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# The Impact of Solar Distributed Generation on Distribution Networks: Case Study of Chipata Distribution Network

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**Abstract:- The installation of solar PV systems in distribution networks is slowly increasing. The study focused on identifying the challenges and benefits of installing Distributed Solar Generation in the Chipata 33kV and 11kV distribution Networks. Chipata Town is in the Eastern Part of Zambia, and it has a peak demand of about 23.3MW. The 2023 version Power Factory Dig Silent Software was used to model the Chipata 33kV and 11kV distribution network and different Solar penetration levels were used to understand the impact of Distributed Solar. Chipata Distribution Network has four major stations operating at 33kV and 11kV voltages and four main distribution lines. The main objective of the study was to determine the impact of distributed solar PV in the Chipata Distribution Network. One of the specific objectives was to determine the hosting capacity of the Chipata Distribution Network. The hosting capacity gives the maximum amount of PV power integrated in a power system network without violating the set operation limits. The study analysed the impact of solar Distributed Generation on network losses, fault levels, voltage stability and line loading. The study revealed that an increase in penetration level resulted in a general increase in the Bus Bar voltages on both 11kV and 33kV voltage levels. Different Penetration levels of solar ranging from 6.66MW to 132MW were studied. Simulations revealed that the hosting capacity for Chipata Distribution Network is 96MW (412% of Solar PV Penetration Level). The voltages in the distribution network at hosting capacity were ranged from 0.93p.u to 1.02p.u. Short Circuit analysis simulations showed negligible impact on the fault level after integration of solar in the distribution network. Some circuits showed both increased and reduced power losses with increased solar penetration. The obtained results indicated that increased installation of distributed Solar PV systems in the Distribution Network impacts voltage stability, line losses and line loading.**

***Keywords:-*** *Photo Voltaic, Distributed Generation, Hosting Capacity, Solar Penetration.*

## I. INTRODUCTION

The energy needs globally are increasing daily and there is need to quickly meet the energy demands. According to the International Energy Outlook Report the global energy consumption will increase by 28% between 2015 and 2040. The increase is attributed to population growth and economic development (EIA, 2017). The population projections by the United Nations is that the global population may grow to around 8.5 billion in 2030, 9.7 billion in 2050 and 10.4 billion in 2100 (UN World Population Prospects, 2022). The research by Mwanza et al 2017 on the Assessment of Solar Energy Source Distribution and Potential in Zambia indicated that Zambia has approximately 20,442TWh/year technical solar energy potential and the country approximately receives about 2109.97kWh/m² of solar energy per year with 4403.12hours of sunshine. The research further concluded that Zambia has approximately 186,121km² available and suitable land area for renewable energy technologies.

Distributed generation has the potential to increase the system efficiency (Doyle, 2002). The penetration of distributed generators has various benefits to the power system operator and the customers. However, penetration of DG in the distribution network comes with different challenges to the operation of the power systems distribution network (Dulặu et al 2014). The research has discussed the many benefits and challenges of installing distributed generators in the power system grid. The research focused on the impact of installing Solar PVs with different penetration levels in the Chipata 33kV and 11kV distribution network. Increasing the number of renewable energy sources and distributed generators requires new strategies for the operation and management of the electricity grid to improve the power supply reliability and quality (Kumar et al, 2020). According to the literature reviewed, it is important to understand how the distribution network behaves when solar DGs are integrated in the distribution network.

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## II. PROBLEM STATEMENT

The electricity generation is predominantly hydro in Zambia. ZESCO recently has signed several Memorandum of Understanding with foreign investors to install Solar Power Plants in the National Grid. Investment in Solar PVs will reduce the over dependency of electricity generation on hydro power (ZESCO,2023). The energy demand is daily increasing and there is need to harness the solar potential that the country has especially that the country has been experiencing a reduction in rainfall activities every year. According to the world bank (World bank, 2020), between 2004 and 2014, electricity demand in Zambia was growing at an average of 4 percent per year, this was triggered by average annual gross domestic product (GDP) growth of about 7.3 percent. In 2015–16, the power sector experienced power supply shortages, with power generation not meeting total energy demand due to low rainfall and drought in most parts of Zambia (Ainembabazi et al 2018). Increasing installation of solar power will help cushion the daily increasing energy demand and reduce an over dependency on hydro power. With the increasing installation of solar power in the power system network, it is important to understand how the distribution network will respond when solar DGs are integrated in the distribution network for reliable operation of the power system network. This research investigated the impact of Solar Distributed Generation on the losses, voltage stability, fault levels and voltage profile using DigSilent Power Factory Software in 33kV and 11kV Chipata *Distribution* Network.

## III. OBJECTIVES

*A. Aim:*

The study will help the Network Operator (ZESCO Limited) understand how the distribution network would respond with increased installation of distributed Solar Generators in the Chipata Distribution Network. Network planners will have a better understanding of how the distribution network would respond with increased solar penetration. With the increasing demand of energy, solar DGs will be installed in different locations of both Transmission and distribution networks.

*B. Objectives:*

➢ *Main Objective –*

The main objective was to investigate the impact of Solar Distributed Generation on the Chipata distribution network.

➢ *Specific Objectives*

- To determine the Solar hosting capacity of the Chipata Distribution Network.
- To investigate the impact of Solar DGs on the line losses, fault level, voltage stability and line loading of the 33kV and 11kV Chipata Distribution Network.
- To identify challenges posed when connecting Solar Distributed Generations in Distribution Networks.

## IV. LITERATURE REVIEW

Distributed generation (DG) is the term used to describe power generation located on the distribution system close to the point of consumption (Masters, 2004). Distributed generation has the potential to impact how the distribution network operates. Sarabia (2011) concluded that a high penetration of DG in the distribution system causes it to lose its radial power flow characteristics and causes an increase in the fault level of the network at any fault location. Installation of DGs in the Distribution Network has many benefits such as deferment in construction of new transmission and distribution lines, reduction in power loss along with improved bus bar voltage profile, power quality enhancement and improved system reliability, (Muthukumar & Jayalalitha ,2016). Increased penetration of DGs introduces new challenges to power systems such as determining their optimal location, protection devices settings such as overcurrent protection, voltage regulation, and Power Quality (PQ) issues, (Kuma et al, 2020). The other effects of distributed generation are increased short circuit (Fault Levels), changes in load losses, load profile and appearance of voltage transients, congestion in the network branch. Additionally, power quality issues may arise, and reliability of the network and network protection (overcurrent protection) may not function properly (Dulắu et al 2014).

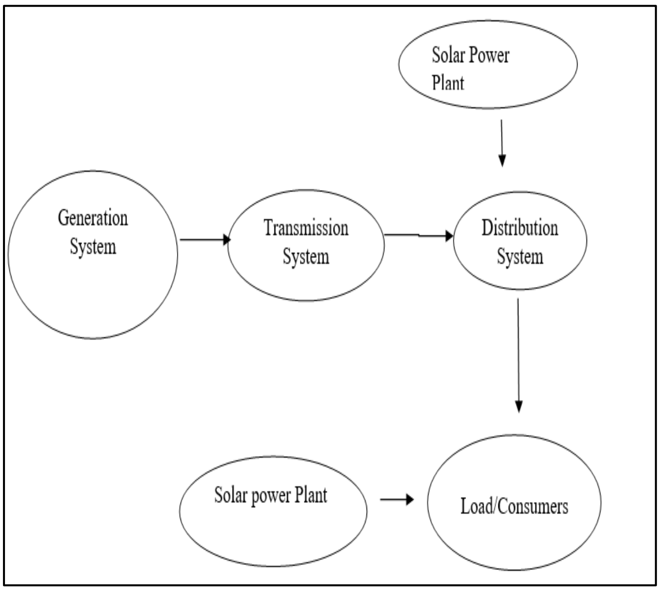


Fig 1: Modern Power System Networks with Distributed Power Plants Near Load Centres

*A. The Impact of Distributed Generation on Power Quality*

Power quality is defined as problem manifested in voltage, current, or frequency deviations that results in failure or mis-operation of customer equipment (Dugan et al, 2004). Power system operators are expected to supply power to customers at the right voltage, frequency, and many other factors. If the equipment is supplied with power outside its working parameters, it can either fail to operate or get damaged. Power quality can have an impact on the overall productivity of industries. Each Distributed Generator has different characteristics and therefore creates different power quality issues. For instance, according to the Zambian

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Standard, consumer voltage must be maintained within ±10% (ZS387Part 1) of the rated voltage. Therefore, the power system operator is expected to supply the consumer equipment within the specified limits. Installation of distributed solar generation can increase the voltage profile of the power system grid thereby affecting the quality of power being supplied to consumers. Most researchers have concluded that both single phase and three phase inverters inject harmonics in the power system grid (Chathurangi et al 2017). Modern inverters which produce almost sinusoidal outputs are also found to inject higher order harmonics into the grid which are a result of their high switching frequencies (Kumar et al 2020).

*B. The Impact of Distributed Generation on Voltage Regulation*

Installed Distributed Generators can adversely impact the voltage control functionality of the power system network (Dulǎu et al 2014). Distributed Solar Generators will have the voltage output dependent on the availability of the Sun, and this can potentially impact the voltage regulation of the distribution network.

*C. The Impact of Distributed Generation on Voltage Profile*

The research by Vittal et al. 2013 discussed that high PV penetration has an impact on the voltage profile of the network and it depends on the loading conditions and the amount of PV integrated in the network. The study concluded that power inverters for solar PVs must have the capability to absorb or generate reactive power for additional voltage regulation. Khan et al. 2022 discussed the voltage regulation challenges in highly solar PV penetrated distribution networks and it was reviewed that the movement of clouds on a cloudy day can change the power generation by up to 80% of the rated capacity of the solar PV within a few minutes.

