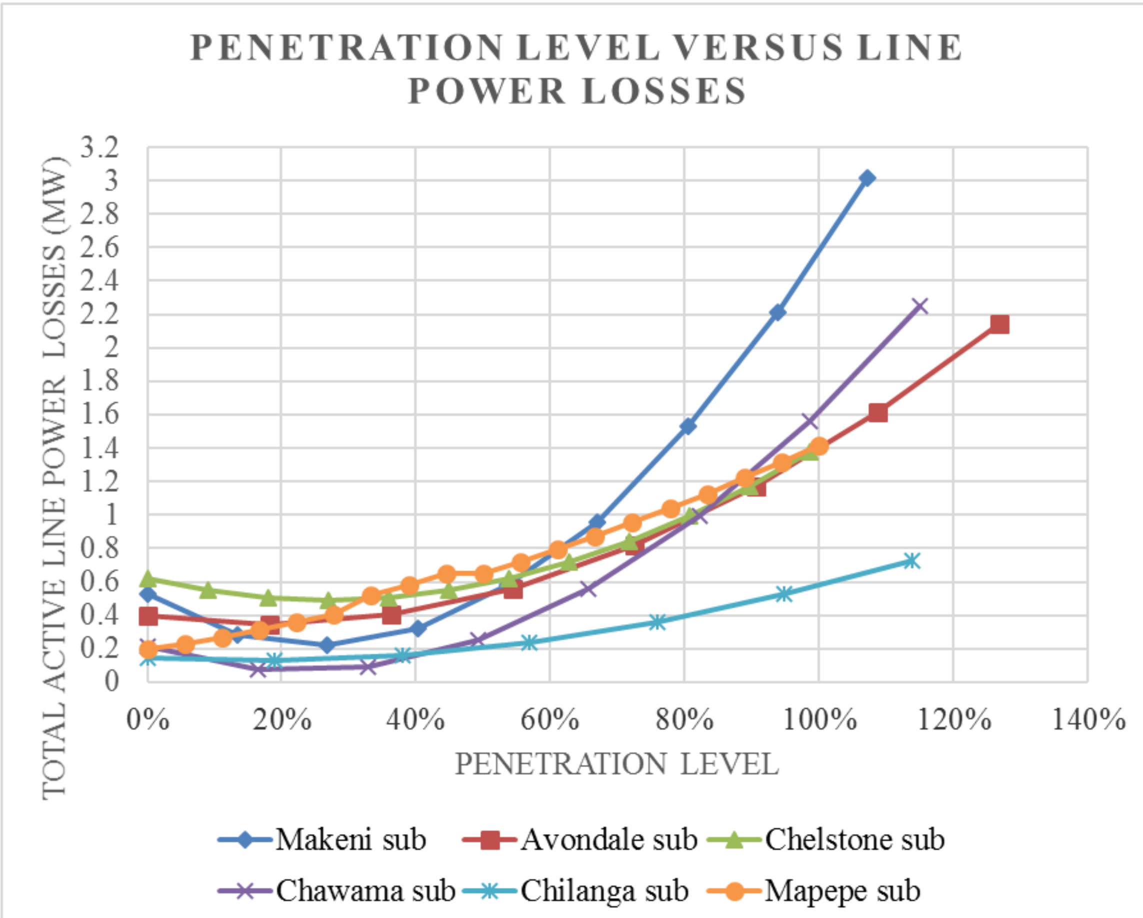

Figure 76: Penetration level versus line power losses analysis for the six substations

When the solar PV was integrated to the substations, the total power losses decreases at penetration levels of 26.80% (Makeni), 18.12% (Avondale), 26.92% (Chelstone), 16.43% (Chawama), 18.97% (Chilanga) and 0% (Mapepe) respectively. As can be seen from the graph, after 20% increase in penetration level, the total power losses start to increase for the substations. The most probable cause for such an outcome could be that the voltage begins to normalize up to a certain level where it starts going into over-voltage which then contributes to the increased active losses.

Based on the fact that 20% penetration level is acceptable for integration for each substation, Table 13 show the comparison between the initial identification of land and required land and size of solar PV plant based on the 20% penetration level. As can be seen from the Table 13, there is adequate land which can be secured for consideration for solar PV plant investment for integration.

Table 13: Area and size solar PV required based on 20% penetration level

No.	Substation	Available Area (m^2)	Maximum Capacity (MW AC)	20% penetration capacity (MW)	Required Area based on 20% penetration (m^2)
1	Avondale	4 930 352	203.05	20.00	485 622
2	Chelstone	944 709	38.91	20.00	485 622
3	Makeni	1 691 270	69.65	20.00	485 622
4	Chawama	1 875 990	77.26	20.00	485 622
5	Chilanga	1 813 794	74.70	20.00	485 622
6	Mapepe	5 121 676	210.93	20.00	485 622

When the penetration level reached 67.05% (Makeni), 90.60% (Avondale), 80.77% (Chelstone), 32.86% (Chawama), 75.88% (Chilanga) and 50.00% (Mapepe) respectively, the power flow direction changed totally by flowing outwards, i.e. away from substations. This is because the load demand from the substations was met by the solar PV power supply. This forced the power needs to be transmitted to the other substations in the Lusaka distribution network. As can be seen from the graph, on average after 50% increase in penetration level, the power flow direction changed.

