An-Najah National University

Faculty of Graduate Studies

ELECTRICAL NETWORK RECONFIGURATION FOR IMPROVING THE RELIABILITY OF DISTRIBUTION SYSTEM CONSISTING OF RENEWABLE ENERGY SOURCES

By

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Dedication

To all Palestinian people who struggle for their free homeland, to my dear brother, Adam, in the occupation prisons.

To all my family, friends, and everyone who believes in me.

I dedicate this thesis.

Acknowledgment

I want to express my deepest gratitude to my supervisor Dr. Moen Omar who has contributed to the completion of this project, supported me all the way, and he never doubted my ability to achieve this thesis, his vast knowledge and insightful feedback have been instrumental in shaping this thesis.

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Additionally, I want to extend my appreciation to my friend Maysa' for supporting me, her belief in me provided me with the motivation I needed to overcome the challenges associated with this project.

Thank you all for your generous support and contribution towards the success of this work.

Declaration

I, the undersigned, declare that I submitted the thesis entitled:

ELECTRICAL NETWORK RECONFIGURATION FOR IMPROVING THE RELIABILITY OF DISTRIBUTION SYSTEM CONSISTING OF RENEWABLE ENERGY SOURCES

I declare that the work provided in this thesis, unless otherwise referenced, is the researcher's own work, and has not been submitted elsewhere for any other degree or qualification.

Student's Name: **Tahreer (Mohammad Daoud) Sulaiman Thiab**

Signature:

Date: **10/10/2024**

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Abstract

This thesis evaluates the impact of network reconfiguration on improving the reliability of an electrical network with high PV penetration. The reliability of the electrical network depends on the failure rates of the components installed within it. However, for loads in the network, the failure rate and outage duration can be affected by voltage conditions. In some cases, improving the voltage can reduce the failure rate of loads, but an increase in PV penetration can lead to voltage rise, which may result in a higher failure rate.

This thesis discusses how variations in PV penetration impact the reliability indices of the network and explores how reconfiguration of the network can improve its reliability. The case study uses the modified IEEE 33-bus network with a PV penetration level of 70% of the installed electrical loads. Without a PV system, the network experiences voltage drops in loads far from the connection point, leading to a high failure rate due to low voltage. However, with high PV penetration, voltage rise also affects reliability. Reconfiguring the network by connecting additional buses improves voltage conditions in both scenarios, leading to enhanced reliability indices. Without PV, the network's reliability indices are as follows: The average Interruption Rate is 83.847 failures per year, and Average Outage Duration is 1.81 hours. The indices are SAIDI: 151.694, SAIFI: 83.847, EENS: 730.407, and CAIDI: 1.809 hours. With 100% PV penetration but without reconfiguration, the Average Interruption Rate is 54.81 failures per year, and the Average Outage Duration is 1.67 hours. The indices are SAIDI: 91.6206, SAIFI: 54.8103, EENS: 441.153, CAIDI: 1.672 hours. When reconfiguration is added, the network's reliability indices improve: the Average Interruption Rate is 56.7532 failures per year, and the Average Outage Duration is 1.65 hours. The indices are SAIDI: 95.6504, SAIFI: 56.7532, EENS: 460.557, and CAIDI: 1.685 hours. The results obtained using ETAP software, show that while adding

PV reduces losses, it may decrease the reliability of the network if reconfiguration is not implemented. However, with reconfiguration, network reliability is enhanced.

Keywords: Reliability Assessment, Network Reconfiguration, PV Penetration, Reliability Indices, Failure Rate.

Chapter One

Introduction

1.1 Introduction

Modern power systems are evolving rapidly, driven by the increasing integration of renewable energy sources, particularly Photovoltaic (PV) systems [1]. The shift towards renewable energy is motivated by the need to reduce carbon emissions, enhance energy security, and promote sustainable development. Meanwhile, as the penetration of renewable energy, especially PV systems, increases in power networks, the complexity of managing these systems also escalates [2]. This is primarily due to the intermittent and variable nature of renewable energy sources, which significantly impacts the power flow within the network and, consequently, the reliability indices that are critical for maintaining a stable and efficient power supply.

The introduction of PV systems into the power grid alters the traditional power flow patterns, transitioning from a unidirectional flow—from centralized power plants to consumers—to a more dynamic and bidirectional flow. This change brings about challenges in maintaining voltage levels, managing power quality, and ensuring system reliability. On the one hand, adding PV generation to the network can enhance reliability by reducing the dependency on centralized power plants and providing localized generation that supports the grid during peak demand periods [3]. Therefore, integrating PV systems can potentially reduce the frequency and duration of power outages, thereby improving reliability indices such as the System Average Interruption Duration Index (SAIDI), the System Average Interruption Frequency Index (SAIFI), Customer Average Interruption Duration Index (CAIDI), and Expected Energy Not Supplied (EENS).

However, the benefits of PV integration are not without limits. There is a threshold beyond which the additional PV capacity can harm network reliability. When PV penetration exceeds this threshold, the power network may experience issues such as voltage instability, reverse power flow, and increased stress on the network components. These issues arise because the excess generation from PV systems, particularly during periods of low demand, can cause voltage rise, leading to overloading of network components and increased failure rates. Nevertheless, it is crucial to recognize that these challenges are not insurmountable. Effective network reconfiguration, along with the implementation of advanced control systems, can mitigate the negative impacts of high PV penetration and enhance overall network reliability [4].

The variation in output power generation from PV systems further complicates the reliability assessment of power networks. The intermittent nature of solar energy means that the power output from PV systems is highly dependent on weather conditions, time of day, and seasonal variations. This variability can lead to fluctuations in power supply, which, if not properly managed, can result in reliability issues such as increased frequency of power interruptions and longer restoration times [5]. Therefore, the reliability of the power network with high PV penetration is directly influenced by the ability to balance generation with load demand and to manage the variability of renewable energy sources.

One of the critical aspects of ensuring reliability in networks with high PV penetration is the strategic reconfiguration of the network. Network reconfiguration involves altering the topology of the power system, such as by changing the connections between different buses or redistributing loads, to optimize performance and enhance reliability. Reconfiguration can help mitigate the negative impacts of high PV penetration by improving voltage profiles, reducing power losses, and balancing the load across the network. On the other hand, without proper reconfiguration, the benefits of PV integration may be overshadowed by the increased risk of component failures and the overall decline in network reliability.

This thesis investigates the dual nature of PV integration on power network reliability, highlighting both the potential benefits and the risks associated with high levels of PV penetration. The study focuses on the modified Institute of Electrical and Electronics Engineers (IEEE) 33-bus network as a case study, examining how different levels of PV penetration affect reliability indices and how network reconfiguration can be employed as a strategy to enhance reliability. The results show that while adding PV generation can reduce losses and improve reliability up to a certain point, exceeding this threshold without reconfiguring the network can lead to a decrease in reliability. Specifically, the study demonstrates that reconfiguring the network by connecting additional buses can improve voltage profiles and, consequently, enhance reliability indices even with high PV penetration.

Electrical Power Systems (EPS) which consist of the main three subsystems: generation, transmission, and distribution have been established to provide electrical power to all customers, they have been developed over the past decades through penetrating power generation units using renewable resources such as wind and PV systems, penetration of these new Distributed Generations (DG) brings several benefits as improved power quality, minimized losses and then less cost needed [6].

This thesis examines how reliable a distribution system using renewable energy sources may be in reducing disruptions and guaranteeing that loads receive electricity. To improve system security and dependability, it is critical to understand where renewable sources are located within the distribution system.

Numerous indicators are employed to assess the distribution system reliability, and the study uses ETAP software to determine the interconnected distribution system dependability while accounting for the location of renewable resources and the suitable reconfiguration.

Combining traditional DG with PV power generation into one power source is an effective way to reduce system disruptions and achieve both financial and environmental rewards. However, if DG units are placed in inappropriate places and of suboptimal sizes, a number of technical issues, including increased power losses and issues with voltage magnitude, may arise, ultimately impacting reliability.

In order to achieve reliability improvement, we must examine the reliability features of renewable energy sources that are linked to the distribution system. This will guarantee minimally interrupted continuous electricity delivery.

The purpose of this research is to assess the distribution system's reliability before including renewable energy sources and reconfiguration, and reevaluating the system within a number of scenarios, taking reliability indices into account. This research system, the IEEE 33-bus system, will be evaluated and analyzed using ETAP software to compare the reliability indices in the scenarios.

SAIFI, SAIDI, CAIDI, and ENS are the reliability indices compared in the suggested scenarios to assess the reliability of the distribution system.

1.2 Literature Review

Improving the market value of the distribution system by balancing reliability and costs, the paper proposed a reliability model to determine the equivalence of DG solutions to distribution facilities, facilitating decision-making in the planning of distribution system studies in the competitive environment [7]. Different scenarios of DG installation location and capacity are applied to assess DG unit installations' effect on power losses, voltage profiles, and reliability indices in distribution systems [8]. Using a proposed methodology to evaluate the effect of PV electric power plants on a utility supply system depending on energy-based models and a load modification approach [9]. A reliability model of distributed generation and an exact analytical stochastic approach to study the effect on the electric power distribution grid was introduced [10].

Modeling techniques were applied to a real Iranian distribution network to investigate the sensitivity of reliability indices to the location of DGs and demonstrate the diminishing returns on reliability improvement with the increasing number of DGs [11]. A paper studies the siting and installation of PV systems in compliance with Greek laws including environmental and geographical factors. The paper measures the reliability enhancement using indices such as SAIDI, SAIFI, and CAIDI. The abstract concludes that the resulting enhancement in reliability is measured in financial terms by decreasing interruption costs [12]. Assessment of the potential improvement of Loss of Load Probability (LOLP) and Loss of Energy Probability (LOEP) using the PV units' estimated power output. This evaluation is implemented for the Interconnected Greek Transmission System (IGTS). It Demonstrates the expected reduction of reliability indices, power output units, and peak shaving for the IGTS in Greece. Finally, reliability improvement is expressed in terms of profit by comparing the cost for every kWh produced by PV units to the corresponding cost for every kWh produced by expensive units, which would otherwise cover a proportion of peak load demand [13]. This paper used a systematic approach to evaluate the reliability of large grid-connected (PV) power systems, considering the variation of input power and ambient-condition-dependent failure rates of critical components such as PV modules, inverters, and capacitors, and defines the reliability indices [14]. Using the Monte Carlo simulation algorithm for the integration of distributed generations, including solar (PV), wind turbine (WT), and diesel turbine generator (DTG) can improve the reliability indices of the distribution network, the paper used it for reliability analysis [15].

Analysis of the effect of adding solar power sources and power storage to a microgrid distribution system and evaluating the overall grid reliability, the evaluation used the Roy Billinton Test System (RBTS) with different load and system indices, including (SAIDI), (SAIFI), (CADI) and (ENS) [16]. the capacity of DGs and their locations are crucial factors that impact the reliability indices, SAIDI, SAIFI, and outage cost (ECOST) which are calculated in the cases in which multi-DG are connected to a distribution system [17]. Examining the effects of changing the penetration levels of PV and synchronous machine-based distributed generation sources on the reliability of a microgrid and conducting evaluations on load point reliability indices, considering fluctuating solar energy and loading conditions are applied [18]. Expressive enhancement in (SAIDI) up to 20% and (SAIFI) up to 24% after reconfiguring the implementation of the network, an algorithm that considers the unique characteristics of Eskom distribution networks, including their radial operation and equipment limitations, to enhance reliability is introduced [19]. Investigate the impact of adding DG technologies and energy storage on the reliability of the distribution system, various reliability indices are applied to evaluate the improvements, and the reliability of the system in islanded microgrid scenarios is also evaluated [20]. Applying the PSAT tool in MATLAB software on a proposed project focusing on the improvement of the reliability of distribution systems by utilizing PV systems as DG. Choosing the perfect location and size of DG through Power flow analysis. By using ETAP software to analyze the demonstrated IEEE 14-bus system, and calculate the reliability indices. The paper suggests that adding DG can enhance bus voltage profiles and reduce power losses [21].to evaluate the effect of the failure accurately of conventional power equipment on reliability, the paper models conventional power equipment to calculate a time-varying failure rate, considering the aging period. Then, to accurately evaluate the reliability improvement with PV systems integration a real case study in China is done [22]. evaluating reliability indices for different case studies by using the Roy Billinton bus 2 Test System. The integration between PV and energy storage can improve the reliability indices of the original distribution system as simulation results demonstrate and then they are optimally sized and sited [23]. The paper illustrates the varying characteristics of reliability indices such as ASAI, SAIDI, SAIFI, and CAIDI concerning PV penetration [24]. Investigating the impact of solar PV systems on the adequacy and reliability of power distribution systems. Monte Carlo simulation is used to obtain the ENS for the RBTS bus 2 system when there is a line outage. The research considers various levels of solar PV integration and different placements to analyze how solar integration affects reliability [25]

1.3 Problem Statement

Reliability assessment is essential for present and future electricity networks, to have continuous electricity with fewer interruptions in frequency and duration, customer satisfaction, and less cost for the suppliers and the end users. The grid's reliability varies according to its configuration, the demand of customers, and the components’ reliability. Integrating a PV system as DG into the network affects the total network reliability, and reliability analysis becomes more complicated; integrated DG improves the reliability sometimes but makes it worse other times according to its size, location, connection way, and components’ failure rates. To have enhanced grid Reliability, we will use modified IEEE 33-bus in ETAB to make grid reconfigurations, adding distributed PV as one scenario and without PV as another scenario, with different situations of reliability of the components compared to the grid components' reliability and investigate the reliability indices such as SAIDI, SAIFI, CAIDI, and ENS.

1.4 Objectives

The primary objectives of this research are to explore and analyze the impact of high photovoltaic (PV) penetration on the reliability of power networks and to develop strategies for mitigating potential adverse effects through network reconfiguration. Specifically, the research aims to achieve the following objectives:

- **Assess the Impact of PV Penetration on Power Network Reliability:**
  To quantify the effects of varying levels of PV penetration on key reliability indices, including SAIDI, SAIFI, and EENS. To evaluate how PV integration alters the power flow dynamics within the network and the subsequent impact on component failure rates.

- **Investigate the Threshold of PV Penetration for Optimal Reliability:**
  To identify the optimal level of PV penetration that maximizes the reliability of the power network without causing voltage instability or increasing the failure rates of network components. To analyze the conditions under which exceeding the identified threshold leads to a decline in network reliability.

- **Develop and Evaluate Network Reconfiguration Strategies:**
  To design and implement network reconfiguration strategies that can mitigate the negative impacts of high PV penetration on reliability.

  To use a modified IEEE 33-bus network as a case study to simulate different reconfiguration scenarios and assess their effectiveness in improving reliability indices under various levels of PV penetration.

- **Analyze the Role of Voltage Management in Enhancing Reliability:**
  To explore how network reconfiguration can reduce the occurrence of voltage rise and mitigate the associated risks of component failures. To assess the potential of reconfiguration in maintaining stable voltage levels across the network, particularly in scenarios of high PV penetration.

- **Provide Practical Insights for Grid Operators and Planners:**
  To offer recommendations for grid operators and planners on how to balance the benefits of PV integration with the potential risks to network reliability.

  To propose guidelines for implementing network reconfiguration as a standard practice in networks with significant renewable energy sources.

- **Contribute to the Field of Renewable Energy Integration:**
  To advance the understanding of how high levels of renewable energy penetration, particularly PV systems, affect power network reliability.

  To contribute to the broader research discourse on renewable energy integration by providing empirical evidence and practical solutions for improving network reliability**.**

1.5 Methodology

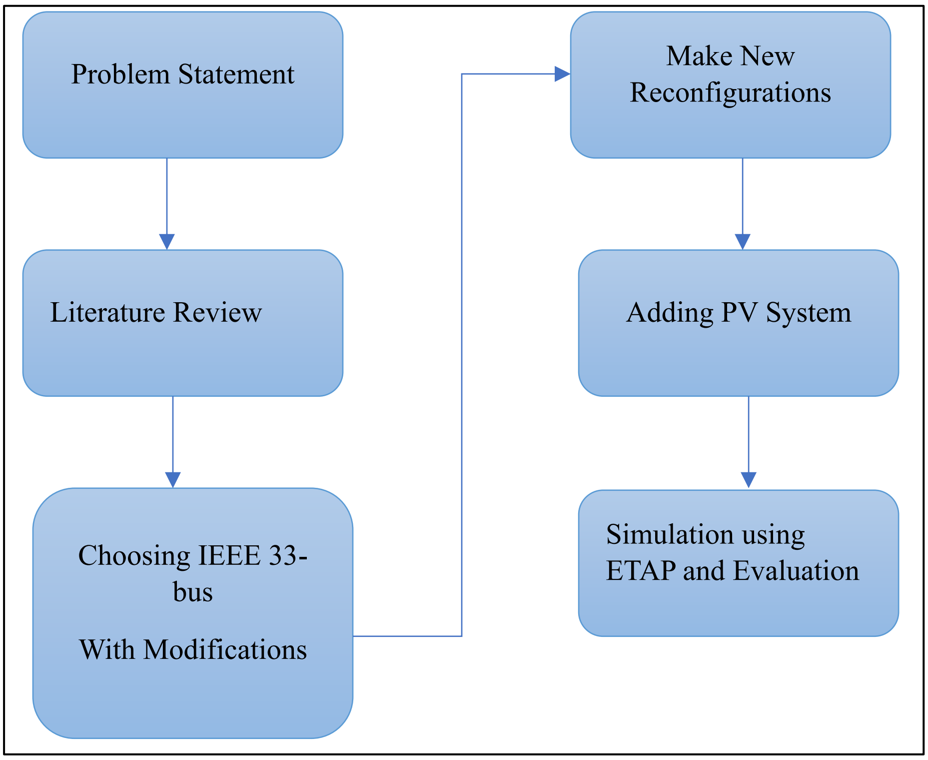
1. Identifying the problem statement related to the network reliability affected by PV installed.
2. Literature review: reviewing the related previous studies connected to the problem statement.
3. Choosing IEEE 33-bus network: depending on the ETAP library IEEE 33-bus network is taken.
4. Modifying the parameters of the network to improve buses’ voltage.
5. Entering assumed values of failure rate and MTTR for the components.

