

Enhancing resilience in the distribution networks to wind storms causing power outages affecting
essential loads

By
Likonge Ndhlovu

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Signature:  Date: 02.05.2023

Likonge Ndhlovu

(Candidate)

We the undersigned have read this thesis and have approved it for examination;

Dr. Lemba. Nyirenda (PhD)

Senior Lecturer

Department of Electrical and Electronics Engineering

The University of Zambia

Signature:

Date:

Abstract

This study, which was conducted and analyzed, examined the causes of power outages affecting essential loads such as hospitals, fire stations and many others due to storms, which caused the power distribution network's wooden poles to fall to the ground. The storm had wind speeds ranging from 30 to 60 meters per second. Due to this, there was a need to enhance the resilience of the distribution network against wind storms.

Therefore, two best options were implemented to solve this problem that was hardening the 33kV lines connecting essential loads and integrating PV plants with battery storage on their buses. In the first method, class 1–4 wooden poles were tested to see if they could withstand the storm. From 30 m/s to 40 m/s, all classes of pole passed the test, however, at 50 m/s, only class 1 wooden poles were successful. At 60 m/s, all classes of wooden poles failed the test, so PV plants with battery storage were integrated into the distribution network and during the storm, the network continued supplying the essential loads in island mode of operation. The Python programming language was used to create a program that determined the failed pole class during the storm based on the fragility curve's probability of failure.

Therefore, after integrating PV plants with battery storage, a grid impact study was conducted to determine if they would operate in accordance with the Zambia grid code, which they did.

To measure the resilience of the distribution network, resilience indices were calculated and analyzed. Therefore, the active power supplied to the distribution network was calculated before, during, and after the storm, keeping in mind that maybe the 33kV lines connecting essential loads fell on the ground, causing an outage. Hence, PowerFactory DIgSILENT 2018 was the computer software that was used to calculate the active power supplied. The test distribution network was the Kasama distribution network.

In conclusion, after implementing the two best options, the distribution network's resilience against storms causing power outages affecting essential loads was enhanced.

Dedications

This research work is dedicated to my father and mother, Kalaso Likonge Ndhlovu and Meidi Kosamu, who have supported me through my academic and professional lives. Special dedications are extended to my wife, Sungwe Lupasha, and to my late grandfather and grandmother for being there for me. And lastly, to my brothers, sisters and cousins.

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List of Symbols

$R_0(t_e)$	System Performance indices before the event
$R_{pe}(t_{pe})$	System Performance indices after the event network failure
$R_{pr}(t_{pr})$	System Performance indices after the network start recovering from the wind storm
$R(t)$	System Performance in time t
$L_c(t)$	Sum of supplied essential and common loads
$L_c^\Omega(t)$	Essential loads of the system
$L_c^c(t)$	Common loads of the system
t_e	Time before the occurrence of the wind storm.
t_{pe}	Duration of the wind storm
t_{pr}	Restoration time of the failed lines
ζ_V	Vulnerability index of the existing Kasama Distribution network
ζ_D	Degradation index of the existing Kasama Distribution network
ζ_E	Energy loss index of the existing Kasama Distribution network
ζ_V^H	Vulnerability index after hardening the Kasama Distribution network
ζ_D^H	Degradation index after hardening the Kasama Distribution network
ζ_E^H	Energy loss index after hardening the Kasama Distribution network
ζ_V^{PV}	Vulnerability index after integrating PV plants with Battery storage into the Kasama Distribution network
ζ_D^{PV}	Degradation index after integrating PV plants with Battery storage into the Kasama Distribution network
ζ_E^{PV}	Energy loss index after integrating PV plants with Battery storage into the Kasama Distribution network

Acronyms and Abbreviations

ANSI	American National Standard Institute
AC	Alternating Current
DC	Direct Current
PCC	Point of common coupling
DER	Distributed Energy Resource
EPM	Electrical Prevention Maintenance
GUI	Graphic user interface
IEEE	Institute of Electrical and Electronics Engineer
IEC	International Electro technical Commission
IRENA	International Renewable Energy Agency
KV	Kilovolt
KWh	Kilowatt-hour
GW	Giga-watt
MVA	Megavolt-Ampere
MW	Mega-watt
NERC	North American Electric Reliability corporation
PV	Photovoltaic
PWM	Pulse Width Modulation
RES	Renewable energy Resources
SLD	Single line diagram
THD	Third Harmonic Distortion

1.0 INTRODUCTION

Catastrophic natural disasters such as wind storms are one of the main causes of widespread power system blackouts. The increasing number of such incidents in recent years and the growing dependence of people's lives and the nation's critical infrastructure on the electric power network have attracted growing attention to power system resilience enhancement (Panteli and Mancarella, 2015). Distribution network resilience is very important as it concerns urban areas such as Lusaka and many others where the impacts of natural disasters such as wind storms can be more devastating and can cause further casualties. Further, many of the critical infrastructures (essential loads), e.g., hospitals, military bases, and rescue centers, rely on electricity provided by the distribution network. Maintaining uninterrupted power supply to the critical infrastructure (essential loads) is demanded, especially during a natural disaster such as a windstorm (Fang et al., 2016).

Zambia has certainly been affected by the foothills of several cyclones (wind storms), which are Ana, Gombe, Idai, Chalane, and Desmond, with maximum speeds of 213 kph (59.17 m/s), 183 kph (50.33 m/s), 111 kph (30.833 m/s), 93 kph (25.833 m/s), and 82 kph (23.1 kph), respectively. The effects of these wind storms on the distribution network essential loads are very devastating if they occur, and as such, there is a need to prepare for them (<https://www.worlddata.info/africa/zambia/cyclones.php>, 28.10.2022).

The preparedness against power cuts caused by wind storms is enhancing the resilience of the distribution network, which has essential loads. Power system resilience enhancement measures are normally categorized into hardening-oriented and operation-oriented categories. Reinforcing poles and substations as well as vegetation management are examples of the former, while rescheduling generation, strategic microgrid islanding, and priority-based load shedding are practical measures of the latter (Panteli and Mancarella, 2015).

In this study, various indices were analysed to measure the essential loads of the distribution network in terms of resilience against power cuts caused by wind storms. The specific indices are performance, vulnerability, degradation, and energy loss (Mahan et al., 2008).

1.1 Statement of the problem

We need to address the issue of the poor state of the distribution network in terms of resilience against power outages caused by wind storms affecting essential loads (critical loads).

1.2 Aim

The aim of this research was to enhance resilience in the distribution network against power outages caused by wind storms affecting essential loads

1.3 Objectives

The following are the objectives of this research work:

1. To investigate the consequences of the distribution network's poor condition in terms of its resilience to wind storms, which cause power outages affecting critical loads.
2. To find the best practical options available from the literature to address the issue of the distribution network's inadequate resilience against storms that cause power outages affecting vital loads.
3. To calculate and analyze the resilience indices so as to measure the state of the distribution network in terms of resilience

1.4 Research Questions

1. What exactly is resilience in the context of power systems?
2. What are the effects of the poor state of the distribution network in terms of resilience to wind storms?
3. What are the best options available to address the issue of the poor state of the distribution network in terms of its resilience to wind storms affecting essential loads?
4. What are the impacts of integrating PV plants with battery storage on the distribution network as one of the best options available to address the issue of resilience?
5. What are the resilience indices?

1.5 Significance of the Study

This study will help power distribution planners, operation and maintenance engineers reduce the number of forced outages caused by fallen wooden poles during wind storms in the distribution network, affecting essential loads.

1.6 Study Site/ Delimitation

The study site for this research work was the Kasama Distribution Network under ZESCO's North, business unit. This distribution network was used to analyze resilience in this study.

2.0 LITERATURE REVIEW

2.1 Resilience

The word "resilience" was first used by Holling (1973) in relation to ecological systems. The Random House Dictionary of English defines resilience as: "the power or ability to return to the original form, position, etc. after being bent, compressed, or stretched; the ability to recover from illness, depression, adversity, or the likelihood to spring back or rebound."

Resilience is defined by the United Nations Office for Disaster Reduction (UNISDR) as the ability of a system, community, or society exposed to hazards to resist, absorb, accommodate for and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions. And according to Bie et al., (2017), resilience is defined as the ability of an entity to anticipate, resist, absorb, respond to, adapt to, and recover from a disturbance.

Flynn (2008) has outlined a four-stage framing of the concept of resilience: (1) preparing to make the system as robust as possible in the face of possible future stresses or attacks; (2) relying on resources to manage and ameliorate the consequences of an event once it has occurred; (3) recovering as quickly as possible once the event is over; and (4) remaining alert to insights and lessons that can be drawn (through all stages of the process) so that if and when another event occurs, a better job can be done in all stages.

Power system resilience is proposed by Liu et al., (2022) to capture the performance of power systems under the influence of extreme events such as wind storms, floods, and others. In general, power system resilience can be defined as the capability of a power system to maintain its performance (e.g., generation, load, and voltage) and speedily recover from damages after a high-impact, low-probability (HILP) event.

Liu et al., (2022) describe the following steps to evaluate the resilience of the power systems:

1. Event modelling

Model extreme event intensity, propagation paths, and influencing radius using either historical or forecast data.

2. Impact assessment

With a modeled event, its impacts on the power system infrastructure are evaluated using historical vulnerability and fragility records.

3. Outage analysis

With identified vulnerable sections of the grid, potential outage scenarios will be generated using probabilistic analysis and Monte Carlo simulation.

4. Resilience evaluation

Simulate power system response using the generated outage scenarios and evaluate resilience using the resilience trapezoid model to calculate the matrices.

As shown statistically, due to the complexity of the distribution system, the restoration process after a low probability event like floods can take weeks compared to the generation and transmission systems (Zhang et al., 2014).

2.2 The effects of the poor state of the distribution network in terms of resilience to wind storms

For overhead systems, the majority of power outages happen because trees are blown into power lines and/or high, intense winds directly blow down poles during hurricanes, windstorms, and winter storms. Overhead distribution lines consist of poles, conductor wires, and other types of equipment. The breakdown of a single pole or conductor results in the disconnection of the entire line. Which have resulted in substantial economic losses in recent years in the United States. For example, Hurricane Sandy (with a peak wind speed of 175 mph) in 2012 paralysed the power systems of several coastal states and resulted in outages that affected over 8.5 million customers. According to reports, 65% of New Jersey's customers were cut off from power grids during this severe storm. Between 2003 and 2012, roughly 679 power outages, each affecting at least 50 000 customers, occurred due to weather events in the United States, and 80–90% of these outages were due to failures in distribution systems. Therefore, enhancing grid infrastructure resilience to protect against extreme weather events is a key task of grid modernization efforts (Ma, 2016).

The cost associated with rebuilding the distribution network infrastructure and recovering lost energy due to the outage after a wind storm is very high. For example, in the United States in 2022, an estimate from the Department of Energy showed that between 2008 and 2012, annual costs due to weather-related power outages ranged from \$25 billion to \$70 billion. These figures are derived from business costs associated with lost output, residential customers' willingness to pay to avoid outages, and other types of lost economic output. Hurricane Sandy alone cost the U.S. economy between \$14 and \$26 billion. In Thailand, the 2011 floods cost the power sector \$285 million in damages and losses and another \$180 million to recover and reconstruct (Brown et al., 2016).

The security of energy Supply has become a major concern worldwide, given modern society's strong dependence on its adequate delivery. Not only does the functioning of industry, transportation, communication and computer systems depend on a continuous energy supply, but our entire lifestyle collapses when energy fails. Surges in fuel prices, political conflicts, wars, and natural disasters directly threaten the energy supply. And important policy concerns are being implemented as countries look to protect themselves (Rudnick, 2011).

2.3 The best strategies available to address the issue of the poor state of the distribution network in terms of resilience to wind storms affecting essential loads

Mahan Fell (2018) classified the best available strategies for addressing the issue of the distribution network's poor state in terms of resilience as hardening and operational. These are described in subsections 2.3.1 to 2.3.5.

2.3.1 Distribution network hardening strategies

Distribution network hardening is one of the most effective strategies to protect systems against extreme wind storms. There are various distribution network hardening methods such as overhead structure reinforcement, vegetation management and undergrounding (Ma, 2016).

2.3.1.1 Overhead structure reinforcement

Overhead structure reinforcement constitutes a primary hardening strategy that involves upgrading distribution poles to a stronger class, enhancing guying, and refurbishing poles (Ma, 2016).

According to Mahan et al., (2018), the design of distribution lines is influenced by the maximum allowable wind span, which is calculated based on the loads on distribution poles. The loading on a distribution pole includes:

1. The weight of the attached equipments, conductors, neutral wires, and the vertical load component of the guy tension force.
2. Tension forces from the conductors and neutral wire during the installation of new lines
3. Wind loadings on the pole, conductors and neutral wire based on the span

Based on these loadings and the ultimate bending moment capacity of the selected wooden pole class and length, the maximum allowable wind span can be determined. This is the maximum separation distance for two distribution poles that also satisfies the structural performance safety criteria.

The American National Standards Institute standard ANSI 05.1 (1992) defines the classification of utility wooden poles. The greatest variations in these classifications are in length and tip circumference. But the classifications also incorporate information about load-bearing capability, which is related to size and other factors regarding the integrity of the material of which the poles are made. On the next page, Table 1 shows the types of wooden poles.

Table 1: classification of wooden Poles (ANSI 05.1, 1992)

Pole Class	Horizontal loads(kg)	Length range(m)	Minimum tip circumference(cm)
H6	5,170.953	13.716-38.1	99.06
H5	4535.924	13.716-38.1	93.98
H4	3,946.254	12.192-38.1	88.9
H3	3,401.943	12.192-38.1	83.82
H2	2,902.991	10.668-38.1	78.74
H1	2449.399	10.668-38.1	73.66
1	2,041.166	10.68-38.1	68.58
2	1678.292	6.096-38.1	63.5
3	1,360.777	6.096-27.432	58.4
4	1,360.777	6.096-21.336	53.34

The H classification indicates the largest utility poles in terms of circumference and height. H5 poles can range from 13.716m to 38.1m tall and are no less than 93.98cm in circumference at their tip. The lower the number after the H, the smaller the pole. The sizes go down incrementally by 5.08cm of tip circumference. So the H1 is 10.668m to 73.66m tall, but it is 73.66cm in circumference at the tips. The horizontal loads that the H-classification poles can hold range from 4535.924kg for H5 to 2449.399kg for H1.

Just below the H classification poles, the scale starts over and goes from 1 to 5, so a Class 1 pole is the next smallest after a Class H1. Class 1 poles range from 10.68m to 68.58m in length and have a minimum 68.58cm circumference at the tips. Their horizontal load-bearing capacity is 1042.166kg. The sizes drop incrementally down to Class 4 (ANSI 05.1, 1992).

2.3.1.2 Wooden pole fragility curves from class 1-4

Dunn et al., (2018) define fragility curves as the relationship between the probability of exceeding a particular damage state (or performance) of an infrastructure component and the intensity of the applied hazard.

Teoh et al., (2019) describe the reliability of the distribution poles and how fragility functions are developed to determine the probability that critical engineering demand parameters will cause the structure to exceed certain limit states for a given hazard intensity. For wood poles, the engineering parameters of interest are the nominal bending moment and the demand moment at ground level, Therefore, the limit state function used for the fragility analysis is defined as follows:

$$Z(t) = M_{ult}(t) - M(t) \dots\dots\dots (1) \text{ (Teoh et al., 2019)}$$

Where $M_{ult}(t)$ is the nominal bending moment at any time t (kN-m), representing the pristine of the pole and $M(t)$ is the moment demand at the ground level of the pole (kN-m).

Figure 1 below on the next page shows the fragility curves for wooden pole from class 1 to 4.

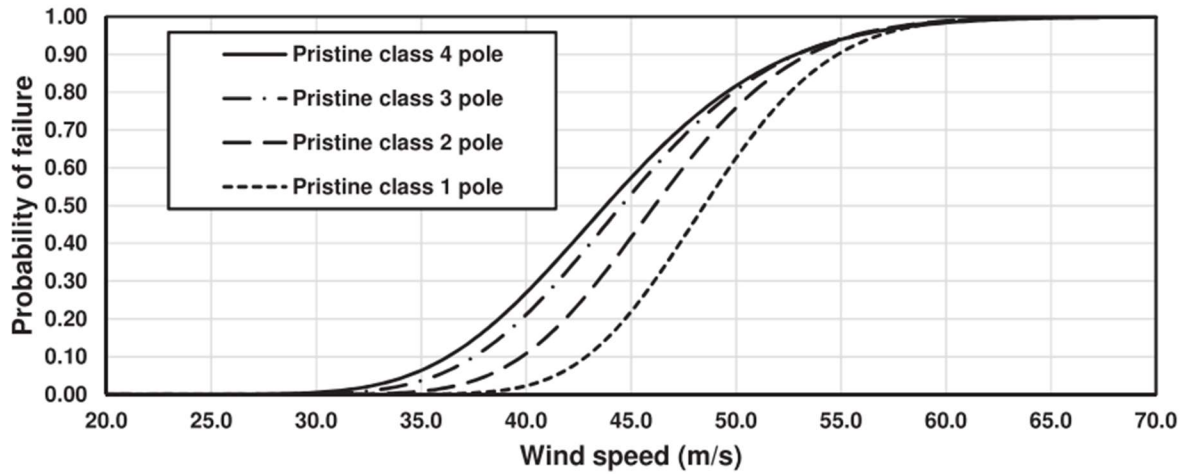


Fig. 1: Fragility curve for wooden poles from class 1-4 (Teoh et al., 2019)

2.3.1.3 Calculation of the Probability of Failure of the Distribution Network

In a distribution network, each line consists of several poles, wires, and supporting arms, each of which has a probability of failure. The calculation of line failure probability depends on the line type, the number of poles crossed and the fragility curve of each pole must be used for an overhead line. For the underground cables, the failure probability will be driven directly by the fragility curves, which are assumed to be uniform for the entire length of this line.

Uniformly, the failing probability of a line can be calculated as follows:-

$$P_l = 1 - \bar{P}_l \dots\dots\dots (2)$$

Where P_l the failing probability of the Distribution line and $\bar{P}_l$ is the not failing probability of the Distribution line.

$$\text{Where } \bar{P}_l = \prod_{k \in k_l} (1 - P_{l,k}) \dots\dots\dots (3)$$

$$\text{And } P_{l,k} = P_{l,k}^w + P_{l,k}^P + P_{l,k}^w P_{l,k}^P \dots\dots\dots (4)$$

k_l Is the set of available poles crossed by line $P_{l,k}^w$ and $P_{l,k}^P$ are the failure probabilities of the wire and the pole, respectively by Mahan F el at., (2018).