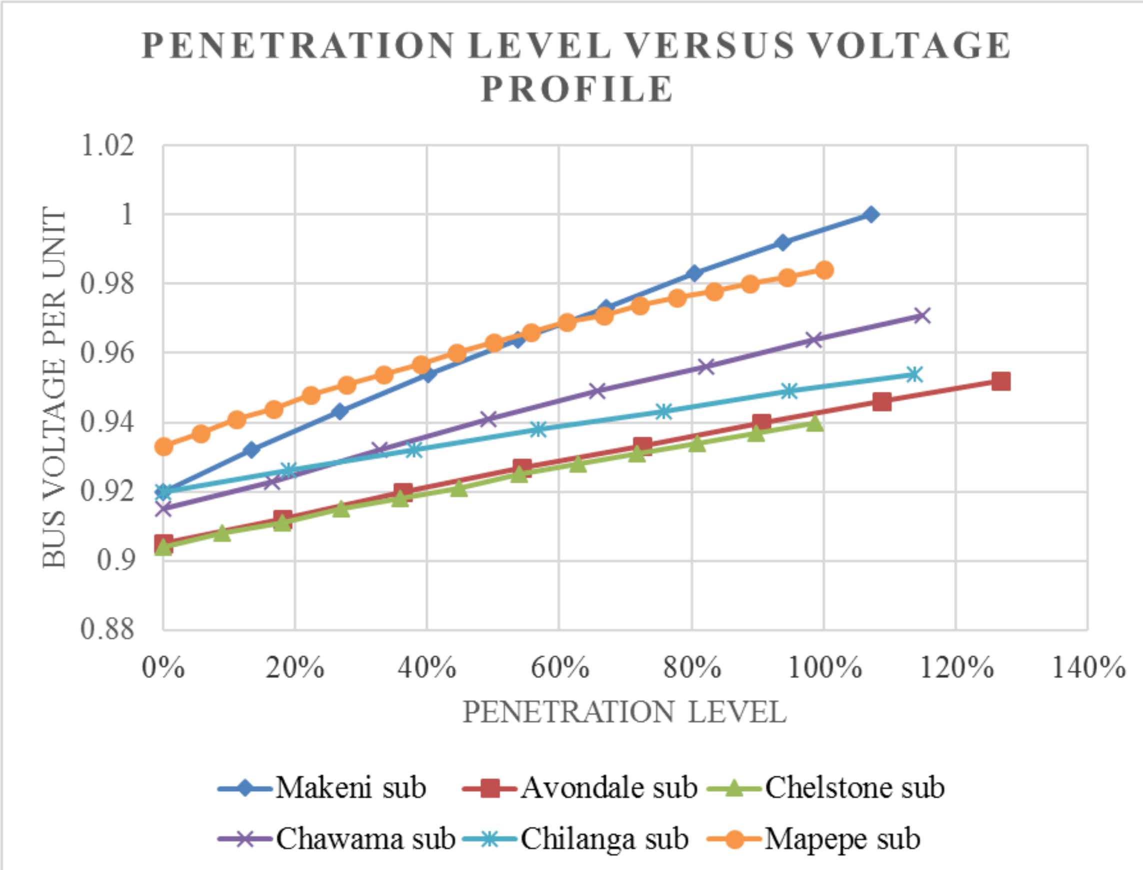

Figure 77: Penetration level versus voltage profile analysis for the six substations

The overall analysis of penetration levels for solar PV plant for voltage profile for the six substations i.e. Makeni, Avondale, Chelstone, Chawama, Chilanga and Mapepe substations is shown above Figure 77. The impact on increasing in penetration level on the voltage profile is shown in graph in Figure 77. As the penetration level increases, the voltage also increases and continues for as long as the solar PV size increases. The increase as can be seen is equivalent to linear line. Based on the analysis, the voltage is also directly proportional to the penetration level increase. From the graph, the voltage profile indicates that the voltage still remains within the statutory limits.

Table 14: Penetration level power flow direction change

SN	Substation	Penetration level initial power flow direction change	Penetration level power loss turning point
1	Makeni	26.82% (20MW)	26.80% (20MW)
2	Avondale	54.36% (30MW)	18.12% (10MW)
3	Chelstone	4.485% (5MW)	26.92% (30MW)
4	Chawama	16.43% (10MW)	16.43% (10MW)
5	Chilanga	47.335% (25MW)	18.97% (10MW)
6	Mapepe	50.00% (90MW)	5.56% (10MW)

Table 14 shows the penetration level power flow direction change for the six substations. The change in direction of the power flow is outward at the point of solar PV integration of the substation. The increase in solar PV penetration level also resulted in subsequent reduction in the line loading. This is because the integration of solar PV provided power locally to the substation and reduced the power flow from the source. This forced the power needs to be transferred to other substations in the Lusaka distribution network and it also provides an opportunity to reduce power generation and the generating stations. At the point the power flow changes direction, the penetration level power loss will have increased as it would have surpassed the power loss turning point as shown in Table 14. The voltage remained in the statutory limits.

5.1. Conclusion

The main objective of the report was to analyze the impact of location and size of solar PV plant for integration in the Lusaka 33kV distribution grid network and how it affects the system losses, the minimum and maximum voltage limits of the power distribution network.

The impact of integration of the solar PV plant into the Lusaka 33kV distribution network has been investigated. It has shown that the impact of location and sizing of solar PV plant implementation affects the distribution network grid. It has the potential to improve distribution system performance when penetration levels are less than 20% however, if the penetration levels go beyond 20% it can affect the system negatively. System loss reduction and maintaining the minimum and maximum voltage limits are the most important concerns in power systems. The following conclusions were drawn from the results and analysis:

Losses variation on Lusaka distribution network due to Solar PV plant integration have a sort of "bathtub curve or Nike mark" shape behavior. The formation is due to the fact that as the penetration level increase, the line losses begin to decrease up to penetration level of 20% where again the line losses start to increase as the penetration level increase. In general, for low Solar PV penetration level, there was a small impact on the losses, but this was changing as the penetration level is increased. It was found that losses decreased but again begun to increase for higher penetration level.

During the analysis of the Solar PV integration into the 33kV Lusaka distribution network, the following are some advantages:

1. The steady increase in the penetration level into the network causes a decrease of power demand from the generation source as shown by the results.
2. The steady increase in penetration resulted in reduction in the transformer loadings as shown by the results.
3. Solar PV integration to the 33kV distribution network system can bring voltage stability to the system for as long as penetration level increases and improvement in the losses for penetration levels less than 20%.
4. Connecting Solar PV at the 33kV distribution substations will result in the increased availability of power for the local demand which will entail an increase in the number of customers to be serviced.

During the analysis of the Solar PV integration into the 33kV Lusaka distribution network, the following are some of the disadvantages of connecting DGs to the main grid are:

1. Penetration of Solar PV into a distribution network system causes an increase in the fault level of the network at any fault location.
2. Penetration of a Solar PV in the distribution network system causes it to lose its radial power flow characteristics for penetration levels more than 50%.
3. Increase in penetration level of Solar PV contributes to the changes in power flow direction which may cause mis-coordination between protection devices.
4. Penetration of a Solar PV in the distribution network system causes increase in the system power losses for penetration levels more than 20%.

Based on the analysis on chapter six figure 71, the six substations have been ranked in the order of priority that gives the best benefits in terms of power losses as follows:

1. Makeni substation
2. Chelstone substation
3. Chawama substation
4. Avondale substation
5. Chilanga substation
6. Mapepe substation

It is concluded that by analyzing the impact of location and size of solar PV plant on the Lusaka 33kV distribution network implementation based on load flow simulation, it helps to determine the penetration levels to improve the system power losses and voltage profiles. This also present as an opportunity to stakeholders such as power system planners and operators, policy makers and regulators, developers and customers in the electricity energy supply industry.

5.2. Recommendations

i. The project findings show that the magnitude of the losses in the current system (base case) are quite high. These can be mitigated by integrating solar PV plants to the 33kV Zesco Lusaka distribution grid network and setting the penetration level to less than 21%.

ii. Improving on meeting power demand at heavy loads, losses and voltage profiles can be achieved by adequate distribution of solar PV plants in relation to impact of penetration levels and land availability near the substations.

iii. Integrating solar PV plants at more than 50MW penetration levels is likely to bring system protection instability due to change or reverse in power flow direction. If it is to be connected to the main grid, then reverse power relays equipment should be employed which in turn increases the cost.

The following are future works for possible consideration but not limited to:

i. Impact of location and size solar PV plants for integration at 11kV distribution network.
ii. Optimal location and size of solar PV plant for integration in the Lusaka distribution grid network.
iii. Impact of location and size of solar PV plant on protection system for integration in the Lusaka distribution grid network.

REFERENCES

Ahmed, K., Alaam M, A., Ahmed, M. A. & Abdelaziz, A. Y., 2013. Protection Coordination of Distribution systems equipped with Distributed Genrations. Electrical and Electronics Engineering: An International journal, 2(2), pp. 1-13.

Alasdair, M. & Lumby, B., 2012. Utility scale solar power plant, a guide for developer and investors. Delhi, India: International Finance Corporation, World Bank group.

Andrew T, M., 2008. Distributed Generation Protection Overview. Ontario: University of Western Ontario.