*D. The Impact of Distributed Generation on Distribution Network Protection*

The increased penetration level of DGs in distribution systems can affect the operation of protection systems of the network (Razavi et al.2020). In radial networks, power flow is in one direction but when sources of supply are installed in the distribution network, the power flow is in both directions and the protection must function for all directions.

*E. The Impact of Distributed Generation on Harmonic*

The research by Dulǎu et al 2014 indicated that connection of a DG in a network has the potential to influence or affect the level of harmonic voltage distortion and this is dependent on whether the DG is a rotating machine or an electronic converter. According to this research, the excessive voltage harmonics may occur anywhere in the network depending on the topology of the network and the impedance at the connection point. The research by Dulǎu et al 2014 used Neplan Software for IEEE 14 Test System.

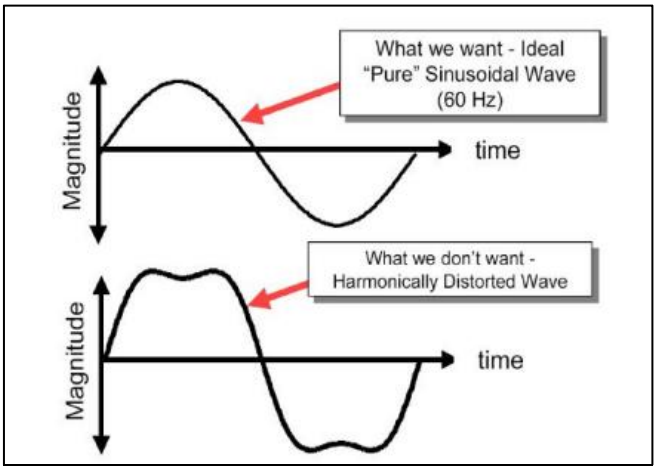


Fig 2: Distortion of a Voltage Waveform (Umar Naseem Khan)

*F. Hosting Capacity of a Power System Network*

Hosting capacity is defined as the measure of how much renewable energy can be added to an existing grid or power system just enough to cause operation within operating regulations (Mulenga, 2015). Hosting capacity is also defined by other researchers as the maximum capacity of solar PV that can be connected to a network without resulting in unacceptable quality and energy security (Chathurangi et al 2017). Hosting capacity gives the maximum amount of PV power integrated in a power system network which cannot alter or violate the set operation limits for a particular distribution or transmission network. This research determined how much renewable energy which can be integrated in the Chipata 33kV and 11kV networks. Different penetration levels were used to analyze the hosting capacity of the Chipata Distribution Network.

*G. Solar Penetration Level*

PV penetration is considered as the ratio of the actual PV output to the actual active power load in a distribution network (Aziz and Ketjoy, 2017). Different PV penetration levels will be used to analyze the impact of Solar integration in the 33kV and 11kV distribution network in Chipata. Penetration level is also defined as the total peak power to peak load apparent power on the feeder (Kroposki et al. 2012).

*PV Penetration = Peak PV Power/Peak Load Apparent Power*

➢ *Benefits of Distributed Generation*

Distributed Generation has some benefits to the network operator and the consumer. Some of the benefits listed by Doles (2002) and Kotamarty (2006) are listed below.

- *Network Operator Benefits*

✓ Reduced losses - As the integration of DGs increases in the distribution network, less power will flow from the grid into the distribution network. The DGs will meet network demand. And the load draws less power from the grid. Reduce power flow in the grid network will also reduce net power losses.

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- ✓ Reduced voltage sags - According to the Zambian Standard ZS387 part 1 a voltage sag is a sudden reduction of the supply voltage to a value between 90% and 1% of the declared system voltage. The reduction is followed by a voltage recovery after a short period of time between 20ms and 3s. Voltage sags can cause detrimental effects on sensitive electrical equipment such as Variable Speed Drives (VSD), programmable logic controllers (PLC), Process Control Equipment and robotics (Kamble et al 2014).
- ✓ Potential Utility Capacity-The generation power capacity of a utility is increased when more DGs are integrated into the network. Increased generation can help meet customer demands.

- *Consumer Benefits*

The following are some of the benefits to customers.

- ✓ The DGs acts as power back when grid supply is lost- When utility power is lost, DGs are used to provide backup supply to the customers, and this ensures continuous availability of electrical energy.
- ✓ DGs provides reliable supply-Grid supply is coupled with forced outages and shutdowns due to maintenance. DGs can provide reliable power to customers with reduced interruptions.

## V. METHODOLOGY

The research involved collection of Chipata Distribution Network Parameters and Modelling of the 33kV and 11kV of Chipata Distribution Network in DigSilent Power Factory Software. Data analysis involved carrying out Network Simulations before and after installing different penetration levels of Distributed Solar Power Plants at different points in the Chipata 33kV and 11kV Distribution Network. A total of 7 bus bar points comprising four 33kV Points and three 11kV points were modelled in power factory power system analysis application tool. Data Collection involved visitation of Transmission and Distribution Substations to collect network paraments such as line loadings, fault levels, transformer parameters and other line parameters which were used as inputs to Power System Simulations in Power Factory. The Chipata 33kV and 11kV Distribution Network was integrated in the current modelled Zambian National Grid power factory case file. The model was integrated to the National grid though 330/132/33kV Chipata West Substation. The model was used to carry out Simulations with different penetration levels of Solar Power Plants in the Distribution Network.

## VI. RESULTS

### A. *Chipata Distribution Network Modelling*

The following is a single line diagram of the Chipata Distribution Network modelled in PowerFactory Power System Analysis Software. The main 33kV double circuit emanates from Chipata West Substation and feeds into Chipata Main 33/11kV Substation. Chipata Main Substation feeds into Lundazi Turn off 33/11 kV Substation and Chandiza 33/11kV Substation.

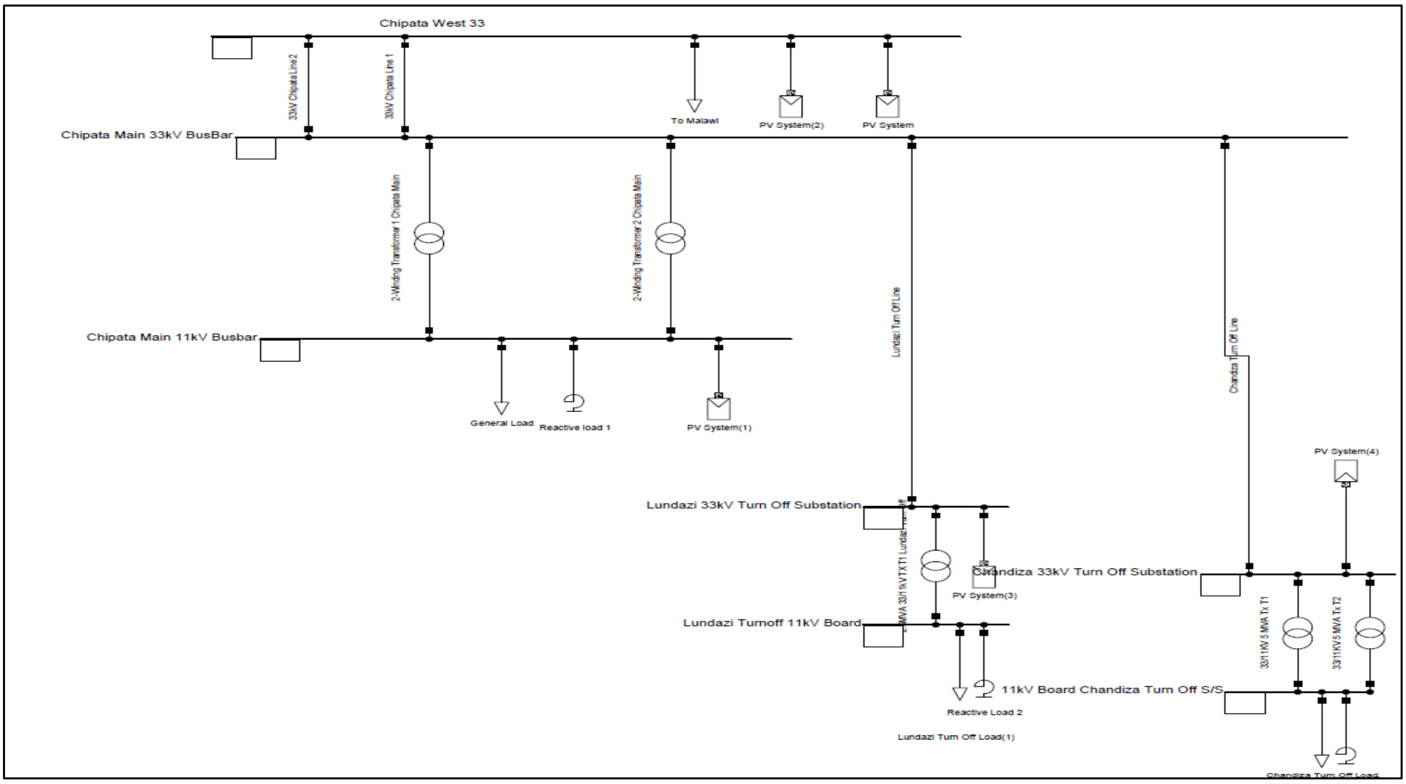


Fig 3: Chipata Distribution Network Modelled in Power Factory Simulation Software

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*B. Network Voltages Without PV*

To fully appreciate the impact of integrating Solar PV in the Chipata 33kV and 11kV Distribution Network, simulations were carried out before Solar PV was integrated. The following figures and tables are showing the obtained results.