2.3.2 Operation strategies: smart grid technology

Smart grid technologies can improve the overall efficiency of the power system's operation and increase the system's visibility and response to faults and outages. These technologies enable the power system to quickly locate power outages and restore loads more efficiently. With the ongoing efforts on the smart grid and smart distribution system, there will be more operational strategies available for the resilient power system, such as:

1. Risk assessment and management for evaluating and preparing
2. Disaster assessment and priority setting
3. Integration of Distributed Energy Resources (DER) into the Distribution Network
4. Accurate estimation of the natural disaster location and severity
5. Fault location, isolation, and service restoration
6. Demand side management
7. microgrid island operation
8. Advanced control and protection schemes

Among the smart grid technologies, advanced metering infrastructure (AMI) can alert the utility grid of outage information in real time. Automatic switches allow the utility grid to isolate the fault and reroute a blackout area to a power supply. Today, utilities build upon smart grid technology to deal with increasing extreme events. (Bie et al., 2017)

2.3.2.1 Integration of Distributed Energy Resources (DER) into the Distribution Network

The CIGRE WG (2003) defines the DG unit as a generation unit that is not centrally planned, not centrally dispatched, usually connected to the distribution network, and smaller than 50 to 100 MW. According to Rani et al. (2015), DG is the generation of electricity by facilities of 10 MW or less in order to allow interconnection at nearly any point in the power system.

Hence, DG includes a variety of small generation units ranging from solar arrays, small hydro, wind turbines, geothermal power, micro turbines, fuel cells, diesel engines, tidal power, and wave power, to name a few. The DGs are now an integral part of most of the distribution systems across the world and are owned and operated by utilities and customers alike.

The integration of distributed energy resources in the modern distribution network provides new opportunities to maintain the power supply to essential loads and enable faster restoration after a wind storm. DER is a localized cluster of power sources that can operate in two different modes.

1. Island mode
2. Grid-connected mode

The ability to maintain self-sufficiency is a critical feature of DER, which makes them suitable to be used to mitigate grid disturbances and facilitate faster system recovery during severe outages. Connecting multiple DERs to the distribution network enhances its resilience to strong winds by supplying critical loads in island mode when the main network has collapsed (Wang, 2017).

2.3.2.1.1 Types of Distributed Energy Resources (DER)

Distributed energy resources (DERs) are not commonly connected to a bulk power transmission system but are interconnected near the load in the electric power distribution system. DER includes renewable energy such as wind and solar, fossil-fuel-based generation (micro turbines and small gas turbines), and distributed energy storage (Benjamin et al., 2013).

The types of DERs are described in sections 2.3.2.1.1 to 2.3.2.1.3, which, when connected to the distribution network, will make it resilient to strong winds by operating in island mode after the main grid has collapsed.

2.3.2.1.1.1 Solar PV energy resource

Solar PV generation has experienced tremendous growth in recent years due to the growing demand for renewable energy sources. PV represents a method of generating electric power with solar panels that are exposed to light. The power generated is based on the conversion of the energy of the sun's radiation. A solar cell that is exposed to light transfers electrons between different bands inside the material. This, in turn, results in a potential difference between two electrodes, which causes direct current (DC) to flow (Barlase, 2017). Numerous benefits are expected for both the utility company and the consumer from the integration of PV energy resources into the utility's conventional resources. This form of energy, besides being renewable, also possesses other advantages, such as its ability to improve service reliability by reducing the number of system outages and by avoiding line extensions to remote areas. Such systems can also relieve thermal overloads in selected utility distribution systems. Other important benefits also exist, such as loss reduction on both distribution and transmission lines and voltage support. There are many such applications that have proven to be cost-effective. Besides the above applications, utilities also benefit from reducing their peak power with the grid-connected PV system as well as avoiding expensive line extensions by installing small standalone PV systems. PV can also support the voltage profile of the system. The rationale is that, besides generating real power, the PV system will also be required to provide reactive power. Voltage drops on a feeder are more prominent in sections with large demands. PV power generation can be placed on those branches where the voltage falls below the limit so as to improve the voltage profile (Chowdhury and Sawab, 1996).

2.3.2.1.1.2 Wind Turbines: A Distributed Energy Resource

Wind power is obtained by using wind turbines to convert the energy of the wind into electricity (Barlase et al., 2017). Grid-connected wind capacity is undergoing the fastest rate of growth of any form of electricity generation, achieving global annual growth rates on the order of 20–30%. For the last decade, capacity has been doubling every three years. The World Energy Council has stated that it is doubtful whether any other energy technology is growing, or has grown, at such a rate. Global installed capacity was 40 GW in 2003. According to industry associations, global wind power capacity was 47.3 GW in 2004. Wind power is increasingly being viewed as a mainstream technology for supplying electricity. Because of its attractiveness as a source of electricity, many countries have set lofty targets for wind power (Milligan et al., 1998).

Wind turbines can, under certain conditions, have high distribution system support value to utilities if installed on stressed distribution systems, or in areas where distribution facility upgrades are anticipated. Strategically located "distributed applications" can offer line or transformer, increase reliability, reduce substation stress, and provide other site-specific benefits. These location-specific distributed benefits also include the energy value of the power delivered and the potential capacity value. However, installation on weak rural distribution lines may have negative impacts as well (Debra, 2005).

2.3.2.1.1.3 Distributed Energy Storage

Energy storage, power electronics, and communications all play important roles in mitigating the intermittency and ramping requirements of large-scale wind and solar energy penetration (Barlase, 2017). Storage is unique in that no single technology fits all applications. Some applications may require fast response, while others may want duration as a key attribute. Energy storage methods can be divided into several groups: chemical, electrical, electrochemical, mechanical, thermal, and biological. Table 2 summarizes some of the most common types of energy storage systems connected to the utility power grid (Akhil et al., 2013).

Table 2. Common types of energy storage systems connected to the utility power grid (Akhil et al., 2013)

No	Storage Technologies	Advantages	Disadvantages
1	Pumped hydro storage	High energy, low operating cost, very high ramp rate, mature technology.	Special site requirements, high project cost.
2	Compressed air energy storage	High energy, low cost, better ramp rate than gas turbines, mature technology.	Special site requirements, need gas fuel, lower efficiency, slower response than flywheels or batteries
3	Flow Batteries	High capacity, independent power and energy ratings, can perform high number of discharge cycles, lower efficiency, and very long life.	Medium-energy density, complicated design, slow dynamic response, developing technology.
4	NaS Batteries	High power and energy densities, long discharge cycles, fast response, long life, mature technology.	High production cost, safety concerns since required to run at high temperatures, limited applications.
5	Li-ion Batteries	High power and energy densities, high efficiency, good cycle life, mature technology.	High production cost, special balancing circuits, safety concerns.
6	Ni-Cd Batteries	High power and energy densities, mature technology	Higher losses, lower lifetime
7	Advanced lead-acid	High power and energy densities, high efficiency, low capital cost, mature battery technology	High production cost, low-energy density, large footprint, limited useful life
8	Traditional lead-acid	Low capital cost, mature technology	Limited cycle life when deeply discharged

2.3.2.2 Resilient load restoration in the distribution system

According to historical data, the distribution system is to blame for 90% of power outages. Therefore, a lot of research efforts concentrate on the distribution level (Electric Power Research Institute, 2014). Fast and efficient restoration is a key step to increasing the resilience of distribution systems, and resilience strategies at the distribution level are urgently needed. In this section, we propose a resilient load restoration algorithm in the distribution system through backup DG and reconfiguration after the extreme weather event and the faults are identified, located, and isolated. Reconfiguration has traditionally been the primary method of restoring supply immediately following a fault. When the fault is isolated by switches, the load in the fault-affected areas could be picked up by tie switches to reconnect to other normally operating feeders. At the same time, the increasing penetration rate of DGs in the distribution system also enhances their ability to perform load restoration. Now intentional islanding of DGs is critical to providing power supply to important loads in the distribution system (Marnay, 2015).

Zhanga and Chen (2015) proposed an optimal DG islanding strategy considering reconfiguration after multiple faults in the distribution system. The main contributions of this method are as follows:

1. In the proposed method, the reconfiguration and DG islanding can be optimized simultaneously to obtain the DG islanding scheme with minimal load shedding.
2. The reconfiguration of a radial distribution system after multiple faults is considered. Furthermore, whether a controllable DG enters islanding operation is optimally determined.
3. The model is a mixed-integer second-order cone programming problem solved by the traditional optimization method.

When line faults occur as a result of a hurricane (wind storm) or earthquake, the power system's radial topology divides into several islands by faulted components, some of which have DGs or tie switches connected to other areas, and some of which are isolated blackout areas. For the former, the island can be redirected to other feeders and be supplied from the transformers, or it can form a DG island and be sustainable for a period of time on its own, regardless of outside faults. For the latter, the area has to be shut off and the load will be shedded.

An example is given in Figure 2, where the dotted lines indicate the tie switches. According to Figure 2 on the next page, after multiple faults, the following types of areas can be formed:

1. Area 1 is an isolated load cluster without DG, and the customers are forced to suffer the load shedding.
2. Area 2 is an area without DG but with a tie switch, and this area can either redirect to the main grid or connect with other areas that have DG inside.
3. Area 3 and Area 4 contain DGs, and they can either form two islands, each supplied by one DG, or reconnect with the main grid through T3, or form a DG cluster by closing T4 (Bie et al., 2015).

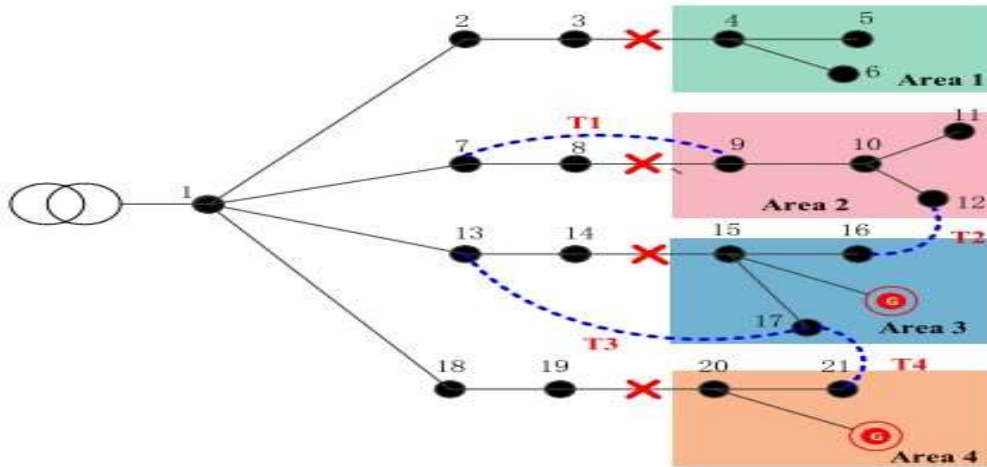


Fig 2: Distribution system after multiple faults due to wind storm (Bie et al., 2015)

In the flowchart in Figure 3, it is assumed that the distribution system is equipped with tie switches, sectionalizing switches, and DGs. When a disaster such as a windstorm happens, the system is split into several unconnected areas by faults (Bie et al., 2015).

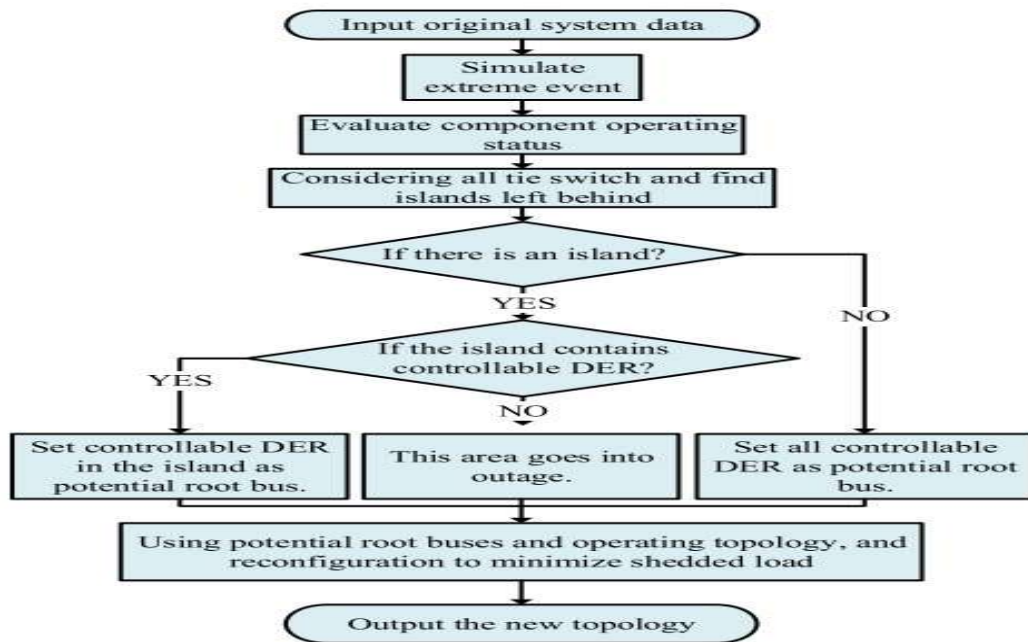


Fig 3: Flowchart of resilient load restoration mechanism (Bie et al., 2015)

2.4 The impact of integrating PV plants with battery storage into the distribution network to enhance resilience

The following are some of the impacts of integrating DER into the distribution network:

2.4.1 Voltage rises, causing an unbalance

The DER, like PV clusters with high PV power generation penetration, may have a negative impact on the voltage profile of the interconnected distribution feeder by raising the voltage above the standard limit at low load and high solar irradiation conditions. The voltage impact is a major concern and a challenging issue for the planning and design of large-scale PV networks. The change in voltage profile is highly dependent on the load pattern, the network configuration, and the number of feeders connected to the same distribution substation. Maximum penetration and the number of PV installations may also differ depending on the voltage regulation method (Katiraei et al., 2017). In accordance with ANSI C84.1 (2006), voltage regulation in distribution power networks is specified, where a nominal voltage of 120 volts is the standard for a residential consumer supply with allowable deviations of 5%. According to IEEE Standard 1547 (2006), the DER shall not actively regulate voltage at the PCC (point of common coupling).

2.4.2 Protective Relaying

The integration of DER, like PV plants, leads to reverse power flows through feeder sections and substations. The distribution grid, in general, has not been designed, built, or prepared for bidirectional power flows. Fuse protection of feeder lateral circuits has long been a practise for utilities. Utilities generally use two philosophies for protection coordination: fuse clearing and fuse saving, and in some cases, a combination of both—fuse clearing where fault currents are high and fuse saving where fault currents are moderate to low. Relays on substation breakers and upstream feeder reclosers trip before the fuse blows in the case of fuse saving. The breaker must trip before the fuse starts to melt. Depending on the severity of the fault, these schemes can sometimes not operate correctly. DER causes fuse-saving schemes to be even more complex because of the increased fault currents. In addition, DER increases the fault current level through the fuse but not necessarily through the substation breaker or feeder recloser. Furthermore, the addition of DER causes issues with fuse-to-fuse coordination. Choosing the correct fuse sizes, relay settings, and DER tripping settings can alleviate this problem, but they may not be optimal (Glover et al., 2008).

2.4.3 Frequency Control

Small-scale DER cannot control or change the system's frequency. Large-scale (MW-size) DER, depending on its size and regulatory framework, may be allowed to provide ancillary services. This can be accomplished by means of distributed generation, the combination of intermittent distributed generation and storage, or by using only distributed storage, according to Glover et al., (2008).

2.4.4 Power Quality

Fluctuations in PV production result in large voltage fluctuations as well as voltage flicker and other power quality issues. Potential impacts of DER integration are voltage rise, voltage fluctuation, flicker, voltage unbalance, voltage sags and swells, and increased total harmonic distortion (THD). Smart grid technologies and intelligent control of DER inverters can help alleviate issues related to voltage rise, voltage fluctuation, and intermittency. Other issues, such as voltage sags and swells due to larger fault currents, may be mitigated using, for example, fast-reacting fault current limiters. Issues related to increased voltage unbalance and harmonic distortion should be addressed in the planning stage of the smart grid, where maximum penetration levels and the location of DER must be carefully evaluated (Glover et al., 2008).

2.4.5 Reactive power requirements

Most grid-connected PV inverters are currently designed to operate at unity power factor, which means they only deliver real power in order to maximize generation performance. Therefore, the grid has to supply the reactive and distortion components of load and distribution network currents when there is no local means of reactive power compensation. A high rate of reactive power supply for the grid is not accepted by utility companies. This is mainly because the excessive reactive current flow reduces the effective capacity of the medium and high voltage feeders and increases the overall power losses of the system. It may also increase the burden on and power losses of the LV distribution transformers when they operate at very low power factors (below $\text{pf} = 0.6$ lag in some cases) (Katiraei et al., 2017).

2.5 Resilience indices of the distribution network

Mahan et al., (2008) article talks about the new resilience indices that are obtained from figure 4 below, called the resilience graph.

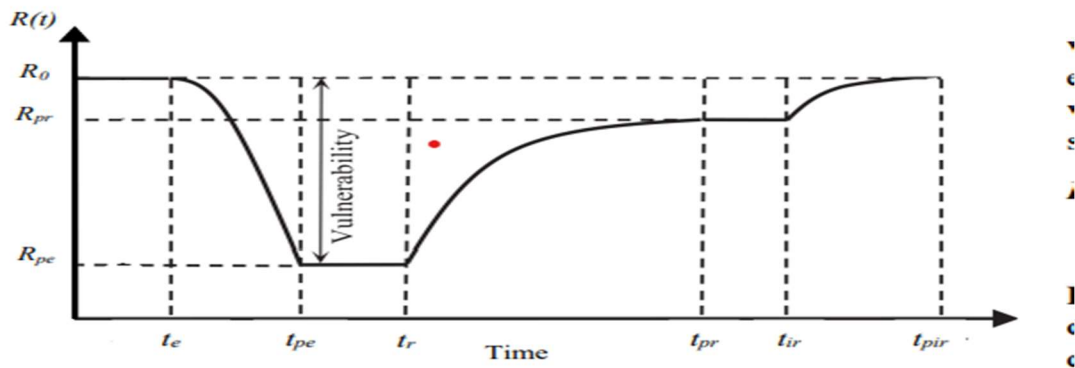


Fig. 4: Resilience graph (Mahan et al., 2008)

Where $R_0(t_e)$ - System performance indices before the event, $R_{pe}(t_{pe})$ - System performance indices after the event and $R_{pr}(t_{pr})$ - system performance after the network recovery from the event.

The following are the Resilience indices of the Distribution network:-

1. Performance index

$$R(t) = \frac{L_c(t)}{L_T(t)} \dots\dots\dots (5)$$

Where $L_c(t)$ is the sum of the supplied essential loads $L_c^\Omega(t)$ and common loads $L_c^C(t)$ of the network, and $L_T(t)$ is the sum of the total loads in the grid, both supplied and unmet. Note that, $R(t) = 1$ in the case of uninterrupted delivery, and $R(t) = 0$ in the case of complete outage, indicating the loss of all loads of the network. After an event occurs at time t_e and in the post event degraded state time interval $[t_{pe}, t_r]$, the supplied load is significantly reduced due to the failure of network equipments.

2. Vulnerability Index

We define the normalized vulnerability index ζ_v as shown below.

$$\zeta_v = \frac{R_0 - R_{pe}}{R_0} \dots\dots\dots (6)$$

Where R_0 the Performance index before the storm and R_{pe} is the Performance index after the storm. ζ_v Whose value is 0 for no degraded state and 1 for complete black out. This vulnerability index determines the decline ratio of the average supplied load after and before the storm.