6. Assignment of the new loads' failure rates according to the dependence on the connected bus voltage variations.
7. Making new reconfigurations: adding two single-throw switches to the network.
8. Adding a PV system with a 70% penetration level to make network improvement.

Simulation: Using ETAP, Load flow and reliability analysis are carried out for both the two base cases with and without PV systems.

Figure 1

Methodology Flowchart



1.6 Thesis Structure

Chapter One

In this chapter, an introduction about the power system's reliability is introduced, a literature review is shown, the problem statement is discussed and solved, the objectives of this thesis are mentioned, and the methodology of the study is discussed.

Chapter Two

This chapter talks about the power distribution system in general, its stages, components, and different classifications, and talks about the modified IEEE 33-bus network as an example of the distribution system. Besides talking about PV Energy in distribution grids including its components, varieties, operation mechanism, advantages, challenges, and considerations. It talks about the three main types of PV systems, on-grid, off-grid, and hybrid systems, demonstrating their advantages and disadvantages. It illustrates also, centralized vs. distributed PV systems based on definition and operation, and benefits and drawbacks.

Chapter Three

This chapter talks about reliability in power systems, its definition, methods of reliability assessment, some definitions related to interruption according to the IEEE guide, and interruption types. Some aspects related to reliability as availability, system adequacy, system security, failure rate, MTTR, and MTTF are discussed. Types of reliability indices, and detailed indices such as SAIFI, SAIDI, CAIDI, and EENS are mentioned. Reliability assessment for PV Systems including critical components such as inverter and PV module, and finally, a numerical example to illustrate calculations in ETAP.

Chapter Four

The case study chapter talks about ETAP, the assignment of some components' Parameters, the case study description, and the simulation results with the discussion and conclusion.

Chapter Two

Electrical Power System

2.1 Power Distribution System

A power production system is the mechanism of delivering power to the customer as shown in Figure (B 1), it is a complicated process consisting of many steps:

1. Power generation.
2. Power transmission.
3. Power distribution.
4. Power storage.

The power distribution system is the final stage of power delivery to the customers, it consists of a complicated network, it carries the power from transmission lines to the household, it is located inside the cities, receives high voltage power from transmission lines through a step-down transformer and converts it to the medium voltage.

Power distribution system aims to deliver electricity to the costumer through voltage transmission system, it is the middle man between the generation, transmission and the point of the consumption. It takes the high voltage and steps it down to convert it to suitable voltage for consumption, ensuring safety and compatibility to commercial use.

Functions

- Voltage reduction.
- Isolation of distribution network.
- Switching and protection.

2.1.1 Power Distribution system components

The power distribution system consists of:

1. Distribution substation: this includes a substation that receives the power from transmission lines through a step-down transformer to convert it from high voltage to medium voltage. A typical distribution substation contains switchgear, busbars, transformers, protection relays, and metering equipment. It serves multiple feeders with distribution lines.

2. Feeders: the step-down voltage which is converted by the substation is carried through copper or aluminum feeders, the main consideration is to choose the right conductor to carry the current.

Characteristics

- High-capacity conductors.
- Minimizes losses and voltage drops.

3. Distribution transformer: it is a step-down transformer that converts the voltage from medium to low voltage 400Y/230 volts that will be delivered to houses, the voltage between any phase and neutral is 230 volts in Palestine, it is different from country to another.
4. Distribution conductors: These conductors usually made from copper or aluminum cables, installed either underground or overhead, they transmit the stepdown low voltage power from the distribution transformer to the consumer, and they can carry a specific current to each customer.

Features

- Typically, overhead or underground.
- Rated for specific current capacities.

1. Service mains conductors: it is a conductor that is connected to the household.

Characteristics

- Direct connection to consumers.
- Must comply with local regulations and safety standards.

2. Switches, protection equipment, measurement equipment, etc.: they consist of several protection devices through the whole process of delivering power to the customer, cutting the power in cases of fire hazard, overload, and in the case of increasing current, to protect the network, equipment, and people.

2.1.2 classification of power distribution system

- Based on the nature of current:

1. DC Distribution System: In DC distribution, the current flows in a single, constant direction without periodic reversal and exhibits significantly less skin effect compared to AC, especially at low frequencies, and then it reduces skin effect.

Power Storage Compatibility: because of its compatibility with batteries, it is ideal for battery-based energy storage applications.

Advantages

- Less Line Losses: DC transmission over long distances experiences lower transmission losses compared to AC.
- Controlled Power Flow: Better control over power flow is achieved, and then better stability in certain applications.

Disadvantages

- Conversion Challenges: There are inherent losses implicated in converting AC to DC and vice versa.
- Infrastructure Compatibility: DC systems construction requires essential modifications to the existing AC infrastructure.

2. AC Distribution System:Types of AC Distribution System are discussed below in detail:

Primary Distribution System

Using underground or overhead cables, the primary distribution system distributes electric power at medium voltage from a substation, feeders carry the power to the lines: commercial loads or residential loads. It is important to keep the level of voltage and keep the losses at the minimum range.

Key Aspects

- Typically operates at voltages ranging from 11 kV to 33 kV.
- Requires robust and well-maintained infrastructure to prevent faults.

Secondary Distribution System

In this stage, voltage is stepped down through a distribution transformer from medium (33kV to 11 kV) to low voltages suitable for consumer usage (240/220V). Of course, all feeders can be connected overhead or underground based on the connection of the system, in this system, transformer taps or voltage regulators are used to regulate the secondary voltage within limits.

This stage aims to ensure the lower voltage delivered to the consumer, to be suitable for household and commercial use.

Typical Voltage Levels

- 230V for single-phase
- 400V for three-phase systems
- Based on the type of construction:

1. Overhead distribution system.

   The overhead distribution system is the easiest way to connect the electrical network which is implemented by using poles, it is common in urban and rural areas and it is known for its cheapest cost and easiest for maintenance.

   Components of Overhead Distribution System

- Poles: The pole is the main component used overhead method, it is usually made of wood or steel, and it supports the connection of the electrical distribution system.

- Conductors: Conductors in overhead systems are used to carry current through the network, it is chosen based on their conductivity and cost, some materials such as copper and aluminum are chosen. They are suspended on insulators attached to poles.

- Insulators: Insulators are used to insulate the wires from the poles to prevent the current flow through the material of the pole, made from a material such as porcelain or polymer, they hold the conductors in place and provide necessary insulation.

- Transformers: they are used to step down the voltage level from medium to low, and so the consumer can use it safely. These transformers are mounted on poles and connected to the conductors.

- Cross-arms and Braces: Crossarms are horizontal beams mounted on poles to support conductors. Braces provide additional support and stability to the cross-arms.

- Lightning Arresters: Lightning arresters protect the distribution system from voltage spikes caused by lightning strikes. They used to ground the high range of voltage to protect the system and people.

- Fuses and Circuit Breakers: they are protection devices connected to the system to protect it from overcurrent, to ensure the safety of the system, and then prevent damages.

Advantages of Overhead Distribution System:

- Cost-Effectiveness
- Ease of Maintenance
- Flexibility and Expandability
- Quick Fault Detection

Disadvantages of Overhead Distribution System:

- Susceptibility to Weather Conditions
- Aesthetic Impact
- Safety Concerns
- Right-of-Way Issues

2. Underground distribution system.

The underground distribution system is an excellent way to connect the system and deliver the electricity to the consumer, it is preferred for its reliability and its benefits, a lot of problems are eliminated because the system is hidden, this system is buried in the ground through many levels.

The system provides better protection because all the system and protection related to it is hidden, this system reduces maintenance requirements.

Characteristics of Underground Distribution Systems Aesthetics: Underground distribution networks help beautify areas by concealing electrical wires and equipment from plain view. This minimal visual impact makes them suitable for most applications.

Weather Resistance: With distribution components safely buried underground, these systems have higher with-stand capability against adverse weather conditions like strong winds, storms, and ice accumulation which often causes disruption on overhead lines.

Space Utilization: As they require less clearance above ground, underground distribution networks prove beneficial where overhead line installation isn't feasible due to right of way or space constraints prevalent in dense urban areas with less vacant airspace.

Advantages of Underground Distribution System:

- Enhanced Aesthetics
- Reliability

Disadvantages of the Underground Distribution System:

- Cost-intensive
- Complex Maintenance
- Based on the scheme of connection:
- Radial Distribution System
- Ring Main Distribution System
- Inter-Connected Distribution System.

1. Radial Distribution System: in radial, we use a single feeder to distribute the electricity to the consumer as shown in Figure (B 2), it is a one-way circuit that distributes power across each designated area.

   It is considered to be the most cost-effective option, and the easiest to implement and connect, we use a single source to multiple users, but when there is a problem, the whole system will shut down until the problem is fixed.
2. Ring Main Distribution System: this system consists of the main source in addition to the connected loads as shown in Figure (B 3), so whenever any failure occurs at any point, power continues to be delivered using the other path, the loop provides a higher reliability standard with this type of connection.
3. Inter-Connected Distribution System: it is the most reliable way used in heavily populated areas, it consists of interlocking loop networks and uses multiple sources to deliver power as shown in Figure (B 4), but also it costs much more than other networks.

2.1.3 IEEE 33-bus Network Description

A distribution network example is the modified IEEE 33-bus network, which is related to the popular test system, IEEE 33-bus, in power system research for distribution network analysis and offers a framework for evaluating different algorithms and techniques for power flow analysis, reliability evaluation, and distribution system optimization. It is a radial distribution network that consists of one connection point, 33 buses with a 12.66 kV base voltage, 32 branches that connect buses to form a radial structure, step down transformer at the beginning of the feeder to step down transmission voltage to distribution voltage, and loads related to buses identified with a range between (45 and 420 kW), to have about 4MW installed load.

Each component of the grid has a failure rate and specific repair times, which are the basic aspects of finding reliability indices of the network, indicating the frequency and duration of power outages experienced by customers.

2.2 Photovoltaic (PV)Energy in Distribution Grids

2.2.1 PV Energy in Distribution System

PV system, which is also called a solar power system, converts sunlight into electricity depending on special solar panels.

Recently, this renewable energy technology has become widely used because of its numerous benefits in power systems and in finding a more sustainable energy landscape [27].

2.2.1.1 Components of PV Systems

A Photovoltaic (PV) System is constructed of several components

which cooperate to get renewable and sustainable energy through converting the strained sunlight.
These components are:
Solar Panels: It is the main component of having direct current (DC) converted from sunlight strained by its composition of photovoltaic cells.
The output power is dependent on the amount of the sun light facing the surface of the cells, the total energy can be used by connecting them on series or parallel dependent on their properties, those cells can be classified into three categories:

1. Monocrystalline: those cells are made from a single crystal, the production method is difficult and expensive, they are expensive and more efficient than the others.
2. Multi Crystalline: it’s easier to implement, it is considered cheaper and less efficient than the previous type.
3. Thin-film: is the cheapest one of them, and the least efficient also, it used less silicon to implement

Inverter: this component converts DC electricity generated by the solar panels into usable alternating current (AC), the inverters can be classified in two categories:

1. Stand-alone inverters: they are designed to operate far away from the electrical network, they are implemented to be connected to batteries for proper operation, the batteries can provide a constant voltage source at the DC input of the inverter, which can be classified to three types:
2. squar wave inverter
3. modified sine wave inverters
4. sine wave inverters

The waveform produced by the inverter of the voltage and current never be preferred to sine wave , because of the harmonics that can result from those waves , the type of the inverter will be chosen according to the type of the load , resistive loads could tolerate square wave inverter which are cheaper and easier to develop, a perfect sine wave inverter is chosen to operate for motors and sensitive electronic machines to operate them in right way , those inverters tend to be more expensive and harder to implement.

- Grid-tied inverters: these inverters are connected to the electrical network, therefor they must produce a perfect sine wave.

Batteries: they are used in stand-alone PV system, there are two main types:

1. Flooded: this is most common to be used, it is the cheapest, for this type, batteries overcharge results in the conversion of water into hydrogen and oxygen gases, which are released to the atmosphere, the batteries request that the water is replaced adding maintenance cost to the system
2. Valve Regulated: the properties of chemical component of these batteries allow for maintenance free operation because the oxygen is allowed to connect with the hydrogen inside the battery.

Racking and mounting: this illustrates and controls the proper position of solar panels to have maximum sunlight exposure and energy production.

Monitoring equipment: this monitors the power produced by the solar panels, checks for problems, and gives performance data.

Electrical wiring: it connects all the power system's components to ensure the electricity flow through the PV system [28]. Figure (B 5) shows the solar system components and operation.

2.2.1.2 Operation Mechanism

PV systems consist of solar panels, or PV modules, which are responsible for generating electricity from sunlight exposure. Because of its composition of semiconductor materials, when the sunlight photons hit these panels, there will be an induced Direct Current (DC), which is converted then into Alternating Current (AC) using an inverter, returning it compatible with homes and building electricity [29].

2.2.1.3 Varieties of PV Systems

PV Systems vary from small-scale residential configurations to large utility-scale solar systems. Familiar types include:

On-grid systems, Off-grid systems, and Hybrid systems.

On-grid systems enable customers to sell the extra electricity to the utility providers because they are interconnected with the electrical grid. Off-grid systems, which operate separately, usually supply electricity during reduced sunlight periods depending on the battery storage used. Hybrid Systems combine PV with alternative energy sources, such as diesel and wind generators, and then enhance overall grid reliability [30].

2.2.1.4 PV System Advantages

They are considered a clean, sustainable energy source, and they mitigate greenhouse gas emissions because of reduced dependability on fossil fuels. They reduce energy costs because they produce on-site electricity and generate income through feed-in tariffs and net metering. PV Systems are widely used, residentially, commercially, industrially, etc. Finally, they have a long operational lifespan and need minimum maintenance [31].

2.2.1.5 Challenges and Considerations

Different challenges are faced by PV Systems. Intermitted sunlight leads to power generation during daylight hours only as in Figure (B 6), and then energy storage or backup power alternatives are needed to get a continuous supply. Despite the relatively high initial installation cost, it has been on a downward path. Efficient system design and installation are affected by important variable factors such as suitable site, shading, orientation, and specific size to get optimized performance and larger energy production [32].

2.2.2 Types of PV System

There are three main types of PV systems, the suitable type is chosen depending on the location and the construction of the network and they are:

1. On-grid system
2. Off-grid system
3. Hybrid system

2.2.2.1 On-Grid PV System

The on-grid system is the most common type used in the cities, it’s connected directly to the electricity network as shown in Figure (B 7), and the main switch will go off if any error occurs in the network, to avoid any electricity shocks while fixing the problem, if the grid goes down the PV system will shut down.

Advantages of On-Grid System

1. Less cost than other systems.
2. It is more effective if the user doesn’t have a proper space to install a PV system that covers all their needs.
3. The user can benefit from the extra generated electricity, and sell it to the grid owners.
4. The extra electricity generated by the PV system provided to the grid can be used at other times during the night or on a cloudy day.
5. The grid is an effective storage system.

Disadvantages of the On-Grid System

1. If the grid goes down the PV system will shut down and we no longer can generate any electricity.
2. The PV system will be dependent on the electricity grid.

2.2.2.2 Off-Grid PV System

The off-grid system can be used in uninhabited places, or in places that are far away from the main grid, the system is connected to batteries, uses the electricity, and the extra production will be saved in the batteries and reused at other times when the sun goes down, as shown in Figure (B 8).

Advantages of Off-Grid system

1. It is an independent system and doesn’t need the grid.
2. It is a very efficient solution for far-away locations.

Disadvantages of the Off-Grid System

1. It is a very expensive system.
2. Any extra production of electricity will be wasted.
3. Batteries are expensive and short-lived equipment that needs maintenance.
4. Can’t rely on the grid in any other condition like cloudy days.

2.2.2.3 Hybrid PV System

It consists of the previous two other systems, combined between on-grid and off-grid systems, it is connected to the grid and to the batteries at the same time as shown in Figure (B 9), the electricity will be consumed and stored in the battery, and the exceeded power will return to the grid through the net meter and the user can get benefit from the extra produced electricity.

Advantages of the Hybrid System

1. Energy independence: the system stores the extra power in the batteries, and doesn’t rely on the power from the grid.
2. Grid support: despite the system's independence from the grid, the system is connected to the grid in the case of any failure occurs or in the case of bad weather and then the system can’t produce power.

3. Maximum energy utilization: the system gets benefits from all the power the system produces.

Disadvantages of Hybrid System

1. High cost.
2. The system is complicated compared to the previous systems.
3. High maintenance cost: batteries have a short life, and the repairing cost and replacing them is very high.

2.2.3 Centralized vs. Distributed PV systems

Installing PV systems in the power grid to get electricity can be divided into centralized PV Systems and decentralized (distributed) PV Systems.

To make an informed decision about the best electrical distribution system design, a comparison of their benefits and drawbacks should be made, taking into account the size, location, type of sources and loads, reliability, and the quality and cost of delivered power [33].

2.2.3.1 Centralized PV System

2.2.3.1.1 Definition and Operation

It refers to a large-scale electricity generation at centralized installations connected usually apart from the end-users. The large amount of generated power, that may be able to power cities, is transmitted through a series of high-voltage transmission lines, then substations which include switching, protection, capacitors, and transformers step down high-voltage power to a lower voltage to be distributed to the end-users.

2.2.3.1.2 Benefits and Drawbacks

Large-scale power plants are concentrated in particular areas, enabling efficient power generation, and allowing the different generating stations connected to its network to distribute energy to different locations as needed. Centralized systems make repairs and maintenance more controllable because it is easier for a small number of large power plants to be monitored and maintained than separated smaller installations. Also, it aids lower tariffs to the end users.