Table 1: Voltages at Different Bus Bars before Solar PV Penetration

| S/N | Substation Name | Bus Voltage pu<br>0% Penetration |
|---|---|---|
| 1 | 33kV Chipata West Substation | 0.96 |
| 2 | 33kV Chipata Main Substation | 0.95 |
| 3 | 33kV Chandiza Turn Off | 0.94 |
| 4 | 33kV Lundazi Turn Off | 0.95 |
| 5 | 11kV Chipata Main | 0.95 |

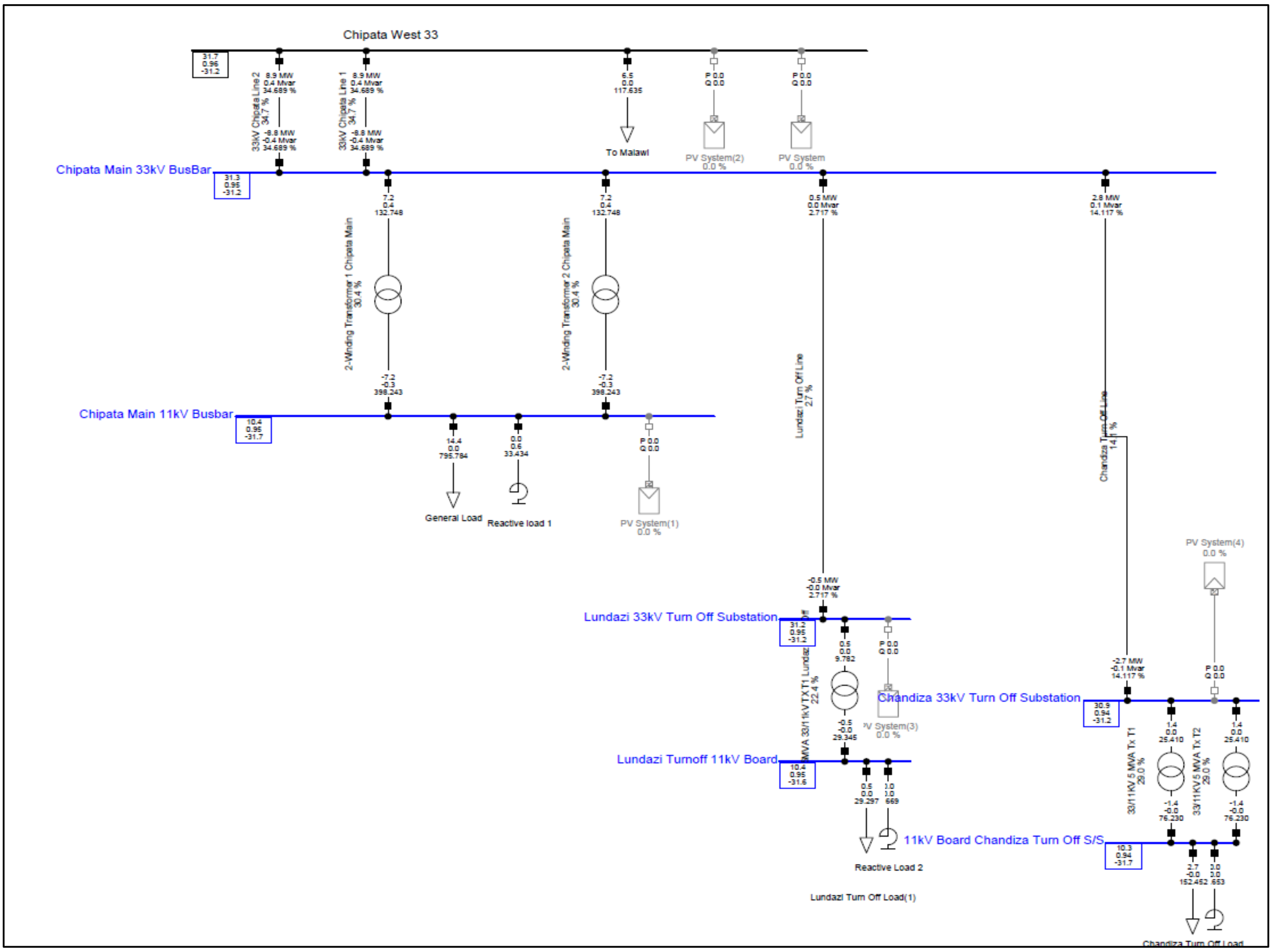


Fig 4: Simulation Results at 0% Solar PV Penetration Level

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➢ *The figure below shows the voltage profile for the Chipata Distribution Network from the source substation to the furthest Substation in the network.*

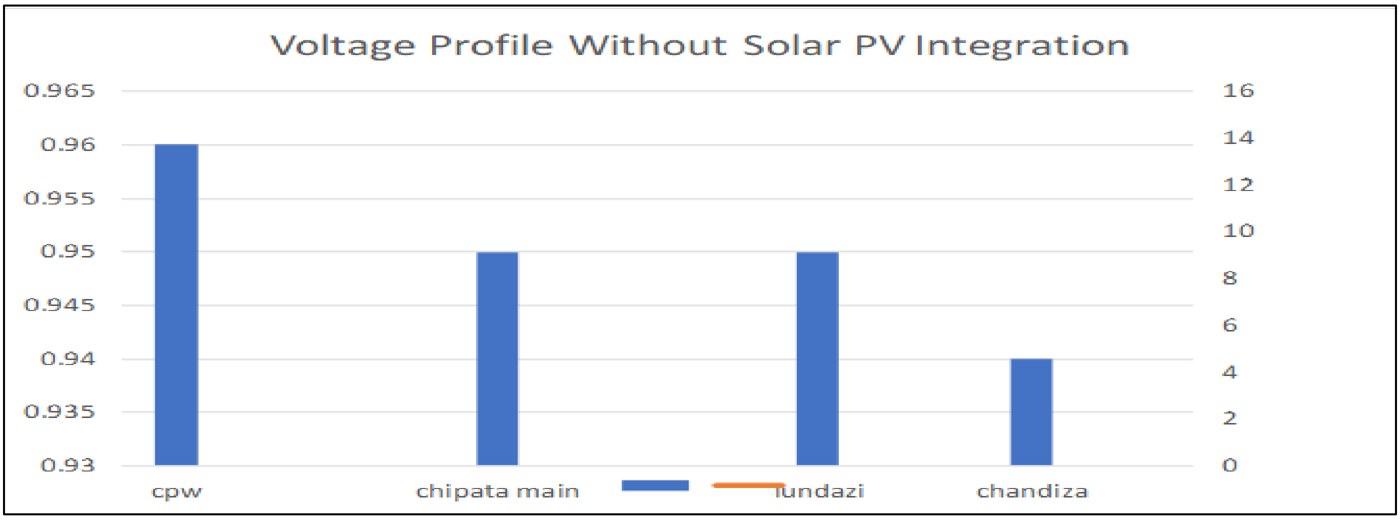


Fig 5: Voltage Profile without Solar PV Integration in Chipata Distribution Network

*C. Network Voltages at 30% Penetration Level*

The total integrated Solar PV Power at 30% Solar Penetration was 7.0MW. *Penetration Capacity at 6.99MW = 6.99MW/23.3MW X 100% = 30% Solar PV Penetration.*

The total Solar PV installed at 30% Solar Penetration was 6.99 MW with various sizes installed as indicated in the table.

Table 2: Solar PV Installed at Different Bus Bars

| S/N | Connection Point | Voltage Level (kV) | Solar PV Size (6.99MW) |
|---|---|---|---|
| 1 | Bus Bar at Chipata West Substation | 33 | 1.4 |
| 2 | Bus Bar at Chipata Main Substation | 33 | 1.4 |
| 3 | Bus Bar at Lundazi Turn Off Substation | 33 | 1.4 |
| 4 | Bus Bar at Chandiza Turn Off Substation | 33 | 1.4 |
| 5 | Bus Bar at Chipata Main Substation | 11 | 1.4 |
| **Total Solar PV Installation** | | | **7.0** |

Table 3: Power Factory Simulation Results at 30% Penetration Level

| S/N | Substation Name | Bus Voltage p.u 0% Penetration | 30% Penetration Level (6.99MW) |
|---|---|---|---|
| 1 | 33kV Chipata West Substation | 0.96 | 0.97 |
| 2 | 33kV Chipata Main Substation | 0.95 | 0.96 |
| 3 | 33kV Chandiza Turn Off | 0.94 | 0.95 |
| 4 | 33kV Lundazi Turn Off | 0.95 | 0.96 |
| 5 | 11kV Chipata Main | 0.95 | 0.96 |
| 6 | 11kV Lundazi Turn Off | 0.95 | 0.96 |
| 7 | 11kV Chandiza Turn Off | 0.94 | 0.95 |

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- *The following Figure Shows the Obtained Results at 30% Solar PV Penetration in the Chipata Distribution Network.*