Athira, J. & Tibin, J., 2013. Optimal placement of solar PV in distribution system using particle swarm optimization. International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, 2(1), pp. 329-337.

Athira, J. & Tibin, J., 2013. Optimal placement of solar PV in Distribution system using particle swarm optimization. International Journal of advanced research in Electrical, Electronics and Instrumentation Engineering, 2(1), pp. 329-337.

Begovic, M., Pregelj, A., Rohatgi, A. & Novosel, D., 2001. Impact of Renewable Distributed Generation on Power Systems. Hawaii, s.n.

Bhanu, B. & Boora, S., 2016. An Analytical approach to find size of Distributed Generator for allocation in Radial Distribution Networks. International Journal of Advanced Research in Electrical. Electronics and Instrumentation Engineering, 5(7), pp. 6073-6082.

DIgSILENT, 2013. DIgSILENT powerfactory version 15 tutorial. Gomaringen, Germany: DIgSILENT GmbH.

Dumitru, F. S., Stanescu, D. & Golovanov, N., 2015. Impact of Distributed Generation on distribution networks. Lyon, International Conference on Electrical Distribution.

Energy Regulation Board, 2013. The Electricity (Grid Code) Regulations. Lusaka: Energy Regulation Board.

Energy Regulation Board, 2017. Energy Sector Report 2016, Lusaka: Energy Regulation Board.

Griffin, T., Tomsovic, K., Secrest, D. & Law, A., 2000. Placement of Dispersed Generations Systems for reduced losses. Hawaii, s.n.

Gupta, D. B., 2014. Power System Analysis and Design. New Delhi: S. Chand and Company PVT Limited.

Institute of Electrical and Electronics Engineers, March/ April 2013. Power and Energy for Electrical power proffessionals. IEEE, 11(2), pp. 18-54.

Institute of Electrical and Electronics Engineers, November/ December 2015. Power and Energy for Electric power proffessionals. IEEE, 13(6), pp. 67-87.

Jegadeesan, M. & Keerthana, V., 2014. Optimal sizing and placement of Distributed Generation in Radial Distribution feeder using Analytical approach. International Journal of Innovative Research in Science, Engineering and Technology, 3(3), pp. 358-364.

Mango, S., 2015. [Online] Available at: www.solarmango/scp/area-required-for-solar-pv-power-plants [Accessed 27 07 2017].

Masoud, F., Azah, M., Hussain, S. & Hadi, Z., 2013. Power Quality of Grid-Connected Photovoltaic Systems in Dsitribution Networks. University Kebangsaan Malaysia, 89(2), pp. 208-213.

Meghana, M., 2011. Optimal siting and sizing of solar PV Distributed Generation to Minimize loss, present value of future Asset upgrades and Peak demand costs on a Real distribution feeder. Ontario, Canada: University of Waterloo.

Ministry of Energy and Water Development, 2011. Power System Master Plan for Zambia, Lusaka: Ministry of Energy and Water Development.

Mohammed, A. & amer, A.-H., 2012. Optimal allocation of Renewable-Based DG Resources in Rural Areas Using Genetic Algorithms. Asia - Pacific, s.n.

Murali, G. & Manivannan, A., 2013. Analysis of power quality problems in solar power distribution system. International Journal of Engineering Research and Applications, 3(2), pp. 799-805.

Naser, M., Njat, M. & Parsaei, A. T., 2014. Optimal sizing and placement of Distributed Generation sources in power systems based on analytical method and DIgSILENT. International Journal on Technical and Physical problems of Engineering, 6(4), pp. 30-36.

Nibedita, G., Sharmistha, S. & Subhadeep, B., 2012. A load flow based approach for optimum allocation of Distributed Generation Units in the Distribution network for voltage improvement and loss minimization. International Journal of computer applications, 50(15), pp. 15-22.

Niti, S., Smarajit, G. & Krishna, M., 2015. Optimal sizing and placement of DG in a Radial Distribution Network using Sensitivity based methods. International Electrical Engineering Journal, 6(1), pp. 1727-1734.

Parknison, G., 2013. Renew Economy. [Online] Available at: http://reneweconomy.com.au/2013/the-top-solar-countries-past-present-and-future-96405 [Accessed 20 July 2016].

Pecas, J. L., Hatziargyriou, N., Mutale, J. & Djapic, P., 2007. Integrating distributed generation into electric power systems: A review of drivers, challenges and opportunities. Electric Power system Research, 77(9), pp. 1189-1203.

Rentechno Group, 2009. Rentechno. [Online] Available at: https://rentechno.ua/en/solar/utility-scale.htm [Accessed 18 12 2018].

Rugthaicharoencheep, N. & Auchariyamet, S., 2012. Technical and Economic impacts of Distributed Generation on Distribution system. International Journal of Electrical, Computer, Energetic, Electronics and Communication Engineer, 6(4), pp. 385-389.

Rugthaicharoencheep, N. & Auchariyamet, S., 2012. Technical and Economic Impacts of Distributed Generation on Distribution System. International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering, 6(4), pp. 385-389.

Salem, E., Mohammed, B. & Joydeep, M., 2014. Analytical approach for placement and sizing of distributed generation on distribution systems. Institution of Engineering and Technology, 8(6), pp. 1038-1049.

Seyed Ali, M. J. & Maryam, M., 2011. Impact of distributed generation on distribution system's relaibility considering recloser-fuse miscoordination - A practical case study. Indian Journal of science and technology, 4(10), pp. 1279-1284.

Sheikhi, A., Maani, A., Safe, F. & Ranjbar, A., 2013. Distributed Generation Penetration Impact on Distribution network loss. Renewable Energy and Power Quality Journal, 1(11), pp. 730-735.

Siliya, D., 2016. Diversifying Zambia's energy mix for a resilient power sector. Mulungushi International conference center, Lusaka, s.n.

Singh, N., 2014. Optimal sizing and placement of DG in a Radial Distribution Network using Sensitivity based methods. Punjab (India): Thapar University.

Sunil, Santosh, K. V. & Basavareddy, 2015. Distributed generation impact on rural distribution network for loss reduction and voltage profile improvement - A case study using PWS. International Journal of Electronics, Electrical and Computational system, 4(3), pp. 36-42.

Surakit, T. & Attapol, N., 2013. Impacts of Electrical Lines Losses Comprising Multi-Distributed Generation in Distribution System. Energy and Power Engineering, 5(1), pp. 1037-1042.

Weedy, B., B.J.Cory, N.Jenkins & J.B.Ekanayake, 2012. Electric Power Systems - Fifth edition. Atrium: A John Wiley & Sons, Ltd.

World Nuclear Association , 2016. World Nuclear Association. [Online] Available at: http://www.world-nuclear.org/information-library/current-and-future-generation/world-energy-needs-and-nuclear-power.aspx
[Accessed 18 12 2018].

Yogendra, S. R., Daka, S. R. & Kesava, G. R., 2016. Optimal siting and sizing of solar power sources in interconnection grid system. Indian Journal of science and Technology, 9(12), pp. 1-9.

Zambezi River Authority, 2017. Lake level. [Online] Available at: www.zahaho.org.zm/hydrology/lake-levels [Accessed 02 May 2017].

Ministry of Energy and Water Development, 2008. National Energy Policy. Lusaka: Ministry of Energy and Water Development.

APPENDICES

Appendix – A

Generation stations, transmission and distribution network map

The map of Zambia shows the generation stations, transmission and distribution network at different voltage levels in Zambia.