On the other hand, establishing large-scale plants requires deep planning, construction processes, and high initial costs. Transmitting power over long distances to reach the end users causes line loss as the longer the distance the larger the line loss reducing overall efficiency, and makes the system more vulnerable to disruptions because of natural disasters affecting the infrastructure causing power outages. Finally, power lines need routine maintenance and operation [34].

2.2.3.2 Decentralized PV Systems

2.2.3.2.1 Definition and Operation

It refers to connecting multiple small-scale power sources to the lower voltage distribution lines and close to the end-users, it can operate independently or in coordination with the main grid. It may serve a single structure such as a home or it may be a part of a microgrid (smaller grid tied into the large main grid), such as industrial facilities [35].

2.2.3.2.2 Benefits and Drawbacks

Small-scale sources are useable for emergency power systems. Decentralized systems reduce dependency on a single or few power supplies, if one component fails, others can substitute, and then reducing extensive outages and improving grid resilience. Various energy sources can be integrated, such as a mix of solar and wind sources. End-users can be allowed to generate their electricity and sell the surplus power to the grid or other users. They reduce the line loss caused during transmission and can help with clean reliable power support when connected to the utility.

On the other hand, decentralized systems tend to be limited to the closer loads, and environmentally they take up space and might be ugly seen and cause land-use concerns because they are close to end-users [36].

Chapter Three

Reliability

The conventional power systems evaluation and assessment techniques are not suitable enough to assess the new power systems, because the power systems were developed and changed a lot, and different new designs and components penetrated such as renewable sources in new power systems make it necessary to make modifications in evaluation techniques regularly. [49]

Reliability is considered an important aspect of any electrical grid, because of its effect on the stability of the electrical supply and its impact on the quality and cost of power.

3.1 Definition of Reliability

Power system reliability is defined as the consistent delivery of high-quality electricity to customers without interruption. The power system's dependability affects economic, political, and technological importance within a nation, and then a reliability assessment provides a current evaluation of the power system's performance and helps in guiding future planning efforts.

The three main subsystems of the electrical power system are generation, transmission, and distribution. Where the electrical power is produced through power generation, and this power is provided to the consumers in the distribution phase, this power is transmitted through a transmission line that connects those two phases [51].

The power system's reliability tends to be more complicated through the distribution phase. And so, this study focuses mainly on the reliability analysis of the distribution system. This assessment aims to supply the power to the customer reliably and safely.

3.2 Methods of Reliability Assessment

Reliability assessment methods in power systems are divided into analytical techniques and simulation methods:

3.2.1 Analytical Techniques

Analytical Techniques depend on using mathematical models and then numerical methods to calculate the reliability indices.

It can be used with any standard application, with the same system and input data, and then result in the same numerical results. The solution time is relatively short for giving expectation indices for analytical techniques. However high solution time is needed for applications that require several reliability assessments which is considered as a drawback [48].

3.2.2 Simulation Methods

Simulation methods are designed to study large-scale and complex systems, they provide numerical solutions to overcome the challenges of analytical solutions, a very common simulation method in distribution network component reliability assessment is the Monte Carlo Function [53]. Simulation methods treat the problem with a series of successive real experiments and can integrate sudden events like outages, component failures, and load variations, so they treat contingencies in the planning, design, and operation of the system to get a more accurate, flexible, and reliable system. However, it can be intensive and needs additional processing time, especially for large systems, which is a drawback.

3.3 Concepts' Definitions Related to Reliability According to the IEEE guide

Here are some definitions related to the interruption according to the IEEE guide [25]:

- distribution system: That portion of an electric system that delivers electric energy from transformation points on the transmission system to the customer.
- outage: The loss of ability of a component to deliver power, which may or may not cause an interruption of service to customers, depending on system configuration.
- Interruption: The loss of electric power completely on one or more normally energized conductors influencing one or more customers connected to the distribution part of the system. Power quality issues such as sags, swells, impulses, or harmonics are not included.
- Interrupting device: A device designed to block the power flow, typically in response to a fault. It can be operated manually, automatically, or remotely. Such as circuit breakers, line reclosers, line fuses, disconnect switches, and others.
- interruption duration: The period from the beginning of an interruption until service has been restored to the affected customers.
- customer: A metered electrical service point for which an active bill account is established at a specific location.

- Total number of customers served: The average number of customers served during the reporting period.

3.4 Types of Interruptions

- Planned interruption: The loss of electric power to one or more customers due to a planned or scheduled outage.
- unplanned interruption: The loss of electric power to one or more customers that does not result from a scheduled outage.
- momentary interruption: The short-time loss of power delivery to one or more customers due to the opening and closing operation of an interrupting device.
- sustained interruption: Any interruption exceeds the momentary interruption to last more than five minutes [25].

3.5 Important Items in Distribution Power System Reliability Assessment

3.5.1 Availability

Availability of the system is a measure of system performance that is related closely to the reliability aspect, which involves equipment delivery of required power within a specific time, and then it can be as the probability of the system to be energized, whereas unavailability is the probability of the system not to be energized, it is typically measured in percent or per unit. [50].

It can be calculated as [52]:

$$Availability\ (A) = \frac{MTBF}{MTBF + MTTR} \tag{3.1}$$

Where:

MTBF (Up Time): Mean Time Between Fails.

MTTR (Down Time): Mean Time to Repair.

As noticed, meaningful optimization of the Uptime and the Downtime, raising the Uptime improves the system's availability, these two values are taken from recorded data or fail and repair history [52].

3.5.2 System Adequacy

Adequacy can be defined as the existence of adequate establishments needed to generate, transmit, and distribute the required energy to the load points [46]. Also, it is defined as the availability of amenities to satisfy a customer’s demand. It is also can be analyzed in the study of the power system [49]. It takes into account increased demand, component failures, etc.

3.5.3 System Security

Security can be defined as the ability of the system to react to emerging disturbances within it, and security evaluation is available nowadays in most probabilistic techniques. Hence, a secure system detects faults such as short circuits and load variations and sets necessary adaptions to isolate faults and avoid interruptions, then delivers electric power to customers conveniently [49].

3.5.4 Failure Rate (λ)

A component or a system failure occurs when it is chosen randomly when it depends on another failed component, or at the end of the component’s lifespan. Then it is unavailable and so doesn’t do its required function [50].

An important factor in reliability assessment is the failure rate (λ), which is the rate of failures occurring during a specific time interval (t1, t2), where t1 refers to the time when the fault begins, and t2 refers to the time of the failure end [51].

A failure rate refers to the frequency of the failures that occur. It can be calculated as in [50]:

$$Failure\ rate\ (\lambda) = \frac{Number\ of\ failures\ occured}{Total\ number\ of\ unit\ operation\ hours} \tag{3.2}$$

or

$$\lambda_{tot} = \sum_{i \in N} num_i \times \lambda_i \tag{3.3}$$

Where:

λ_i : the failure rate of the i-th element

N: number of elements in the power system

num_i : number of i-th elements in the power system

The component failure rate function goes with the shape of the bathtub curve as shown in Figure (B 10), as it is a function of time. It is divided into three periods, the first is called the early life period or debugging period, in which the failure rate is decreasing. Generally, design and manufacturing errors are the causes of failure during this period. The second period is called the useful life or normal period, it is characterized by the constant and lower value of failure rate, and the failures are random and unpredictable. The third period is called the wear-out period, in which the failure rate increases because of equipment aging. If the component-rated life is considered and t2 could be predicted, this period can be avoided by replacing this component [51]. A constant failure rate of period two is the value used in reliability studies [18].

3.5.5 Mean Time to Repair (MTTR)

It is the average time needed to repair the failure of the component and revive it to work, it is called downtime during the cycle time, and it includes detecting failure time and repairing time. It can be defined as the inverse of the average repair rate (μ):

$$MTTR = \bar{r} = \frac{1}{\mu} \tag{3.4}$$

Where:

$\bar{r}$: Mean Time to Repair

μ: mean repair rate.

Also, if the data of cycles are given, then it can be estimated as:

$$MTTR = \bar{r} = \frac{\sum_{i=1}^{n} r_i}{n} \tag{3.5}$$

Where:

$\bar{r}$: Mean Time to Repair.

r_i: the time needed to repair for i-th cycle.

n: total number of cycles.

3.5.6 Mean Time to Fail (MTTF)

It is the average time to the first failure occurring for replaceable and not renewed components, it is called the downtime during the cycle time. It can be defined as the inverse of the constant failure rate (λ):

$$MTTF = \bar{m} = \frac{1}{\lambda} \tag{3.6}$$

Where λ: the constant failure rate.

Also, if the data of cycles are given, then it can be estimated as:

$$MTTF = \bar{m} = \frac{\sum_{i=1}^{n} m_i}{n} \tag{3.7}$$

Where:

$\bar{m}$: Mean Time to Fail.

mi: predicted time to failure for the i-th cycle.

n: total number of cycles [51].

Including higher quality components or adopting a reliable monitoring system and regular preventive maintenance aids in detecting expected faults earlier to reduce failure probabilities and then improve the MTTF [52].

3.5.7 Mean Time Between Failures (MTBF)

It is the same definition of MTTF except that the MTBF is used with the renewed components.

And it can be calculated as the summation of MTTR and MTTF

$$MTBF = MTTR + MTTF \tag{3.8}$$

But these days, it is familiar to use MTBF in some applications like reliability assessment of nuclear power plants, for both renewed and non-renewed components, as it is used in the availability formula [47]:

$$Availability\ (A) = \frac{MTBF}{MTBF + MTTR} \tag{3.9}$$

3.6 Types of Reliability Indices

1. Momentary Indices as MAIFI.
2. Sustained load Indices such as SAIDI, SAIFI, and CAIDI which are discussed in this thesis.
3. Load- And Energy- Indices such as ENS which is investigated here and AENS.

These indices, together, give a whole representation of how reliable a power network is and help in comparing reliability levels between several electric utility companies. These indices are taken from the ETAP report, where every index is calculated through the program independent of each other as illustrated in Figure (B 25-B 26). They include the frequency of interruptions, their durations, the number of interrupted customers, the response time, and economic impact which enables the operators and planners in the sector to make informed decisions for improving the distribution, transmission, and substation systems reliability. Monitoring these trends helps in better maintenance practices, resource allocation, and overall grid management.

3.7 Reliability Indices

3.7.1 System Average Interruption Frequency Index (SAIFI)

It is a vital load index of reliability that describes how often the average customer experiences a sustained interruption over a predefined period [25].

It is calculated by [26][27]:

It is commonly measured by (f / customer. yr).

$$SAIFI = \frac{Total\ number\ of\ customer\ interruptions}{Total\ number\ of\ customer\ served} = \frac{\sum_{i=1}^{NT} N_i}{N_T} \qquad (3.10)$$

Where:

N_i: Customer number interrupted by the i-th interruption.

N_T: Total system customer number.

The above five-minute lasting interruption can be assessed by SAIFI, the system's operators and planners can identify the parts and areas requiring improvement and then improve the reliability of the grid depending on informed decisions adopted through monitoring this index and analyzing its directions.

3.7.2 System Average Interruption Duration Index (SAIDI)

It is a vital index of reliability that describes the total duration of interruptions that the average customer undergoes throughout a predefined period of time.

It is commonly measured in minutes or hours of interruptions (hr./customer. yr).

It is calculated by: [26][27]

$$SAIDI = \frac{\sum customer\ interruptions\ durations}{Total\ number\ of\ customer\ served} = \frac{\sum_{i=1}^{NT} r_i N_i}{N_T} \quad (3.11)$$

Where:

ri: restoration time related to the i-th interruption for customers interrupted during the specified time.

N_i: Customer number interrupted by the i-th interruption.

N_T: Total system customer number.

It can be calculated based on the SAIFI value as:

$$SAIDI = SAIFI \times D \quad (3.12)$$

Where:

D is the average interruption duration time, calculated by:

$$D = \frac{\sum_{i=1}^{N_T} (\lambda_i \times r_i)}{\lambda_{tot}} \quad (3.13)$$

Where:

λ_i : the value of the failure rate at component i.

The above five-minute interruption can be assessed by SAIDI, and the system's operators and planners can improve the reliability of the grid depending on informed decisions adopted through monitoring this index and analyzing its directions.

3.7.3 Customer Average Interruption Duration Index (CAIDI)

This index represents the average time needed to restart the system interruption and restore electricity to the average customer per sustained interruption.[25]

It is calculated as the total minutes of customer interruption divided by the total number of interruptions. The fewer the minutes, the faster the utility restored customer service.

It is commonly measured in (hr. / customer interruption)

It is calculated by (based on parameters given):

$$CAIDI = \frac{total\ customer\ interruption\ durations\ in\ hours}{total\ number\ of\ customers\ interruptions} \tag{3.14}$$

$$CAIDI = \frac{\sum(ri\ \times Ni)}{\sum Ni} \tag{3.15}$$

Where:

r_i = duration of interruption.

Ni= No. of customer interruptions.

Also, it can be calculated depending on SAIDI and SAIFI:

$$CAIDI = \frac{SAIDI}{SAIFI} \tag{3.16}$$

3.7.4 Expected Energy Not Supplied Index (EENS)

An important load-energy-oriented index which represents the average energy that the system is expected not to supply per year because of interruption, its value indicates the system's reliability, lower EENS leads to a more reliable system, it specifies energy losses and then it is used in controlling electricity supply.

It is commonly measured in kilo/Megawatt hours per year [kWh/yr].

It is calculated by:

$$EENS = \sum_{j=1}^{N_T} L_i \times r_{ij} \times \lambda_{ij} \tag{3.17}$$

Where:

N_T : total number of the system elements

L_i : average load at point i

r_{ij} : failure duration at point i due to failure component j

λ_{ij} : is the failure rate at load point i due to failure component j

It can be calculated depending on another reliability index:

$$EENS = L_{avg} \times N_T \times SAIDI \tag{3.18}$$

Where:

L_{avg}: average load

N_T: Total number of customers

3.8 Reliability Assessment for PV System

This assessment concerns evaluating the grid capacity to ensure continuous sustained electricity production with the least interruptions through their lifetimes.

3.8.1 Reliability Assessment Includes These Aspects

3.8.1.1 Fault Analysis

Identifying expected failures that the power system components may have, such as the solar panels, inverters, lines, and the overall system balance. Then analyzing these conditions to be ready and face them with emergency strategies.

3.8.1.2 Performance Degradation

PV declination is expected over time, especially in PV modules, because of some weather conditions like temperature and humidity. Reliability assessment includes estimating the degradation in the performance and the output power through the lifetime, which leads to system development, maintenance arrangement, and expected energy production.

3.8.1.3 Environmental Factors

Reliability assessment includes studying the environment, and weather conditions that affect the reliability of the system such as temperature, humidity, dust, wind, etc. This helps in designing a reliable system against continuously varying conditions.

3.8.1.4 Aging and Durability

The system must be reliable for this period because its lifetime is expected to last 25 years. Also, the reliability assessments incorporate aging mechanisms and durability of system components and materials as a basis for the estimation of its lifespan; and consequently, plan for necessary improvement and replacement.

3.8.1.5 Maintenance and Monitoring

To ensure a dependable system, it needs compatible maintenance and monitoring; this assessment comprises monitoring system performance, planning maintenance schedules, as well as checking deviations from normal operation. It helps in detecting possible variations as well as treating them so that there would never occur a failure in the system.

3.8.2 Reliability Evaluation of Critical Components in PV System

3.8.2.1 Inverter Reliability Evaluation

An inverter is a major component of PV systems, composed of semiconductor modules. [45]

The overall grid reliability is affected by how the inverter is connected to the grid; in the centralized case where a main inverter is connected in series to support the grid, if an inverter failure occurs, the grid's reliability decreases directly. But in the distributed case as many small string inverters are connected to the loads, if any inverter fails the others continue working and supporting the loads, and then the reliability of the utility is not affected.

The reliability of the inverter depends on the functioning way of its components including switching devices. Inverters usually treat with a large amount of power while working in high temperatures, which reduces their reliability over time and increases the exposure to failures depending on the aging components.

3.8.2.2 PV Modules Reliability Evaluation

PV modules (or PV panels) consist of the most reliable interconnected components, PV cells, typically 7-14% of the solar insulation converted into electrical energy through a PV standard module [32], [33], [34], [35]. The efficiency of this conversion depends on crucial factors such as solar radiation, operating temperature, and electrical loads [36], [37]. As components, they experience performance degradation over time [38], [39]. Research directed to study PV modules' reliability, as in [34], this paper outlined the failure and degradation modes of PV modules and proposed an approach to evaluate them and their effects on the PV module parameters. On the other hand, reference [40] proposed a methodology to study degradation effects through the Maximum Power Point (MPP) and the loss of power hours due to accumulative dust. This study requires further techniques, reference [41] presents a mathematical model to predict PV module reliability, which includes that the reliability parameters degrade linearly and the Gaussian distribution is followed by the output power of the PV modules. PV module configuration is a main factor that impacts their reliability, so since the 1980s and before research on these configurations conducted [42], [43].

To investigate large-scale PV module array dependability, recent research applied reliability principles. For example, the minimum cut-set method is applied to investigate the reliability of various connections as series, parallel, and series-parallel [44].

3.9 Numerical Example

For the system shown, depending on the given information in Table (1) below, calculate the total failure rate (λ tot), and the average interruption duration (D) then compare them to the values resulting in ETAP simulation.