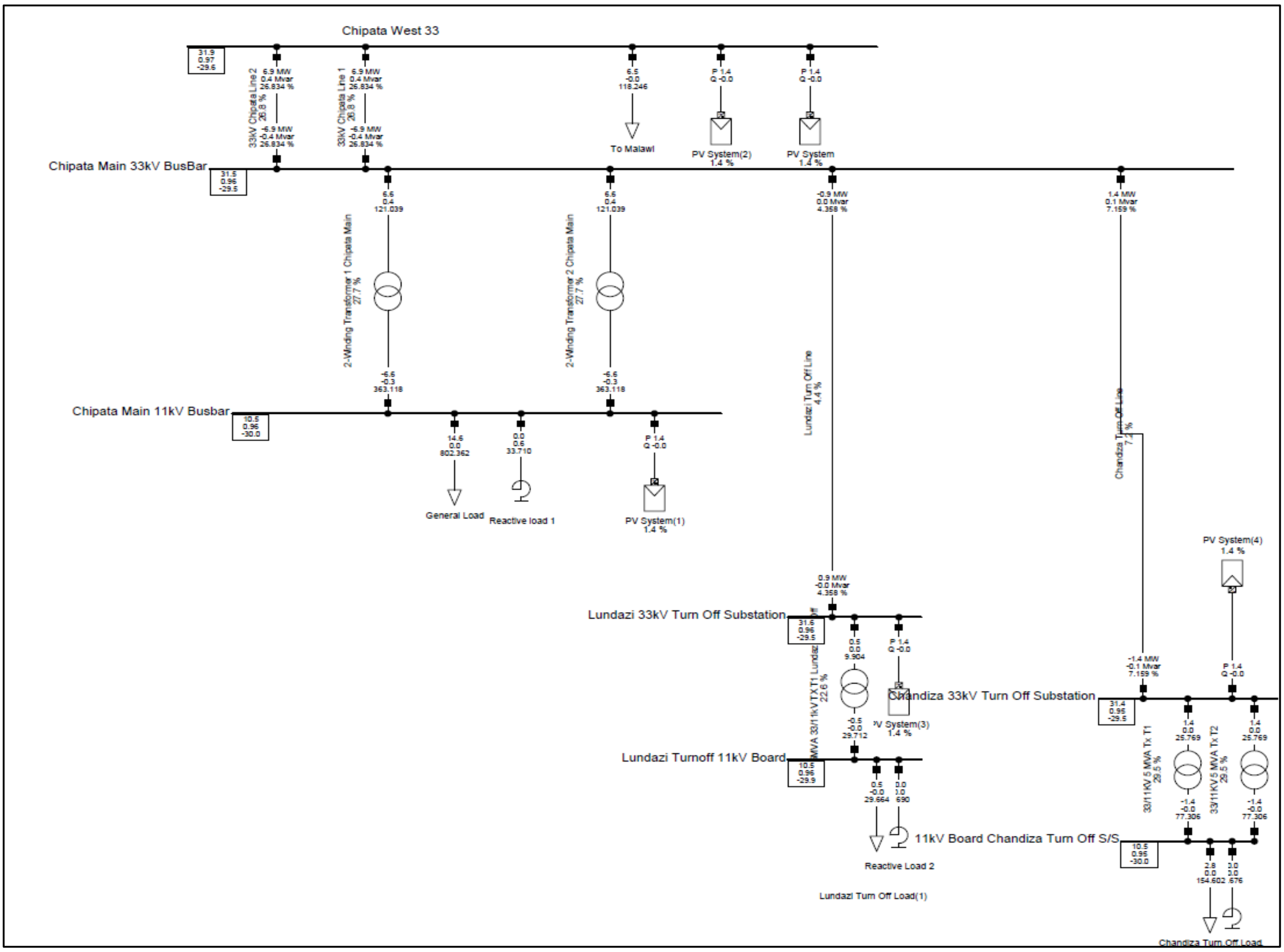

Fig 6: Simulation Results at 30 % Solar PV Penetration Level

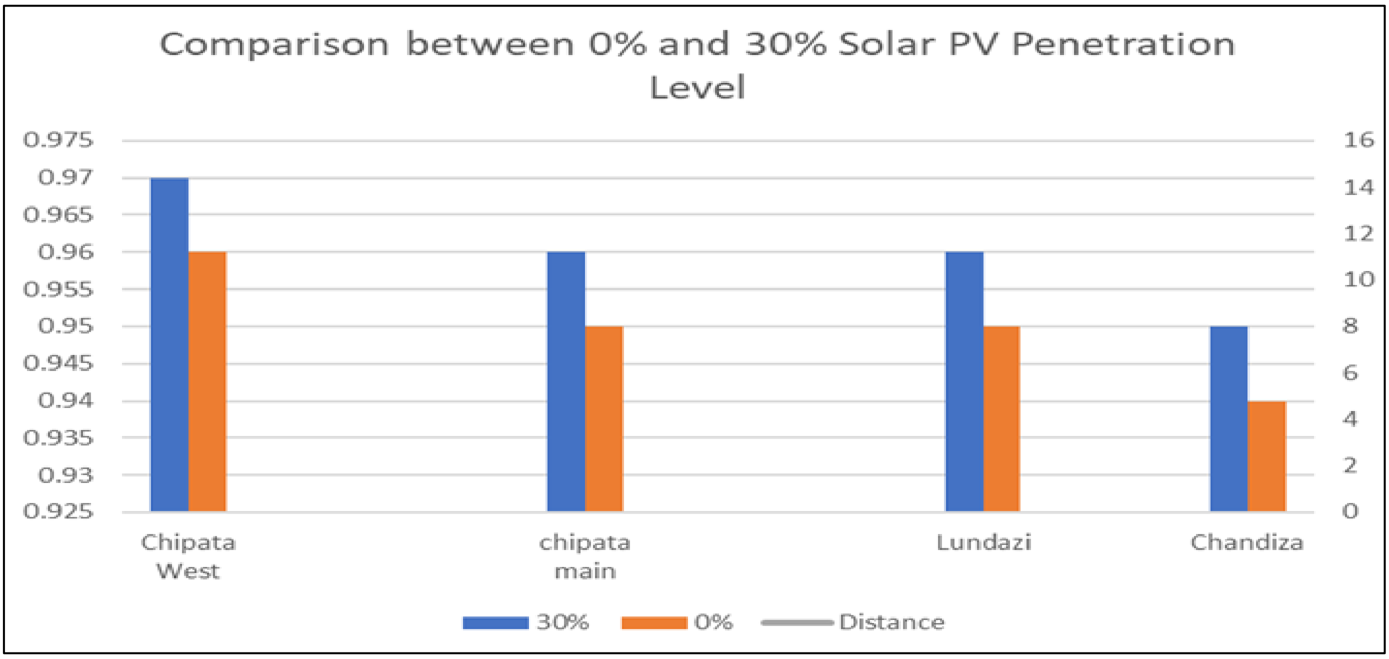

Fig 7: Comparison between 0% and 30% Solar PV Penetration

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*D. Network Voltages at 129% Penetration Level*

The total integrated Solar PV Power at 129% Solar Penetration was 30.0MW. Penetration Capacity at 129% = 30MW/23.3MW X 100% = 129% Solar PV Penetration.

The total Solar PV installed at 129% Solar Penetration was 30.0 MW with various sizes installed as indicated in the table.

Table 4: 30MW Solar PV Installed at Different Bus Bars

| S/N | Connection Point | Voltage Level (kV) | Solar PV Size (30MW) |
|---|---|---|---|
| 1 | Bus Bar at Chipata West Substation | 33 | 6 |
| 2 | Bus Bar at Chipata Main Substation | 33 | 6 |
| 3 | Bus Bar at Lundazi Turn Off Substation | 33 | 6 |
| 4 | Bus Bar at Chandiza Turn Off Substation | 33 | 6 |
| 5 | Bus Bar at Chipata Main Substation | 11 | 6 |
| **Total Solar PV Installation** | | | **30** |

Table 5: Power Factory Simulation Results at 129% Penetration Level

| S/N | Substation Name | Bus Voltage pu 0% Penetration | 129% Penetration Level (30MW) |
|---|---|---|---|
| 1 | 33kV Chipata West Substation | 0.96 | 0.98 |
| 2 | 33kV Chipata Main Substation | 0.95 | 0.98 |
| 3 | 33kV Chandiza Turn Off | 0.94 | 0.99 |
| 4 | 33kV Lundazi Turn Off | 0.95 | 0.99 |
| 5 | 11kV Chipata Main | 0.95 | 0.98 |
| 6 | 11kV Lundazi Turn Off | 0.95 | 0.99 |
| 7 | 11kV Chandiza Turn Off | 0.94 | 0.99 |

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➢ *The Following Figure Shows the Obtained Results at 129% Solar PV Penetration in the Chipata Distribution Network.*