3. Degradation index

To see the impact of time, we introduce the degradation index as below

$$\zeta_D = \int_{t_e}^{t_{pe}} \frac{R_0 - R(t)dt}{R_0(t_{pe} - t_e)} \dots\dots\dots (7)$$

Which takes the value of 1 for a sudden complete blackout that lasts until recovery begins, and 0 for no lost load.

4. Energy loss index

This evaluates the amount of energy not provided due to the occurrence of the event as below:

$$\zeta_E = \int_{t_e}^{t_{pir}} \frac{R_0 - R(t)dt}{R_0(t_{pir} - t_e)} \dots\dots\dots (8)$$

Which indicates the rate of performance decrease over the entire storm. ζ_E Assumes the value of zero (0) in the ideal state without a drop and assumes the value of one (1) in the worst-case scenario, indicating the maximum drop in the fastest time.

3.0 METHODOLOGY

This chapter provides an overview of the methodologies and methods used in carrying out this study to achieve the objectives.

3.1 Study Design

To achieve the objectives of this study, various methods were identified in the literature review. The following are the three objectives and methods to apply to achieve them:

1. To investigate the consequences of the distribution network's poor condition in terms of its resilience to wind storms, which cause power outages affecting critical loads.

To achieve the first objective, resilience indices were calculated and analyzed before implementation of the two best available options to enhance the resilience of the distribution network.

2. To find the best practical options available from the literature to address the issue of the distribution network's inadequate resilience against storms that cause power outages affecting vital loads.

To achieve the second objective, the two best options, which are hardening and resilient load restoration, were implemented during the storm. In the hardening method, pole class 1–4 were subjected to wind speeds ranging from 30 m/s to 60 m/s to determine if they could withstand and continue supplying the essential loads. A programme coded in the Python programming language was used to determine if these pole classes failed or not during the storm. In the resilient load restoration method, PV plants with battery storage were integrated into the buses connecting essential loads to operate in island mode during the storm so as to continue supplying the essential loads.

3. To calculate and analyze the resilience indices so as to measure the state of the distribution network in terms of resilience.

To achieve this objective, the active power supply to the essential, common loads and the whole distribution network before, during, and after the storm were calculated in PowerFactory 2018. These indices were used to measure the resilience of the distribution network before and after the implementation of the two best options.

3.2 Data collection

Key to the development of this study was the acquisition of data. Various avenues were employed in acquiring data, and these included:

3.2.1. Site visits for Data collection

For the purpose of data collection, various substations in the Kasama distribution network were visited. The following are the substations:

- Lualuo 66/33/11kV Substation
- Kasama Town 33/11kV Substation
- Forest 33/11kV Substation
- Chilubula 33/11kV Substation
- Tazara 33/11kV Substation
- Lukashya 33/11kV Substation
- Kasama 330/66/11kV Substation

3.2.2. Data collected from the ZESCO Kasama Distribution network

The following information was gathered from the ZESCO Kasama distribution network.

1. 33kV Line Data

Table 3: 33kV Line data for the Kasama Distribution Power System

NO	Line	Distance(km)	Reactance mΩ/km	Susceptance μS/km
1	Lualuo - Kasama Town	4.2	400	2.9
2	Lualuo - Forest	5	400	2.9
3	Lualuo – Tazara	10	400	2.9
4	Kasama Town – Chilubula	35.6	400	2.9
5	Forest – Lukashya	6.8	400	2.9

2. Transformer Substation Data

Table 4: Transformer Substation Data

Substation	MVA rating	HV kV	LV kV	%impedance	NO of taps	Nominal tap	Vector group
Lualuo T1	10	66	33	8.07	17	6	Dyn11
Lualuo T2	10	66	33	8.07	17	6	Dyn11
Kasama Town T1	10	33	11	8.2	17	5	Dyn11
Kasama Town T2	5	33	11	7.25	5	1	Dyn11
Lunkashya T1	2.5	33	11	4.02	5	1	Dyn1
Tazara T1	5	33	11	4.06	5	0	Dyn11
Tazara T2	5	33	11	4.06	5	0	Dyn11
Forest T1	5	33	11	4.65	5	0	Dyn11
Forest T2	5	33	11	4.65	5	0	Dyn11
Chilubula T1	1.25	33	11	3.5	5	0	Dyn11

2. Substation Loading data

Table 5: Substation Loading

No	Substation	MW Loading
1	Forest	2.23
2	Kasama Town	4.57
3	Tazara	1.55
4	Lukashya	0.66
5	Chilubula	0.75

3. The probability of failure of wooden poles for class 1-4 at different wind speeds is given by the fragility curve in figure 1

Table 6: Probability of failure of wooden poles from class 1-4

Wooden pole class	Wind speed(m/s)	Probability of failure
1	30	0.01
	40	0.5
	50	0.62
	60	0.9
2	30	0.05
	40	0.22
	50	0.75
	60	0.92
3	30	0.2
	40	0.3
	50	0.75
	60	0.93
4	30	0.3
	40	0.5
	50	0.88
	60	0.98

4. Existing classes of poles in the lines in the Kasama Distribution network

Table 7: Classes of wooden poles in the Kasama Distribution network

No	Distribution line	Wooden pole class
1	33kV Lualuo Tazara	4
2	33kV Lualuo Kasama	3
3	33kV Lualuo Forest	3
4	33kV Forest Lukashya	4

3.3. Modelling of the Kasama Distribution Network

The aim of this study was to maximize the amount of essential load provided during the storm, hence improving the resilience indices. To calculate the load supplied to the distribution network and its loads before, during and after the storm, load flow calculation was conducted in PowerFactory DIgSILENT 2018. PowerFactory DIgSILENT (2018), a commercially available simulation software package and Kasama's distribution network was used as the test network for this study.

3.3.1. PowerFactory DIgSILENT

Power Factory DIgSILENT is a computer-aided engineering tool for the analysis of the Transmission, Distribution, and Industrial electrical power systems. The term DIgSILENT is an acronym for Digital Simulation of Electrical Networks and DIgSILENT Version 7 was the world's first power system analysis software with an integrated graphical single-line interface. The software does not require advanced software programming skills due to its enhanced graphical user interface (GUI).

DIgSILENT has been designed as an advanced integrated and interactive software package dedicated to the electrical power system and control analysis in order to achieve the main objectives of planning and operation optimization. It is easy to use and fully compatible with Windows platforms and can be integrated with other packages to meet the requirements of all power system analysis applications.

According to Akihiro.A et al., 2015 there are many other power system simulation software such as, PSSE, MATLAB, ETAP, PSCAD, PSAT, Power World Simulator, ASPEN and others. DIgSILENT, apart from being a robust software, is best fitted for this study.

3.3.1.1 Modelling of Nodes in Power factory DIgSILENT

Two different types of node elements are used, Terminals () and Busbars (). A terminal is the simplest node representation and is used in those cases where neither generators nor transformers were connected. PowerFactory gives many alternatives for the representation of a Busbar such as Busbar, Single Busbar System with Tie Breaker, Double Busbar System etc.

3.3.1.2 Modelling of Lines in PowerFactory DIgSILENT

Lines in PowerFactory are simply represented as one-to-one connection between two nodes.

Using the icon () and left clicking on the appropriate nodes a connection between them is established. A line is represented by an Elmlne object in the database which can be edited after double-clicking on the line.

3.3.1.3 Modelling of the Load in PowerFactory DIgSILENT

The loads in PowerFactory are selected with the () button from the Drawing Toolbox and dragging them to the Bus or the Terminal that are connected. Doing so, an Elmlod object is created in the database which describes the load. Loads are edited by double clicking on them and information about the active and reactive consumption can be assigned.

3.3.1.4 Modelling of the Synchronous Generators in PowerFactory DIgSILENT

Synchronous generators are selected using the () button from the Drawing Toolbox. After placing them to the Bus that are connected the ElmSym object is created in the database.

3.3.1.5 Modelling of the Transformers in PowerFactory DIgSILENT

PowerFactory incorporates the modeling of different types of transformers, such as two winding

Transformer () , two winding-Neutral Transformer () , three winding Transformer () , Auto Transformer () and Boosting Transformer () .

3.3.1.6 Modelling of the Shunt Impedances in PowerFactory DIgSILENT

PowerFactory supports five combinations of shunt impedances such as Shunt RLC () , Shunt RL () , Shunt C () , Shunt RLCRp () and Shunt RLCCRp () .

3.3.2 Modeling of the Kasama distribution network

This section shows the modeling of the Kasama distribution network in Power Factory DIgSILENT 2018.

Figure 7 depicts single-line diagrams of the Kasama distribution network operated by ZESCO Limited:-

The Kasama distribution network was modelled in PowerFactory Digital 2018 for the purposes of this study, as shown in Figure 5.

Below:-

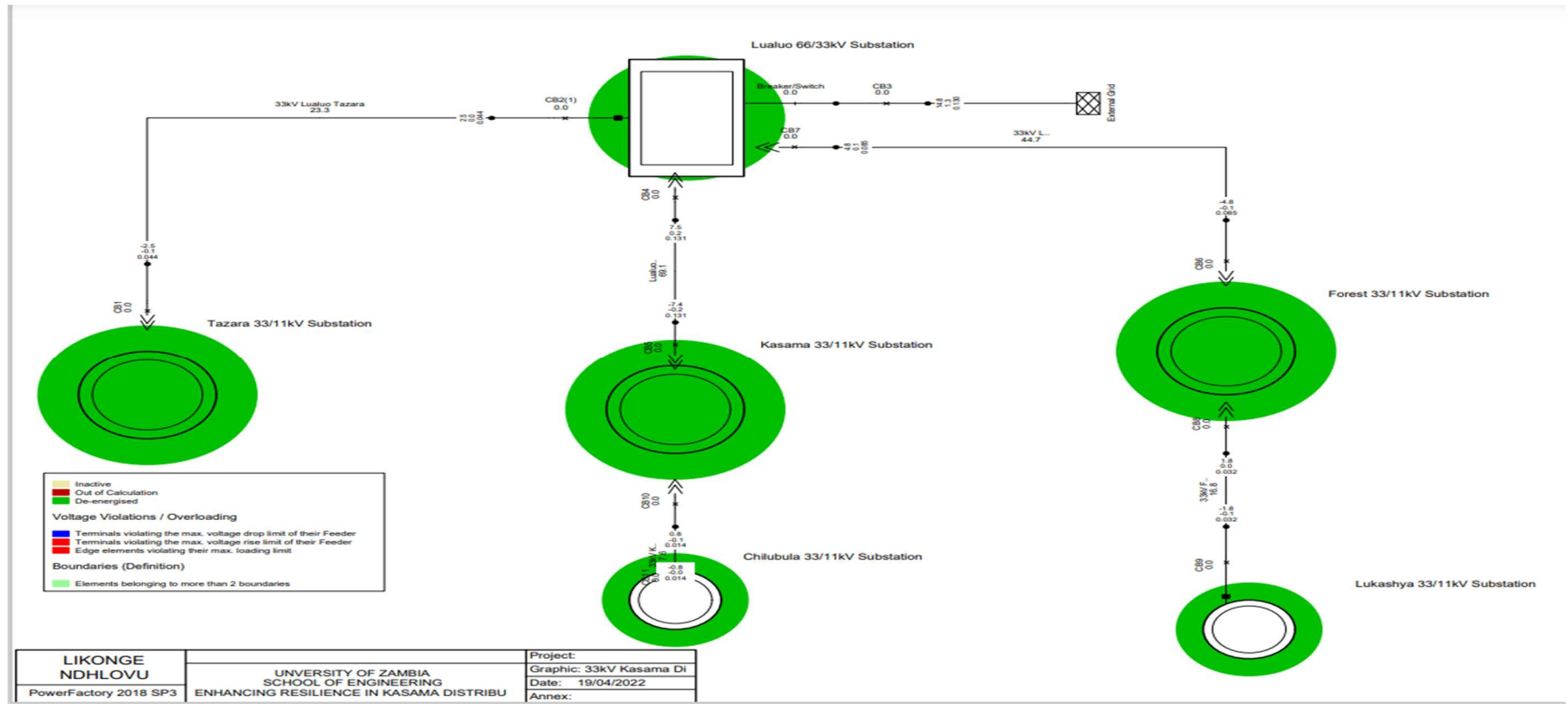


Fig. 5: Depiction of the Model of the Kasama Distribution Grid

Figure 6 on the next page is the modeling of the Lualuo 66/33/11kV substation in PowerFactory 2018. The substation is the source of electrical energy for the Kasama distribution network and the installed capacity is 20MVA with 2X10MVA, 66/33kV transformers.

33kV/BB1

1T1
1T2
1T3
1T4
1T5
1T6

33/11kV T

1T7
1T8

11kV/BB2

CB 11

CB 2

St. Theresa Sc.

26

The figure 9 shows the modelling of Forest 33/11kV Substations in PowerFactory DIgSILENT 2018, the station total installed capacity is 10MVA.

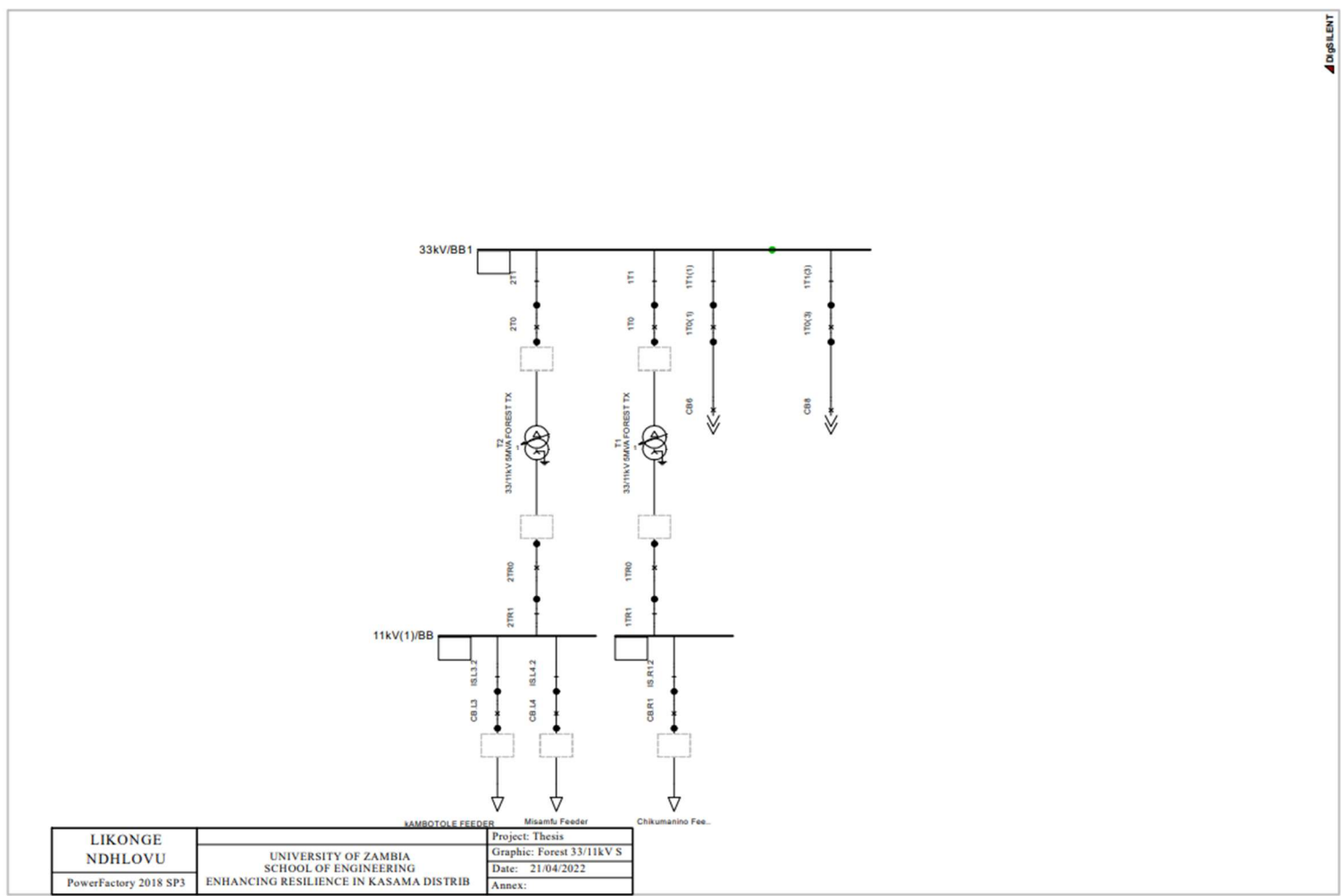


Fig. 9: Modelling of the Forest 33/11kV Substation in PowerFactory DIgSILENT 2018

28

Figure 11 shows the modeling of Tazara 33/11kV substations in PowerFactory DIgSILENT 2018. The substation has a total installed capacity of 2.5MVA.

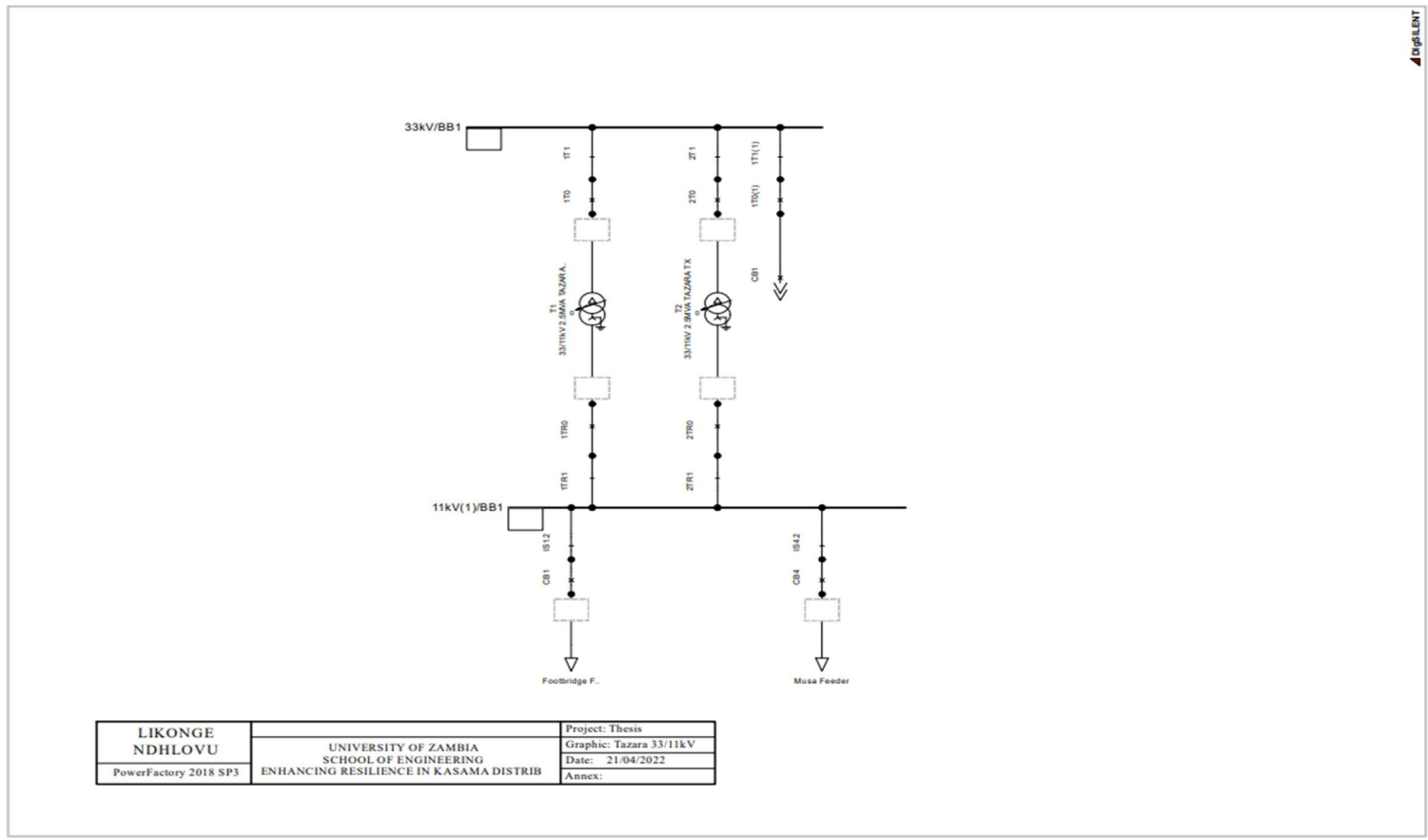


Fig.11: Modelling of the Tazara 33/11kV Substation in PowerFactory DIgSILENT 2018

3.4 Implementation of hardening and system-resilient load restoration methods to improve the Kasama Distribution network's resilience

3.4.1 Network resilience evaluation

1. Determined the failed lines during the storm at wind speeds varying from 30 m/s to 60 m/s. The code was written in python programming software 2022 to determine these lines that failed.
2. Calculated the load flow to determine the loads supplied during the storm for both the common and essential loads in PowerFactory 2018.
3. Recovery phase. Recovered one failed line per three hours until full restoration.
4. Calculated the resilience indices.
5. Drew the resilience curve.