Table 1

Values of failure rate and MTTR of the system's components

Component	λ (failure per year)	MTTR (hr.)
Connection Point	0.5	2
Feeder	2	2
PV (inverter)	1	1
Load	0.5	1

Solution:

1-Total Failure Rate (λ_{tot}) $= \sum_{i\in N} num_i \times \lambda_i$

= (no. of connection points × failure rate (cp)) + (no. of feeders × failure rate (feeder)) + (no. of PV × failure rate (PV)) + (no. of loads × failure rate(load))

$= (1\times0.5) + (1\times2) + (1\times1) + (1\times0.5) = 4$ f /yr

2- Average Outage duration (D) $= \frac{\sum_{i=1}^{N_T}(\lambda_i \times r_i)}{\lambda_{tot}}$

$= \frac{(0.5\times2)+(2\times2)+(1\times1)+(0.5\times1)}{4} = \frac{6.5}{4} = 1.625$ hr./ yr

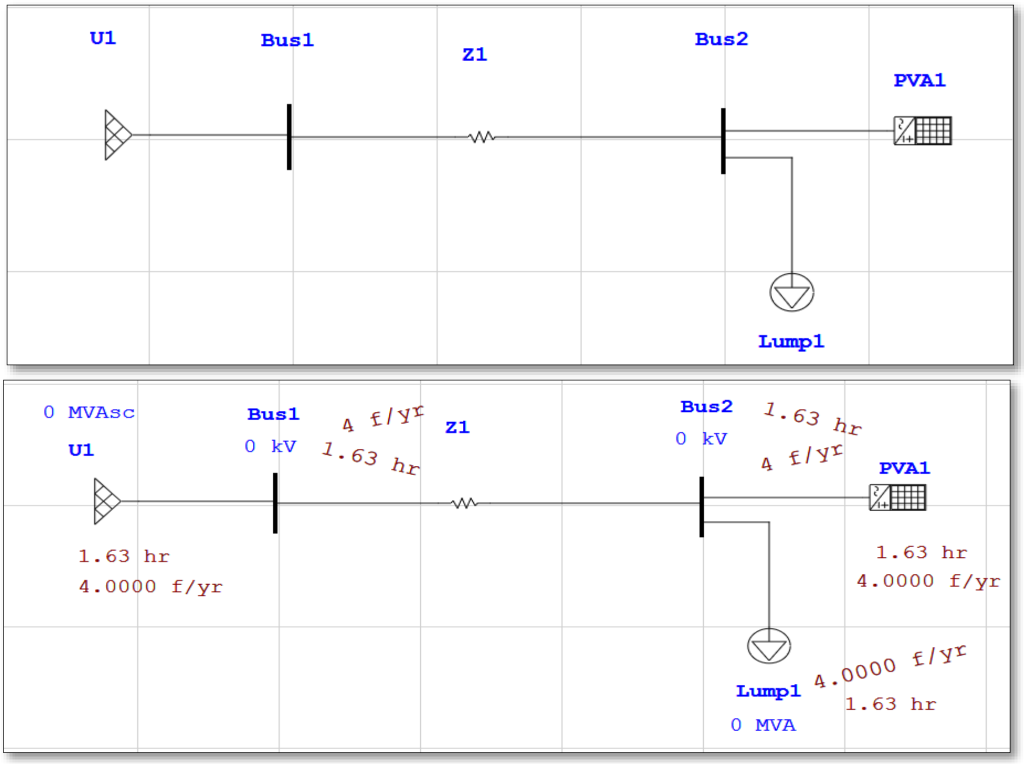
Results shown below by the simulation, which are the same as our calculations;

D= 1.625 hr./ yr (by calculation), D= 1.63 hr./ yr (by simulation)

λ_{tot} = 4f/ yr (by both calculation and simulation)

Figure 2

The Power System Before and After the ETAP Simulation



Chapter Four

Case Study

In this thesis, ETAP (Electrical Transient Analyzer Program) is adopted with the IEEE 33-bus network to illustrate the objectives of the study.

4.1 ETAP

ETAP is an extensive software forum used for electrical power systems for design, analysis, monitoring, and operation.

It is dependable for engineers and operators in industries such as utilities; it is used in the planning of the grid, making reliability assessments, and operational optimization, also it is used in transportation, and manufacturing because its simulation and analysis are advanced and powerful.

4.1.1 ETAP Offers A lot of Important Tasks in Many Fields as

1. Power System Design and Analysis: it supports Load Flow analysis to help in determining voltage drop and power flow through the power system, also it supports the analysis of Transient Stability, Arc Flash, and Harmonic Analysis.
2. Real-Time Monitoring and Automation: it can integrate with SCADA systems for real-time data acquisition, it has energy consumption optimizing tools and reliability improvement, and it predicts failures before they occur through monitoring.
3. Optimizing And Planning: it helps in optimizing generation dispatch to operate less costly, it determines the best program to turn on and off generation units and assesses the impacts of integrating generation sources to the grid.
4. It provides coordination of protective device settings and makes fault insulation at a suitable time and location.

4.2 Some Component Parameters Assignment

4.2.1 Failure Rate and MTTR Assignment

For all cases and reconfigurations of our study, the values of the failure rate and MTTR for the network components are assigned as in Table (2):

Table 2

Values of Failure Rate and MTTR of the System Components

	Failure rate (λ) (Failure/year)	MTTR (Hour)
Load	2	2
Connection Point	0.5	2
Inverter	Active Failure Rate $\lambda_A = 1$ Passive Failure Rate $\lambda_P = 0$	1
Feeder (Impedance)	0.5	1
Bus	0.0001	2
Sensitivity Constant K	20	20

4.2.2 The Relationship Between the New Values of The Loads' Failure Rate and The Bus Voltage Values.

Depending on the resulting bus voltage values, failure rates of the loads connected to the buses vary with the absolute deviation value from the nominal voltage. Then the new failure rate is calculated according to the equation as a function of voltage deviation:

$$\lambda(V) = \lambda_{nom} \times (1 + K \times |\Delta V(t)|) \quad (4.1)$$

Where:

Vnom: Nominal Voltage.

V(t): instantaneous voltage of a specific bus at time t.

λ_{nom} : Nominal load failure rate at nominal voltage

$\lambda(V)$: the failure rate of the load at voltage V(t).

$|\Delta V(\boldsymbol{t})|$: the absolute value of the voltage deviation from the nominal voltage at each bus which can be calculated by taking the absolute value of:

$$\Delta V(t) = \frac{V(t) - V_{nom}}{V_{nom}} \tag{4.2}$$

K: sensitivity factor which illustrates how much the value of failure rate changes with per unit deviation from the nominal voltage.

4.3 Case Study Description

The modified IEEE 33-bus network is used in two main cases and four reconfigurations related to them. Case 1 is the base case of the network without PV which suffers high voltage drop at the far busses that affect the total reliability indices, a reconfiguration using two single-throw switches is done to make the total results better. Case 2, as a base case with 70% PV penetration, which leads to a very high voltage rise in the network and then high failure rates and reliability indices, three reconfigurations are done to investigate the effect on the bus voltages, total losses, and total reliability indices. Both voltage rise and voltage drop cause failure rate rise based on equation (4.1), for all cases new failure rate values are calculated depending on the equation and set in the simulation parameters.

Reliability failure rates were assumed to align with those of a distributed network, where transformer failure rates are considered lower than feeder failure rates, these values are assumed to be representative of a distributed system.

Modifying the feeders' resistances and reactance (R and X) values of the network: original values of the feeders' resistances and reactance are modified and assumed as in the following Table (3) in addition to the values of the loads at the receiving end bus:

Table 3

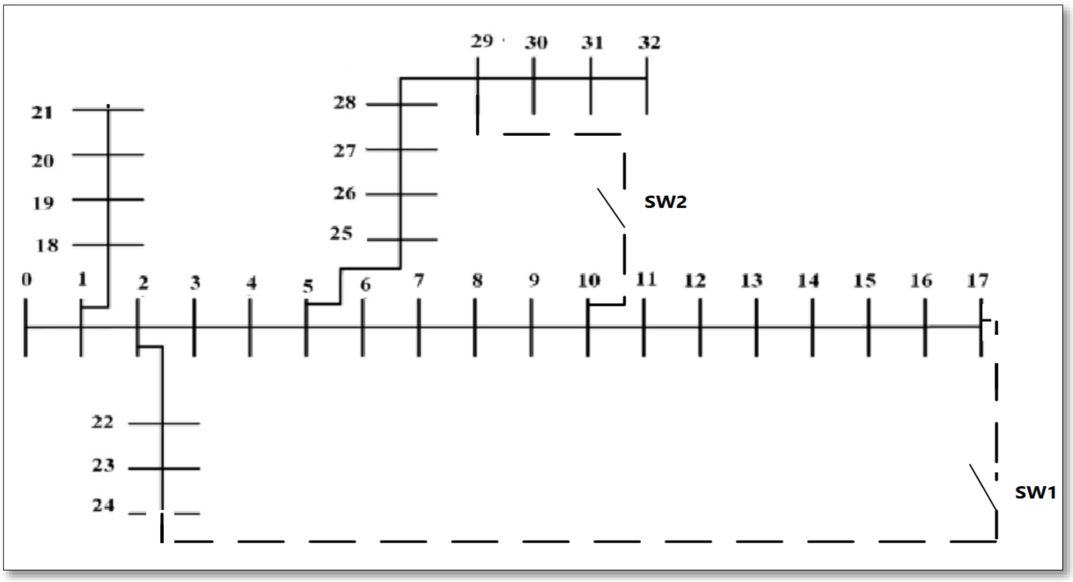
Modified Resistance, Reactance and connected loads in the network

line number	sending bus	Receiving bus	Resistance R (Ω)	Reactance X (Ω)	Load at Receiving End Bus	
					Real Power (kW)	Reactive Power (kVAr)
1	1 main SS	2	0.0922	0.0477	100	
2	2	3	0.493	0.2511	90	40
3	3	4	0.366	0.1864	120	90
4	4	5	0.3811	0.1941	60	30
5	5	6	0.819	0.707	60	20
6	6	7	0.1872	0.6188	200	100
7	7	8	1.7114	1.2351	200	100
8	8	9	1.03	0.74	60	20
9	9	10	1.04	0.74	60	20
10	10	11	0.1966	0.055	45	30
11	11	12	0.3744	0.1238	60	35
12	12	13	1.468	1.155	60	35
13	13	14	0.5416	0.7129	120	80
14	14	15	0.591	0.526	60	10
15	15	16	0.7463	0.545	60	20
16	16	17	1.289	1.721	60	20
17	17	18	0.732	0.574	90	40
18	18	19	0.164	0.1565	90	40
19	19	20	1.5042	1.3554	90	40
20	20	21	0.4095	0.4784	90	40
21	21	22	0.7089	0.9373	90	40
22	22	23	0.4512	0.3083	90	50
23	23	24	0.898	0.7091	420	200
24	24	25	0.896	0.7011	420	200
25	25	26	0.203	0.1034	60	25
26	26	27	0.2842	0.1447	60	25
27	27	28	1.059	0.9337	60	20
28	28	29	0.8042	0.7006	120	70
29	29	30	0.5075	0.2584	120	70
30	30	31	0.9744	0.963	150	70
31	31	32	0.3105	0.3619	150	70
32	32	33	0.341	0.5302	210	100

Figure (3) shows the modified IEEE 33-Bus Configuration.

Figure 3

Modified IEEE 33-Bus Configuration



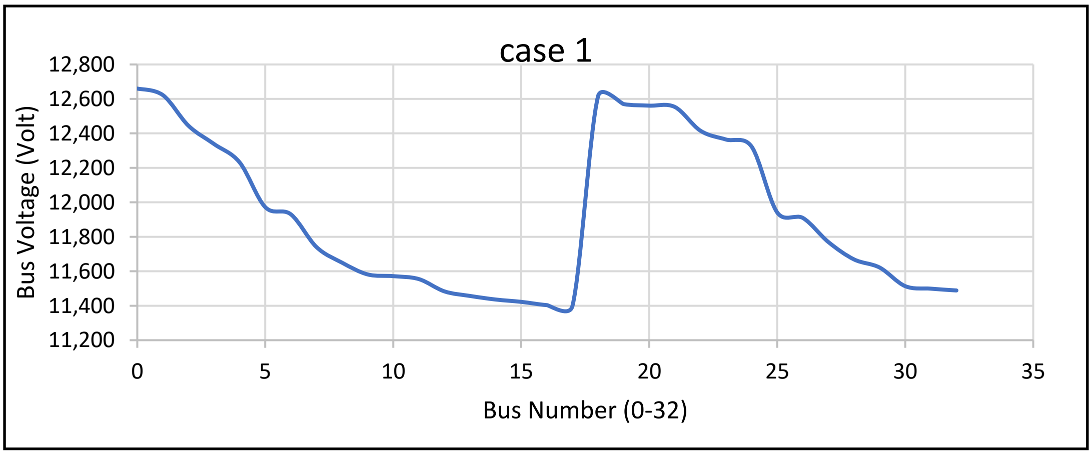
4.4 Simulation Results

In case 1, the base case of the network without PV, PV penetration is zero, load flow analysis is carried out by using ETAP software and shows that far loads from the connection point experience high voltage drops below the nominal voltage which leads to high values of the failure rates. Figure (4) shows the 33-bus voltages in this case.

The resulting total losses are 388.2 kW.

Figure 4

The Modified IEEE 33-bus Voltages of Case 1



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As a result of using data in Table 2 and applying equation (4.1), new failure rates are set parallel to the values in Table (2), the average interruption rate 83.8470 failure/year, and the average Interruption duration is 1.81 hours.

Reliability analysis shows the indices as in the Table (4):

Table 4

Reliability Indices of Case 1

Average Interruption Rate (f/yr)	Average Interruption Duration (Hour)	SAIDI (hr./customer. yr)	SAIFI (f./customer. yr)	CAIDI (hr./customer interruption)	EENS (MW.hr. /yr)
83.8470	1.81	151.6940	83.8470	1.809	730.407

In case 2, which is the base case in PV presence, 2 PVs are added to the network with a penetration level of 70% of the installed loads; PV1 is connected to bus 17 with 2090 kW and PV2 is connected to bus 32 with 1045 kW, load flow analysis shows that the most bus voltages are around the nominal voltage while buses (11-17) show a voltage rise above the nominal voltage. Figure (B 11) shows the modified 33-bus voltages in this case.

The resulting total losses are 365.2 kW.

This absolute voltage deviation from the nominal voltage increases the failure rate according to equation (4.1) and using data in Table 2, the new failure rates are set to make a reliability analysis which shows the indices as in Table (5), the average interruption rate 54.81 failure/year, and average interruption duration 1.67 hours.

Table 5

Reliability Indices of Case 2

Average Interruption Rate (f/yr)	Average Interruption Duration (Hour)	SAIDI (hr./customer. yr)	SAIFI (f./customer. yr)	CAIDI (hr./customer interruption)	EENS (MW.hr. /yr)
54.81	1.67	91.6206	54.8103	1.672	441.153

Reconfiguration 1 is done on case 1 without PV to improve the state of the network, two single-throw switches are added to the network, SW1 connects buses 17 and 24, and SW2 connects buses 10 and 29, load flow analysis shows an improvement in bus voltages and total losses. Figure (B 12) shows the 33-bus voltages in this case.

The resulting total losses are 300.6 kW.

The new failure rates resulting from the changing bus voltages are obtained using equation (4.1). The reliability analysis provides the reliability indices, as shown in Table (6), the average interruption rate decreases from 83.8 failures per year in Case 1 to 72.03 failures per year, representing an improvement.

Table 6

Reliability Indices of Reconfiguration 1

Average Interruption Rate (f/yr)	Average Interruption Duration (Hour)	SAIDI (hr./customer. yr)	SAIFI (f./customer. yr)	CAIDI (hr./customer interruption)	EENS (MW.hr. /yr)
72.0283	1.78	128.3445	72.0283	1.782	617.979

Reconfiguration 2 is done on case 2 by adding a single-throw switch SW1, to connect buses 17 and 24 to improve the network, load flow analysis shows a small reduction in losses and a clear improvement at bus voltages that become closest to the nominal value. Figure (B 13) shows the 33-bus voltages in this case.

The resulting total losses are 158.4 kW

The voltage deviations increase failure rates to have new failure rates based on equation (4.1) and are assigned to make a reliability analysis, which shows the indices as follows in Table (7), the average interruption rate increases from 54.81 failures per year in Case 2 to 56.75 failures per year, representing an increment of the values of the reliability indices (less reliable system).

Table 7

Reliability Indices of Reconfiguration 2

Average Interruption Rate (f/yr)	Average Interruption Duration (Hour)	SAIDI (hr./customer. yr)	SAIFI (f./customer. yr)	CAIDI (hr./customer interruption)	EENS (MW.hr. /yr)
56.75	1.69	95.6504	56.7532	1.685	460.557

Reconfiguration 3 is done on case 2 network, by adding a single-throw switch SW2, to connect buses 10 and 29 to improve the network, load flow analysis shows a small reduction in losses, and bus voltages become less but still suffering voltage rise. Figure (B 14) shows the 33-bus voltages in this case.

The resulting total losses are 348.3 kW

According to the bus voltage changes from the nominal value, new load failure rates are found through equation (4.1), and reliability analysis is done to show that the reliability indices are as in Table (8), the average interruption rate decreases from 54.81 failure/year at case 2 to 53.3398 failure/year, representing a small improvement.

Table 8

Reliability Indices of Reconfiguration 3

Average Interruption Rate (f/yr)	Average Interruption Duration (Hour)	SAIDI (hr./customer. yr)	SAIFI (f./customer. yr)	CAIDI (hr./customer interruption)	EENS (MW.hr. /yr)
53.3398	1.67	88.8236	53.3398	1.665	427.686

Reconfiguration 4 is done on the case 2 network, by adding two single-throw switches, SW1 to connect buses 17 and 24, and SW2 connects buses 10 and 29 to improve the network, load flow analysis shows a big reduction in losses. Bus voltages also become a little improved. Figure (B 15) shows the 33-bus voltages in this case.

The resulting total losses are 147.2 kW.

New failure rates resulting from the changing bus voltages are obtained depending on equation (4.1), and the reliability analysis shows the reliability indices as shown in Table (9), the average interruption rate increases clearly from 54.81 failure/ year at case 2 to 85.85 failure/year representing a high increment of the indices values.