Appendix – B

Lusaka 33kV geographical and distribution network drawings

Appendix shows the following attached hard copies drawings obtained from Zesco:

1. Lusaka 33kV Distribution network drawing No. LUS-GEN-DE-08-A-11746 rev 4;
2. Lusaka Division 33kV Distribution Network Operation configuration drawing No. LUS-GEN-DE-08-G-12253 rev 8 and
3. Lusaka 33kV Network geographical representation drawing No. LUS-GEN-DE-08-E-11829 as obtained from Zesco.

Appendix – C

System parameters from Zesco

Table C 1 Overhead line parameters for 33kV Single Circuit – Earthed

Earth wire No.	Description	Type	Strand	Dia(mm)	Resistance (W/km)	Earth Resist (Ohm-m)	Wind speed (cm/sec)	Solar Rad (W/sqm)	Line Altitude (m)	Max Amb Temp (^{0}C)
1	Gal. Steel	22mm^2	7/2.0	5.29	6.94	500	100	1100	1500	35
2	Gal. Steel	22mm^2	7/2.0	5.29	6.94	500	100	1100	1500	35

Table C 2 Earth wire data

Conductor Name	Cond Type	Stranding (No. & Strand dia)	Dia (mm)	No. of Cond per ph	Bundle spacing (mm)	Rating (Amps/ph)	Sequence Impedance	Resistance (W/km)	Reactance (W/km)	Susceptance (ms/km)
Dog 100mm^2	ACSR	Al: 6/4.72 St: 7/1.57	14.15	1		313	Z1	0.323	0.349	3.147
							Z0	0.622	1.615	1.783
Wolf 150mm^2	ACSR	Al:30/2.59 St: 7/2.59	18.13	1		399	Z1	0.216	0.334	3.294
							Z0	0.515	1.599	1.829
Panther 200mm^2	ACSR	Al: 30/3.0 St: 7/3.0	21.00	1		474	Z1	0.162	0.324	3.388
							Z0	0.460	1.590	1.858
Bison 300mm^2	ACSR	Al: 54/3.0 St: 7/3.0	27.00	1		659	Z1	0.090	0.309	3.562
							Z0	0.389	1.574	1.909

Appendix – D

DIgSILENT diagram colouring scheme

To get visible information about the system loading of element comparison with the baseline case against after solar PV plant integration, it was necessary to determine the results from simulation through graphic colouring. The diagram below shows the 'Diagram colouring scheme setting' and the 'Project colour settings for voltage limits of node elements and loading limits of edge elements' which was used during simulation.

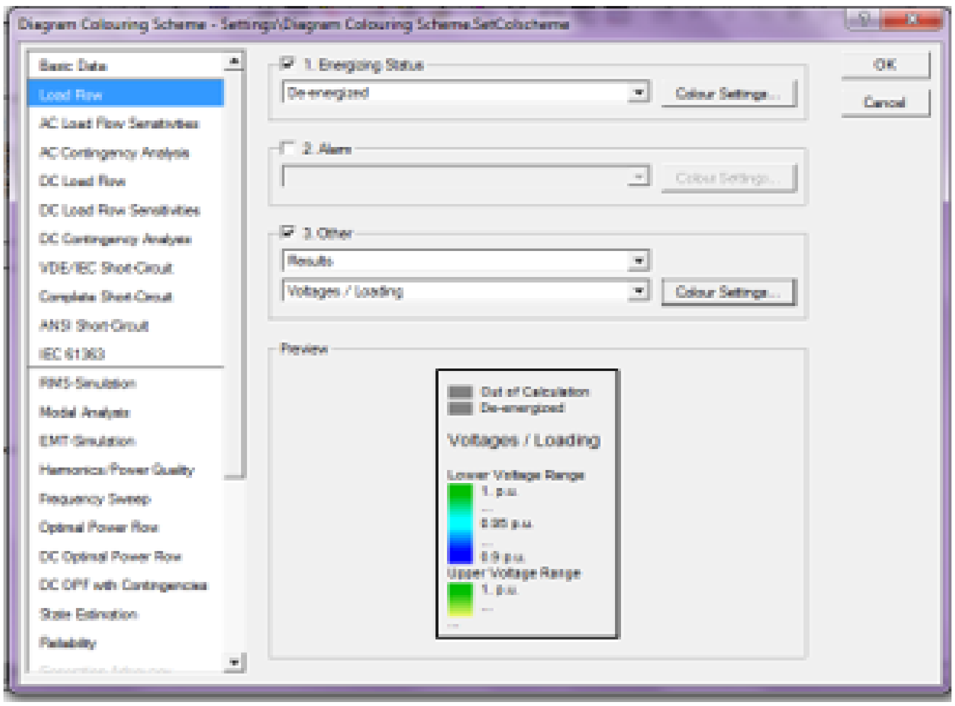

Figure D 1 Diagram Colouring Scheme – Setting

Appendix – E

Load flow results from DIgSILENT

IMPACT OF VARYING THE SIZE OF SOLAR PV PLANT AT MAKENI SUBSTATION

Table E 1 Solar PV plant penetration level effect on bus voltage and line losses at Makeni substation

PENETRATION LEVEL	BUS VOLTAGE (P.U)	TOTAL LINE LOSSES (MW)
0%	0.920	0.526
13.41%	0.932	0.283
26.82%	0.943	0.219
40.23%	0.954	0.322
53.64%	0.964	0.582
67.05%	0.973	0.958
80.46%	0.983	1.534
93.87%	0.992	2.212
107.28%	1.000	3.017

Table E 2 Major Transformers capacity relief impact due to integration at Makeni substation

MAJOR TRANSFORMERS	0%	13.41%	26.82%	40.23%	53.64%	67.05%	80.46%	93.87%	107.28%
Kafue Town 45MVA 330/88/33kV Tx	66.8	65.3	63.8	62.4	61.1	59.8	58.5	57.3	56.2
Lusaka West 125MVA 330/132/33kV Tx1	94.1	91.7	89.5	87.3	85.3	83.4	81.6	79.9	78.3
Lusaka West 125MVA 330/132/33kV Tx2	94.1	91.7	89.5	87.3	85.3	83.4	81.6	79.9	78.3
Leopards 150MVA 330/132/88kV Tx1	116	114.9	113.8	112.8	111.9	111	110.2	109.3	108.6
Leopards 150MVA 330/132/88kV Tx2	116	114.9	113.8	112.8	111.9	111	110.2	109.3	108.6
Leopards 108MVA 330/88kV Tx1	89.6	88.8	88.1	87.4	86.7	86.1	85.5	84.9	84.3
Leopards 108MVA 330/88kV Tx2	89.6	88.8	88.1	87.4	86.7	86.1	85.5	84.9	84.3

Table E 3 Inter grid power flow for 330kV power supply for the Lusaka distribution network impact due to integration at Makeni substation