3.4.2 Study Criteria

The focus of this case study was to enhance resilience in the Kasama distribution network so as to maximize the amount of essential supplies provided during the wind storm.

The study criteria was to analyze the Kasama Distribution network under storms of wind speeds varying from 30m/s to 60m/s before and after the implementation of the two best options to address this issue of power outages caused by poor system resilience affecting essential loads. The following were the two best options to address the problem:

1. Hardening of the Kasama Distribution Network's wooden poles in the 33kV lines connecting to essential loads
2. Integration of PV plants with battery storage for buses connecting critical loads. For this option, an investigation was conducted on the effects of the integration of PV plants with battery storage to determine if the test network could not collapse in terms of voltage.

3.4.2.1 Hardening of the distribution network

This step determines possible strategies to harden the network lines. Depending on the locations of the essential loads and the network structure, various strategies can be proposed. Each strategy is a set of lines, each of which connects the essential loads and the available power resources in the network. In this study, wooden poles from class 1–4 were tested to determine if they could withstand the storm. To enhance the resilience of the distribution network against storms affecting essentials loads, only lines connecting them were tested.

The Kasama distribution network's critical loads are connected at the 11kV buses of Kasama 33/11kV and Chilubula 33/11kV substations. At Kasama 33/11kV Substation, the loads are Kasama General Hospital, Kasama business District, and Lukupa water pumping station and at Chilubula 33/11 kV Substation; Chilubula mission hospital and ZNS Camp.

3.4.2.2 Integration of a solar PV plant with battery storage

Since the primary goal of this study was to ensure continuous supply of power to essential loads during and after the wind storms, the solar PV plants with battery storage remained in service in case of the 33kV Lualuo-Kasama Town and 33kV Kasama Town Chilubula lines, respectively failed.

The models of operation of these solar PV plants with battery storage were as follows:

1. Normal state of the Kasama Distribution network before the storm

The PV plants with battery storage operated in grid-connected mode.

2. Degraded state of the Kasama distribution network

This is the state during the wind storm, and the expectation is that the 33kV lines with a high probability of failure have failed. Therefore, the PV plants with battery storages islanded and continued supplying the essential loads.

3. The Kasama Distribution Network's Recovery Status

This is the state after the wind storm (event) and the recovery of the failed lines.

3.5 Data Analysis

To analyze the Kasama Distribution network's resilience, the following resilience indices were calculated before, during, and after the storm.

1. Performance index ($R(t)$)
2. Normalized Vulnerability index (ζ_V)
3. Degradation index (ζ_D)
4. Energy Loss index (ζ_E)

To determine the resilience indices, from the resilience graph in figure 4 of section 2.5, let $R_0 = R(t_e)$, $R_{pe} = R(t_{pe})$ and $R_{pr} = R(t_{pr})$ be the system performance indices before, during and after the storm respectively. The Performance, Normalized Vulnerability, Degradation and Energy indices will be calculated using formula 5 – 8 in part two (2) of this study.

Usually, wind storms take days to completely damage the network, unlike earthquakes, which take a few hours. For the purposes of this study, we assumed that the wind storm (event) lasted six (06) hours and that the repair time for each line was three (03) hours. These assumptions helped us to draw the resilience curve and analyze the Kasama distribution network's resilience.

4.0 RESULTS AND DISCUSSIONS

This chapter provides an overview of the results and findings of the research.

4.1 Overview

Chapter three (3) above identified two strategies to implement in this study to enhance the resilience of the Kasama distribution network (test network) against wind storms with speeds varying from 30m/s to 60m/s that causes outages affecting essential loads.

The study scenarios are categorized as follows:

1. Evaluation and analysis of the resilience indices of the Kasama Distribution Network after implementation of the two (2) best options
2. To conduct an analysis of the effects of incorporating PV plants with battery storage into the test network.

The findings of the above investigations are outlined as follows in Section 4.2:

4.2 Evaluation and analysis of the resilience indices of the Kasama Distribution Network

In this study, it was assumed that the storms occurred at 10:00 a.m. and normalized at 16:00 pm. In PowerFactory DIgSILENT 2018, load flow calculations were carried out before, during, and after the event to determine the active power supplied to both the common and essential loads. Storms. A code written in python programming software 2022, was able to determine the failed lines during the storm.

4.2.1 Evaluation and analysis of the resilience indices of the Kasama Distribution Network during the storm of 30m/s wind speed

To evaluate and analyze the resilience indices of the Kasama distribution network during a storm of 30m/s wind speed, class 1–4 poles were analyzed. It was noted that their probabilities of failure are 1%, 5%, 20%, and 38%, respectively and as such, they were able to withstand the storm, as was determined by a code written in python 2022 programming software (pycharm) in figure 21 in appendix 7.2. Table 8 below shows the resilience indices of the Kasama distribution network. As the calculation can be seen in appendix 7.3

Table 8: Resilience indices of the Kasama Distribution network during the storm of 30m/s

ζ_V	ζ_D	ζ_E	% of essential Load supplied during the event(wind storm)
0	0	0	100

$\zeta_V = 0$, indicates that 100% of network loads were supplied during the storm and $\zeta_E = 0$, indicates 100% of the network demanding energy is provided in the whole process. And essential customers were on supplied before, during and after the storm.

4.2.2 Evaluation and analysis of the resilience indices of the Kasama Distribution network during the storm of 40m/s wind speed

To evaluate and analyze the resilience indices of the Kasama distribution network during a storm of 40m/s wind speed, class 1–4 wooden poles were tested. It was noted that their probabilities of failure were 5%, 22%, 30%, and 45%, respectively, and as such, they were able to withstand the storm. As was determined by a code written in python 2022 programming software (pycharm) in figure 22 in appendix 7.2. Table 9 below shows the resilience indices of the Kasama distribution network. As the calculation can be found in appendix 7.3

Table 9: Resilience indices of the Kasama Distribution network during the storm of 40m/s

ζ_V	ζ_D	ζ_E	% of essential Load supplied during the event(wind storm)
0	0	0	100

$\zeta_V = 0$, indicates that 100% of network loads were supplied during the storm and $\zeta_E = 0$, indicates 100% of the network demanding energy is provided in the whole process of the storm. And essential customers were on supplied during the storm

4.2.3 Evaluation and analysis of the resilience indices of the Kasama Distribution network during the storm of 50m/s wind speed

To evaluate the resilience indices of the Kasama distribution network, during a storm of 50 m/s wind speed, class 1–4 wooden poles were tested. Only class 1 poles were able to withstand the storm due to their failure probabilities of 62%, 75%, 80%, and 83%, respectively. As was determined by a code written in python 2022 programming software (pycharm) in figure 23 in appendix 7.2. Table 10 below shows the resilience indices of the Kasama distribution network. As the calculation can be found in appendix 7.3

Table 10: Resilience indices of the Kasama Distribution network for class 1 poles during the storm of 50m/s wind speed

ζ_V	ζ_D	ζ_E	% of essential Load supplied during the event(wind storm)
0	0	0	100

$\zeta_V = 0$, indicates that 100% of network loads were supplied during the wind storm and $\zeta_E = 0$, indicates 100% of the network demanding energy is provided in the whole process of storm. And essential customers were on supplied.

4.2.3.1 Restoration of the failed lines after the storm of 50m/s wind speed

Table 11: Resilience indices of the Kasama Distribution network during and after the storm of 50m/s wind speed

ζ_V	ζ_D	ζ_E	% of essential Load supplied during the event(wind storm)
1	1	1	0

As can be seen from table 11, $\zeta_V = 1$ which indicates 100% of the loads lost supply during the event, $\zeta_D = 1$ which indicates sudden loss of supply of the entire network and $\zeta_E = 1$ which indicates 100% of the network demanding energy is not provided in the whole process. And during the storm, the essential loads were off supply.

The table 12 below shows the calculated performance indices before, during, and after the event. These calculated performance indices were used to come up with figure 12, called the resilience graph.

Table 12: Calculated Performance indices before, during and after the storm of 50m/s wind speed

Time in hours	Stage of the event	Performance Index
06:00-10:00	Before the event	1
10:00-16:00	During the event	0
16:00-19:00	Restoration of 33kV Lualuo Kasama town line	0.46823
19:00-22:00	Restoration of 33kV Kasama town Chilubula line	0.5450
22:00-01:00	Restoration of 33kV Lualuo Tazara line	0.70323
1:00-04:00	Restoration of 33kV Lualuo Forest line	0.932
04:00-07:00	Restoration of 33kV Forest Lukashya line	1

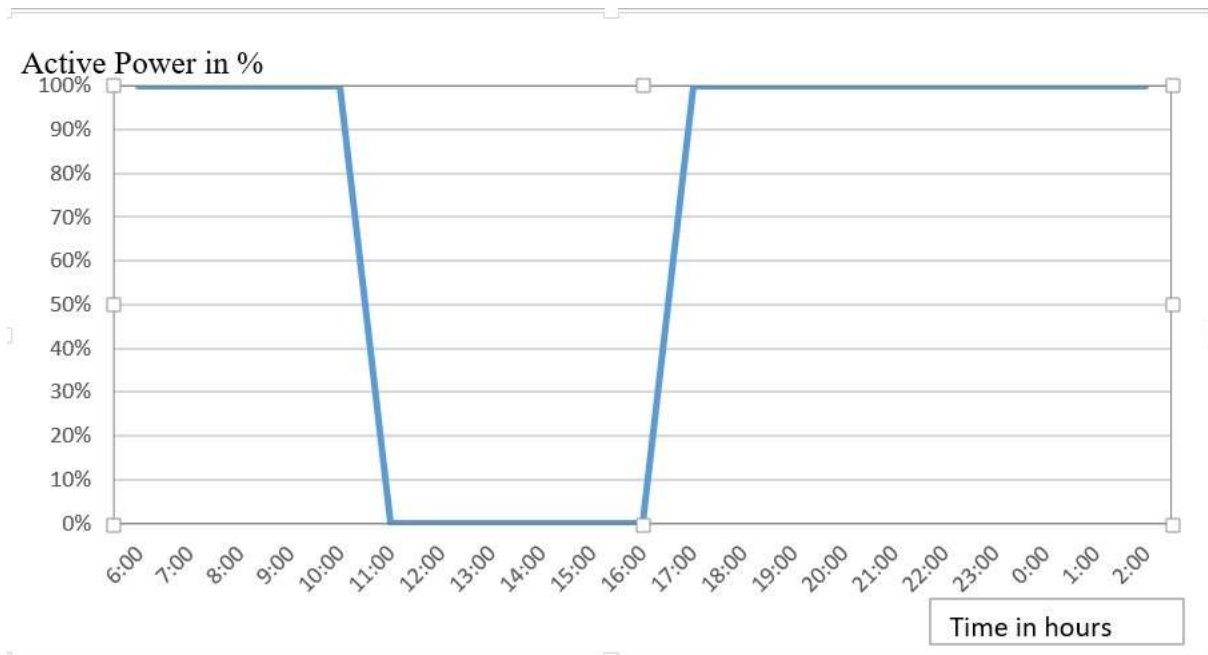


Fig. 12: Resilience graph of the Kasama Distribution network before, during and after the event at wind speed of 50m/s

As can be clearly seen from Figure 12, class 2-4 poles cannot withstand this storm.

4.2.4 Evaluation of the Resilience Indices of the Kasama Distribution Network during the storm of 60m/s wind speed

At this wind speed, class 1-4 poles were unable to withstand the storm, causing the network to lose all essential and common loads. Figure 13 is the resilience graph before, during and after the event. As was determined by a code written in python programming language 2022 in figure 24 in appendix 7.3.

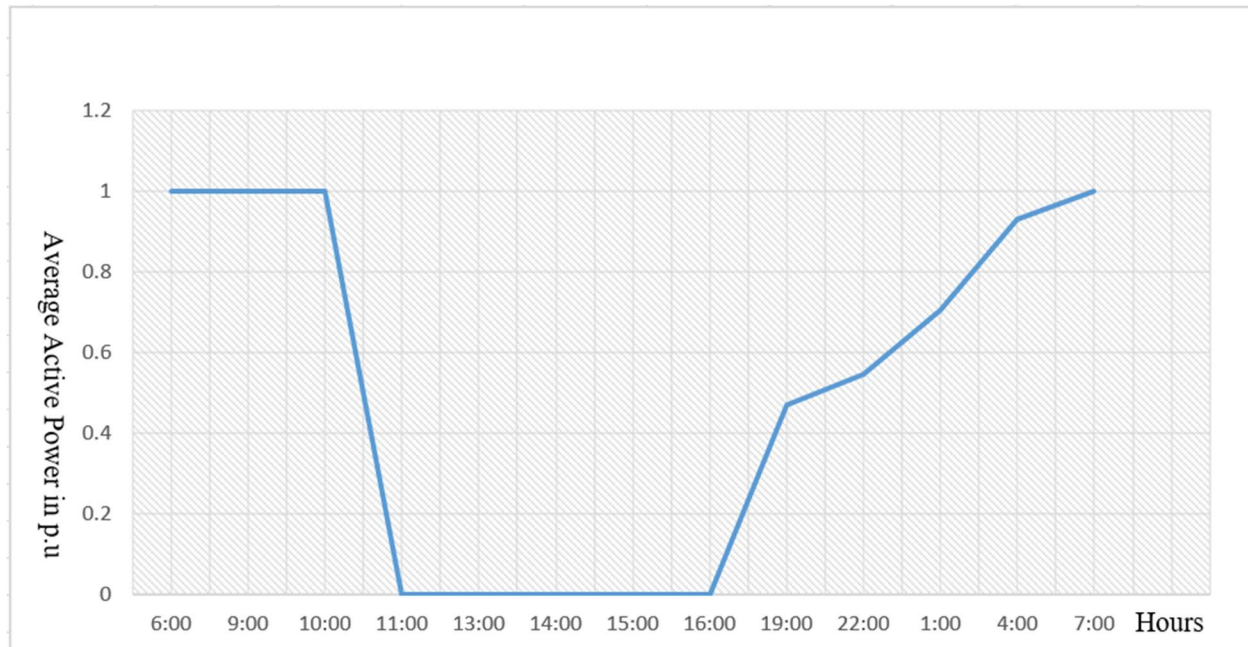


Fig.13 Resilience graph of the Kasama Distribution network before, during and after the event at wind speed of 60m/s

As can be seen from figure 13, before the storm, all distribution network loads were supplied, but at 10:00 hours when it occurred, all 33kV lines failed, and as a result, all network loads were cut off until restoration, when it normalized at 16:00 hours.

The table 13 below shows the classes of poles to be installed in the distribution network depending on the maximum wind speed of that geographical location.

Table 13: Selection of pole class depending on geographical location

NO	Geographical location maximum wind speed in m/s	Pole class
1	30	1-4
2	40	1-4
3	50	1
4	60 and above	None

4.3 Evaluation of the Resilience Indices of the Kasama Distribution Network after Integration of PV Plants with Battery Storage

The focus of this study is to maximize the amount of essential load provided during the event by improving the resilience indices of the Kasama Distribution network. Since class 1-4 poles failed during the storm with wind speeds of 60 m/s, PV plants with battery storage were integrated on the buses connecting them as the second-best option available to enhance resilience against storms.

Therefore, at Kasama Town substation on 11kV feeders, namely Lukupa and Hospital, 2.1MW and 2.2MW PV plants with battery storage were installed to supply Lukupa water pumping station and Kasama general hospital, respectively. And at Chilubula substation, on the 11kV bus, a 1.75MW PV plant with battery storage was installed to supply the mission hospital and ZNS camp.

The figures 14 and 15 on the next pages shows the integration of PV plants with battery storage at Kasama Town 33/11 kV and Chilubula 33/11 kV substations respectively, modelled in PowerFactory DIgSILENT, 2018.