Table 9

Reliability Indices of Reconfiguration 4

Average Interruption Rate (f/yr)	Average Interruption Duration (Hour)	SAIDI (hr./customer. yr)	SAIFI (f./customer. yr)	CAIDI (hr./customer interruption)	EENS (MW.hr. /yr)
85.85	1.79	153.9940	85.8530	1.794	741.481

4.5 Comparing Reliability Indices

4.5.1 Reliability Indices of Case 1 and Reconfiguration 1 Comparison

In the absence of PV production, the voltage drops increase in the network, especially on buses far from the connection point. This, in turn, leads to a higher failure rate, as the voltage may drop to levels that cause load shutdowns. On the other hand, reconfiguration can help distribute power flow more effectively and improve the voltage profile. Therefore, it enhances the reliability indices. As shown in Figure 5, the average interruption duration decreases from 1.81 to 1.78 hours. Meanwhile, similar improvements are observed for all other reliability indices, as shown in Figures 4 to 10. For instance, the average interruption duration decreased from 1.81 to 1.78 hours, as illustrated in Figure 4. Respectively, the average interruption rate decreased from 83.847 to 72.0238 failures per year, as shown in Figure 10. Accordingly, the frequency of failures (SAIFI) decreased from 83.847 to 72.0238 failures per customer per year in Figure 7. SAIDI decreased from 151.694 to 128.3445 hours per customer per year, as shown in Figure 6. CAIDI decreased from 1.809 to 1.782 hours per customer interruption, as illustrated in Figure 9. Additionally, Figure 8 shows the EENS reduction from 730.407 MWh/year in Case 1 to 617.979 MWh/year after reconfiguration. All reliability index improvements shown in the mentioned figures highlight the importance of reconfiguration to enhance the overall reliability of the network.

Figure 5

Average Interruption Duration of Case 1 and Reconfiguration 1

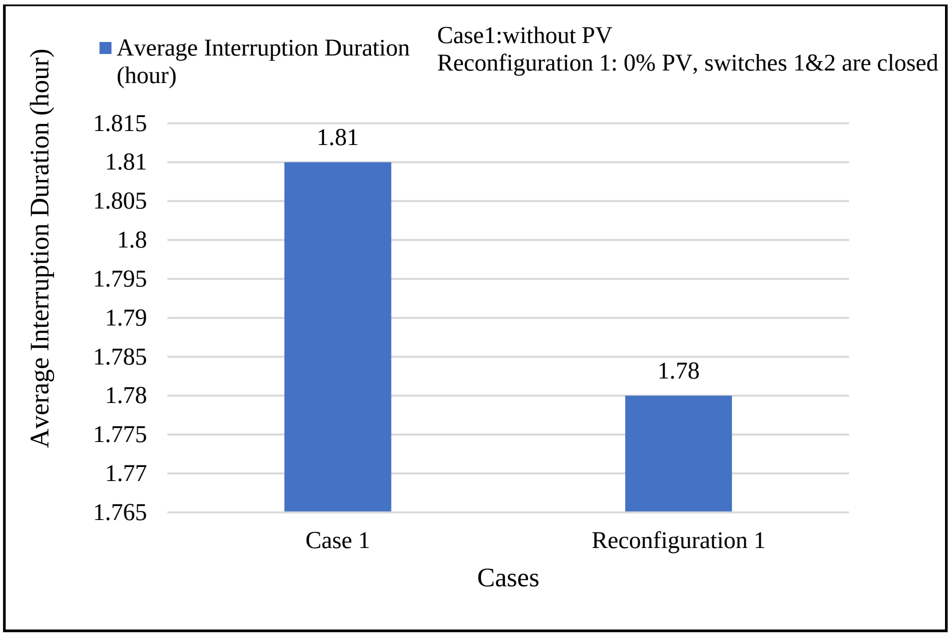


Figure 6

SAIDI of Case 1 and Reconfiguration 1

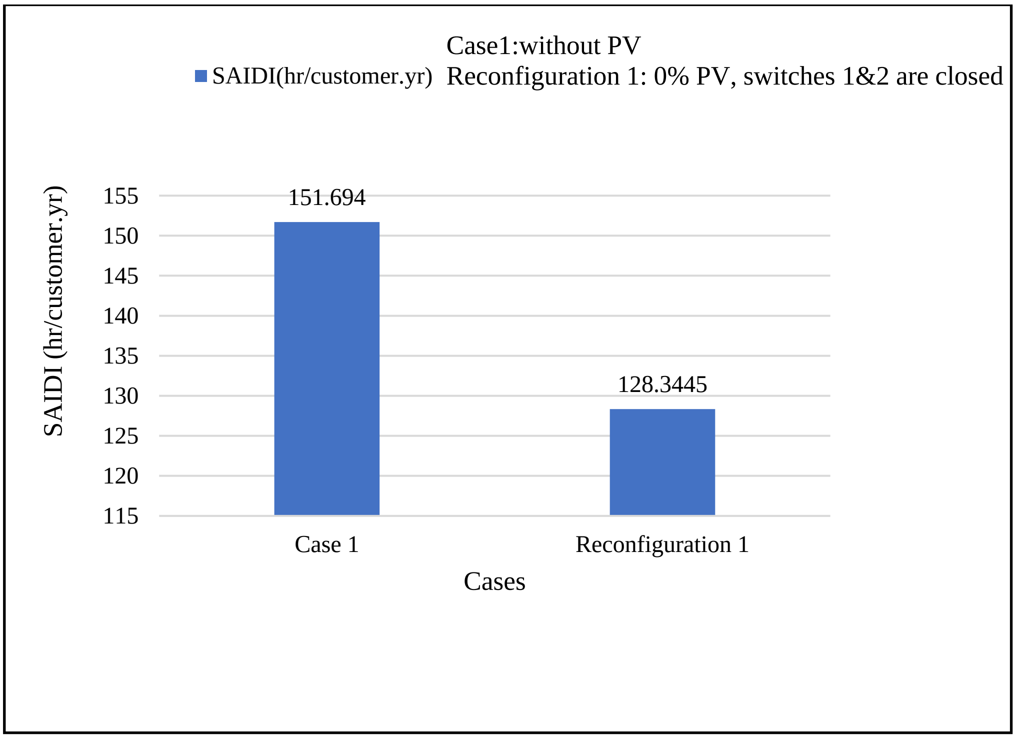


Figure 7

SAIFI of Case 1 and Reconfiguration 1

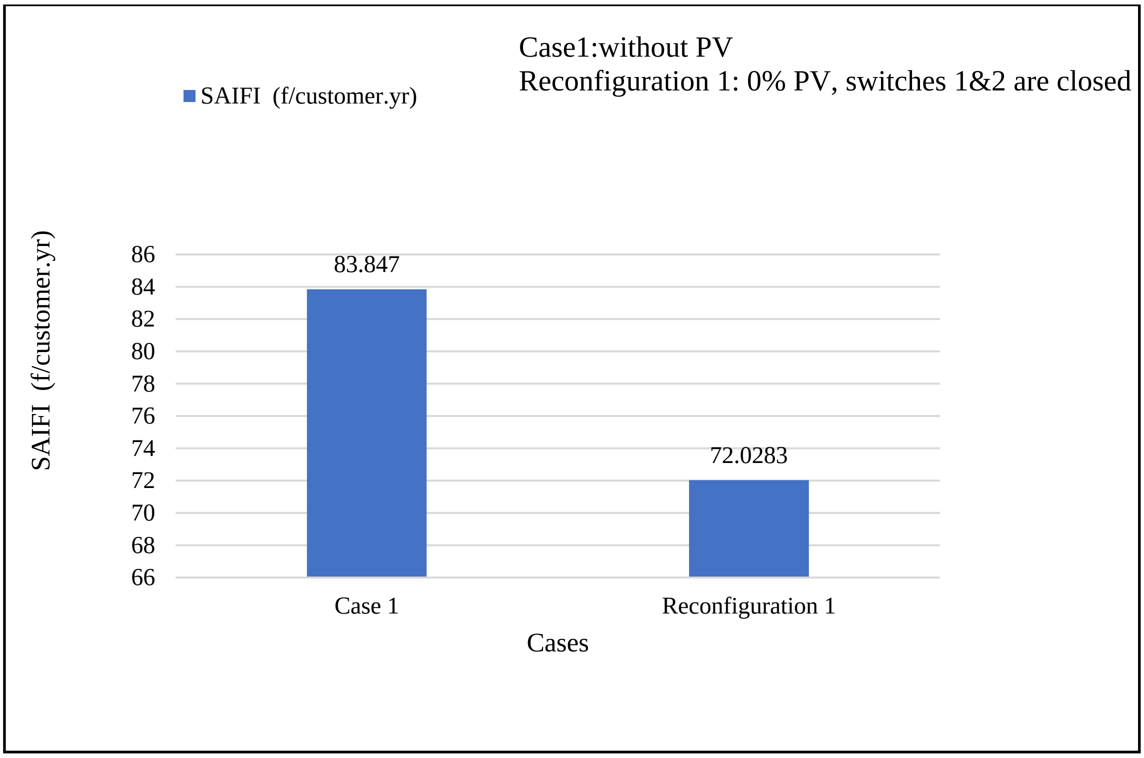


Figure 8

EENS of Case 1 and Reconfiguration 1

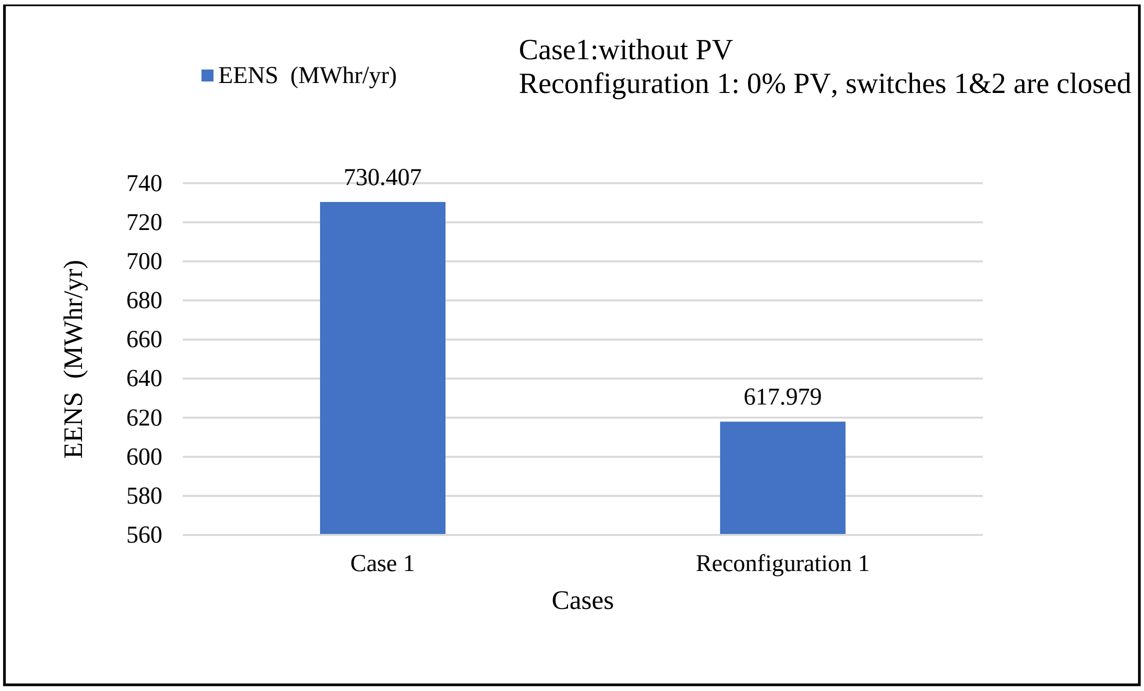


Figure 9

CAIDI of Case 1 and Reconfiguration 1

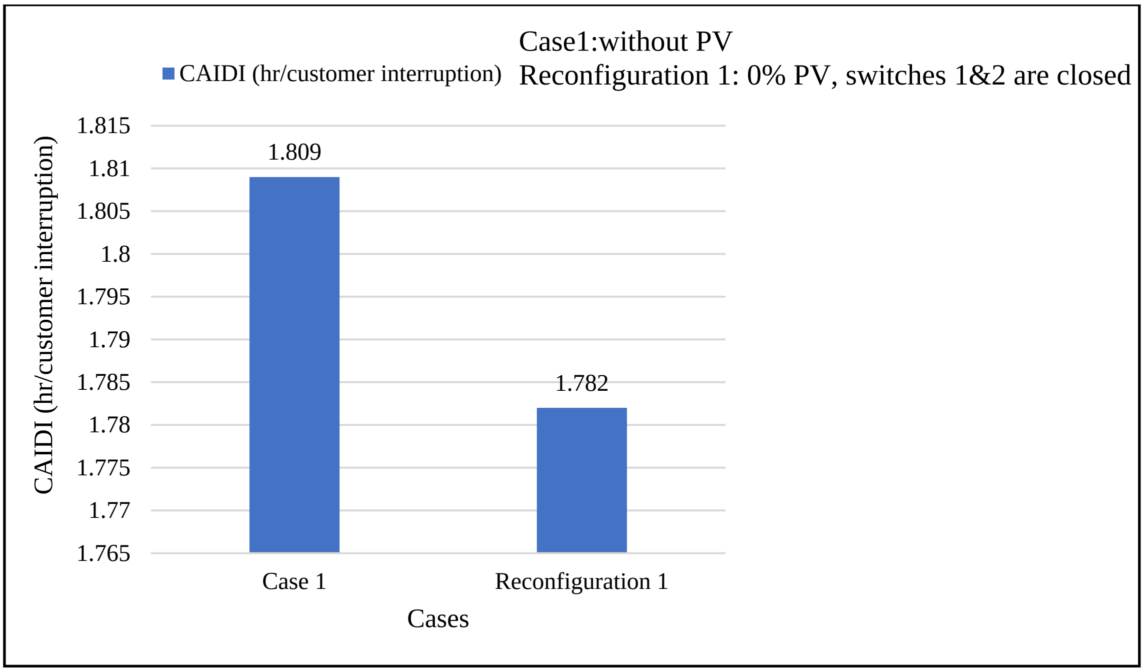
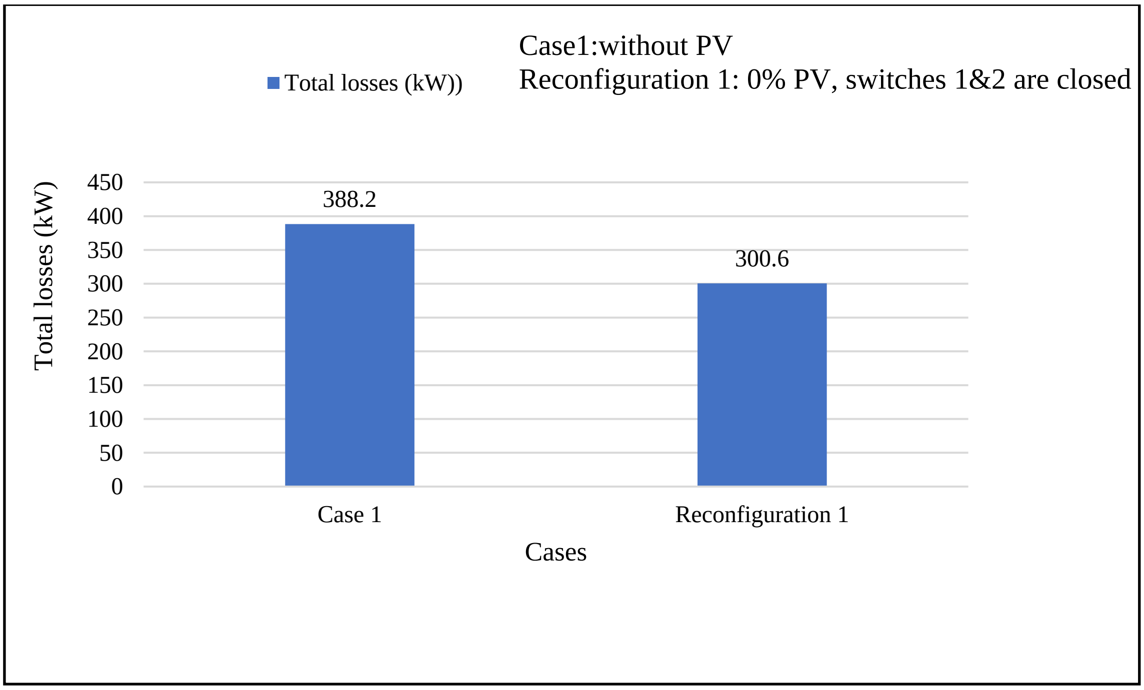


Figure 10

Total Losses of Case 1 and Reconfiguration 1



4.5.2 Reliability Indices of Case 2 and Reconfigurations 2, 3, and 4 Comparison

In this case of high PV penetration, during periods when the PV system generates maximum power — representing the moments when PV generation is at its peak — the voltage rise results in a decreased reliability factor on the load side. Reconfiguring of the network can help improve reliability indices, as shown in Figures B 16 to B 22.

In these figures, Case 2, which serves as the base case with high PV penetration, is compared with three reconfigurations: Reconfiguration 2, Reconfiguration 3, and Reconfiguration 4. All reliability indices show a noticeable reduction in Reconfiguration 3 (70% PV with only SW 2 closed). For example, the Average Interruption Rate in Case 2 is 54.81 failures per year, which decreases to 53.3398 failures per year in Reconfiguration 3, as shown in Figure B22. The Average Interruption Duration remains the same at 1.67 hours in Figure B 16, whereas it increases significantly in the other two reconfigurations. SAIDI decreases from 91.6206 to 88.8236 hours per customer per year in Figure B 17, while in Figure B 18, SAIFI decreases from 54.8103 to 53.3398 failures per customer per year. EENS drops from 441.153 to 427.686 MWh per year, as shown in Figure B 21, and CAIDI is reduced from 1.672 to 1.665 hours per customer interruption, as shown in Figure B 19.