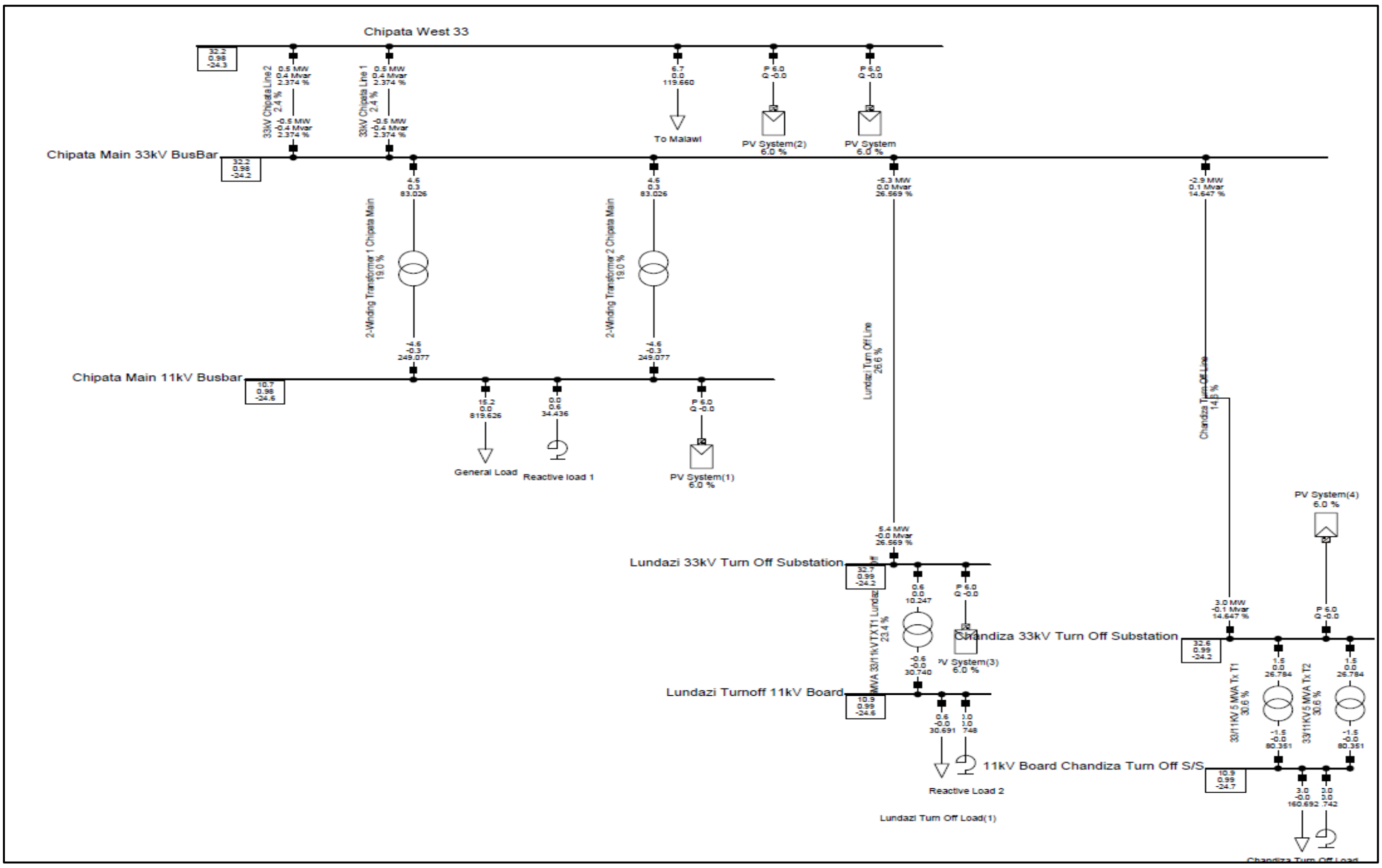


Fig 7: Simulation Results at 129% Solar PV Penetration Level

*E. Network Voltages at 412% Penetration Level*

The total integrated Solar PV Power at 412% Solar Penetration was 96MW. Penetration Capacity at 96MW = 96MW/23.3MW X 100% = 412% Solar PV Penetration.

The total Solar PV installed at 412% Solar Penetration was 96 MW with various sizes installed as indicated in the Table 5 below.

Table 6: Network Voltage at 412% Penetration Level

| S/N | Connection Point | Voltage Level (kV) | Solar PV Size (MW) |
|---|---|---|---|
| 1 | Bus Bar at Chipata West Substation | 33 | 21 |
| 2 | Bus Bar at Chipata Main Substation | 33 | 21 |
| 3 | Bus Bar at Lundazi Turn Off Substation | 33 | 21 |
| 4 | Bus Bar at Chandiza Turn Off Substation | 33 | 21 |
| 5 | Bus Bar at Chipata Main Substation | 11 | 12 |
| **Total Solar PV Installation** | | | **96** |

The table below shows the results obtained when distributed generation of 96MW was integrated into the Chipata 33kV and 11kV Distribution Network.

Table 7: Power Factory Simulation Results at 412% Penetration Level

| S/N | Substation Name | Bus Voltage pu 0% Penetration | 412% Penetration Level (96MW) |
|---|---|---|---|
| 1 | 33kV Chipata West Substation | 0.96 | 0.93 |
| 2 | 33kV Chipata Main Substation | 0.95 | 0.96 |
| 3 | 33kV Chandiza Turn Off | 0.94 | 1.02 |
| 4 | 33kV Lundazi Turn Off | 0.95 | 1.01 |
| 5 | 11kV Chipata Main | 0.95 | 0.96 |
| 6 | 11kV Lundazi Turn Off | 0.95 | 1.01 |
| 7 | 11kV Chandiza Turn Off | 0.94 | 1.02 |

➢ *The Figure Below Shows the Results Obtained when a Total of 96MW was Integrated in the Chipata Distribution Network.*

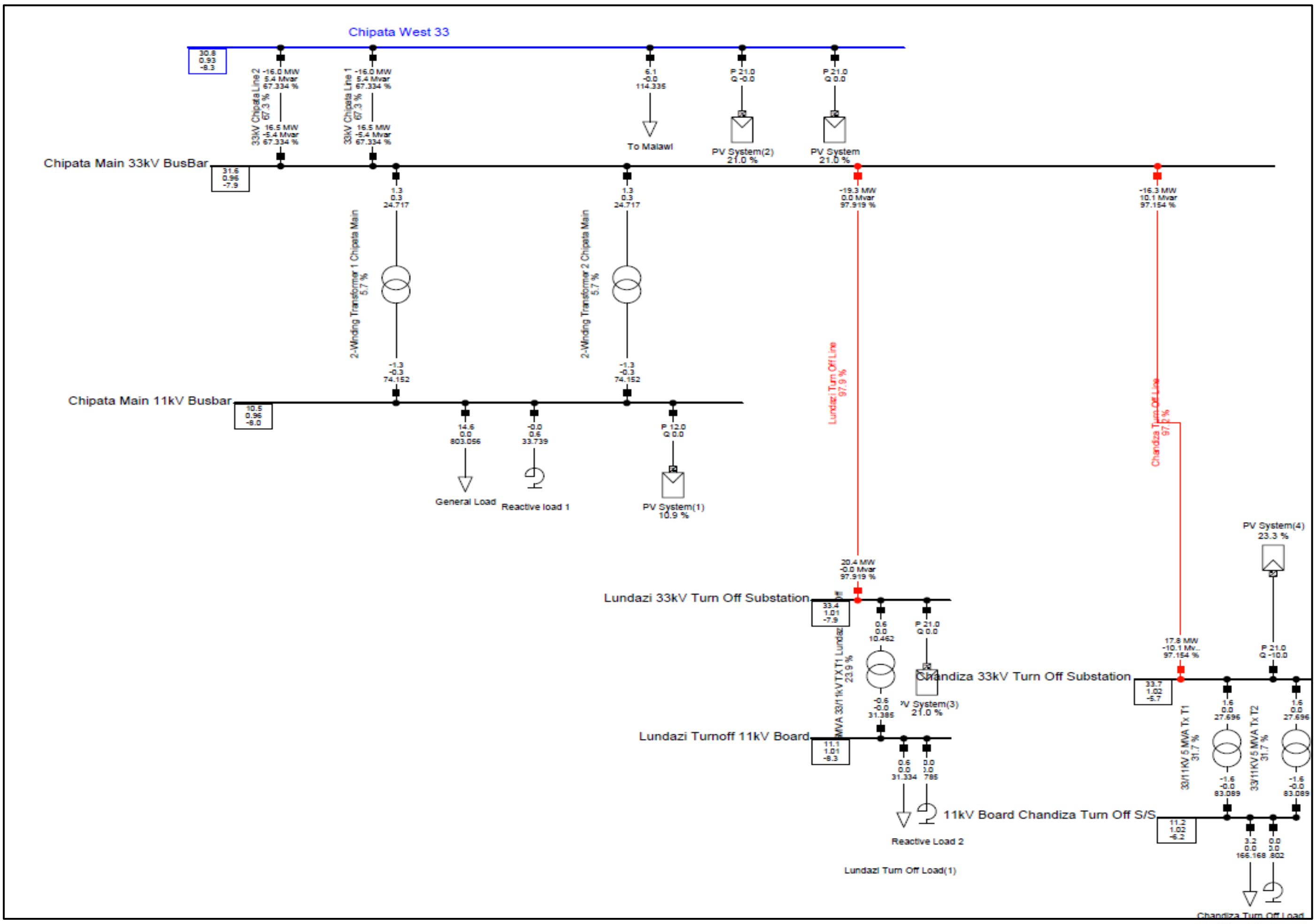


Fig 8: Simulation Results at 412% Solar PV Penetration Level

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*F. Network Voltages at 429% Penetration Level*

The total integrated Solar PV Power at 429% Solar Penetration was 100MW. Penetration Capacity at 100MW = 100MW/23.3MW X 100% = 429% Solar PV Penetration.

The total Solar PV installed at 429% Solar Penetration was 100MW with various sizes installed as indicated in the table below.

Table 8: 100MW Solar PV installed at Different Bus Bars

| S/N | Connection Point | Voltage Level (kV) | Solar PV Size (100MW) |
|---|---|---|---|
| 1 | Bus Bar at Chipata West Substation | 33 | 22 |
| 2 | Bus Bar at Chipata Main Substation | 33 | 22 |
| 3 | Bus Bar at Lundazi Turn Off Substation | 33 | 22 |
| 4 | Bus Bar at Chandiza Turn Off Substation | 33 | 22 |
| 5 | Bus Bar at Chipata Main Substation | 11 | 12 |
| Total Solar PV Installation | | | 100 |

The table below shows the results obtained when distributed generation of 100MW was integrated into the Chipata 33kV and 11kV Distribution Network.