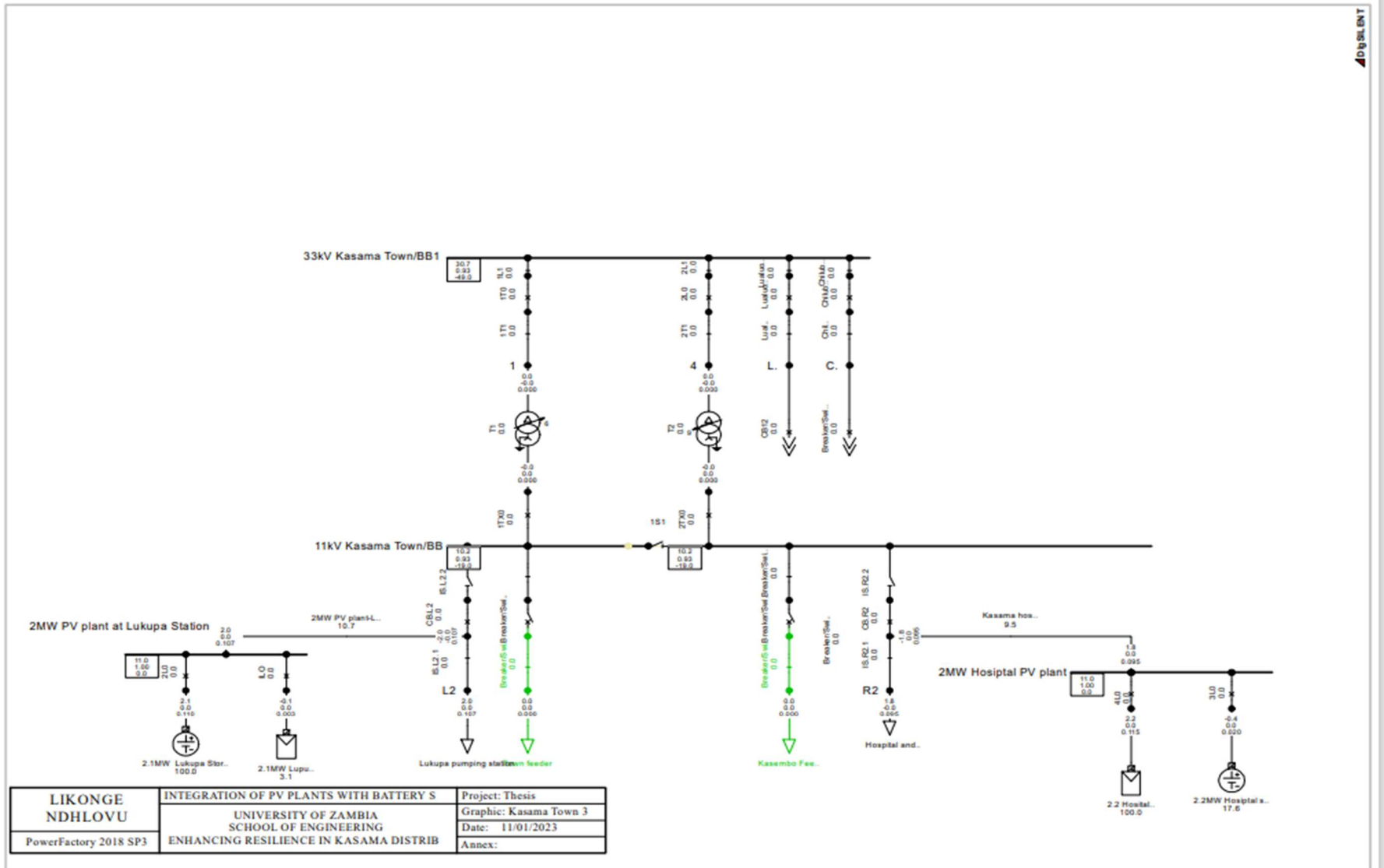
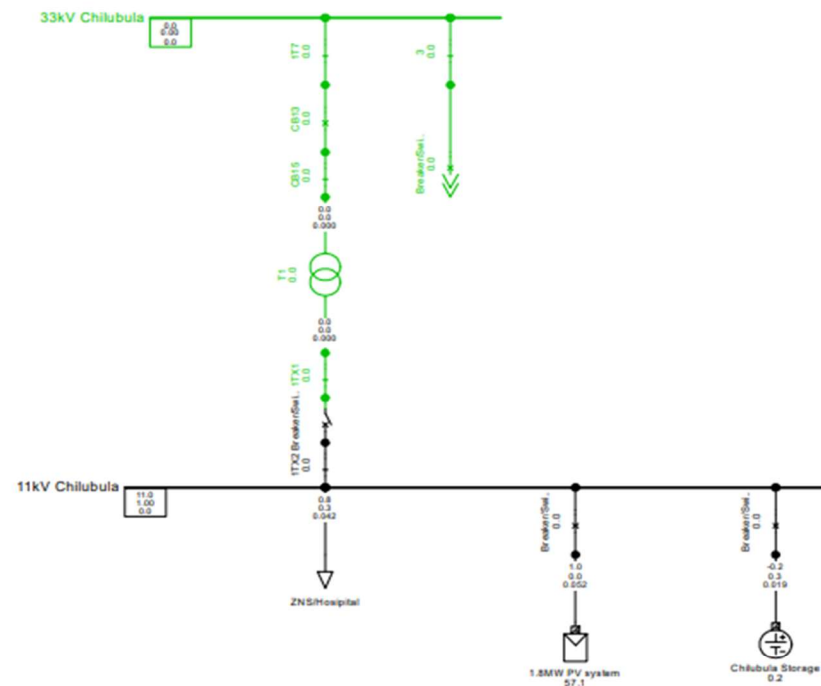


Fig. 14: Integration of PV plants with Battery storage at Kasama Town 33/11kV Substation on the 11kV bus



LIKONGE NDHLOVU	INTEGRATION OF PV PLANTS WITH BATTERY ST UNIVERSITY OF ZAMBIA SCHOOL OF ENGINEERING ENHANCING RESILIENCE IN THE KASAMA DIST	Project:
		Graphic: Chilubula 33/11k
PowerFactory 2018 SP3		Date: 11/01/2023
		Annex:

Fig. 15: Integration of PV plants with battery storage at Chilubula 33/11kV Substation

4.3.1 Evaluation and analysis of the resilience indices of the Kasama distribution network when PV plants with battery storage are integrated during the storm with a maximum speed of 60m/s

The table 14 below shows the resilience indices after the integration of the PV plants with battery storage into the Kasama distribution network.

Table 14: Resilience indices after injecting of the solar energy in the Kasama Distribution network

ζ_V^{PV}	ζ_D^{PV}	ζ_E^{PV}	% of essential Load supplied during the event(wind storm)
0.54	0.539	0.539	100%

$\zeta_V = 0.54$, indicates that 54% of network loads are disconnected at the time of network failure and $\zeta_E = 53.99$, indicates 53.99% of the network demand energy is not provided in the whole process of wind storm . And all of the essential customers were on supply during and after the event because the PV plants with battery storage islanded.

The table 15 below shows the calculated performance indices after injecting solar energy into the Kasama distribution network. The calculated performance indices are used to come up with figure 16, called the resilience graph.

Table 15: Calculated Performance indices after integrating PV plants with battery storage in to the Kasama Distribution network

Duration	Stage of the event	Performance Index-PV plant Injection
06:00-10:00	Before the event(wind storm)	1
10:00-16:00	During the event (wind storm)	0.4601
17:00-19:00	Restoration 33kV Lualuo Kasama new line	0.4601
19:00-22:00	Restoration of 33kV Kasama town Chilubula line	0.4601
22:00-01:00	Restoration of 33kV Lualuo Tazara line	0.70323
1:00-04:00	Restoration of 33kV Lualuo Forest line	0.932
04:00-07:00	Restoration of 33kV Forest Lukashya line	1

Figure 16 is called the "resilience graph," which shows how power was supplied after integration of PV plants with battery storage into the network before, during, and after the event.

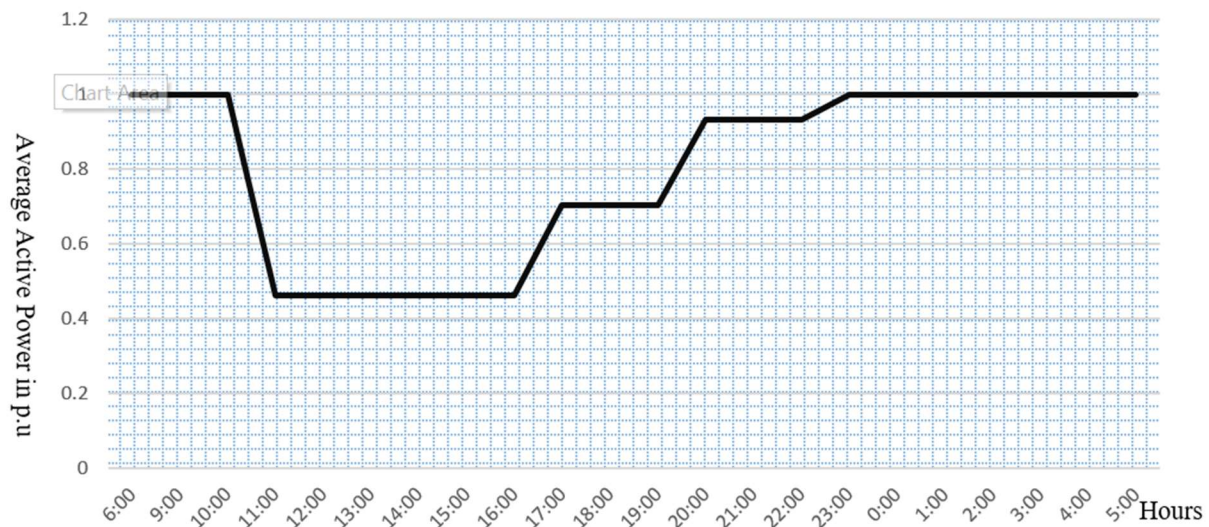


Fig. 16: Resilience graph after integration of PV plants with battery storage into the Kasama Distribution Network before, during and after the storm

From figure 16 above, it clearly shows that at 10:00 hours, the event occurred and all 33kV lines tripped due to the failure of the wooden poles. However, until the situation stabilized, essential loads were still supplied by PV plants with battery storage connected to their buses. At 16:00 hours, restoration of 33kV lines began, and it took three hours to restore each line. The aim was to restore the lines connected to the loads that were not on supply first.

4.4 Effects of integration of the PV plant with battery storage into the Kasama distribution network

The purposes of this analysis was to establish whether the PV plants with battery storage can be safely be integrated into the existing Kasama distribution network in accordance with ZS 387-1 of 2009 and the Zambia grid code of 2006.

ZS 387-1, 2009 and the Zambia grid code describe the system voltage limits, as can be seen in Table 16..

Table 16: Technical Voltage limits for the Zambia system

S/N	Voltage level	Compatibility level in %
1	≤ 11000	± 10
2	≥ 11000	± 5

In the absence of any agreement to the contrary, the supply voltage shall not deviate from the compatibility level for any period longer than 10 consecutive minutes.

Table 17 below shows the voltage deviation recorded in the Kasama distribution network after the PV plants with battery storage were integrated.

Table 17: Voltage deviation recorded in the Kasama distribution network after integration of the PV plants with battery storage

Steady state analysis after injecting of PV Plants				DigSILENT PowerFactory 2018 SP3		Project: Date: 12/01/2023	
Load Flow Calculation				Complete System Report: Substations, Voltage Profiles, Grid Interchange			
AC Load Flow, balanced, positive sequence Automatic tap adjustment of transformers Consider reactive power limits			No No	Automatic Model Adaptation for Convergence Max. Acceptable Load Flow Error for Nodes Model Equations		No 1.00 kVA 0.10 %	
Grid: 33kV Network		System Stage: 33kV Network		Study Case: Study Case		Annex: / 5	
	rtd.V [kV]	Bus - voltage [p.u.] [kV] [deg]		-10	-5	Voltage - Deviation [%] 0 +5 +10	
11kV Forest							
BB	11.00	1.043	11.48 -3.82				
BB2	11.00	1.043	11.47 -4.08				
33kV Forest							
BB1	33.00	0.991	32.71 27.26				
11kV Kasama Town							
BB	11.00	0.981	10.79 58.48				
BB2	11.00	0.987	10.86 60.78				
33kV Kasama Town							
BB1	33.00	0.988	32.61 29.37				
33kV Lualuo							
BB1	33.00	0.989	32.65 29.21				
BB2	33.00	0.998	32.94 27.76				
66kV Lualuo							
MB	66.00	1.000	66.00 0.00				
RB	66.00	1.000	66.00 0.00				
11kV Lukashya							
BB	11.00	0.988	10.87 25.33				
33kV Lukashya							
BB	33.00	0.988	32.61 27.03				
11kV Tazara							
BB1	11.00	0.982	10.80 57.48				
33kV Tazara							
BB1	33.00	0.982	32.41 28.67				
11kV Chilubula							
33kV Chilubula							
2MW Hosiptal PV plant							
	11.00	1.003	11.04 61.40				
2MW PV plant at Lukupa Station							
	11.00	1.002	11.02 59.27				

And table 18 below shows the loading of the lines when PV plants with battery storage are integrated into the Kasama distribution network.

Table 18: Loading of distribution lines when PV plants with battery storage are integrated to the Kasama Distribution network

S/N	Line	Loading (%)
1	33kV Forest Lukashya	16.8
2	33kV Kasama Chilubula	9.8
3	33kV Lualuo Forest	44.6
4	33kV Lualuo Tazara	23.4
5	33kV Lualuo Kasama Town	14.1

Table 19 below shows the loading of the transformers when solar PV plants with battery storage are integrated into the Kasama distribution network.

Table 19: Loading of Transformer when PV Plants with battery storage are integrated to the Kasama Distribution network

S/N	Line	Loading (%)
1	33/11kV Transformer T1 at Chilubula 33/11kV Substation	84.9
2	33/11kV Transformer T1 at Tazara 33/11kV Substation	50.9
3	33/11kV Transformer T2 at Tazara 33/11kV Substation	50.9
4	33/11kV Transformer T1 at Kasama Town 33/11kV Substation	20.5
5	33/11kV Transformer T2 at Kasama Town 33/11kV Substation	33.6
6	33/11kV Transformer T1 at Lualua 66/33/11kV Substation	48.5
7	33/11kV Transformer T2 at Lualua 66/33/11kV Substation	21.6
8	33/11kV Transformer T1 at Forest 33/11kV Substation	33.5
9	33/11kV Transformer T2 at Forest 33/11kV Substation	27
10	33/11kV Transformer T1 at Lukashya 33/11kV Substation	72.9

As can be seen from tables 18 and 19, all equipments are loaded within the acceptable ranges in accordance with ZS 387-1, 2009 and the Zambian grid code of 2006.

5.0 CONCLUSIONS AND RECOMMENDATIONS

This chapter provides the conclusion and recommendations arising from the study founded on the Problem definition, Aim, and Objectives.

We addressed the issue of the poor state of the distribution network in terms of resilience against power outages caused by wind storms affecting essential loads (critical loads) in this study. And the aim and objectives were achieved.

5.1 Consequences of the poor state of the distribution network in terms of resilience against wind storms

This study analyzed the consequences of the poor state of the test distribution network, which was the first objective. The existing Kasama distribution network's wooden poles are of class 3 and 4, which failed during the storm of 50 m/s, causing a loss of supply to the essential loads, as can be seen in Table 11 below.

Table 11: Resilience indices of the Kasama Distribution network during the storm

ζ_V	ζ_D	ζ_E	% of essential Load supplied during the event(wind storm)
1	1	1	0

From table 11, all the resilience indices are equal to one, indicating that during the event, the distribution network's essential loads were out of supply.

Figure 13, clearly shows the power supplied before, during, and after the storm in the Kasama distribution network. As can be seen during the event, the essential loads were off supply until restoration. Therefore, the consequence of a poor state in terms of the resilience of the distribution network against storms are that every time the it happens, the wooden poles will fail and cause long duration outages affecting essential loads. And the cost of these outages is very high. These outages results in some of the followings:-

1. Disrupt communications, water, and transportation
2. Cause food spoilage and water contamination
3. Effects operation of special installations like hospitals, banks and many others

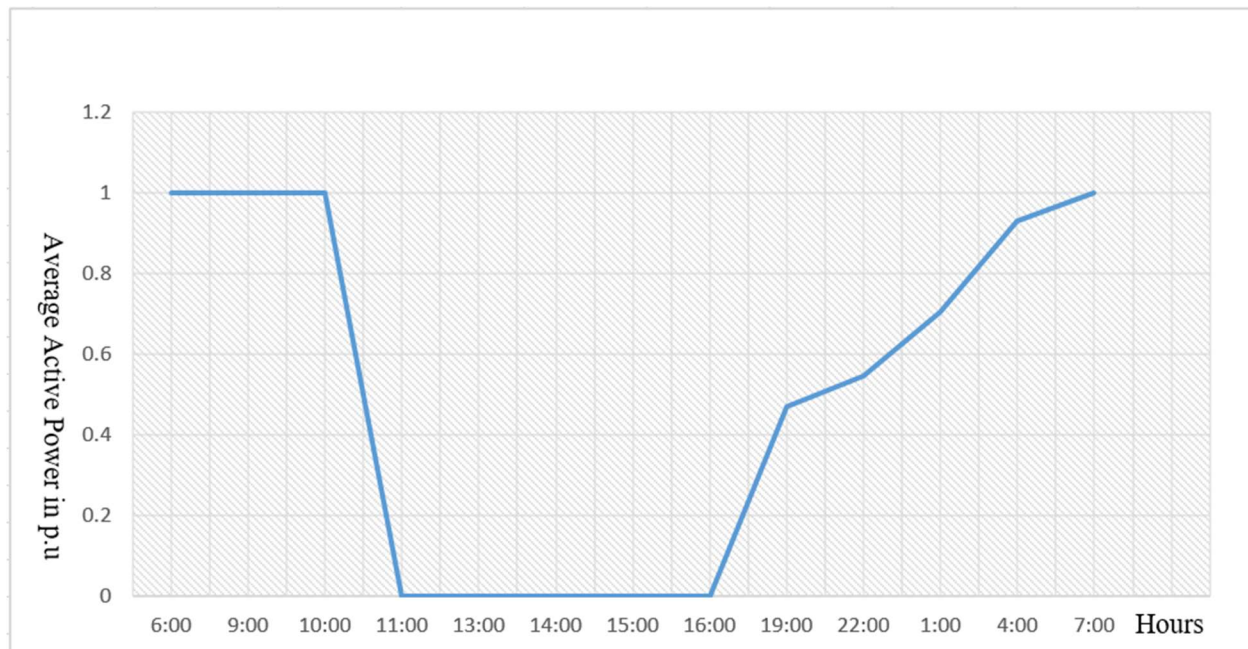


Fig.13 Resilience graph of the Kasama Distribution network before, during and after the storm of 60m/s wind speed

As such the first objective was achieve.

5.2 Implementation of the best options to enhance resilience of the distribution network

The second objective of this study was to find the best practical options available from the literature to address the issue of the distribution network's inadequate resilience against storms that cause power outages affecting vital loads. Therefore, two best options were found, hardening the 33kV lines and resilient load restoration, which was achieved by the integration of PV plants

with battery storage in the distribution network. This objective was achieved, as can be seen in Section 5.2.1 below.

5.2.1 Hardening methods

In this method, class 1–4 wooden poles were installed in 33kV lines connecting essential loads and exposed to storms with wind speeds ranging from 30 to 60m/s, and resilience indices were calculated to determine if they could withstand the storms.

5.2.1.1 Class 1–4 wooden poles exposed to a storm with a 30m/s wind speed

The table 8 below shows the resilience indices of the Kasama distribution network when class 1-4 wooden poles were exposed to this storm. As can be seen, none of the classes of wooden poles failed during the event.

Table 9: Resilience indices of the Kasama Distribution network during a storm of 30m/s wind speed

ζ_V	ζ_D	ζ_E	% of essential Load supplied during the event(wind storm)
0	0	0	100

$\zeta_V = 0$, indicates that 100% of network loads were supplied during the storm and $\zeta_E = 0$, indicates 100% of the network demanding energy is provided in the whole process of storm occurrence. And essential customers were on supplied before, during and after the storm.

In conclusion, during the storm with a speed of 30 m/s, class 1-4 poles can be used as support structures.

5.2.1.2 Class 1–4 wooden poles exposed to a storm with a 40m/s wind speed

The table 8 below shows the resilience indices of the Kasama distribution network when class 1-4 wooden poles were exposed to this storm. As can be seen, none of the classes of wooden poles failed during the event.