Reconfiguration 2 (70% PV with only SW 1 closed) results in the least kW losses, decreasing from 365.2 kW to 158.4 kW. However, Reconfigurations 2 and 4 showed increases in most reliability indices, with the exception of total losses, which decreased to the least.

Case 2 exhibited a significant voltage rise at certain buses (especially 12-17). Reconfiguration 2 provided the best voltage improvement, while Reconfigurations 3 and 4 still suffered from voltage rise issues. Overall, Reconfiguration 2 achieved the best results in terms of both total losses and voltage profile.

4.6 Conclusion

The thesis discusses the impacts of integrating PV systems into the electrical network. Since PV generation is variable, it influences reliability due to fluctuations in voltage, both drops and rises. Up to a certain limit, PV integration improves reliability indices. However, with high penetration levels, reliability worsens due to voltage rise. Therefore, reconfiguring the network based on PV production levels—both low and high—can help improve reliability.

Using ETAP, the modified IEEE 33-bus system was simulated to evaluate the effects on reliability indices in different scenarios. The results demonstrate that network reconfiguration offers a solution to enhance reliability, even with the intermittent nature of high PV penetration. For instance, reliability indices such as SAIDI, SAIFI, and EENS improved noticeably after reconfiguration. Specifically, in one scenario, SAIDI decreased from 91.62 to 88.82 hours per customer per year, while SAIFI dropped from 54.81 to 53.34 failures per customer per year. EENS also saw a reduction from 441.15 MWh/year to 427.69 MWh/year, highlighting the effectiveness of reconfiguration in mitigating the negative impacts of high PV penetration on the network.

List of Abbreviations

Abbreviation	Meaning
AC	Alternating Current
AENS	Average Energy Not Supplied
CAIDI	Customer Average Interruption Duration Index
DC	Direct Current
DG	Distributed Generations
DTG	diesel turbine generator
EENS	Expected Energy Not Supplied
EPS	Electrical Power Systems
ETAP	Electrical Transient Analyzer Program
IEEE	Institute of Electrical and Electronics Engineers
IGTS	Interconnected Greek Transmission System
LOEP	Loss of Energy Probability
LOLP	Loss of Load Probability
MPP	Maximum Power Point
MTBF	Mean Time Between Failures
MTTF	Mean Time to Fail
MTTR	Mean Time to Repair
PV	Photovoltaic
R	Resistance
RBTS	Roy Billinton Test System
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SCADA	Supervisory Control and Data Acquisition
WT	Wind Turbine
X	Reactance

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Appendices

Appendix A

Tables

Table A1

33-Bus Voltages Through Study Cases

Bus	case 1	case 2	Recon.1	Recon.2	Recon.3	Recon.4
0	12,660	12,660	12,660	12,660	12,660	12,660
1	12,621.90	12,642	12,622.20	12,643.30	12,642	12,643.30
2	12,444.20	12,572.30	12,446.50	12,580.40	12,572.90	12,580.80
3	12,338.20	12,546.40	12,365.90	12,531.20	12,547.50	12,532.10
4	12,231.10	12,523.10	12,285.40	12,483.40	12,524.60	12,484.80
5	11,972	12,443.70	12,094.70	12,360.70	12,446.20	12,366.20
6	11,930	12,424.90	12,062.10	12,347.80	12,417.30	12,341.00
7	11,740.40	12,475.90	11,938.90	12,297.70	12,395.70	12,278.50
8	11,649.60	12,530	11,887.90	12,290.10	12,406	12,263.70
9	11,581.60	12,608.20	11,859.70	12,305.10	12,439.40	12,271.70
10	11,571.60	12,626.20	11,856.90	12,308.70	12,449.40	12,275.60
11	11,554.50	12,662.40	11,862.40	12,317.40	12,486.20	12,283.90
12	11,483.10	12,797.10	11,904.40	12,365.10	12,622.70	12,336.30
13	11,456.70	12,846	11,930.50	12,390.30	12,672	12,366.00
14	11,436	12,908.40	11,957.50	12,418.80	12,735.50	12,396.90
15	11,422.30	12,999.90	11,999.30	12,463.40	12,828.10	12,443.60
16	11,403.50	13,162.10	12,104.90	12,565.80	12,992.50	12,556.90
17	11,398.80	13,261.50	12,155.80	12,618.90	13,093.20	12,612.30
18	12,615.20	12,635.30	12,615.50	12,636.60	12,635.40	12,636.70
19	12,570	12,590.20	12,570.40	12,591.50	12,590.30	12,591.60
20	12,561.10	12,581.30	12,561.50	12,582.60	12,581.40	12,582.70
21	12,553.10	12,573.30	12,553.50	12,574.60	12,573.40	12,574.70
22	12,415.30	12,543.60	12,384.90	12,584.40	12,544.20	12,583.70
23	12,364.30	12,492.90	12,265.40	12,596.70	12,493.50	12,592.90
24	12,322.90	12,451.70	12,155.80	12,618.90	12,452.30	12,612.30

25	11,940.80	12,428.80	12,069.90	12,345.80	12,439.90	12,352.00
26	11,909.30	12,419.80	12,047.30	12,336.80	12,442.80	12,344.00
27	11,769.10	12,364.30	11,953.70	12,281.30	12,434.30	12,304.90
28	11,668.70	12,328.50	11,888.40	12,245.40	12,434.40	12,281.00
29	11,621.50	12,321.80	11,856.90	12,238.70	12,449.40	12,275.60
30	11,513.50	12,292.30	11,750.30	12,209.30	12,419.80	12,246.20
31	11,498.90	12,302.10	11,735.90	12,219.20	12,429.50	12,256.00
32	11,488.50	12,318.10	11,725.60	12,235.40	12,445.30	12,272.10

Appendix B

Figures

Figure B 1

The Electrical Power System [54]

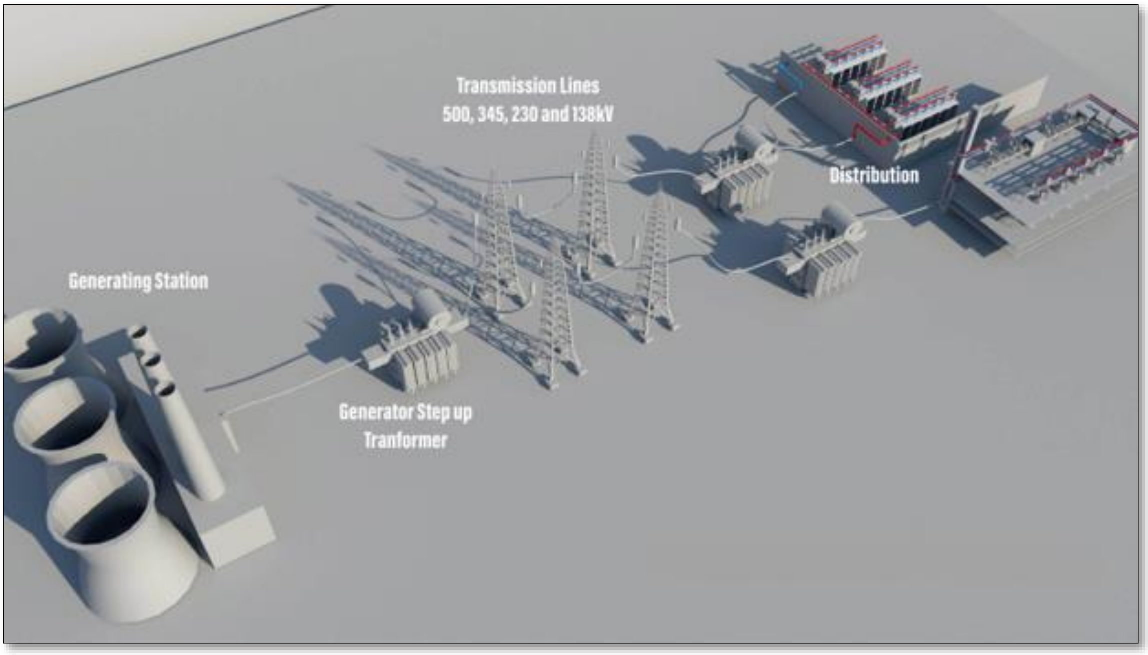


Figure B 2

Radial Distribution System [55]

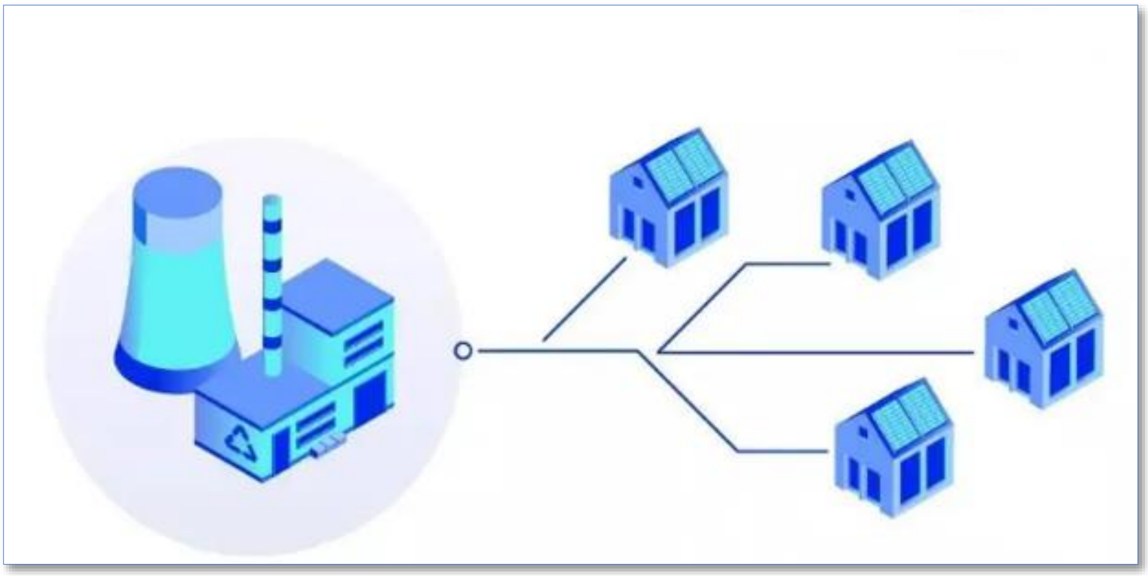


Figure B 3

Ring Main Distribution System [55]

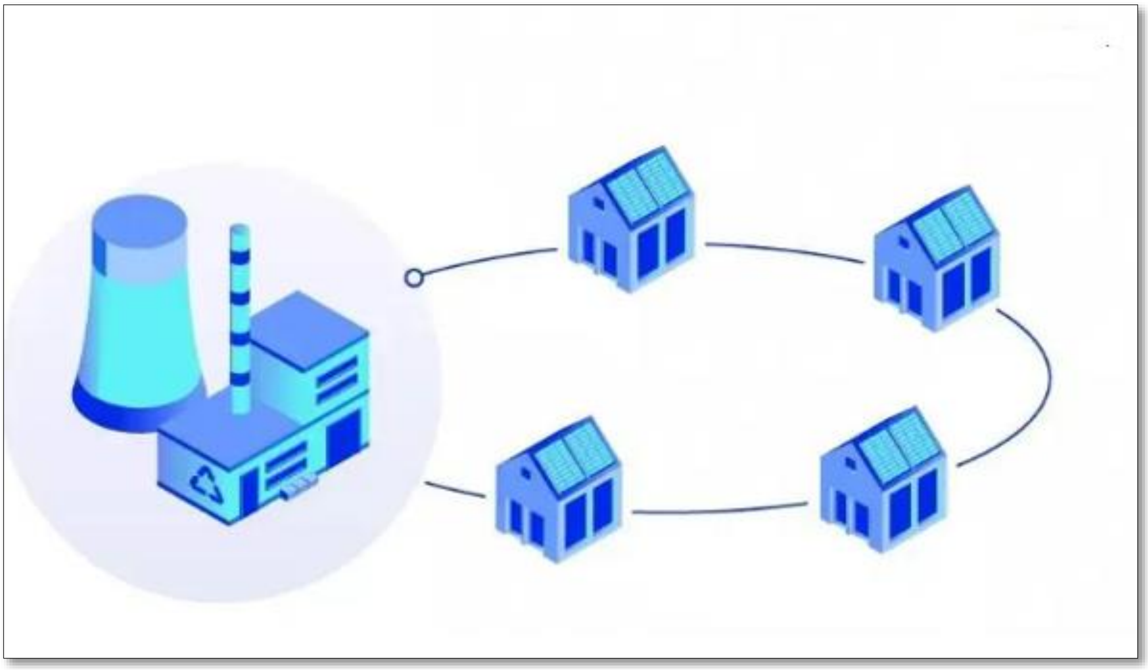


Figure B 4

Inter-Connected Distribution System [55]

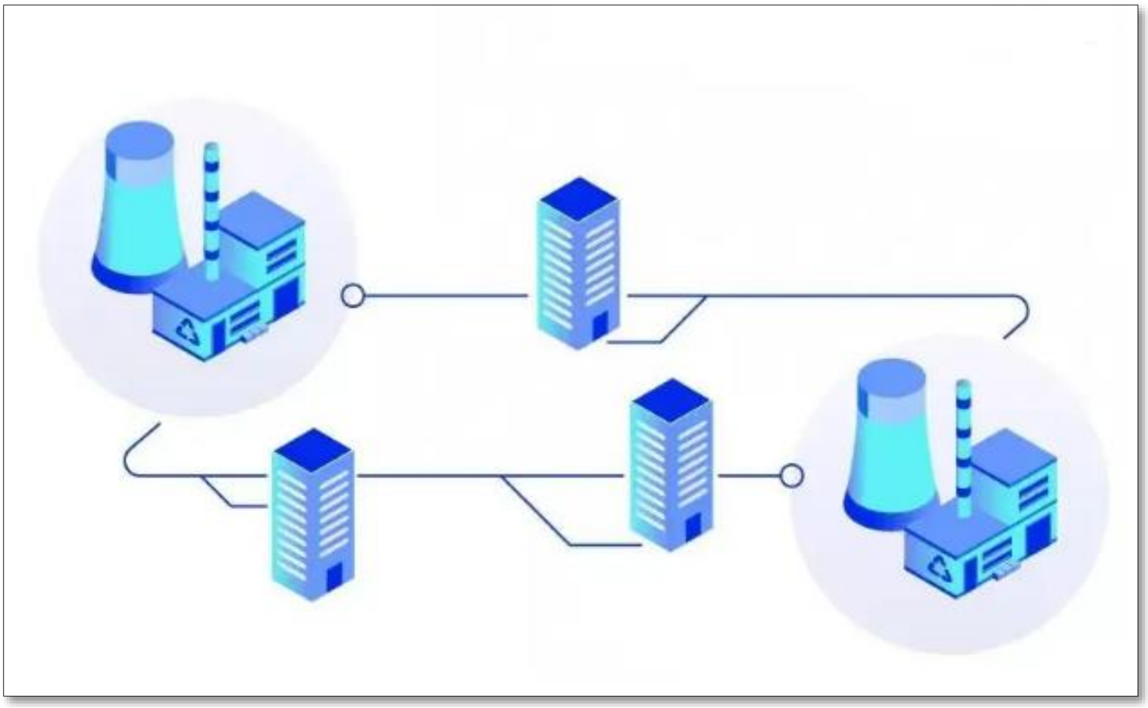


Figure B 5

Solar PV System Components and Operation [56]