Table 9: 429% Solar PV Installed at Different Bus Bars

| S/N | Substation Name | Bus Voltage pu 0% Penetration | 429% Penetration Level (100MW) |
|---|---|---|---|
| 1 | 33kV Chipata West Substation | 0.96 | 0.93 |
| 2 | 33kV Chipata Main Substation | 0.95 | 0.96 |
| 3 | 33kV Chandiza Turn Off | 0.94 | 1.02 |
| 4 | 33kV Lundazi Turn Off | 0.95 | 1.01 |
| 5 | 11kV Chipata Main | 0.95 | 0.96 |
| 6 | 11kV Lundazi Turn Off | 0.95 | 1.01 |
| 7 | 11kV Chandiza Turn Off | 0.94 | 1.02 |

➢ *The Figure Below Shows the Results Obtained when a Total of 100MW was Integrated in the Chipata Distribution Network.*

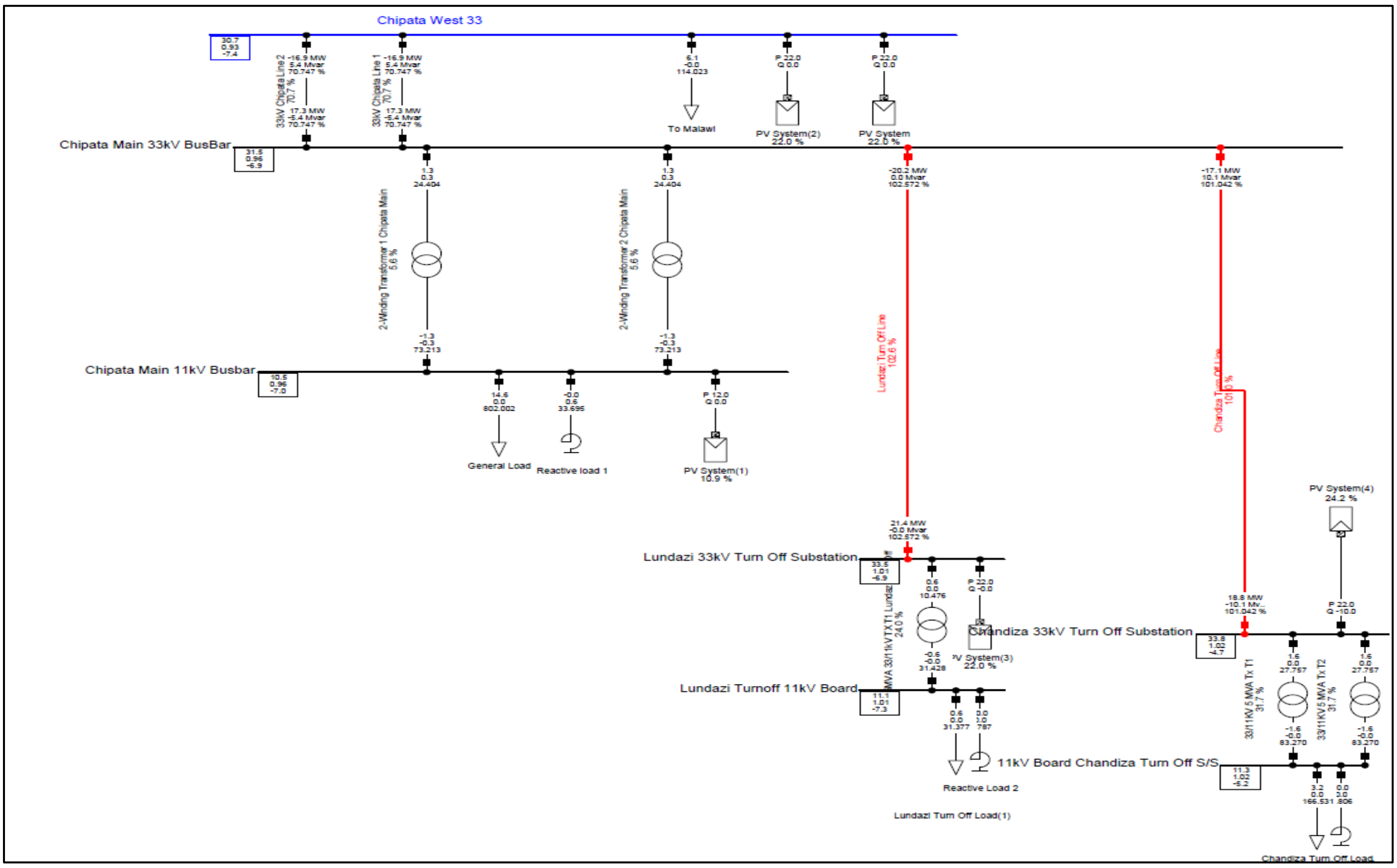


Fig 9: Simulation Results at 429% Solar PV Penetration Level

*G. Network Voltages at 567% Penetration Level above Hosting Capacity*

The total integrated Solar PV Power at 567% Solar Penetration was 132MW. Penetration Capacity at 132MW = 132MW/23.3MW X 100% = 567% Solar PV Penetration.

The total Solar PV installed at 567% Solar Penetration was 132MW with various sizes installed as indicated in the table.

Table 10: 132MW Solar PV Installed at Different Bus Bars.

| S/N | Connection Point | Voltage Level (kV) | Solar PV Size (132MW) |
|---|---|---|---|
| 1 | Bus Bar at Chipata West Substation | 33 | 30 |
| 2 | Bus Bar at Chipata Main Substation | 33 | 30 |
| 3 | Bus Bar at Lundazi Turn Off Substation | 33 | 30 |
| 4 | Bus Bar at Chandiza Turn Off Substation | 33 | 30 |
| 5 | Bus Bar at Chipata Main Substation | 11 | 12 |
| Total Solar PV Installation | | | 132 |

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The table below shows the results obtained when distributed generation of 132MW was integrated into the Chipata 33kV and 11kV Distribution Network.

Table 11: 567% Solar PV Installed at Different Bus Bars

| S/N | Substation Name | Bus Voltage pu<br>0% Penetration | 567% Penetration<br>Level (132MW) |
|---|---|---|---|
| 1 | 33kV Chipata West Substation | 0.96 | 0.95 |
| 2 | 33kV Chipata Main Substation | 0.95 | 0.98 |
| 3 | 33kV Chandiza Turn Off | 0.94 | 1.07 |
| 4 | 33kV Lundazi Turn Off | 0.95 | 1.06 |
| 5 | 11kV Chipata Main | 0.95 | 0.98 |
| 6 | 11kV Lundazi Turn Off | 0.95 | 1.06 |
| 7 | 11kV Chandiza Turn Off | 0.94 | 1.07 |

The figure below shows the results obtained when a total of 132MW was integrated in the Chipata Distribution Network.

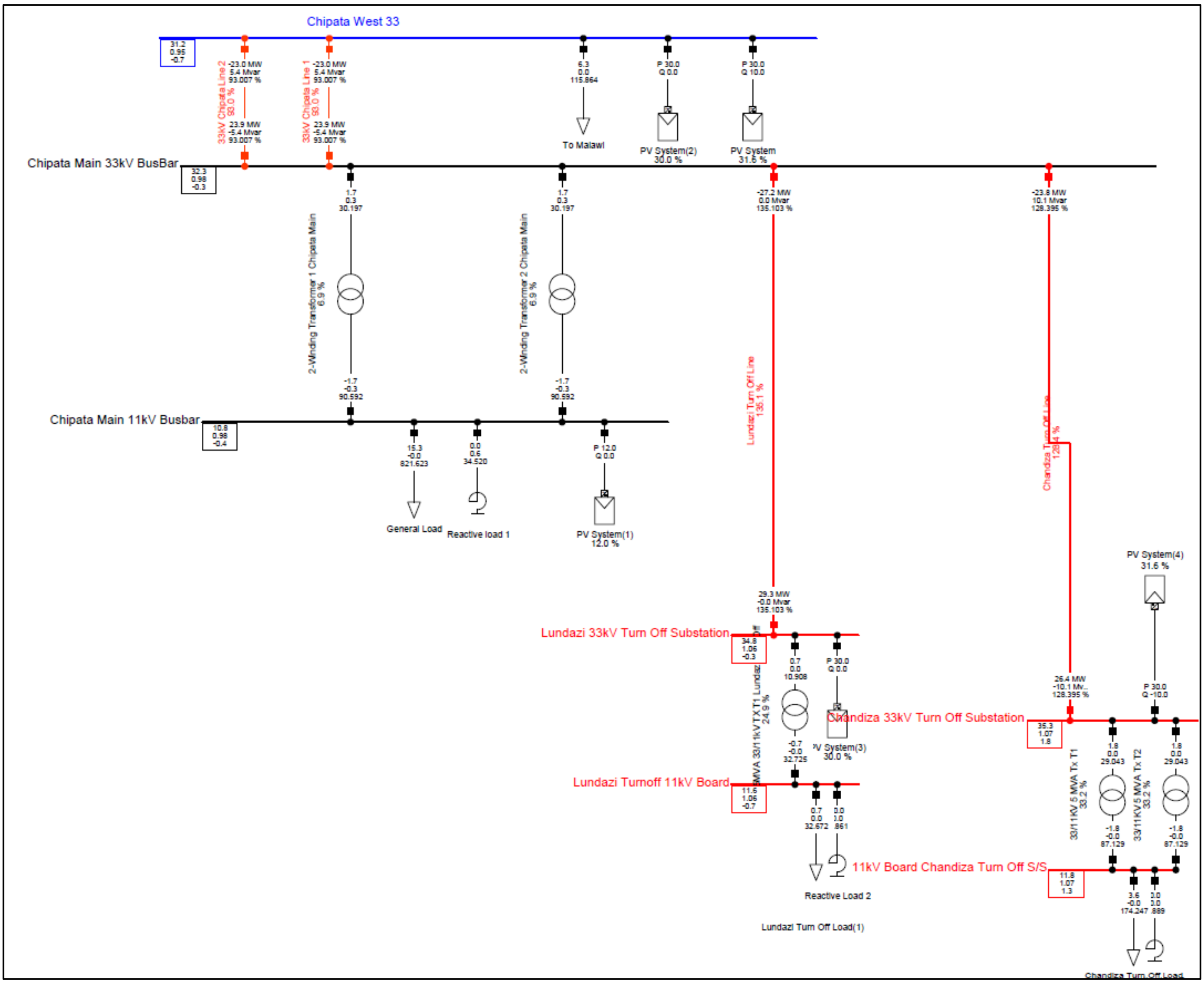


Fig 10: Simulation Results at 567% Solar PV Penetration Level

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*H. Distribution Line Loading*

The table below shows the loading of the lines before Solar PV integration and after integration of different sizes of Distributed Solar PVs at different Bus Bars in the 33kV and 11kV Chipata Distribution Network.