Table 9: Resilience indices of the Kasama Distribution network during a storm of 40m/s wind speed

ζ_V	ζ_D	ζ_E	% of essential Load supplied during the event(wind storm)
0	0	0	100

$\zeta_V = 0$, indicates that 100% of network loads were supplied during the storm and $\zeta_E = 0$, indicates 100% of the network demanding energy is provided in the whole process of storm occurrence. And essential customers were on supplied during the storm

In conclusion, during this storm, class 1–4 poles can be used as support structures.

5.2.1.3 Class 1–4 wooden poles exposed to a storm with a 50m/s wind speed

Only class 1 was able to withstand the storm of 50 m/s wind speed. As can be seen in Section 5.2.1.3.1 below:-

5.2.1.3.1 Class 1 wooden pole exposed to a storm with a 50m/s wind speed

The table 10 below shows the Resilience indices of the Kasama Distribution network when class 1 poles were exposed to the storm.

Table 10: Resilience indices of the Kasama Distribution network for class 1 poles during the storm of 50m/s wind speed

ζ_V	ζ_D	ζ_E	% of essential Load supplied during the event(wind storm)
0	0	0	100

$\zeta_V = 0$, indicates that 0% of network loads were not disconnected at the time of the network loss and $\zeta_E = 0$, indicates 0% of the network demanding energy is not provided in the whole process of storm occurrence and recovery. And 100% essential customers were on supplied.

In conclusion, during a storm with a wind speed of 50 m/s, only class 1 wooden poles can be used as support structures.

5.2.1.3.2 Class 2-4 wooden pole exposed to a storm with a 50m/s wind speed

When class 2–4 wooden poles were exposed to a storm of 50m/s wind speed in the distribution network and failed as a result, the essential load lost power supply during this period until restoration, when it normalized.

Table 11: Resilience indices of the Kasama Distribution network

ζ_V	ζ_D	ζ_E	% of essential Load supplied during the event(wind storm)
1	1	1	0

As can be seen in the table 11, $\zeta_V = 1$ which indicates 100% of the loads lost supply during the event, $\zeta_D = 1$ which indicates sudden loss of supply of the entire network and $\zeta_E = 1$ which indicates 100% of the network demanding energy is not provided in the whole process of wind storm occurrence. And during the storm, the essential loads were off.

Figure 12 is the resilience graph showing the supply of energy to the loads before, during and after the storm.

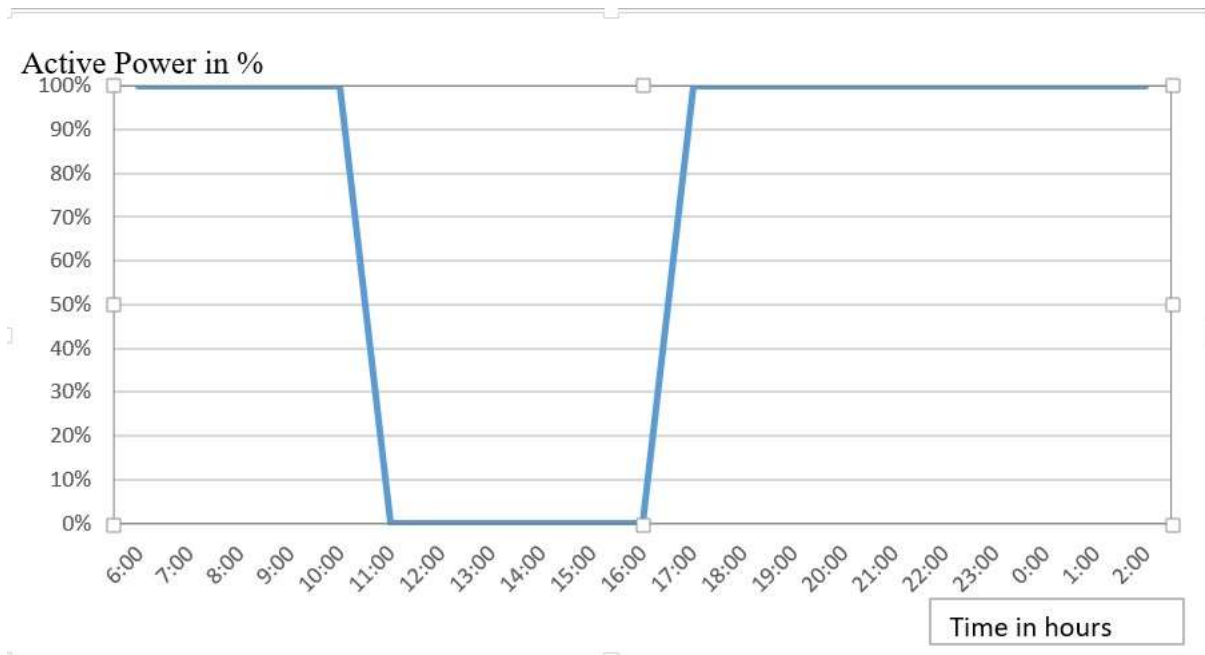


Fig. 12: Resilience graph of the Kasama Distribution network before, during and after the storm of 50m/s wind speed

As can be clearly seen from Figure 12, class 2-4 poles cannot withstand the maximum wind speed of 50 m/s. And as such, they cannot serve as support structures in the geographical location where storms reach such wind speeds.

5.2.1.4 Class 1–4 wooden poles exposed to a storm with a 60m/s wind speed

At this speed, class 1–4 poles failed during the storm, and as such, essential loads were cut off from power. The calculated resilience in indices are in table 12 below,

Table 12: Resilience indices of the Kasama Distribution network during the storm of 60m/s wind speed

ζ_V	ζ_D	ζ_E	% of essential Load supplied during the event(wind storm)
1	1	1	0

As can be seen in table 12, during the storm, both common and essential loads lost power supply. Therefore, to enhance resilience during a storm of such magnitude, other types of poles are recommended, like the H or reinforced concrete poles. However, the second method of enhancing the resilience of the distribution network against storms causing power outages affecting essential loads was implemented (see Section 5.3 below).

5.3 Resilient load restoration (integration of PV plants with battery storage in to the distribution network)

The table 15 below shows the resilience indices after the integration of the PV plants with battery storage into the Kasama distribution network.

Table 15: Resilience indices after integration of the PV plants in the Kasama Distribution network

ζ_V^{PV}	ζ_D^{PV}	ζ_E^{PV}	% of essential Load supplied during the event(wind storm)
0.54	0.539	0.539	100%

$\zeta_V = 0.54$, indicates that 54% of network loads are disconnected at the time of network failure and $\zeta_E = 0.53$, indicates 53% of the network demand energy is not provided in the whole process of wind storm occurrence. And all of the essential customers were on supply during and after the storm because the PV plants with battery storage islanded

Figure 16 is called the "resilience graph," which shows how power was supplied after integration of PV plants with battery storage into the network before, during and after the storm of 60m/s wind speed.

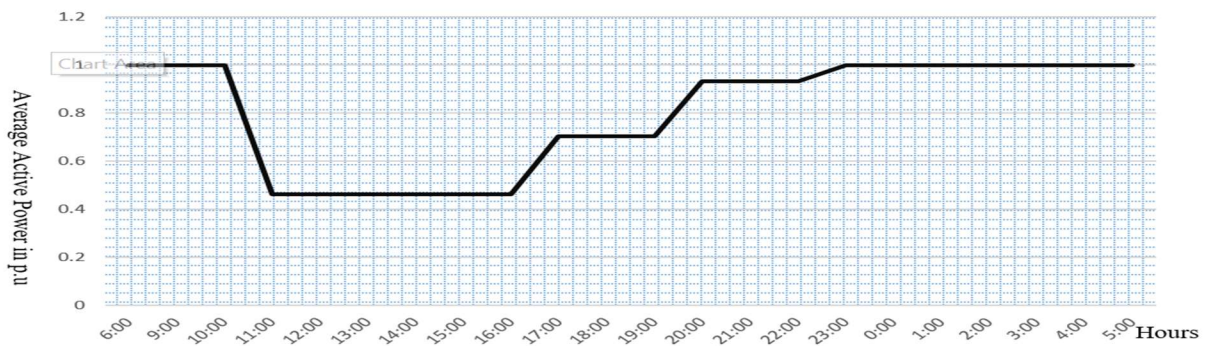


Fig. 16: Resilience graph after integration of PV plants with battery storage into the Kasama Distribution Network before, during and after the storm

From figure 16 above, it clearly shows that after integrating PV plants with battery storage into the Kasama distribution network, no essential loads lost supply during the storm. This is due to the fact that they are integrated on their feeders and islanded. In conclusion, this method enhanced the resilience of the distribution network against storms.

5.3 Calculate and analyze the resilience indices so to measure the state of the distribution network in term of resilience.

As can see from tables 8, 9, 10 and 12, the resilience indices were calculate and analyzed therefore the third objective was achieved.

5.4 Effects of the integration of PV plants with battery storage into the Kasama distribution network

Table 17: Voltage deviation recorded in the Kasama distribution network after integration of the PV plants with battery storage

	Steady state analysis after injecting of PV Plants				Digsilent PowerFactory 2018 SP3		Project: Date: 12/01/2023		
Load Flow Calculation				Complete System Report: Substations, Voltage Profiles, Grid Interchange					
AC Load Flow, balanced, positive sequence Automatic tap adjustment of transformers Consider reactive power limits				No No	Automatic Model Adaptation for Convergence Max. Acceptable Load Flow Error for Nodes Model Equations			No 1.00 kVA 0.10 %	
Grid: 33kV Network		System Stage: 33kV Network			Study Case: Study Case		Annex: / 5		
	rtd.V [kV]	Bus - voltage [p.u.]	Bus - voltage [kV]	[deg]	-10	-5	Voltage - Deviation [%] 0	+5 +10	
11kV Forest									
BB	11.00	1.043	11.48	-3.82					
BB2	11.00	1.043	11.47	-4.08					
33kV Forest									
BB1	33.00	0.991	32.71	27.26					
11kV Kasama Town									
BB	11.00	0.981	10.79	58.48					
BB2	11.00	0.987	10.86	60.78					
33kV Kasama Town									
BB1	33.00	0.988	32.61	29.37					
33kV Lualuo									
BB1	33.00	0.989	32.65	29.21					
BB2	33.00	0.998	32.94	27.76					
66kV Lualuo									
MB	66.00	1.000	66.00	0.00					
RB	66.00	1.000	66.00	0.00					
11kV Lukashya									
BB	11.00	0.988	10.87	25.33					
33kV Lukashya									
BB	33.00	0.988	32.61	27.03					
11kV Tazara									
BB1	11.00	0.982	10.80	57.48					
33kV Tazara									
BB1	33.00	0.982	32.41	28.67					
11kV Chilubula									
BB1	11.00	0.976	10.74	61.78					
33kV Chilubula									
BB1	33.00	0.988	32.62	29.39					
2MW Hosiptal PV plant									
BB1	11.00	1.003	11.04	61.40					
2MW PV plant at Lukupa Station									
BB1	11.00	1.002	11.02	59.27					

From table 17, it clearly shows that the voltage deviations in the test network are within acceptable limits.

Table 18: Loading of distribution lines when PV plants with battery storage are integrated into the Kasama Distribution network

S/N	Line	Loading (%)
1	33kV Forest Lukashya	16.8
2	33kV Kasama Chilubula	9.8
3	33kV Lualuo Forest	44.6
4	33kV Lualuo Tazara	23.4
5	33kV Lualuo Kasama Town	14.1

Table 19: Loading of Transformer when PV Plants with battery storage are integrated to the Kasama Distribution network

S/N	Line	Loading (%)
1	33/11kV Transformer T1 at Chilubula 33/11kV Substation	84.9
2	33/11kV Transformer T1 at Tazara 33/11kV Substation	50.9
3	33/11kV Transformer T2 at Tazara 33/11kV Substation	50.9
4	33/11kV Transformer T1 at Kasama Town 33/11kV Substation	20.5
5	33/11kV Transformer T2 at Kasama Town 33/11kV Substation	33.6
6	33/11kV Transformer T1 at Lualua 66/33/11kV Substation	48.5
7	33/11kV Transformer T2 at Lualua 66/33/11kV Substation	21.6
8	33/11kV Transformer T1 at Forest 33/11kV Substation	33.5
9	33/11kV Transformer T2 at Forest 33/11kV Substation	27
10	33/11kV Transformer T1 at Lukashya 33/11kV Substation	72.9

As can be seen from tables 18 and 19, all equipment is loaded with acceptable ranges in accordance with ZS 387-1, 2009 and the Zambian grid code of 2006.

In conclusion, it's very safe to integrate small-scale PV plants with battery storage into the Kasama distribution network, as can be seen in tables 17, 18, and 19 above.

5.5 Recommendations

Recently, due to climate change, the rate at which storms are occurring around the world is alarming, and as such, we need to prepare our distribution network to be able to hold them.

In this study, two methods were implemented to solve this problem, and both proved successful. Therefore, it is recommended to enhance the resilience of the distribution network against storms causing outages affecting essential loads by implementing hardening and resilient load restoration (integration of PV plants with battery storage into the distribution network) methods. The table below shows recommended support structure for a specific wind speed at given geographical location.

Table 14: Selection of pole class depending on geographical location

NO	Geographical location maximum wind speed in m/s	Pole class
1	30	1-4
2	40	1-4
3	50	1
4	60 and above	RCC and H poles

At any wind speed, the integration of PV plants with battery storages is the most recommended option.

5.6 Further Studies

Further studies can be carried out on the enhancement of resilience of the Distribution networks in an effort to prepare for wild fires, floods, earthquakes and volcanic eruption.

6.0 REFERENCES

- Akhil, A.A., Huff, G., Currier, A.B., Kaun, B.C., Rastler, D.M., Chen, S.B., Cotter, A.L., Bradshaw, D.T. and Gauntlett, W.D., 2013. DOE/EPRI 2013 electricity storage handbook in collaboration with NRECA (Vol. 1, p. 340). Albuquerque, NM, USA: Sandia National Laboratories.
- Brown, R., Wang, X. and Page, C., 2016. Are Power Utilities in Tonga and New Zealand Resilient?
- Borlase, S., Ganji, M., Shahidehpour, M., Tian, W., Burgess, P., Hourdouillie, R. and Zheng, A., 2017. Microgrids. In Smart Grids (pp. 591-604). CRC Press.
- Bie, Z., Lin, Y., Li, G. and Li, F., 2017. Battling the extreme: A study on the power system resilience. *Proceedings of the IEEE*, 105(7), pp.1253-1266.
- Dunn, S., Wilkinson, S., Alderson, D., Fowler, H. and Galasso, C., 2018. Fragility curves for assessing the resilience of electricity networks constructed from an extensive fault database. *Natural Hazards Review*, 19(1).
- Fang, Y.P., Pedroni, N. and Zio, E., 2016. Resilience-based component importance measures for critical infrastructure network systems. *IEEE Transactions on Reliability*, 65(2), pp.502-512.
- Fakouri Fard, M., Sahraei-Ardakani, M., Ou, G. and Liu, M., 2021. Targeted Hardening of Electric Distribution System Components for Enhanced Resilience against Earthquakes. *ArXiv e-prints*, pp.arXiv-2111.
- Flynn, S.E., 2008. America the resilient-defying terrorism and mitigating natural disasters. *Foreign Aff.* 87, p.2.
- Glover, J.D., Sarma, M.S. and Overbye, T., 2008. *Power system analysis & design*, SI version. Cengage Learning.
- Kroposki, B., Sen, P.K. and Malmedal, K., 2013. Selection of distribution feeders for implementing distributed generation and renewable energy applications. *IEEE Transactions on Industry Applications*, 49(6), pp.2825-2834.
- Holling, C.S., 1973. Resilience and stability of ecological systems. *Annual review of ecology and systematics*, pp.1-23.
- Hegazy, Y.G. and Chikhani, A.Y., 2003, October. Intention islanding of distributed generation for reliability enhancement. In *CIGRE/IEEE PES International Symposium Quality and Security of Electric Power Delivery Systems*, 2003. CIGRE/PES 2003. (pp. 208-213). IEEE.
- Lee, S.Y., Jin, Y.G. and Yoon, Y.T., 2015. Determining the optimal reserve capacity in a microgrid with islanded operation. *IEEE Transactions on Power Systems*, 31(2), pp.1369-1376.
- Ma, S., Chen, B. and Wang, Z., 2016. Resilience enhancement strategy for distribution systems under extreme weather events. *IEEE Transactions on Smart Grid*, 9(2), pp.1442-1451.

Milligan, M., Porter, K., Parsons, B. and Caldwell, J., 2002. Wind energy and power system operations: A survey of current research and regulatory actions. *The Electricity Journal*, 15(2), pp.56-67.

NEM Association, 2006. American National Standards Institute (ANSI) C84. 1-2006, Voltage Ratings for Electric Power Systems and Equipment. Rosslyn, VA.

Panteli, M. and Mancarella, P., 2015. Modeling and evaluating the resilience of critical electrical power infrastructure to extreme weather events. *IEEE Systems Journal*, 11(3), pp.1733-1742.

Photovoltaics, D.G. and Storage, E., 2009. IEEE Application Guide for IEEE Std 1547™, IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems.

Rani, P., Mishra, A.R., Mardani, A., Cavallaro, F., Alrasheedi, M. and Alrashidi, A., 2020. A novel approach to extended fuzzy TOPSIS based on new divergence measures for renewable energy sources selection. *Journal of Cleaner Production*, 257, p.120352.

Rudnick, H., 2011. Impact of natural disasters on electricity supply [guest editorial]. *IEEE Power and Energy Magazine*, 9(2), pp.22-26.

Shi, Q., Liu, W., Zeng, B., Hui, H. and Li, F., 2022. Enhancing distribution system resilience against extreme weather events: concept review, algorithm summary, and future vision. *International Journal of Electrical Power & Energy Systems*, 138, p.107860

Teoh, Y.E., Alipour, A. and Cancelli, A., 2019. Probabilistic performance assessment of power distribution infrastructure under wind events. *Engineering Structures*, 197, p.109199.

Wolfe, R.W. and Moody, R.C., 1994. ANSI pole standards: Development and maintenance. In *Proceedings of the first Southeastern pole Conference*. For. Prod. Society. Madison, USA (pp. 143-149).

Wang, Y., Chen, C., Wang, J. and Baldick, R., 2015. Research on resilience of power systems under natural disasters-A review. *IEEE Transactions on Power Systems*, 31(2), pp.1604-1613.

Zhang, Y., Yang, N. and Lall, U., 2016. Modeling and simulation of the vulnerability of interdependent power-water infrastructure networks to cascading failures. *Journal of Systems Science and Systems Engineering*, 25(1), pp.102-118.

Zhang, M. and Chen, J., 2014. Islanding and scheduling of power distribution systems with distributed generation. *IEEE Transactions on Power Systems*, 30(6), pp.3120-3129.

7.0 APPENDIX

7.1 Simulation Packages available in PowerFactory DIgSILENT

7.1.1 Load Flow Analysis

DIgSILENT PowerFactory offers a range of load flow calculation methods, including a full AC Newton-Raphson technique (balanced and unbalanced) and a linear DC method. The enhanced non-decoupled Newton-Raphson solution technique with current or power mismatch iterations, typically yields round-off errors below 1 kVA for all buses. The implemented algorithms exhibit excellent stability and convergence. Several iteration levels guarantee convergence under all conditions, with optional automatic relaxation and modification of constraints. The DC load flow, solving for active power flows and voltage angles, is extremely fast and robust (linear system, no iterations required). This package will assist in this study to determine the power flows during force outages due to wind storm affecting essential loads. (Critical loads)

7.1.2 Modelling of a PV System in PowerFactory DIgSILENT

In PowerFactory DIgSILENT, the interfacing converter can be represented by either a static generator or a PWM converter. In PowerFactory DIgSILENT when PV system is represented by the static generator, then there is no need to physically represent interfacing converter. In this case static generator includes the PV array and interfacing converter in it.