INTER GRID POWER FLOW	0%	13.41%	26.82%	40.23%	53.64%	67.05%	80.46%	93.87%	107.28%
Mapepe 132/88/33Kv	60.67	59.24	57.84	56.46	55.11	53.77	52.46	51.16	49.88
Lusaka West 132/33Kv	193.65	187.22	180.94	174.79	168.77	162.87	157.09	151.41	145.84
Coventry 132/33Kv	185.14	183.09	181.09	179.15	177.27	175.43	173.63	171.88	170.16
Waterworks 88/33Kv	59.62	59.14	58.68	58.24	57.81	57.40	57.00	56.61	56.24
Fig tree 88/33Kv	47.41	47.31	47.21	47.12	47.03	46.94	46.86	46.79	46.72
Total Inter grid flow	**546.49**	**536.00**	**525.76**	**515.76**	**505.99**	**496.41**	**487.04**	**477.85**	**468.84**

Table E 4 Lusaka Distribution Grid summary power losses at bulk supply substations impact due to integration at Makeni substation

BULK SUPPLY POINTS	**0%**	**13.41%**	**26.82%**	**40.23%**	**53.64%**	**67.05%**	**80.46%**	**93.87%**	**107.28%**
330kV Power Supply	2.26	2.25	2.25	2.25	2.25	2.25	2.26	2.26	2.27
Coventry	2.17	2.17	2.21	2.28	2.38	2.51	2.67	2.85	3.06
Coventry 132/33kV	3.26	3.21	3.16	3.12	3.07	3.03	3.00	2.96	2.93
Fig tree 33Kv	2.76	2.76	2.76	2.76	2.76	2.76	2.76	2.76	2.76
Fig tree 88/33kV	1.24	1.24	1.23	1.23	1.23	1.23	1.23	1.23	1.22
Lusaka West	3.58	3.23	3.10	3.15	3.39	3.80	4.38	5.10	5.98
Lusaka West 132/ 33kV	0.48	0.48	0.48	0.49	0.49	0.49	0.49	0.49	0.49
Mapepe 132/ 88/ 33kV	1.31	1.25	1.20	1.15	1.10	1.05	1.01	0.97	0.93
Roma	2.25	2.24	2.23	2.22	2.21	2.20	2.19	2.19	2.18
Waterworks	1.47	1.46	1.46	1.45	1.45	1.45	1.45	1.44	1.44
Waterworks 88/33kV	1.53	1.51	1.49	1.48	1.46	1.44	1.43	1.42	1.40
Total (MW)	**22.31**	**21.8**	**21.57**	**21.58**	**21.79**	**22.21**	**22.87**	**23.67**	**24.66**

IMPACT OF VARYING THE SIZE OF SOLAR PV PLANT AT AVONDALE SUBSTATION

Table E 5 Solar PV plant penetration level effect on bus voltage and line losses at Avondale substation

PENETRATION LEVEL	BUS VOLTAGE (P.U)	TOTAL LINE LOSSES (MW)
0%	0.905	0.397
18.12%	0.912	0.347
36.24%	0.920	0.403
54.36%	0.927	0.562
72.48%	0.933	0.819
90.60%	0.940	1.170
108.71%	0.946	1.612
126.83%	0.952	2.141

Table E 6 Major Transformers capacity relief impact due to integration at Avondale substation

MAJOR TRANSFORMERS	0%	18.12%	36.24%	56.36%	72.48%	90.60%	108.71%	126.83%
Kafue Town 45MVA 330/88/33kV Tx	66.8	66.2	65.6	65	64.5	63.9	63.4	62.9
Lusaka West 125MVA 330/132/33kV Tx1	94.1	92.7	91.3	90	88.8	87.6	86.4	85.3
lusaka West 125MVA 330/132/33kV Tx2	94.1	92.7	91.3	90	88.8	87.6	86.4	85.3
Leopards 150MVA 330/132/88kV Tx1	116.0	114.1	112.3	110.6	108.9	107.2	105.6	104.0
Leopards 150MVA 330/132/88kV Tx2	116.0	114.1	112.3	110.6	108.9	107.2	105.6	104.0
Leopards 108MVA 330/88kV Tx1	89.6	87.7	85.9	84.1	82.3	80.6	79.0	77.4
Leopards 108MVA 330/88kV Tx2	89.6	87.7	85.9	84.1	82.3	80.6	79.0	77.4

Table E 7 Inter grid power flow for 330kV power supply for the Lusaka distribution network impact due to integration at Avondale substation

INTER GRID POWER FLOW	0%	18.12%	36.24%	56.36%	72.48%	90.60%	108.71%	126.83%
Mapepe 132/88/33Kv	60.67	60.50	60.34	60.18	60.03	59.88	59.74	59.60
Lusaka West 132/33Kv	193.65	189.68	185.78	181.90	178.19	174.50	170.86	167.28
Coventry 132/33kV	185.14	182.10	179.11	176.16	173.25	170.38	167.54	164.73
Waterworks 88/33Kv	59.62	59.12	58.64	58.17	57.71	57.26	56.82	56.39
Fig tree 88/33Kv	47.41	44.43	41.49	38.58	35.71	32.87	30.06	27.28
Total Inter grid flow	**546.49**	**535.84**	**525.37**	**515.05**	**504.89**	**494.88**	**485.01**	**475.28**

Table E 8 Lusaka Distribution Grid summary power losses at bulk supply substations impact due to integration at Avondale substation

BULK SUPPLY POINTS	**0%**	**18.12%**	**36.24%**	**56.36%**	**72.48%**	**90.60%**	**108.71%**	**126.83%**
330kV Power Supply	2.26	2.31	2.37	2.43	2.49	2.55	2.62	2.69
Coventry	2.17	2.10	2.03	1.98	1.92	1.88	1.84	1.81
Coventry 132/33kV	3.26	3.13	3.01	2.90	2.79	2.69	2.60	2.51
Fig tree 33kV	2.76	2.74	2.72	2.71	2.70	2.68	2.67	2.66
Fig tree 88/33kV	1.24	1.13	1.04	0.95	0.86	0.79	0.72	0.66
Lusaka West	3.58	3.52	3.45	3.39	3.33	3.28	3.23	3.18
Lusaka West 132/ 33kV	0.48	0.46	0.44	0.42	0.40	0.39	0.37	0.36
Mapepe 132/ 88/ 33kV	1.31	1.30	1.30	1.30	1.30	1.30	1.29	1.29
Roma	2.25	2.09	2.07	2.17	2.40	2.75	3.21	3.78
Waterworks	1.47	1.42	1.37	1.33	1.30	1.26	1.23	1.19
Waterworks 88/33 kV	1.53	1.51	1.49	1.47	1.45	1.43	1.41	1.39
Total (MW)	**22.31**	**21.71**	**21.29**	**21.05**	**20.94**	**21.00**	**21.19**	**21.52**

IMPACT OF VARYING THE SIZE OF SOLAR PV PLANT AT CHELSTONE SUBSTATION

Table E 9 Solar PV plant penetration level effect on bus voltage and line losses at Chelstone substation

PENETRATION LEVEL	BUS VOLTAGE (P.U)	TOTAL LINE LOSSES (MW)
0%	0.904	0.622
8.97%	0.908	0.549
17.95%	0.911	0.506
26.92%	0.915	0.493
35.90%	0.918	0.508
44.87%	0.921	0.551
53.85%	0.925	0.622
62.82%	0.928	0.719
71.80%	0.931	0.843
80.77%	0.934	0.993
89.74%	0.937	1.168
98.72%	0.940	1.378

Table E 10 Major Transformers capacity relief impact due to integration at Chelstone substation