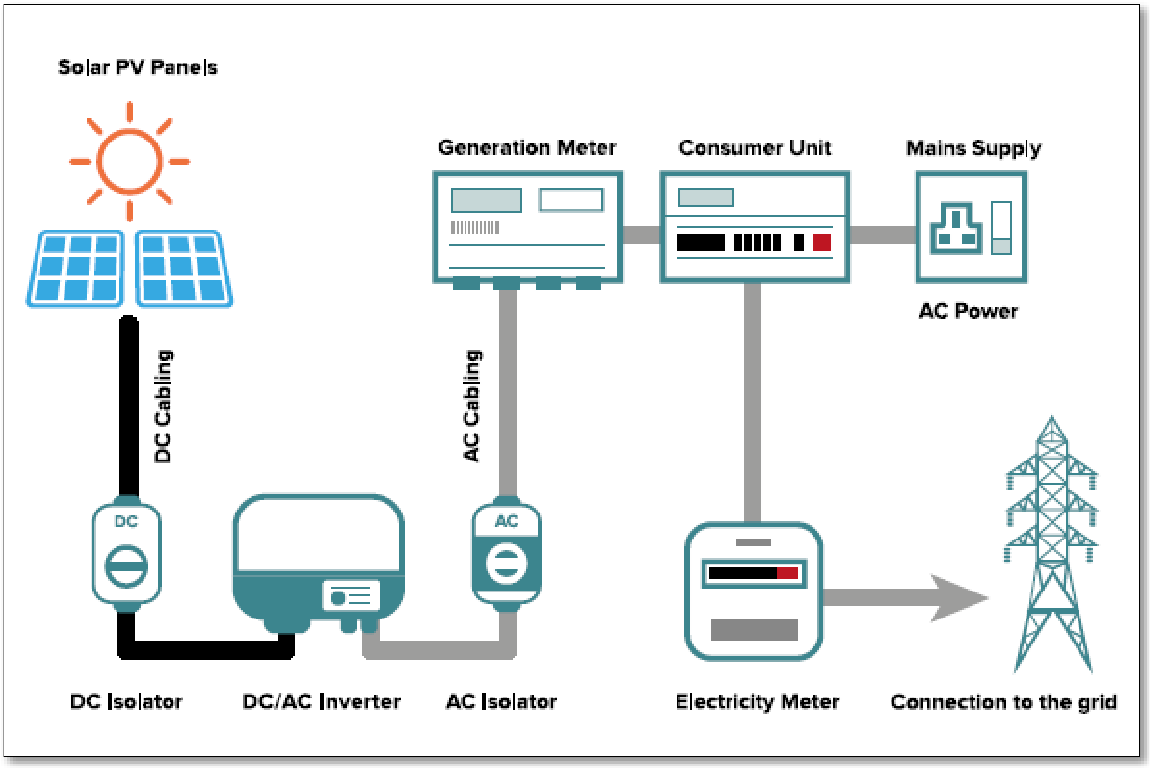


Figure B 6

24-Hour Solar Power Profile

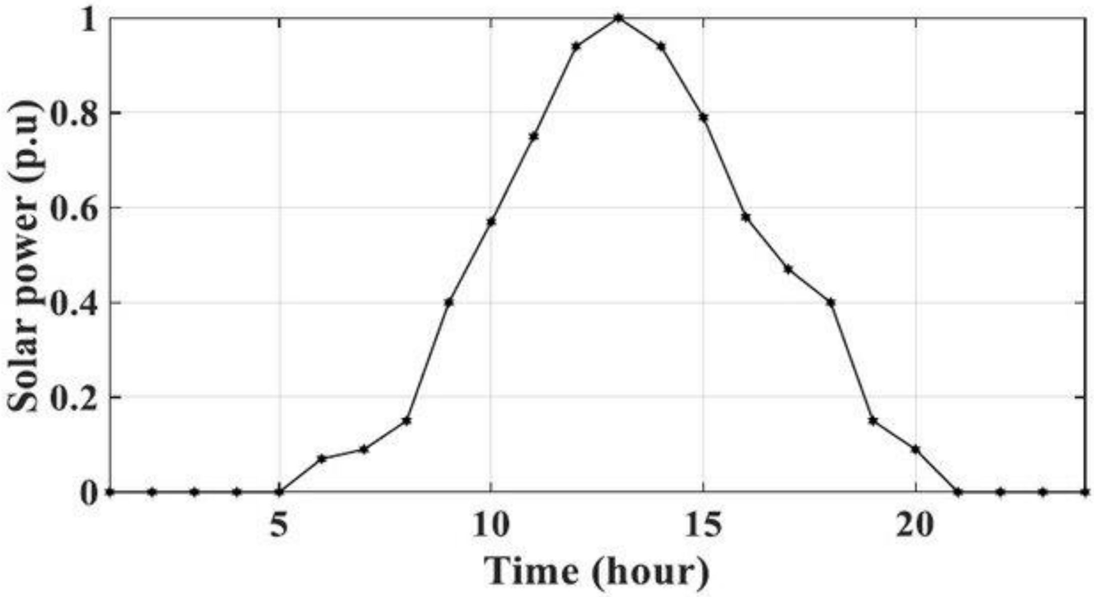


Figure B 7

The On-Grid System [57]

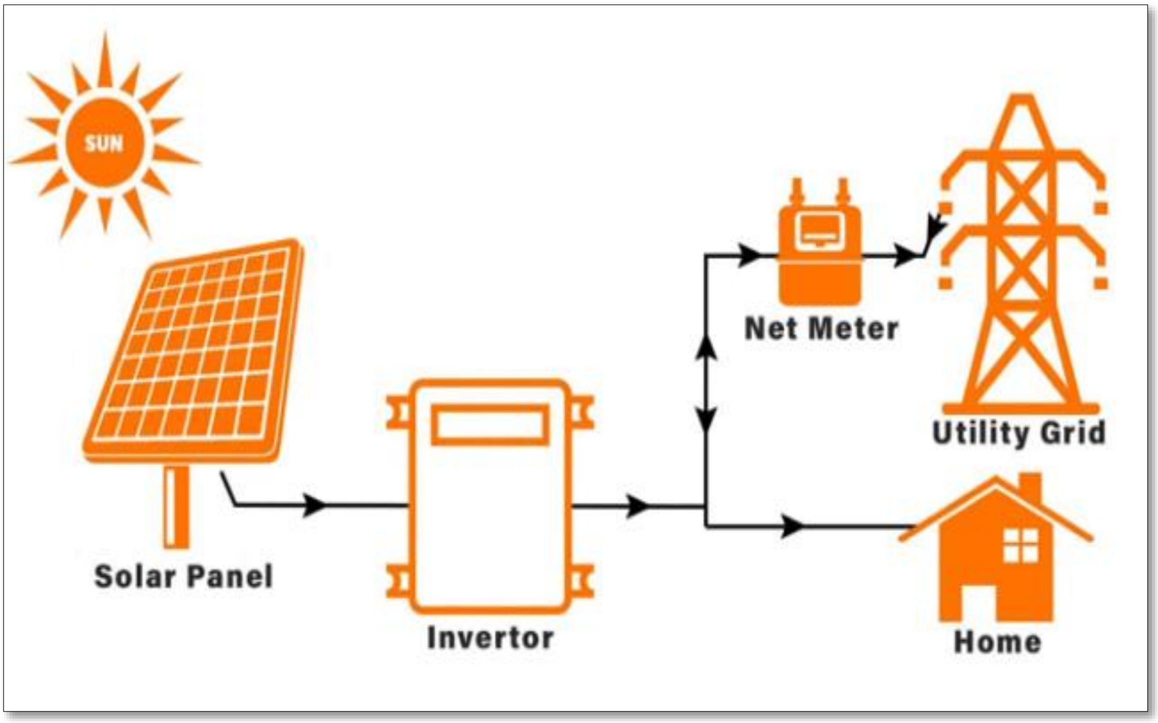


Figure B 8

The Off-Grid System [57]

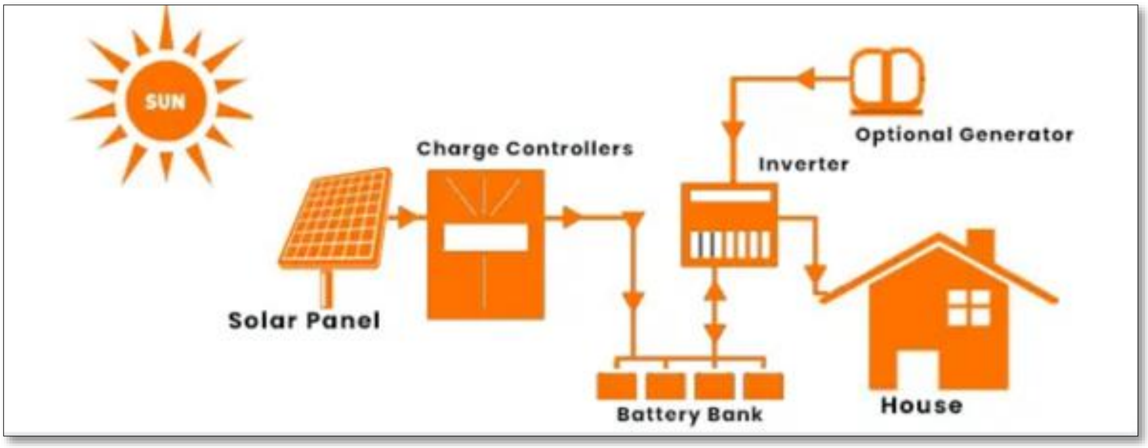


Figure B 9

The Hybrid System [57]