But in case of a PWM converter, PV array needs to be physically represented with a current source connected to a DC bus along with a DC link capacitor. PWM converter is also separately represented. The two different possible ways of PV system modeling in Power Factory are shown in Figure 17 below.

In the PowerFactory DIgSILENT there is a PV system component called the PV generator that is available for PV studies which is modeled with the help of a static generator. In PSCAD a PWM converter based PV system is developed and is currently available for grid studies. But in this study static generator is used to model PV generator and will be explained in details in section 7.1.2.1.

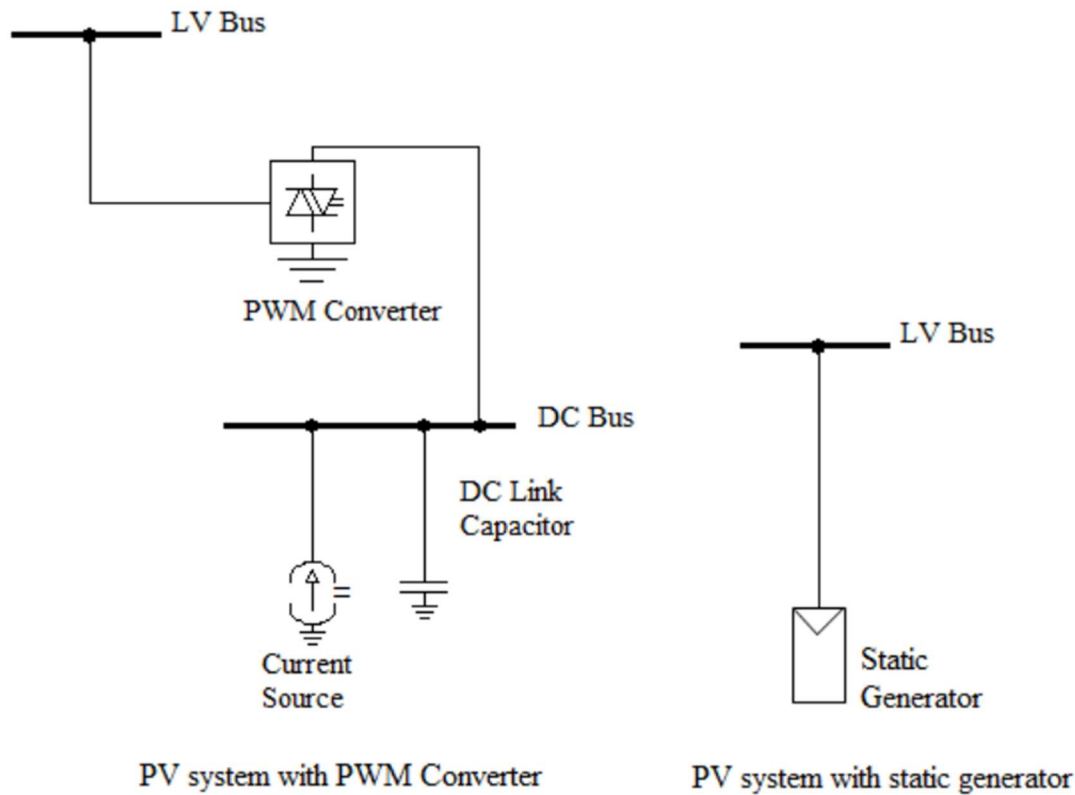


Fig. 17: Different PV System Modeling in PowerFactory DIgSILENT

7.1.2.1 Static generator

Static generator is an easy to use model of any kind of static (no rotating) generator in Power Factory DIgSILENT. It can be used for following:-

1. Photovoltaic Generators
2. Fuel Cells
3. Storage devices
4. HVDC Terminals
5. Reactive Power Compensators
6. Wind Generators

As in this study, static generator is used as photovoltaic generator, so it is selected from category list as “Photovoltaic”. Any number of parallel machines can be used according to system rating requirements. In this respect, the total rating of generator would be equal to the rating of a single generator multiplied by the number of parallel machines used. Also under the ratings tab, it is required to specify the rating for one generator in MVA and the power factor at which machine is designed as shown in Figure 18 below.

State Estimator	Reliability	Generation Adequacy	Tie Open Point Opt.	Description
ANSI Short-Circuit	IEC 61363	RMS-Simulation	EMT-Simulation	Harmonics
Basic Data	Load Flow	VDE/IEC Short-Circuit	Complete Short-Circuit	Optimization

Name:

Terminal: RMS Model\LV TERMINAL\Cub_2 LV TERMINAL

Zone: ...

Area: ...

☐ Out of Service

Category: ▼

Number of parallel Machines:

Ratings

Nominal Apparent Power: MVA

Power Factor:

Fig. 18: Basic Data for Static Generator

A typical interface window of the static generator in load flow is shown in Figure 18. All values can be changed according to the requirement. The active power tab shows the power rating of the PV system which is the active power output out of the static generator. For the load flow, the variables need to be defined initially to calculate the load flow analysis; can be set using static generator. In Fig 19, it can be seen that active power and reactive power are defined in the start to calculate the load flow of the system. These variables can be changed according to the requirement of the system.

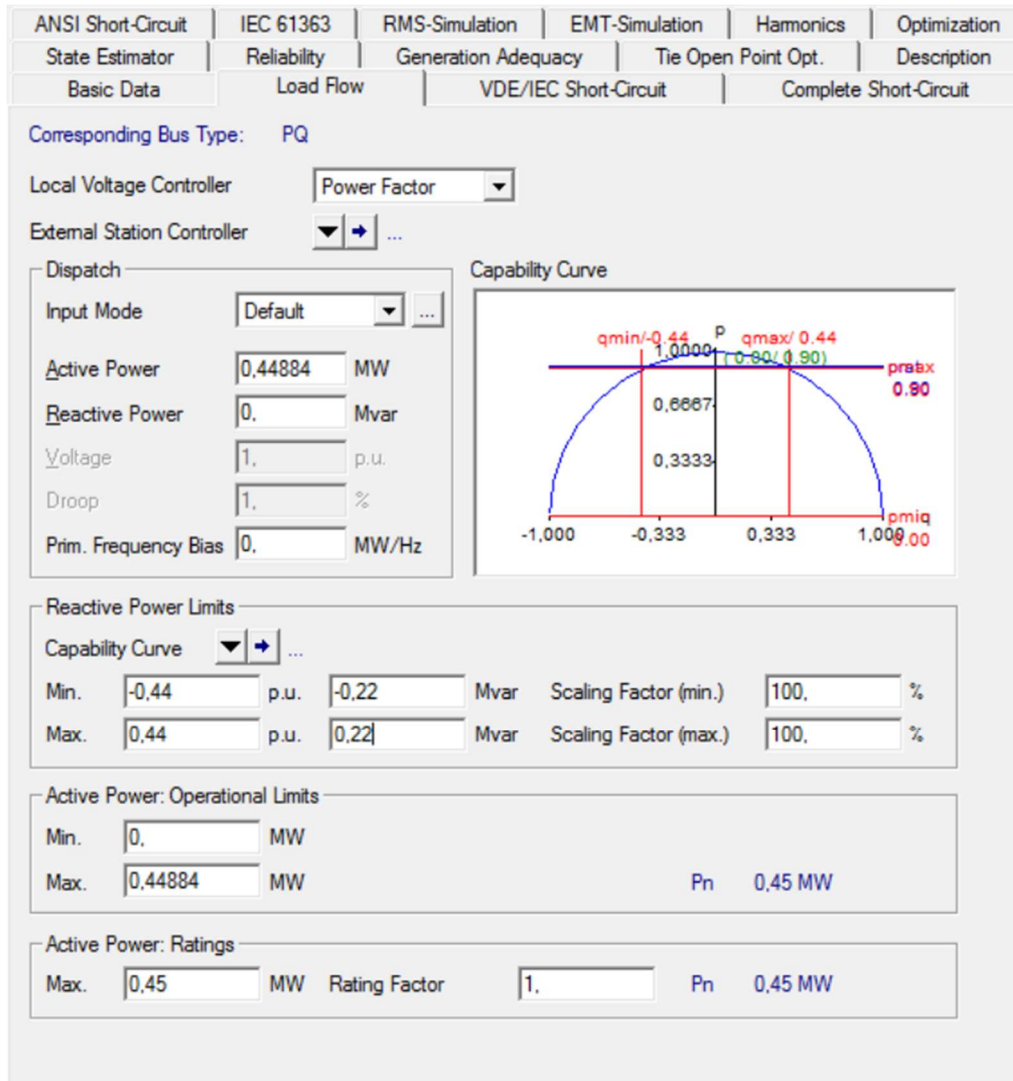


Fig. 19: Static generator power flow under steady state conditions

7.1.2.2 Frame of Generic PV Model

The control frame of the PV System in generic model is shown in Figure 20. As mentioned previously it is necessary to model the PV array, DC link capacitor dynamics by DSL functions. The same can be observed in the control frame and the main blocks will be explained in brief in the following sections.

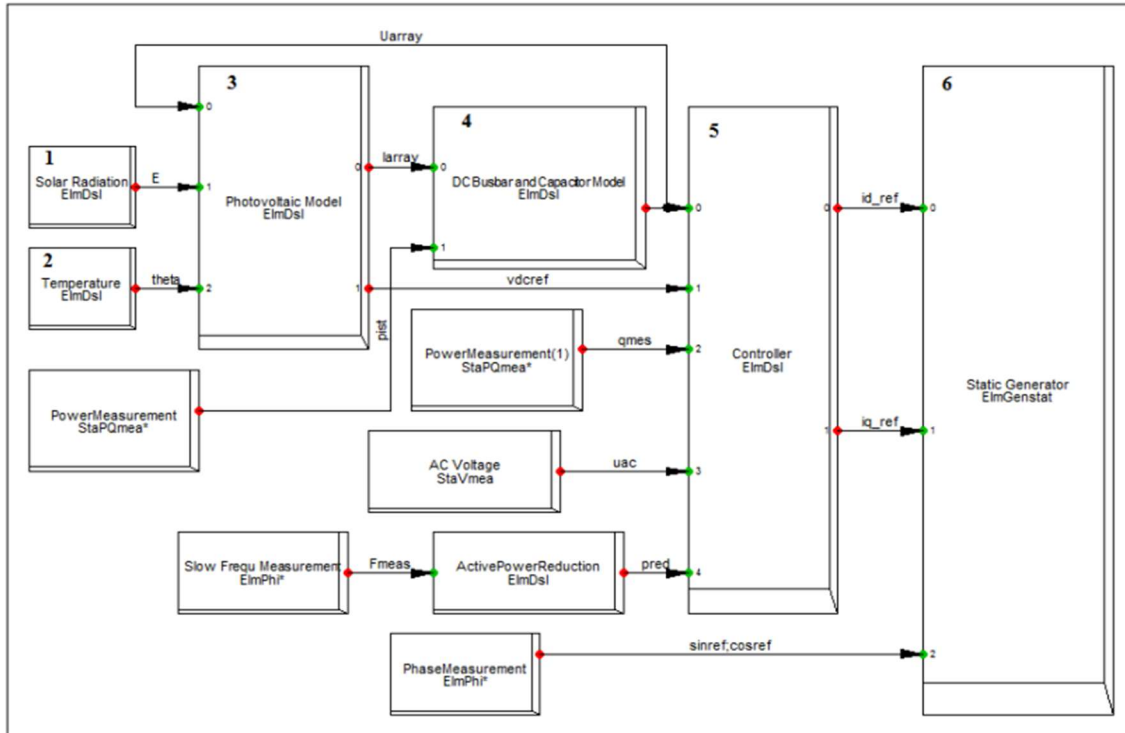


Fig. 20: Frame of Generic PV Model

Slot 1 & 2: Solar radiation and temperature

Solar radiation and temperature both are modeled as limited time integrators. The purpose of these slots is to accumulate change of irradiance per second or change of temperature per second and integrate them over a period of time. The output of these blocks is given to slot 3 which is the photovoltaic model.

Slot 3: Photovoltaic model Photovoltaic model

Takes DC voltage, irradiance and temperature as the inputs. Based upon PV equations written as DSL codes, the PV array is modeled and provides array current and reference DC voltage as the outputs.

Slot 4: DC bus bar and capacitor model

This slot represents the mode of DC bus bar and capacitor. With the help of this block the dynamics of the DC side capacitor is included in the PV system.

Slot 5: Controller block

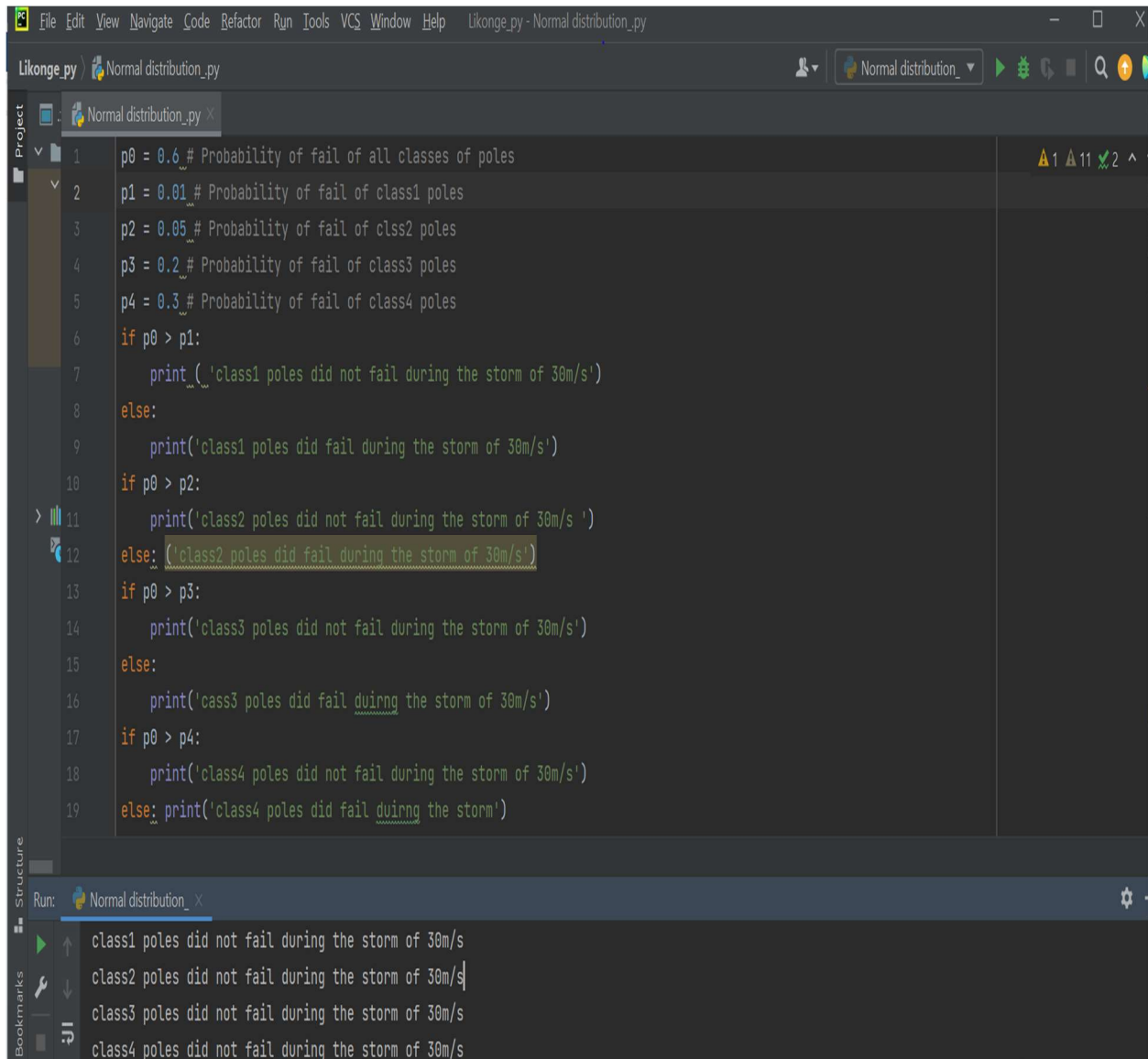
Controller is one of the most important part of the PV system, Its regulate the active and reactive power outputs of the static generator according to the DC side output of the PV system consisting of the PV array and the DC side capacitor.

Slot 6: Static generator block

This block represents the static generator in the control frame. The additional inputs that are to be given to the static generator can be given to this block which is internally connected to the actual one.