MAJOR TRANSFORMERS	0%	8.97%	17.95%	26.92%	35.90%	44.87%	53.85%	62.82%	71.80%	80.77%	89.74%
Kafue Town 45MVA 330/88/33kV Tx	66.3	65.7	65.2	64.7	64.2	63.7	63.2	62.8	62.4	61.9	61.5
Lusaka West 125MVA 330/132/33kV Tx1	92.4	90.8	89.2	87.6	86.1	84.6	83.2	81.8	80.4	79.0	77.7
lusaka West 125MVA 330/132/33kV Tx2	92.4	90.8	89.2	87.6	86.1	84.6	83.2	81.8	80.4	79.0	77.7
Leopards 150MVA 330/132/88kV Tx1	113.7	111.4	109.2	107.0	104.8	102.7	100.6	98.5	96.5	94.4	92.4
Leopards 150MVA 330/132/88kV Tx2	113.7	111.4	109.2	107.0	104.8	102.7	100.6	98.5	96.5	94.4	92.4
Leopards 108MVA 330/88kV Tx1	88.5	87.3	86.2	85.1	84.1	83.0	82.0	81.0	80.0	79.1	78.1
Leopards 108MVA 330/88kV Tx2	88.5	87.3	86.2	85.1	84.1	83.0	82.0	81.0	80.0	79.1	78.1

Table E 11 Inter grid power flow for 330kV power supply for the Lusaka distribution network impact due to integration at Chelstone substation

INTER GRID POWER FLOW	0%	8.97%	17.95 %	26.92 %	35.90 %	44.87 %	53.85 %	62.82 %	71.80 %	80.77 %	89.74 %	98.72 %
Mapepe 132/88/33kV	60.67	60.40	60.13	59.89	59.61	59.36	59.11	58.86	58.62	58.38	58.15	57.91
Lusaka West 132/33kV	193.65	189.08	184.54	180.03	175.57	171.13	166.73	162.36	158.02	153.72	149.44	145.20
Coventry 132/33kV	185.14	181.42	177.71	174.03	170.37	166.72	163.09	159.48	155.88	152.30	148.74	145.19
Waterworks 88/33kV	59.62	58.73	57.86	56.99	56.14	55.29	54.45	53.61	52.78	51.96	51.15	50.34
Fig tree 88/33kV	47.41	46.16	44.91	43.68	42.46	41.24	40.04	38.84	37.66	36.48	35.31	34.16

INTER GRID POWER FLOW	0%	8.97%	17.95 %	26.92 %	35.90 %	44.87 %	53.85 %	62.82 %	71.80 %	80.77 %	89.74 %	98.72 %
Total Inter grid flow	**546.49**	**535.78**	**525.16**	**514.61**	**504.14**	**493.74**	**483.41**	**473.15**	**462.97**	**452.84**	**442.79**	**432.80**

Table E 12 Lusaka Distribution Grid summary power losses at bulk supply substations impact due to integration at Chelstone substation

BULK SUPPLY POINTS	0%	8.97%	17.95 %	26.92 %	35.90 %	44.87 %	53.85 %	62.82 %	71.80 %	80.77 %	89.74 %	98.72 %
330kV Power Supply	2.26	2.30	2.34	2.39	2.44	2.49	2.54	2.60	2.66	2.73	2.79	2.86
Coventry	2.17	2.08	1.99	1.92	1.86	1.80	1.76	1.72	1.69	1.67	1.66	1.66
Coventry 132/33kV	3.26	3.11	2.96	2.82	2.69	2.56	2.44	2.33	2.23	2.13	2.04	1.95
Fig tree 33kV	2.76	2.75	2.74	2.72	2.71	2.71	2.70	2.69	2.68	2.67	2.67	2.66
Fig tree 88/33kV	1.24	1.20	1.15	1.11	1.07	1.04	1.00	0.97	0.93	0.90	0.87	0.84
Lusaka West	3.58	3.50	3.43	3.35	3.28	3.21	3.15	3.09	3.03	2.97	2.91	2.86
Lusaka West 132/ 33kV	0.48	0.46	0.43	0.41	0.39	0.37	0.35	0.33	0.32	0.30	0.29	0.28
Mapepe 132/ 88/ 33kV	1.31	1.30	1.29	1.29	1.28	1.28	1.27	1.27	1.26	1.26	1.25	1.25
Roma	2.25	2.07	1.94	1.86	1.82	1.83	1.89	1.99	2.14	2.32	2.55	2.82
Waterworks	1.47	1.40	1.33	1.27	1.21	1.16	1.11	1.06	1.01	0.97	0.93	0.89
Waterworks 88/33 kV	1.53	1.49	1.45	1.41	1.38	1.34	1.31	1.27	1.24	1.21	1.18	1.15
Total (MW)	**22.31**	**21.66**	**21.05**	**20.55**	**20.13**	**19.79**	**19.52**	**19.32**	**19.19**	**19.13**	**19.14**	**19.22**

IMPACT OF VARYING THE SIZE OF SOLAR PV PLANT AT CHAWAMA SUBSTATION

Table E 13 Solar PV plant penetration level effect on bus voltage and line losses at Chawama substation

PENETRATION LEVEL	BUS VOLTAGE (P.U)	TOTAL LINE LOSSES (MW)
0%	0.915	0.2173
16.43%	0.923	0.0763
32.86%	0.932	0.0917
49.30%	0.941	0.255
65.73%	0.949	0.558
82.16%	0.956	0.995
98.59%	0.964	1.560
115.02%	0.971	2.247

Table E 14 Major Transformers capacity relief impact due to integration at Chawama substation

MAJOR TRANSFORMERS	0%	16.43%	32.86%	49.30%	65.73%	82.16%	98.59%	111.02%
Kafue Town 45MVA 330/88/33kV Tx	66.8	63.2	59.8	56.5	53.3	50.2	47.3	44.6
Lusaka West 125MVA 330/132/33kV Tx1	94.1	92.6	91.1	89.7	88.4	87.1	85.9	84.7
lusaka West 125MVA 330/132/33kV Tx2	94.1	92.6	91.1	89.7	88.4	87.1	85.9	84.7
Leopards 150MVA 330/132/88kV Tx1	116.0	114.9	113.8	112.9	111.9	111.0	110.1	109.2
Leopards 150MVA 330/132/88kV Tx2	116.0	114.9	113.8	112.9	111.9	111.0	110.1	109.2
Leopards 108MVA 330/88kV Tx1	89.6	88.0	86.4	84.9	83.5	82.1	80.7	79.4
Leopards 108MVA 330/88kV Tx2	89.6	88.0	86.4	84.9	83.5	82.1	80.7	79.4

Table E 15 Inter grid power flow for 330kV power supply for the Lusaka distribution network impact due to integration at Chawama substation

INTER GRID POWER FLOW	0%	16.43%	32.86%	49.30%	65.73%	82.16%	98.59%	111.02%
Mapepe 132/88/33Kv	60.67	56.95	53.28	49.67	46.10	42.57	39.10	35.66
Lusaka West 132/33Kv	193.65	189.447	185.37	181.34	177.39	173.51	169.70	165.95
Coventry 132/33kV	185.14	183.25	181.40	179.58	177.81	176.06	174.35	172.66
Waterworks 88/33Kv	59.62	59.00	58.39	57.80	57.23	56.66	56.11	55.57
Fig tree 88/33Kv	47.41	47.31	47.22	47.13	47.04	46.96	46.88	46.80
Total Inter grid flow	**546.49**	**535.97**	**525.66**	**515.52**	**505.56**	**495.77**	**486.13**	**476.65**