Table 12: Distribution Line Loading at Different Penetration Levels

| Distribution Line Name | Loading 0% PV | Loading with Integrated PV | | | | | |
|---|---|---|---|---|---|---|---|
| | | 6.99MW | 30MW | 60MW | 70MW | 96MW | 100MW |
| 33kV Chipata West – Chipata Main | 34.7% | 26.8% | 2.4% | 29.6% | 36.3% | 67.3% | 70.7% |
| 33kV Chipata Main – Lundazi Turn Off | 2.7% | 4.4% | 26.6% | 54.1% | 63.1% | 97.9% | 102.6% |
| 33kV Chipata Main – Chandiza Turn Off | 14.1% | 7.2% | 14.6% | 41.5% | 50.3% | 97.2% | 101.0% |

*I. Lines Loses*

The table below shows the losses in the distribution network before and after integrating distributed solar generation in 33kV and 11kV Chipata Distribution Network.

Table 13: Line Losses at Different Penetration Levels

| Distribution Line Name | Losses 0% PV | Line Losses at different Penetration Levels (MW) | | | | |
|---|---|---|---|---|---|---|
| | | 6.99MW | 30MW | 60MW | 70MW | 100MW |
| 33kV Chipata West – Chipata Main | 1.1% | 0.0% | 0.0% | 1.3% | 1.0% | 2.3% |
| 33kV Chipata Main – Lundazi Turn Off | 0.0% | 0.0% | 1.85% | 3.5% | 3.7% | 5.6% |
| 33kV Chipata Main – Chandiza Turn Off | 3.6% | 0.0% | 3.3% | 2.30% | 3.7% | 9.04% |

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*J. Substation Fault Level*

➢ *Single Phase to Ground*

Short Circuit analysis was performed for each penetration levels of solar PV and the obtained results are presented below for phase to ground faults.

Table 14: Short Circuit – Single Phase to Ground

| S/N | Substation Name | Fault Level (kA) | Penetration Level | | |
|---|---|---|---|---|---|
| | | | 60MW | 70MW | 100MW |
| 1 | 33kV Chipata West Substation | 7.306 | 7.306 | 7.306 | 7.306 |
| 2 | 33kV Chipata Main Substation | 6.992 | 6.992 | 6.992 | 6.992 |
| 3 | 33kV Chandiza Turn Off | 4.340 | 4.340 | 4.340 | 4.340 |
| 4 | 33kV Lundazi Turn Off | 5.237 | 5.237 | 5.237 | 5.237 |
| 5 | 11kV Chipata Main | 18.862 | 18.862 | 18.862 | 18.862 |
| 6 | 11kV Lundazi Turn Off | 3.898 | 3.898 | 3.898 | 3.898 |
| 7 | 11kV Chandiza Turn Off | 9.651 | 9.651 | 9.651 | 9.651 |

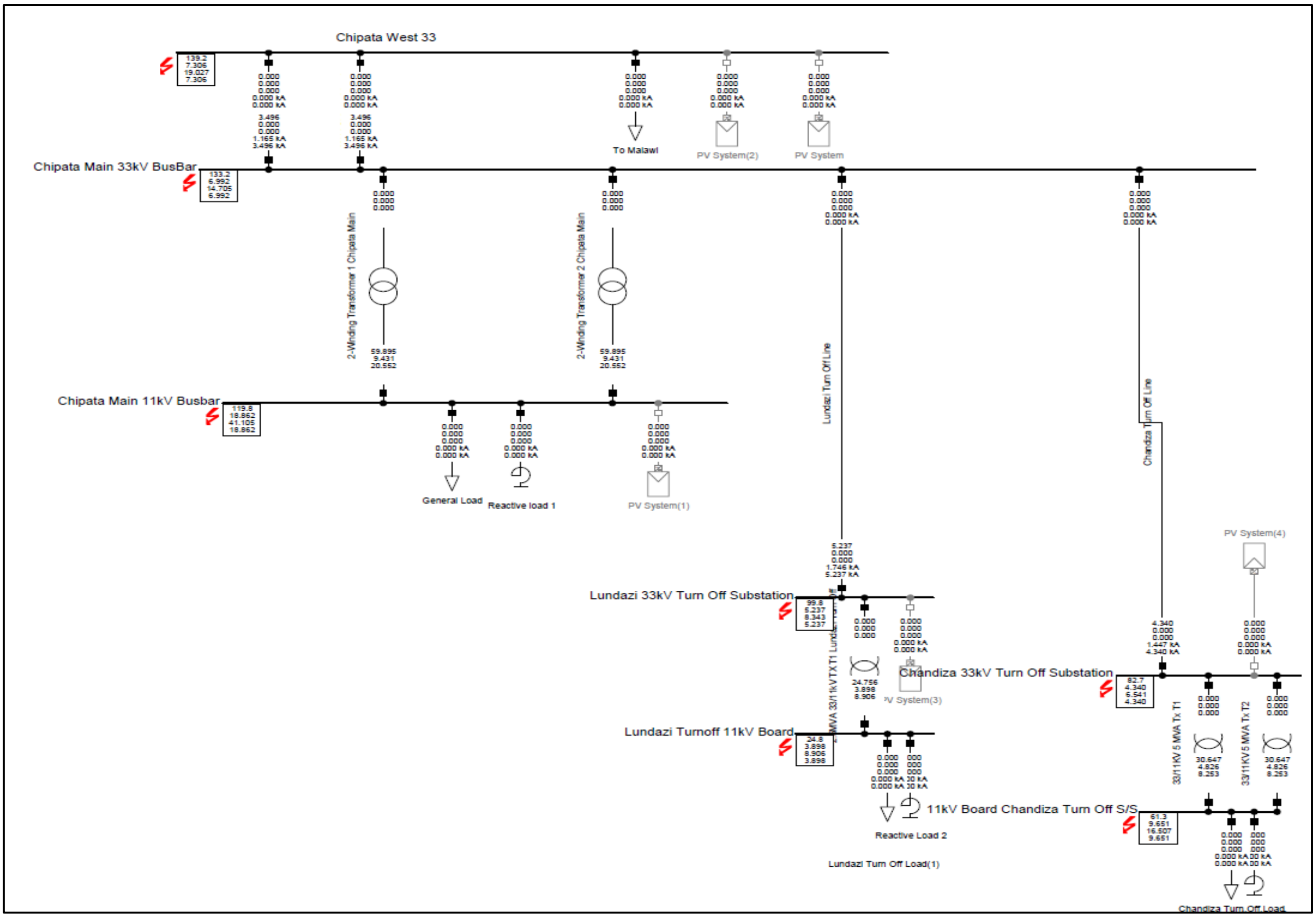


Fig 11: Single Phase to Ground Short Circuit Simulation Results

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➢ *Three Phase to Ground*

Short Circuit analysis was performed for each penetration levels of solar PV and the obtained results are presented below for three phase to ground faults.

Table 15: Short Circuit – Three Phase to Ground

| S/N | Substation Name | Fault Level (kA) | Penetration Level | | |
|---|---|---|---|---|---|
| | | | 30MW | 60MW | 70MW |
| 1 | 33kV Chipata West Substation | 4.85 | 5.396 | 5.396 | 5.396 |
| 2 | 33kV Chipata Main Substation | 4.70 | 4.954 | 5.247 | 5.247 |
| 3 | 33kV Chandiza Turn Off | 2.95 | 3.007 | 3.288 | 3.288 |
| 4 | 33kV Lundazi Turn Off | 3.39 | 3.441 | 3.778 | 3.778 |
| 5 | 11kV Chipata Main | 12.18 | 12.957 | 13.526 | 13.526 |
| 6 | 11kV Lundazi Turn Off | 3.22 | 3.509 | 3.544 | 3.544 |
| 7 | 11kV Chandiza Turn Off | 6.35 | 6.787 | 7.124 | 7.124 |

## VII. DISCUSSION

### A. *Impact of Distributed Solar PV on Voltage Limits*

The studies showed that the bus voltages increased with increased solar penetration in the distribution network. At 0% Solar penetration level the distribution network voltages ranged from 0.94pu (11kV Lundazi Substation Bus Bar) to 0.96pu (33kV Chipata West Bus Bar). At 30% Solar Penetration the Bus Bar Voltages increased and ranged from 0.95pu to 0.97pu. The results showed that the bus bar voltages within the network increased with the increase in solar PV penetration The voltage at 33kV Chipata West Substation bus bar increase from 0.96pu at 0% (0MW) penetration to 0.98pu at 300% (70MW) penetration and further decreased to 0.93pu at 96MW following the addition of more solar generators in the network. The voltage at 11kV Chipata Main Substation bus bar increased from 0.95pu at 0% penetration to 0.99pu at 300% (70MW) penetration. The voltage at 33kV Bus Bar Chandiza Turnoff Substation increased from 0.95pu at 0% penetration to 1.02pu at 412% (96MW) penetration. The studies showed that increased solar penetration in the distribution network increases bus bar voltages. Consumer equipment is designed to operate withing specified voltages range and voltages outside this range can result into equipment damage or failure to operate. Further simulations were carried out at 132MW Solar PV penetration level, it was observed that the 33kV and 11kV Chandiza Turn Off and Lundazi Turn Off recorded 1.07 pu and 1.06 per unit respectively. The voltages on these bus bars were beyond the set voltage operating units of 0.95pu and 1.05pu. This shows that installation of Distributed Solar PVs in the distribution network increases the distribution system voltages and lead to equipment failure if system studies are not conducted before implementation of Solar PV integration. Voltage regulation equipment must be well set to ensure that the voltages in the network are operating withing set operating points after installation of Solar PVs.