7.2 Python programming language

7.2.1 Python codes used to determine the class of poles that failed during the storm



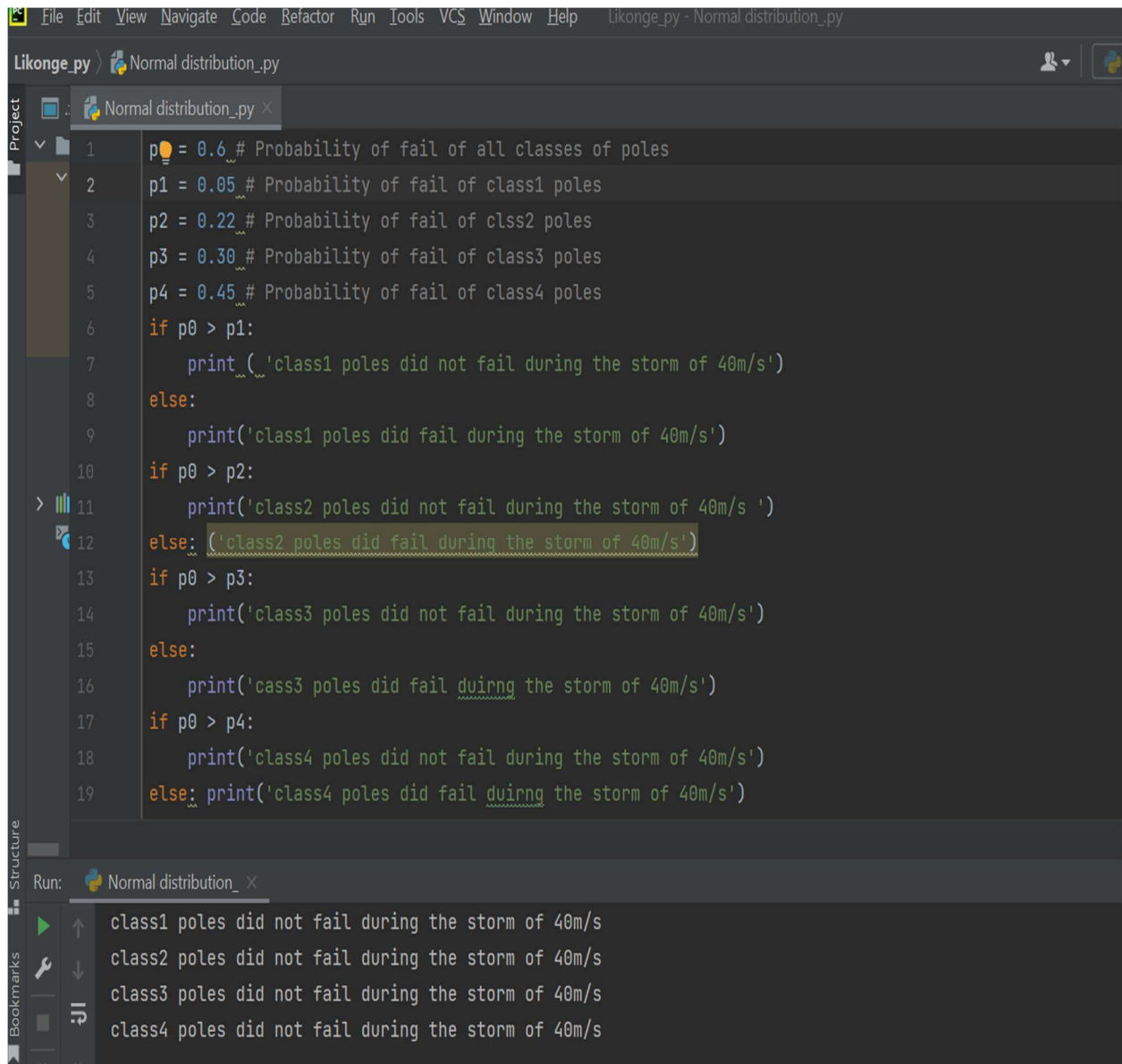
The screenshot shows an IDE window titled 'Likonge_py - Normal distribution_py'. The main editor displays a Python script with the following code:

```
1 p0 = 0.6 # Probability of fail of all classes of poles
2 p1 = 0.01 # Probability of fail of class1 poles
3 p2 = 0.05 # Probability of fail of class2 poles
4 p3 = 0.2 # Probability of fail of class3 poles
5 p4 = 0.3 # Probability of fail of class4 poles
6 if p0 > p1:
7     print('class1 poles did not fail during the storm of 30m/s')
8 else:
9     print('class1 poles did fail during the storm of 30m/s')
10 if p0 > p2:
11     print('class2 poles did not fail during the storm of 30m/s ')
12 else: print('class2 poles did fail during the storm of 30m/s')
13 if p0 > p3:
14     print('class3 poles did not fail during the storm of 30m/s')
15 else:
16     print('class3 poles did fail during the storm of 30m/s')
17 if p0 > p4:
18     print('class4 poles did not fail during the storm of 30m/s')
19 else: print('class4 poles did fail during the storm')
```

The 'Run' output at the bottom shows the following messages:

```
Run: Normal distribution_ x
↑ class1 poles did not fail during the storm of 30m/s
↓ class2 poles did not fail during the storm of 30m/s
↑ class3 poles did not fail during the storm of 30m/s
↓ class4 poles did not fail during the storm of 30m/s
```

Fig 21: Python code to determine the class of poles that failed during the storm of 30 m/s wind speed



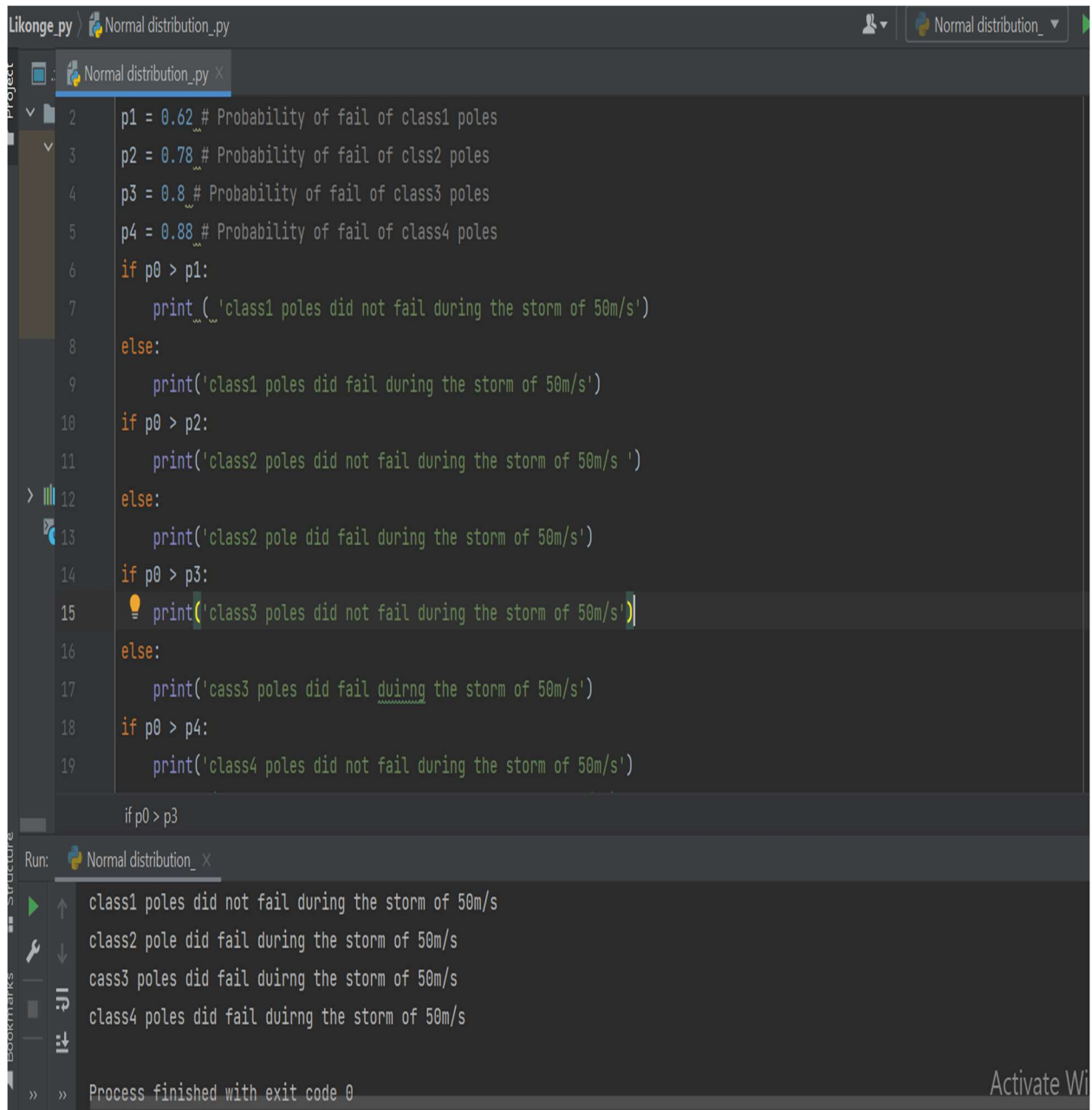
The image shows a screenshot of an IDE with a Python script named 'Normal distribution_py'. The script defines a variable `p0` as 0.6, representing the probability of failure for all pole classes. It then defines four variables (`p1`, `p2`, `p3`, `p4`) representing the failure probabilities for four different pole classes. The code uses a series of `if` statements to check if `p0` is greater than each class's probability. If true, it prints that the poles did not fail; if false, it prints that they did fail. The output window at the bottom shows that for all four classes, the poles did not fail during the storm.

```
1 p0 = 0.6 # Probability of fail of all classes of poles
2 p1 = 0.05 # Probability of fail of class1 poles
3 p2 = 0.22 # Probability of fail of class2 poles
4 p3 = 0.30 # Probability of fail of class3 poles
5 p4 = 0.45 # Probability of fail of class4 poles
6 if p0 > p1:
7     print('class1 poles did not fail during the storm of 40m/s')
8 else:
9     print('class1 poles did fail during the storm of 40m/s')
10 if p0 > p2:
11     print('class2 poles did not fail during the storm of 40m/s ')
12 else: print('class2 poles did fail during the storm of 40m/s')
13 if p0 > p3:
14     print('class3 poles did not fail during the storm of 40m/s')
15 else:
16     print('class3 poles did fail during the storm of 40m/s')
17 if p0 > p4:
18     print('class4 poles did not fail during the storm of 40m/s')
19 else: print('class4 poles did fail during the storm of 40m/s')
```

Run: Normal distribution_

```
class1 poles did not fail during the storm of 40m/s
class2 poles did not fail during the storm of 40m/s
class3 poles did not fail during the storm of 40m/s
class4 poles did not fail during the storm of 40m/s
```

Fig 22: Python code to determine the class of poles that failed during the storm of 40 m/s wind speed



```
Normal distribution_py
2 p1 = 0.62 # Probability of fail of class1 poles
3 p2 = 0.78 # Probability of fail of class2 poles
4 p3 = 0.8 # Probability of fail of class3 poles
5 p4 = 0.88 # Probability of fail of class4 poles
6 if p0 > p1:
7     print('class1 poles did not fail during the storm of 50m/s')
8 else:
9     print('class1 poles did fail during the storm of 50m/s')
10 if p0 > p2:
11     print('class2 poles did not fail during the storm of 50m/s ')
12 else:
13     print('class2 pole did fail during the storm of 50m/s')
14 if p0 > p3:
15     print('class3 poles did not fail during the storm of 50m/s')
16 else:
17     print('class3 poles did fail during the storm of 50m/s')
18 if p0 > p4:
19     print('class4 poles did not fail during the storm of 50m/s')
20 if p0 > p3
```

Run: Normal distribution_py

```
class1 poles did not fail during the storm of 50m/s
class2 pole did fail during the storm of 50m/s
class3 poles did fail during the storm of 50m/s
class4 poles did fail during the storm of 50m/s
Process finished with exit code 0
```

Fig 23: Python code to determine the class of poles that failed during the storm of 50 m/s wind speed

```
File Edit View Navigate Code Refactor Run Tools VCS Window Help Likonge.py - Normal distribution_.py

Likonge.py > Normal distribution_.py

Project
  Normal distribution_.py x
    1 p0 = 0.7 # Probability of fail of all classes of poles
    2 p1 = 0.9 # Probability of fail of class1 poles
    3 p2 = 0.92 # Probability of fail of class2 poles
    4 p3 = 0.93 # Probability of fail of class3 poles
    5 p4 = 0.98 # Probability of fail of class4 poles
    6 if p0 > p1:
    7     print('class1 poles did not fail during the storm of 60m/s')
    8 else:
    9     print('class1 poles did fail during the storm of 60m/s')
   10 if p0 > p2:
   11     print('class2 poles did not fail during the storm of 60m/s ')
   12 else:
   13     print('class2 pole did fail during the storm of 60m/s')
   14 if p0 > p3:
   15     print('class3 poles did not fail during the storm of 60m/s')
   16 else:
   17     print('class3 poles did fail during the storm of 60m/s')
   18 if p0 > p4:
   19     print('class4 poles did not fail during the storm of 60m/s')
   20 else: print('class4 poles did fail during the storm of 60m/s')

Structure
Run: Normal distribution_ x
  class1 poles did fail during the storm of 60m/s
  class2 pole did fail during the storm of 60m/s
  class3 poles did fail during the storm of 60m/s
  class4 poles did fail during the storm of 60m/s
```

Fig 24: Python code to determine the class of poles that failed during the storm of 60 m/s wind speed

total load connected to the distribution network is 9.76 MW. Therefore, the performance index is calculated as below:

$$R_0 = \frac{L_c(t_0)}{L_T(t_0)} = \frac{9.76}{9.76} = 1$$

Since during the storm, none of the pole classes failed, meaning the loads were not affected, and as such, and the performance indices before, during, and after are the same.

.b) Calculation of the Normalized Vulnerability index using formulae six (6) in part two (2) of this thesis.

$$\zeta_V = \frac{R_0 - R_{pe}}{R_0} = \frac{1-1}{1} = 0$$

c) Calculation of the Degradation index using formulae seven (7) in part two (2) of this thesis.

$$\begin{aligned} \zeta_D &= \frac{\int_{t_e}^{t_{pe}} (R_0 - R(t))dt}{R_0(t_{pe} - t_e)} = \\ &= \frac{\int_{10}^{16} (1-1)dt}{1(16-10)} = \\ &= \frac{\int_{10}^{16} 0dt}{6} = 0 \end{aligned}$$

d) Calculation of the Energy Loss index using formulae eight (8) in part two (2) of this study.

$$\begin{aligned}\zeta_E &= \frac{\int_{t_e}^{t_{pir}} (R_0 - R_{pe}) dt}{R_0(t_{pir} - t_e)} = \\ &= \frac{\int_{10}^{21} (1-1) dt}{1(21-10)} = \\ &= \frac{\int_{10}^{21} 0 dt}{11} = 0\end{aligned}$$

7.3.2 Calculation of the performance indices of the Kasama distribution network before, during, and after the storm of 40m/s wind speed

a) Calculation of the Performance index before, during and after the event using formula five (5) and the load flow calculation in the table 21.

Table 21: Load flow calculation before, during and after the event (wind storm) in PowerFactory DIgSILENT at wind speed of 40m/s

		DigSILENT PowerFactory 2018 SP3		Project: Date: 27/04/2022				
Load Flow Calculation				Complete System Report: Substations, Voltage Profiles, Grid Interchange				
AC Load Flow, balanced, positive sequence		Automatic Model Adaptation for Convergence		No				
Automatic tap adjustment of transformers		Max. Acceptable Load Flow Error for		1.00 kVA				
Consider reactive power limits		Nodes		0.10 %				
		Model Equations						
Total System Summary			Study Case: Study Case		Annex: / 6			
Generation	Motor Load	Load	Compensation	External Infeed	Inter Area Flow	Total Losses	Load Losses	No-load Losses
[MW] / [Mvar]	[MW] / [Mvar]	[MW] / [Mvar]	[MW] / [Mvar]	[MW] / [Mvar]	[MW] / [Mvar]	[MW] / [Mvar]	[MW] / [Mvar]	[MW] / [Mvar]
\lndhlovu\Project Kasama Distribution\Network Model\Network Data\33kV Network								
0.00	0.00	9.76	0.00	9.81	0.00	0.06	0.06	-0.00
0.00	0.00	1.46	0.00	2.07	0.00	0.62	0.70	-0.08
Total:								
0.00	0.00	9.76	0.00	9.81		0.06	0.06	-0.00
0.00	0.00	1.46	0.00	2.07		0.62	0.70	-0.08

The total active power supplied to the Kasama distribution network is 9.76MW, as shown in Table 21, and the total active power consumed by both common and essential loads is 9.76MW. The total load connected to the distribution network is 9.76MW. Therefore, the performance index is calculated as below:

$$R_0 = \frac{L_c(t_0)}{L_T(t_0)} = \frac{9.76}{9.76} = 1$$

Since during the wind storm, none of the pole classes failed, meaning the loads were not affected, as such the performance indices before, during, and after are the same.

b) Calculation of the Normalized Vulnerability index using formulae six (6) in part two (2) of this thesis.

$$\zeta_V = \frac{R_0 - R_{pe}}{R_0} = \frac{1-1}{1} = 0$$

c) Calculation of the Degradation index using formulae seven (7) in part two (2) of this thesis.

$$\begin{aligned} \zeta_D &= \frac{\int_{t_e}^{t_{pe}} (R_0 - R(t))dt}{R_0(t_{pe} - t_e)} = \\ &= \frac{\int_{10}^{16} (1-1)dt}{1(16-10)} = \\ &= \frac{\int_{10}^{16} 0dt}{6} = 0 \end{aligned}$$

d) Calculation of the Energy Loss index using formulae eight (8) in part two (2) of this study.

$$\begin{aligned} \zeta_E &= \frac{\int_{t_e}^{t_{pir}} (R_0 - R_{pe})dt}{R_0(t_{pir} - t_e)} = \\ &= \frac{\int_{10}^{21} (1-1)dt}{1(21-10)} = \\ &= \frac{\int_{10}^{21} 0dt}{11} = 0 \end{aligned}$$

7.2.3 Calculation of the performance indices of the /Kasama distribution network before, during and after the storm of 50m/s wind speed

a) Calculation of the Performance Index before, during, and after the event using formula 5 and the load flow calculation in table 22

Table 22: Load flow calculation before, during and after the event (wind storm) in PowerFactory DIgSILENT at wind speed of 50m/s wind speed

		DigSILENT PowerFactory 2018 SP3		Project: Date: 27/04/2022				
Load Flow Calculation								
Complete System Report: Substations, Voltage Profiles, Grid Interchange								
AC Load Flow, balanced, positive sequence			Automatic Model Adaptation for Convergence		No			
Automatic tap adjustment of transformers			Max. Acceptable Load Flow Error for		1.00 kVA			
Consider reactive power limits			Nodes		0.10 %			
			Model Equations					
Total System Summary			Study Case: Study Case		Annex: / 6			
Generation	Motor Load	Load	Compensation	External Infeed	Inter Area	Total Losses	Load Losses	Noload Losses
[MW]/	[MW]/	[MW]/	[MW]/	[MW]/	[MW]/	[MW]/	[MW]/	[MW]/
[Mvar]	[Mvar]	[Mvar]	[Mvar]	[Mvar]	[Mvar]	[Mvar]	[Mvar]	[Mvar]
\indhlovu\Project Kasama Distribution\Network Model\Network Data\33kV Network								
0.00	0.00	9.76	0.00	9.81	0.00	0.06	0.06	-0.00
0.00	0.00	1.46	0.00	2.07	0.00	0.62	0.70	-0.08
Total:								
0.00	0.00	9.76	0.00	9.81		0.06	0.06	-0.00
0.00	0.00	1.46	0.00	2.07		0.62	0.70	-0.08

The total active power supplied to the Kasama distribution network is 9.76 MW, as shown in Table 22 and the total power consumed by both common and essential loads is also 9.76 MW. The total load connected to the distribution network is 9.76 MW. Therefore, the performance index is calculated as below:

$$R_0 = \frac{L_c(t_0)}{L_T(t_0)} = \frac{9.76}{9.76} = 1$$

b) Calculation of the Normalized Vulnerability index using formulae six (6) in part two (2) of this thesis for class 1 poles

$$\zeta_V = \frac{R_0 - R_{pe}}{R_0} = \frac{1-1}{1} = 0$$

c) Calculation of the Degradation index using formulae seven (7) in part two (2) of this thesis for class 1 poles

$$\begin{aligned}
\zeta_D &= \frac{\int_{t_e}^{t_{pe}} (R_0 - R(t))dt}{R_0(t_{pe} - t_e)} = \\
&= \frac{\int_{10}^{16} (1-1)dt}{1(16-10)} = \\
&= \frac{\int_{10}^{16} 0dt}{6} = 0
\end{aligned}$$

d). Calculation of the Energy Loss index using formulae eight (8) in part two (2) of this study for class 1 poles

$$\begin{aligned}
\zeta_E &= \frac{\int_{t_e}^{t_{pir}} (R_0 - R_{pe})dt}{R_0(t_{pir} - t_e)} = \\
&= \frac{\int_{10}^{21} (1-1)dt}{1(21-10)} = \\
&= \frac{\int_{10}^{21} 0dt}{11} = 0
\end{aligned}$$