Table E 16 Lusaka Distribution Grid summary power losses at bulk supply substations impact due to integration at Chawama substation

BULK SUPPLY POINTS	0%	16.43%	32.86%	49.30%	65.73%	82.16%	98.59%	111.02%
330kV Power Supply	2.26	2.29	2.32	2.35	2.39	2.42	2.46	2.50
Coventry	2.17	2.00	2.00	2.16	2.47	2.93	3.53	4.26
Coventry 132/33kV	3.26	3.21	3.16	3.11	3.07	3.02	2.98	2.94
Fig tree 33Kv	2.76	2.76	2.76	2.75	2.75	2.75	2.75	2.75
Fig tree 88/33kV	1.24	1.24	1.23	1.23	1.23	1.23	1.23	1.22
Lusaka West	3.58	3.50	3.42	3.34	3.28	3.21	3.15	3.09
Lusaka West 132/ 33kV	0.48	0.46	0.44	0.42	0.40	0.39	0.37	0.36
Mapepe 132/ 88/ 33kV	1.31	1.17	1.04	0.93	0.82	0.73	0.64	0.57
Roma	2.25	2.24	2.23	2.22	2.21	2.21	2.20	2.20
Waterworks	1.47	1.46	1.46	1.45	1.45	1.45	1.45	1.44
Waterworks 88/33 kV	1.53	1.51	1.48	1.46	1.43	1.41	1.39	1.37
Total (MW)	**22.31**	**21.84**	**21.54**	**21.42**	**21.5**	**21.75**	**22.15**	**22.7**

IMPACT OF VARYING THE SIZE OF SOLAR PV PLANT AT CHILANGA SUBSTATION

Table E 17 Solar PV plant penetration level effect on bus voltage and line losses at Chilanga substation

PENETRATION LEVEL	BUS VOLTAGE (P.U)	TOTAL LINE LOSSES (MW)
0%	0.920	0.147
18.97%	0.926	0.132
37.94%	0.932	0.163
56.91%	0.938	0.240
75.88%	0.943	0.361
94.85%	0.949	0.524
113.82%	0.954	0.728

Table E 18 Major Transformers capacity relief impact due to integration at Chilanga substation

MAJOR TRANSFORMERS	0%	18.97%	37.94%	56.91%	75.88%	94.85%	113.82 %
Kafue Town 45MVA 330/88/33kV Tx	66.8	61.2	55.7	50.5	45.5	40.8	36.4
Lusaka West 125MVA 330/132/33kV Tx1	94.1	93.0	91.9	90.9	90.0	89.0	88.1
lusaka West 125MVA 330/132/33kV Tx2	94.1	93.0	91.9	90.9	90.0	89.0	88.1
Leopards 150MVA 330/132/88kV Tx1	116.0	115.4	114.8	114.3	113.8	113.3	112.8
Leopards 150MVA 330/132/88kV Tx2	116.0	115.4	114.8	114.3	113.8	113.3	112.8
Leopards 108MVA 330/88kV Tx1	89.6	87.5	85.4	83.4	81.4	79.5	77.6
Leopards 108MVA 330/88kV Tx2	89.6	87.5	85.4	83.4	81.4	79.5	77.6

Table E 19 Inter grid power flow for 330kV power supply for the Lusaka distribution network impact due to integration at Chilanga substation

INTER GRID POWER FLOW	0%	18.97%	37.94%	56.91%	75.88%	94.85%	113.82%
Mapepe 132/88/33Kv	60.67	54.64	48.65	42.70	36.80	30.94	25.12
Lusaka West 132/33kV	193.65	190.43	187.26	184.14	181.07	178.05	175.07
Coventry 132/33kV	185.14	184.05	182.98	181.94	180.93	179.93	178.95
Waterworks 88/33kV	59.62	59.47	59.33	59.19	59.06	58.93	58.81
Fig tree 88/33kV	47.41	47.43	47.45	47.46	47.48	47.50	47.53
Total Inter grid flow	**546.49**	**536.01**	**525.66**	**515.44**	**505.34**	**495.36**	**485.49**

Table E 20 Lusaka Distribution Grid summary power losses at bulk supply substations impact due to integration at Chilanga substation

BULK SUPPLY POINTS	**0%**	**18.97%**	**37.94%**	**56.91%**	**75.88%**	**94.85%**	**113.82%**
330kV Power Supply	2.26	2.30	2.34	2.38	2.43	2.47	2.52
Coventry	2.17	2.05	2.03	2.10	2.25	2.50	2.82
Coventry 132/33kV	3.26	3.23	3.21	3.18	3.15	3.13	3.11
Fig tree 33kV	2.76	2.76	2.76	2.76	2.76	2.76	2.76
Fig tree 88/33kV	1.24	1.24	1.24	1.24	1.24	1.24	1.25
Lusaka West	3.58	3.49	3.41	3.33	3.26	3.20	3.14
Lusaka West 132/ 33kV	0.48	0.47	0.46	0.45	0.44	0.43	0.42
Mapepe 132/ 88/ 33kV	1.31	1.09	0.89	0.72	0.58	0.45	0.35
Roma	2.25	2.24	2.24	2.24	2.23	2.23	2.23
Waterworks	1.47	1.47	1.47	1.47	1.47	1.47	1.47
Waterworks 88/33 kV	1.53	1.53	1.52	1.52	1.51	1.51	1.51
Total (MW)	**22.31**	**21.87**	**21.57**	**21.39**	**21.32**	**21.39**	**21.58**

IMPACT OF VARYING THE SIZE OF SOLAR PV PLANT AT MAPEPE SUBSTATION

Table E 21 Solar PV plant penetration level effect on bus voltage and line losses at Mapepe substation

PENETRATION LEVEL	BUS VOLTAGE (P.U)	TOTAL LINE LOSSES (MW)
0%	0.933	0.199
5.56%	0.937	0.232
11.11%	0.941	0.269
16.67%	0.944	0.311
22.22%	0.948	0.357
27.78%	0.951	0.407
33.33%	0.954	0.520
38.89%	0.957	0.582
44.44%	0.960	0.649
50.00%	0.963	0.649
55.56%	0.966	0.719
61.11%	0.969	0.793
66.67%	0.971	0.871
72.22%	0.974	0.953
77.78%	0.976	1.039
83.33%	0.978	1.128
88.89%	0.980	1.221
94.44%	0.982	1.318
100%	0.984	1.419

Table E 22 Major Transformers capacity relief impact due to integration at Mapepe substation

MAJOR TRANSFORMERS	0%	5.56%	11.11%	16.67%	22.22%	27.78%	33.33%	38.89%	44.44%
Kafue Town 45MVA 330/88/33kV Tx	66.8	60.2	53.7	47.6	41.8	36.6	32.2	28.8	26.9
Lusaka West 125MVA 330/132/33kV Tx1	94.1	93.3	92.6	91.8	91.1	90.4	89.8	89.1	88.5
lusaka West 125MVA 330/132/33kV Tx2	94.1	93.3	92.6	91.8	91.1	90.4	89.8	89.1	88.5
Leopards 150MVA 330/132/88kV Tx1	116.0	115.6	115.4	115.1	114.8	114.6	114.3	114.1	113.9
Leopards 150MVA 330/132/88kV Tx2	116.0	115.6	115.4	115.1	114.8	114.6	114.3	114.1	113.9
Leopards 108MVA 330/88kV Tx1	89.6	87.2	84.8	82.5	80.3	78.0	75.9	73.7	71.6
Leopards 108MVA 330/88kV Tx2	89.6	87.2	84.8	82.5	80.3	78.0	75.9	73.7	71.6