### B. *Impact of Distributed Solar PV on Distribution Network Line Loading*

The studies showed that increased solar penetration in the distribution network increased distribution line loading. The line loading for 33kV Chipata West – Chipata Main line decreased from 34.7 % at zero solar integration to 2.4% (30MW). The line loading was reducing because the loads in the networks were supplied by the installed solar and hence the power flow from the grid was reducing. Above 30MW Solar PV installation (129%), there was reverse power flow from the distribution network to the grid and the line loading started increasing with increased solar. The loading for 33kV Chipata Main – Lundazi Turnoff line increase from 2.7% at 0% penetration to 102.6% at 429% (100MW). The loading for 33kV Chipata Main – Chandiza Turnoff line increase from 14.1 % at 0% Solar PV penetration to 101.0% at 429% (100MW). The distribution network started feeding back into the grid at 30MVA (129%) solar integration. Above the 96MW (412%) capacity, some distribution lines started operating above their current carrying capacity. This can lead to damage of the conductor due to overheating. The line loading for 33kV Chipata Main – Lundazi Turn Off and 33kV Chipata Main – Chandiza Turn Off recorded above 100% loading capacity. When a large amount of solar PV above the network load is installed in the distribution network, the power flow reverses flow, and the distribution network begins to feed back into the grid. Network operators are required to put up measures to ensure that the power system network continues to operate withing the set parameters at this point.

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*C. Hosting Capacity of the Chipata Distribution Network*

The Chipata Distribution Network was integrated with different sizes of Solar PVs at different substations.

The Hosting capacity of a power system network is the maximum amount of PV power integrated in the network without violating the set operation limits. Each power network has different characteristics based on equipment parameters which effects how much power can flow in it. The studies showed that Chipata Distribution Network can operate within the set points with a maximum PV Solar integration of 96MW which is 412% penetration level. The distribution network started operating outside its set operating limits when the solar integration was above 96MW. Above the hosting capacity, (100MW) the line loading for 33kV Chipata Main – Lundazi Turn Off and Chipata Main – Chandiza Turn was above the 100% threshold. 33kV Chipata Main – Lundazi Turn Off recorded 102.6% line loading and 33kV Chipata Main – Chandiza Turn Off recorded 101.0% line loading. Overloading a distribution line increases the chance of operating a line above its thermal capacity. A conductor operating above its thermal capacity will lead to increased losses due to heating.

A further increase to 132MW of solar PV Penetration resulted into an increase of bus bar voltages above set points and increased distribution line loading above 100%. At 132MW the voltages ranged from 0.95pu to 1.07pu. All the bus bars recorded voltages above the set limits except for 33kV Chipata Main Substation and 11kV Chipata Main bus bars which recorded 0.98pu. The line loading for 33kV Chipata Main – Chandiza Turn Off was 128.4% and the line loading for 33kV Chipata Main – Lundazi Turn Off was 135.1%. These results shows that the Chipata Distribution Network could only operate within the set operating limits at a solar PV penetration level of 96MW which was determined as its Solar Hosting Capacity.

*D. Impact of Distributed Solar PV on Distribution Line Losses*

The line losses before solar penetration for 33kV Chipata West -Chipata Main and Chipata Main – Chandiza was 1.1% and 3.6% respectively with overall power flow from the Grid. After integration of 6.99MW of Solar PV in the network, the losses for these lines decreased to 0%. This was because the load demand was met by the installed Solar PVs. At 30MW of installed Solar PV, the line losses started increasing, and the power flow reversed from the distribution network to the grid. The losses is mainly attributed to the line capacity which is not designed to transmit power. The losses increased with an increase in solar PV penetration as the Distribution Network was feeding into the grid. The losses are reduced from the grid only when the solar PV generation can meet the local power demand.

*E. Impact of Distributed Solar PV on Distribution Network Fault Levels*

The fault levels for phase to ground faults were the same for all Solar PV penetration levels. The results for short circuit analysis showed that the fault level values were the same at all buses at 0% penetration and at increased Solar PV penetration level. The fault levels for three phase to ground faults increased slightly between 0 and 30MW solar penetration levels for all the Bus Bars in the distribution network. 33kV Chipata West Substation Bus Bar recorded the highest increase of 10.1% in the fault level and 33kV Chandiza Turn Off Bus recorded the lowest increase of 1.5% in fault level at 30MW Solar PV penetration level. An increase in fault level averaging 5.5% was recorded on all bus bars except for 33kV Chipata West Substation when the solar PV penetration was increased from 30MW to 60MW. Further increase in Solar PV installation from 60MW did not result into increased fault level for the simulated levels. This shows that increased Solar PV integration in the distribution network has minimum impact on bus bar fault level. The fault level for each substation is key in providing correct protection equipment required. The protection equipment must be able to carry the maximum recorded fault level currents to ensure reliability of supply from each substation.

*F. Challenges on Connection of Solar DGs in the Distribution Network*

- Intermittent Power Flow – Power from Solar PV is dependent on the availability of sunlight. Cloud cover causes intermitted power flow which can lead to an imbalance between load demand and generation. When power from Solar PVs is reduced, there must be deliberate ways to ensure that power system synchronism is maintained.
- Violation of Voltage Limits - Addition of Solar PVs in the distribution network will generally result in increased voltages in the network. Voltage levels can be violated, and deliberate voltage regulation methods must be put in place to ensure network operation is maintained withing set voltage limits.
- Determination of the Hosting Capacity - Before more solar PV plants are integrated in the distribution network, the hosting capacity of the network has must be determined to prevent violation of the network operation limits.
- Overcurrent Protection in Distribution Network- The network with installed distributed Solar PVs must have well-coordinated overcurrent protection implemented in the network. The fault current flow is bidirectional even if the network is radial.

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## VIII. CONCLUSION AND RECOMMENDATION

### *A. Conclusion*

The hosting capacity of a distribution network is dependent on elements such as conductor rating, line length, bus bar rating and the network load. The studies showed that the maximum solar PV which can be integrated in the 33kV and 11kV Chipata Distribution network without violating the network set limits was 96MW. The studies showed that increased solar penetration in the distribution network increased distribution line loading and the power flows reversed at 30MW of Solar PV integration. The simulation results further showed that the bus voltages in the distribution network increased with increased solar penetration, and increased solar penetration in the distribution network increased distribution line as the distribution network was feeding back into the grid. The power flow reversed at 129% (30MW) of solar integration. The integration of solar PV resulted in some lines having reduced loses and others had increased losses. When Solar PV plants equal to the local demand were installed in the distribution network, the overall line losses reduced. When the amount of installed Solar PVs increased and the distribution network started feeding back into the grid, the losses increased. This is attributed to the size of the conductor as it is not designed for power transmission. The obtained results for short circuit analysis showed that increased Solar PV integration in the distribution network has minimum impact on bus bar fault level.

### *B. Recommendations*

- Distribution Networks with smaller loads can be integrated with smaller Solar PVs. Integration of larger Solar PV Units in distribution networks with small peak loads will mean that the distribution network will be feeding back into the network as most of the generated power cannot be utilised by the local load demand. Higher Load Distribution networks have the potential to allow much large amounts of Solar PV integration with minimised possibilities of feeding back into the grid. Highly loaded distribution networks will have higher hosting capacity compared to low loaded distribution networks.
- The protection settings especially for overcurrent and earth fault must be revised before distributed Solar is integrated in the distribution network. This is because there will be a bi-direction flow of power. The tripping matrix for the conventional supply and the Solar PVs must be well coordinated to prevent possibilities of feeding into the fault.
- It was also observed that the distribution infrastructure such as distribution line conductor rating limits how much solar power can be integrated in the distribution network. Distribution Networks with higher rated conductors such as High Temperature Low Sag (HTLS) with a higher range current carrying capacity have a higher Solar PV integration Capacity. Upgrading or uprating the distribution line equipment increases the hosting capacity of the network.
- During the studies, solar PVs integrated at 11kV Bus Bars were limited to the load connected on the 11kV Bus Bar as integrating a much higher Solar PV generator on the 11kV Bus Bar would mean that excess power must flow back into the transformation equipment into the grid. This can result into increased high voltages on the high voltage side, and it can cause damage to equipment.

## FUTURE RESEARCH CONSIDERATIONS

Based on the determined hosting capacity of the Chipata Distribution Network, further research can be carried out by determining the size of land, type and number of solar panels required and the number of batteries for energy storage needed and the cost of integrating distributed Solar PV Plants in the Chipata 33kV and 11kV distribution Network.

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