MAJOR TRANSFORMERS	50.00 %	55.56 %	61.11 %	66.67 %	72.22 %	77.78 %	83.33 %	88.89 %	94.44 %	100%
Kafue Town 45MVA 330/88/33kV Tx	26.8	28.4	31.4	35.6	40.4	45.8	51.4	57.3	63.4	69.5
Lusaka West 125MVA 330/132/33kV Tx1	87.9	87.4	86.8	86.3	85.8	85.3	84.8	84.4	84.0	83.6
Lusaka West 125MVA 330/132/33kV Tx2	87.9	87.4	86.8	86.3	85.8	85.3	84.8	84.4	84.0	83.6
Leopards 150MVA 330/132/88kV Tx1	113.7	113.5	113.3	113.2	113.0	112.9	112.7	112.6	112.5	112.4
Leopards 150MVA 330/132/88kV Tx2	113.7	113.5	113.3	113.2	113.0	112.9	112.7	112.6	112.5	112.4
Leopards 108MVA 330/88kV Tx1	69.6	67.6	65.7	63.8	62.0	60.3	58.6	57.0	55.5	54.0
Leopards 108MVA 330/88kV Tx2	69.6	67.6	65.7	63.8	62.0	60.3	58.6	57.0	55.5	54.0

Table E 23 Inter grid power flow for 330kV power supply for the Lusaka distribution network impact due to integration at Mapepe substation

INTER GRID POWER FLOW	0%	5.56%	11.11 %	16.67 %	22.22 %	27.78 %	33.33 %	38.89 %	44.44 %
Mapepe 132/88/33kV	60.67	53.17	45.71	38.27	30.87	23.49	16.14	8.82	1.53
Lusaka West 132/33kV	193.65	191.23	188.84	186.47	184.13	181.83	179.54	177.29	175.06
Coventry 132/33kV	185.14	184.55	183.97	183.41	182.87	182.33	181.81	181.29	180.79
Waterworks 88/33kV	59.62	59.71	59.81	59.91	60.01	60.11	60.21	60.32	60.42
Fig tree 88/33kV	47.41	47.48	47.56	47.63	47.70	47.77	47.85	47.92	47.99
Total Inter grid flow	**546.49**	**536.15**	**525.89**	**515.70**	**505.58**	**495.53**	**485.55**	**475.64**	**465.79**

INTER GRID POWER FLOW	50.00 %	55.56 %	61.11 %	66.67 %	72.22 %	77.78 %	83.33 %	88.89 %	94.44 %	100%
Mapepe 132/88/33kV	-5.74	-12.98	-20.20	-27.39	-34.55	-41.69	-48.81	-55.90	-62.97	-70.02
Lusaka West 132/33kV	172.86	170.68	168.53	166.41	164.30	162.23	160.17	158.14	156.14	154.15
Coventry 132/33kV	180.86	179.82	179.35	178.90	178.45	178.02	177.59	177.17	176.77	176.38
Waterworks 88/33kV	60.53	60.64	60.74	60.85	60.96	61.08	61.19	61.30	61.41	61.53
Fig tree 88/33kV	48.06	48.13	48.20	48.27	48.34	48.41	48.48	48.55	48.62	48.69
Total Inter grid flow	**456.01**	**446.29**	**436.64**	**427.04**	**417.51**	**408.03**	**398.62**	**389.27**	**379.97**	**370.73**

Table E 24 Lusaka Distribution Grid summary power losses at bulk supply substations impact due to integration at Mapepe substation

BULK SUPPLY POINTS	0%	5.56%	11.11%	16.67%	22.22%	27.78%	33.33%	38.89%	44.44%	50.00%
330kV Power Supply	2.26	2.31	2.36	2.41	2.46	2.51	2.57	2.62	2.68	2.74
Coventry	2.17	2.17	2.20	2.27	2.37	2.51	2.67	2.87	3.10	3.35
Coventry 132/33kV	3.26	3.25	3.23	3.22	3.20	3.19	3.18	3.17	3.16	3.15
Fig tree 33Kv	2.76	2.76	2.76	2.76	2.76	2.76	2.76	2.76	2.76	2.76
Fig tree 88/33kV	1.24	1.24	1.24	1.25	1.25	1.25	1.25	1.26	1.26	1.26
Lusaka West	3.58	3.52	3.47	3.41	3.36	3.32	3.27	3.23	3.20	3.16
Lusaka West 132/ 33kV	0.48	0.47	0.47	0.46	0.45	0.44	0.43	0.43	0.42	0.41
Mapepe 132/ 88/ 33kV	1.31	1.05	0.82	0.63	0.47	0.35	0.25	0.19	0.16	0.16
Roma	2.25	2.25	2.25	2.25	2.24	2.24	2.24	2.24	2.24	2.24
Waterworks	1.47	1.47	1.47	1.47	1.47	1.48	1.48	1.48	1.48	1.49
Waterworks 88/33 kV	1.53	1.54	1.54	1.55	1.55	1.56	1.56	1.57	1.58	1.58
Total (MW)	**22.31**	**22.03**	**21.81**	**21.68**	**21.58**	**21.61**	**21.66**	**21.82**	**22.04**	**22.3**

BULK SUPPLY POINTS	55.56%	61.11%	66.67%	72.22%	77.78%	83.33%	88.89%	94.44%	100%
330kV Power Supply	2.80	2.87	2.93	3.00	3.06	3.13	3.20	3.27	3.35
Coventry	3.64	3.96	4.30	4.68	5.08	5.51	5.96	6.45	6.96
Coventry 132/33kV	3.14	3.13	3.12	3.11	3.11	3.10	3.09	3.09	3.08
Fig tree 33Kv	2.76	2.76	2.76	2.76	2.76	2.76	2.76	2.76	2.77
Fig tree 88/33kV	1.26	1.27	1.27	1.27	1.27	1.28	1.28	1.28	1.28

BULK SUPPLY POINTS	55.56%	61.11%	66.67%	72.22%	77.78%	83.33%	88.89%	94.44%	100%
Lusaka West	3.13	3.10	3.07	3.05	3.02	3.01	2.99	2.97	2.96
Lusaka West 132/ 33kV	0.41	0.40	0.40	0.40	0.39	0.39	0.38	0.38	0.38
Mapepe 132/ 88/ 33kV	0.19	0.25	0.34	0.45	0.60	0.77	0.97	1.20	1.45
Roma	2.24	2.25	2.25	2.25	2.25	2.25	2.25	2.26	2.26
Waterworks	1.49	1.49	1.55	1.50	1.50	1.50	1.51	1.51	1.51
Waterworks 88/33 kV	1.59	1.59	1.60	1.61	1.61	1.62	1.63	1.63	1.64
Total (MW)	**22.65**	**23.07**	**23.59**	**24.08**	**24.65**	**25.32**	**26.02**	**26.8**	**27.64**