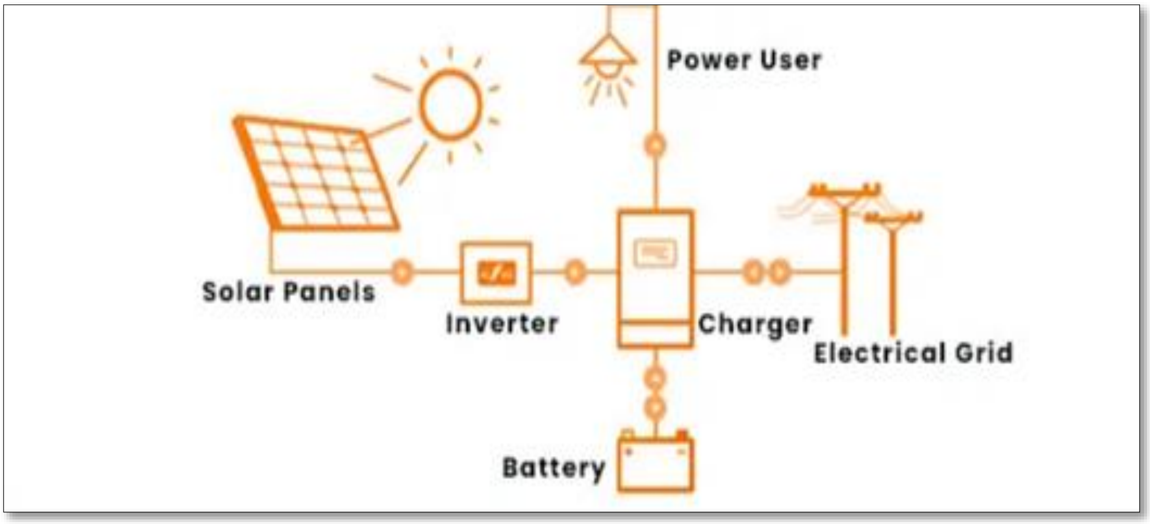


Figure B 10

Bathtub Curve

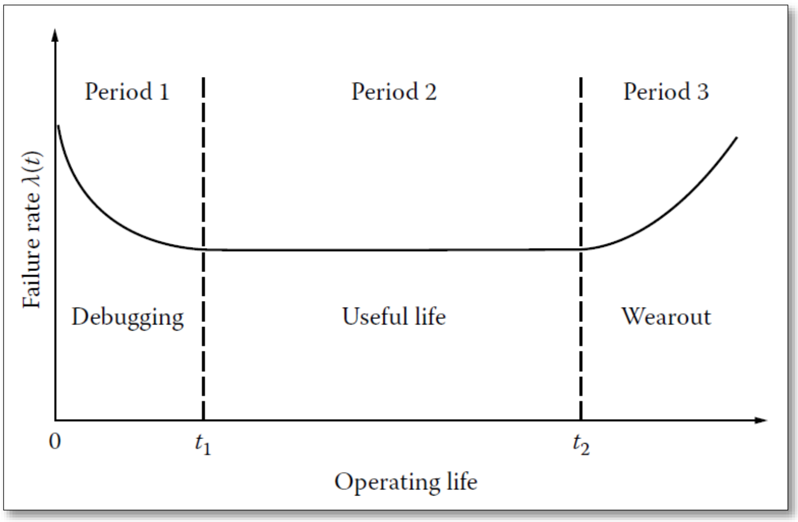


Figure B 11

The Modified IEEE 33-bus Voltages of Case 2

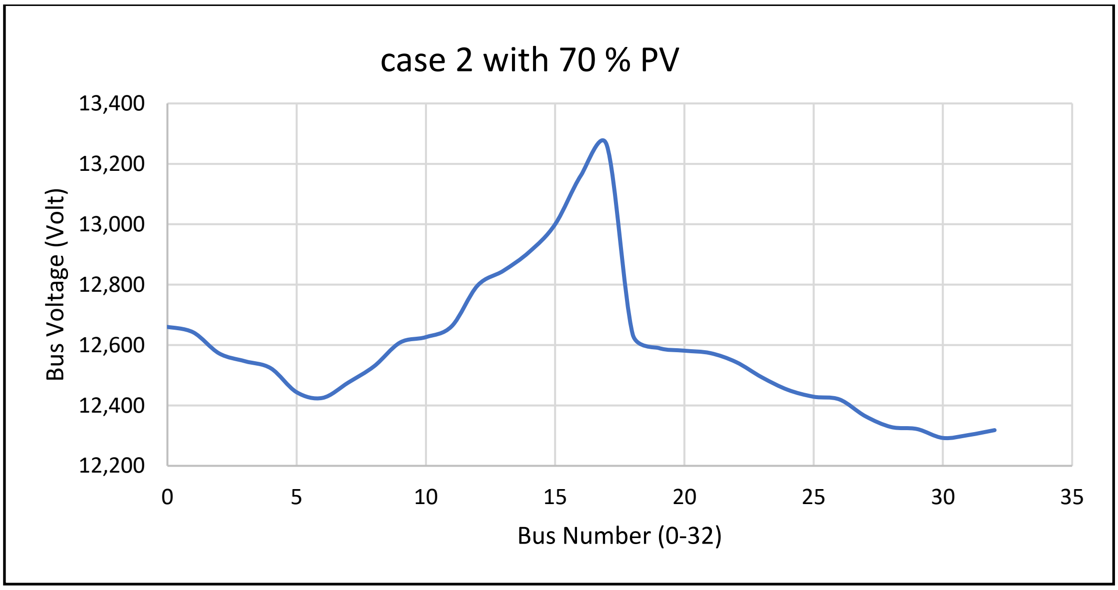


Figure B 12

The Modified IEEE 33-bus Voltages of Reconfiguration 1

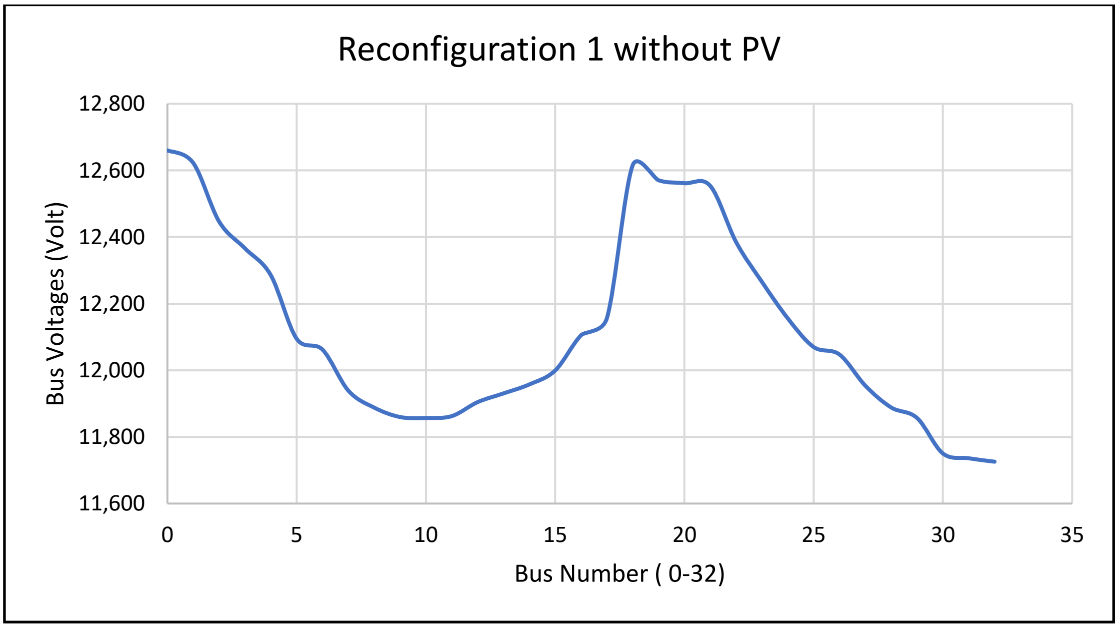


Figure B 13

The Modified IEEE 33-bus Voltages of Reconfiguration 2

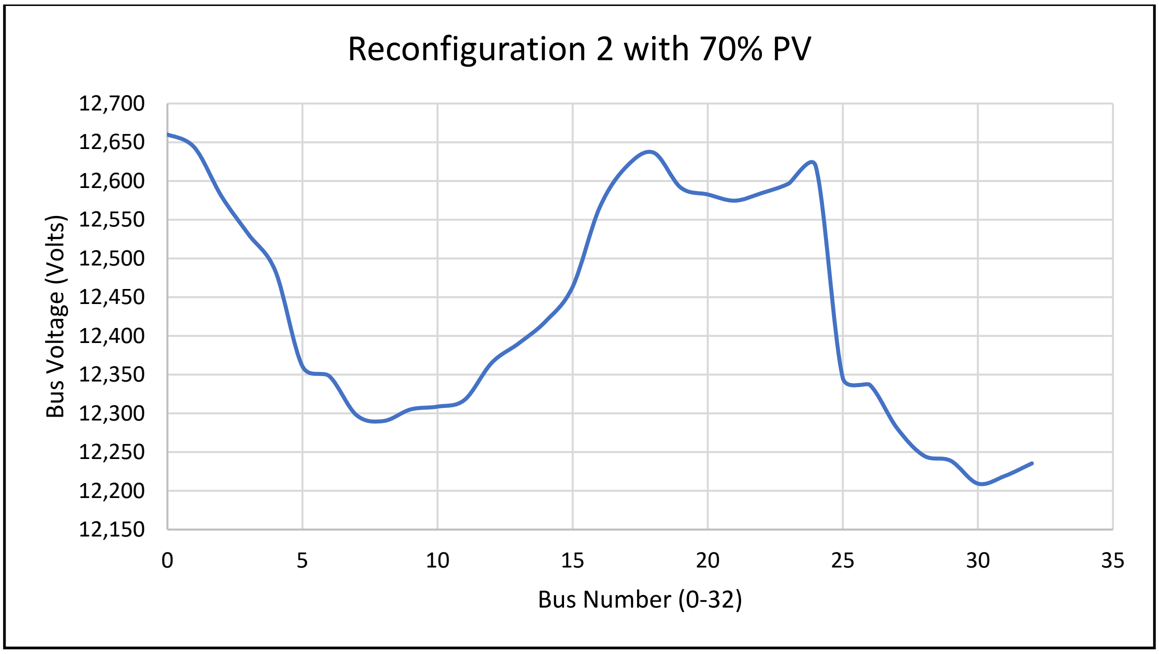


Figure B14

The Modified IEEE 33-bus Voltages of Reconfiguration 3

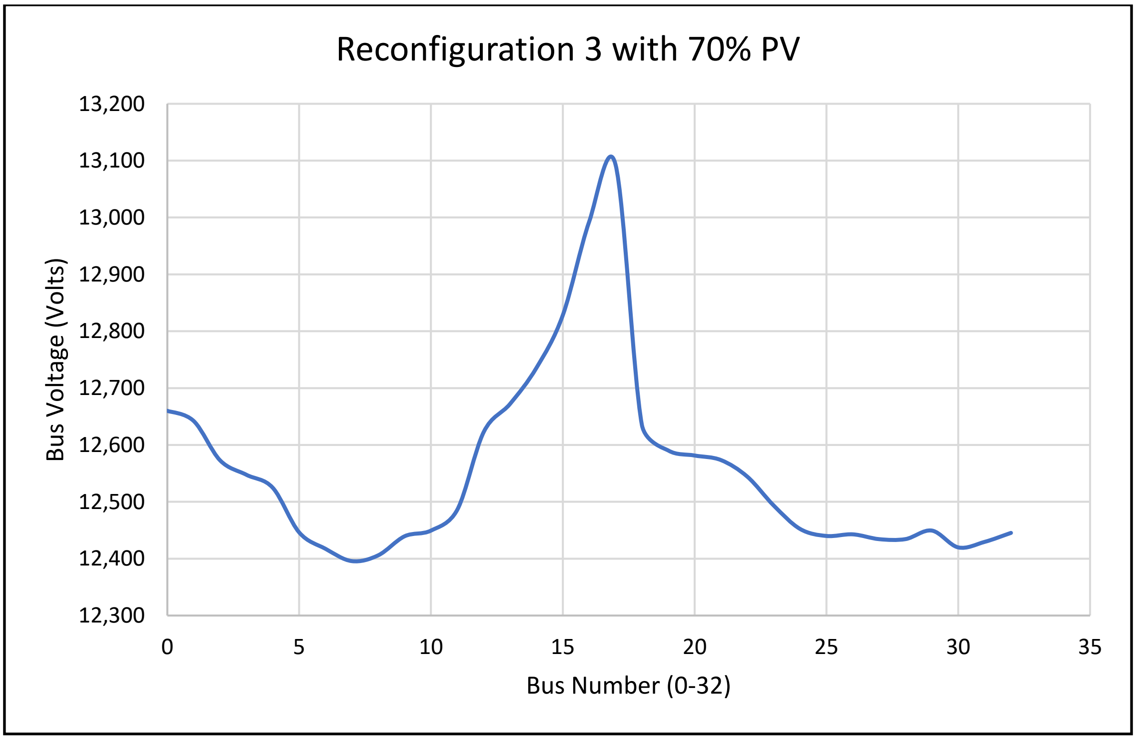


Figure B 15

The Modified IEEE 33-bus Voltages of Reconfiguration 4

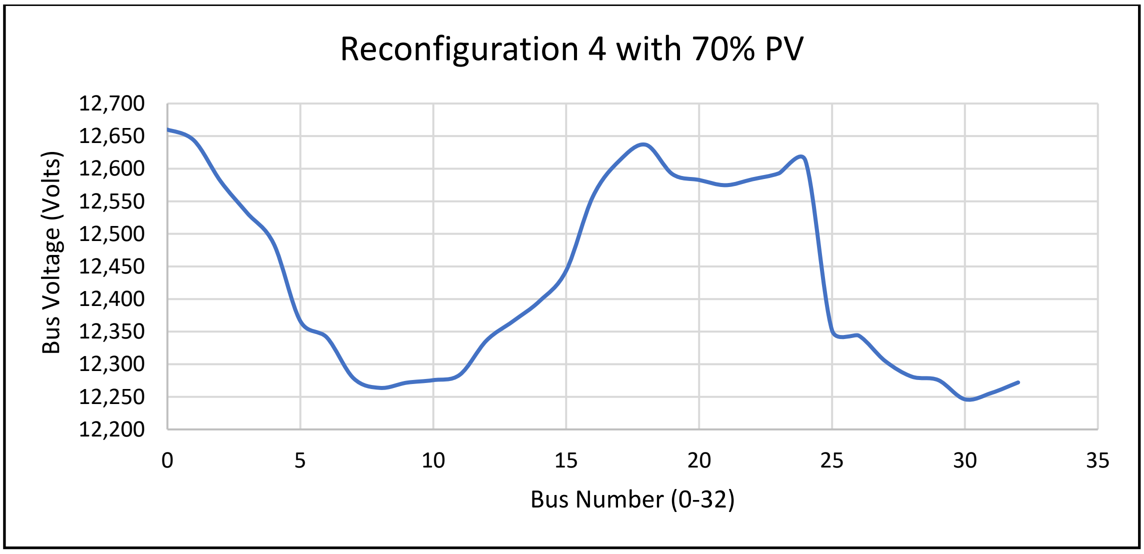


Figure B 16

Average Interruption Duration of Case 2 and Reconfigurations 2, 3, and 4.

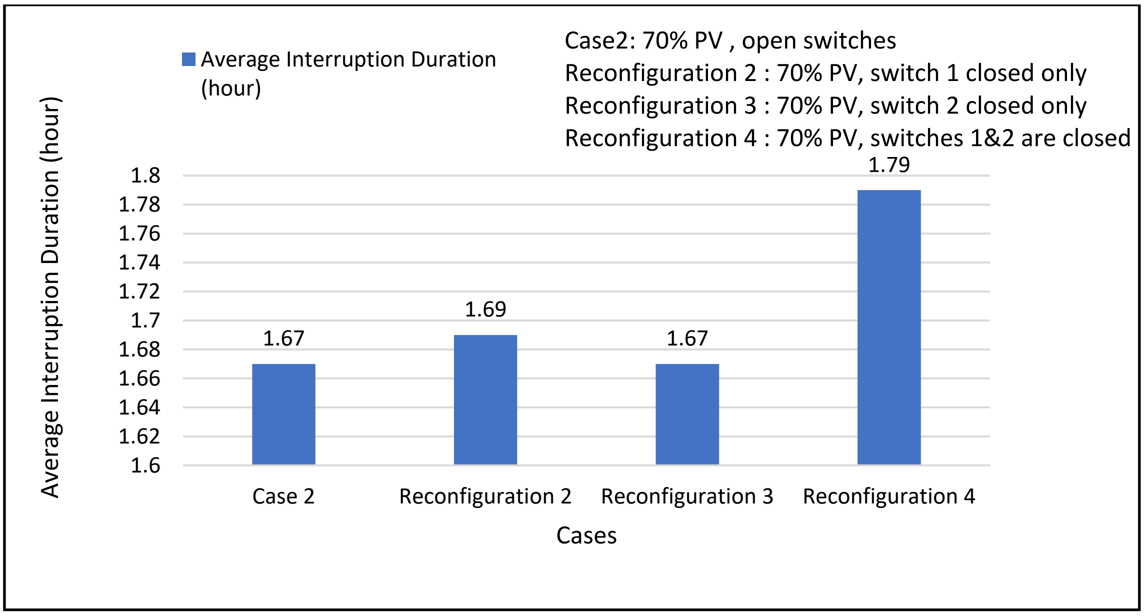


Figure B 17

SAIDI of Case 2 and Reconfigurations 2, 3, and 4.

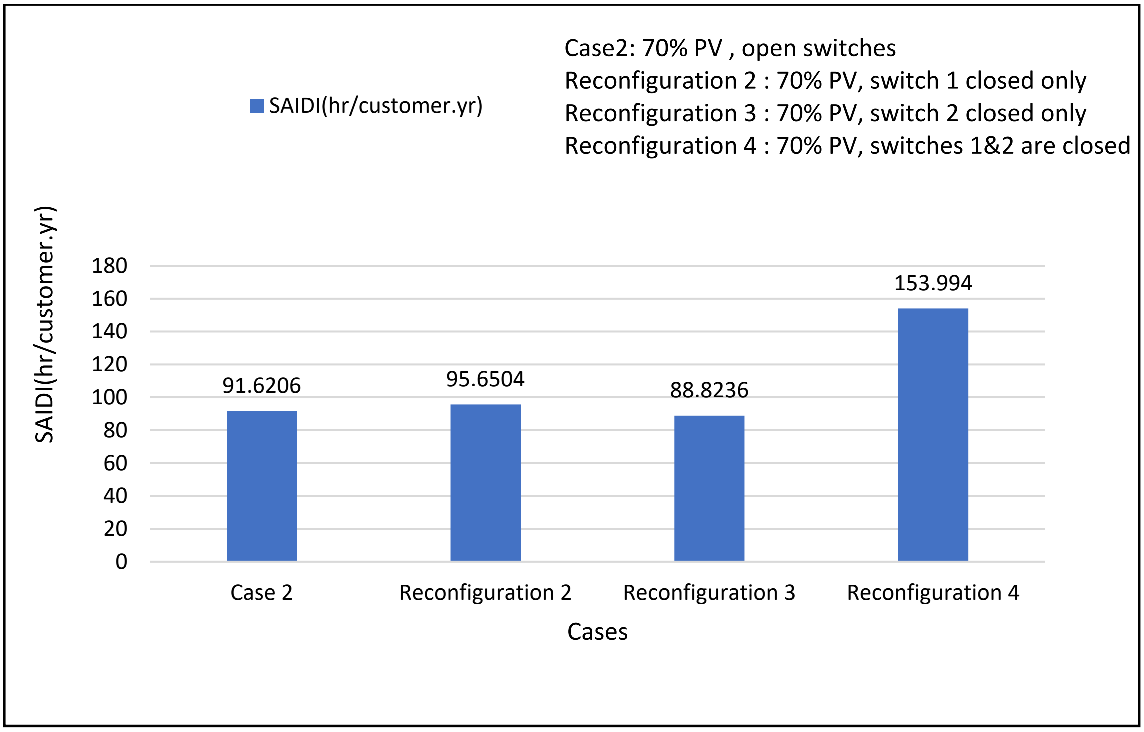


Figure B 18

SAIFI of Case 2 and Reconfigurations 2, 3, and 4.

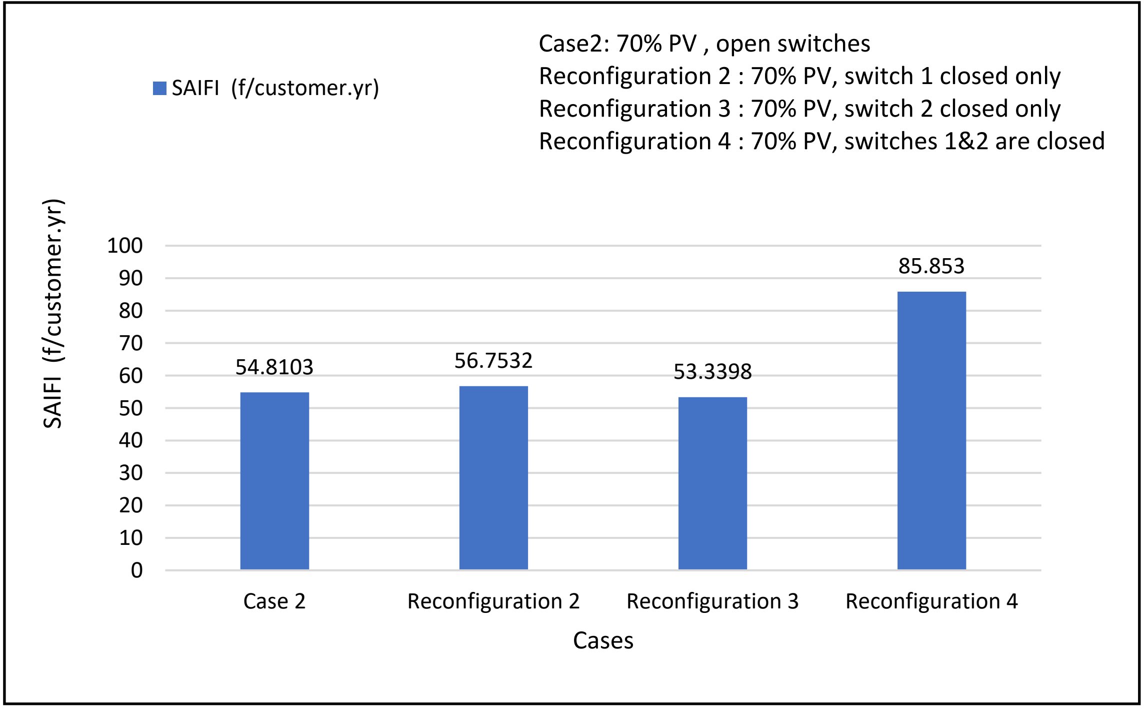


Figure B 19

CAIDI of Case 2 and Reconfigurations 2, 3, and 4.

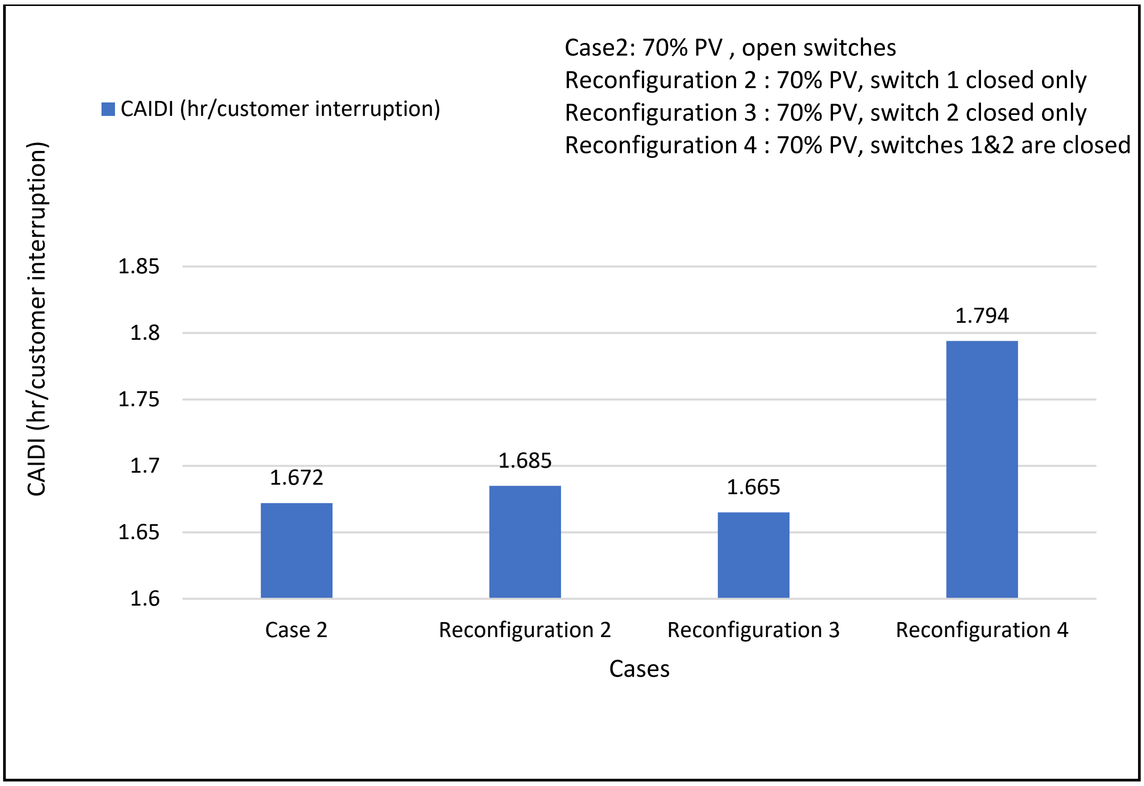


Figure B 20

Total Losses of Case 2 and Reconfigurations 2, 3, and 4.

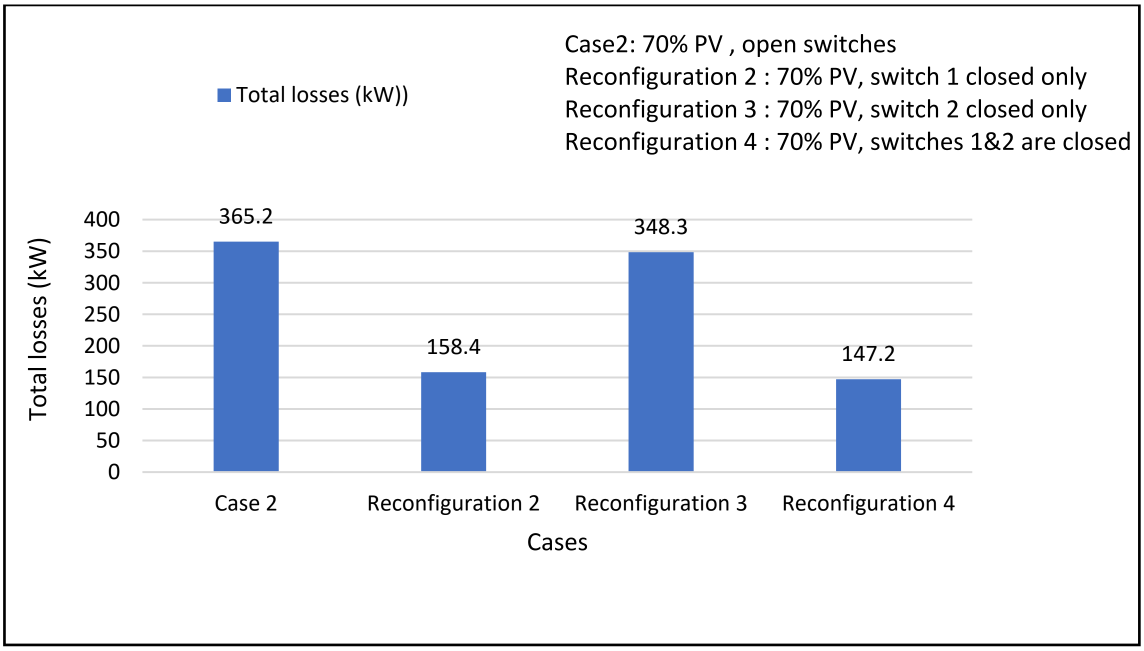


Figure B 21

EENS of Case 2 and Reconfigurations 2, 3, and 4

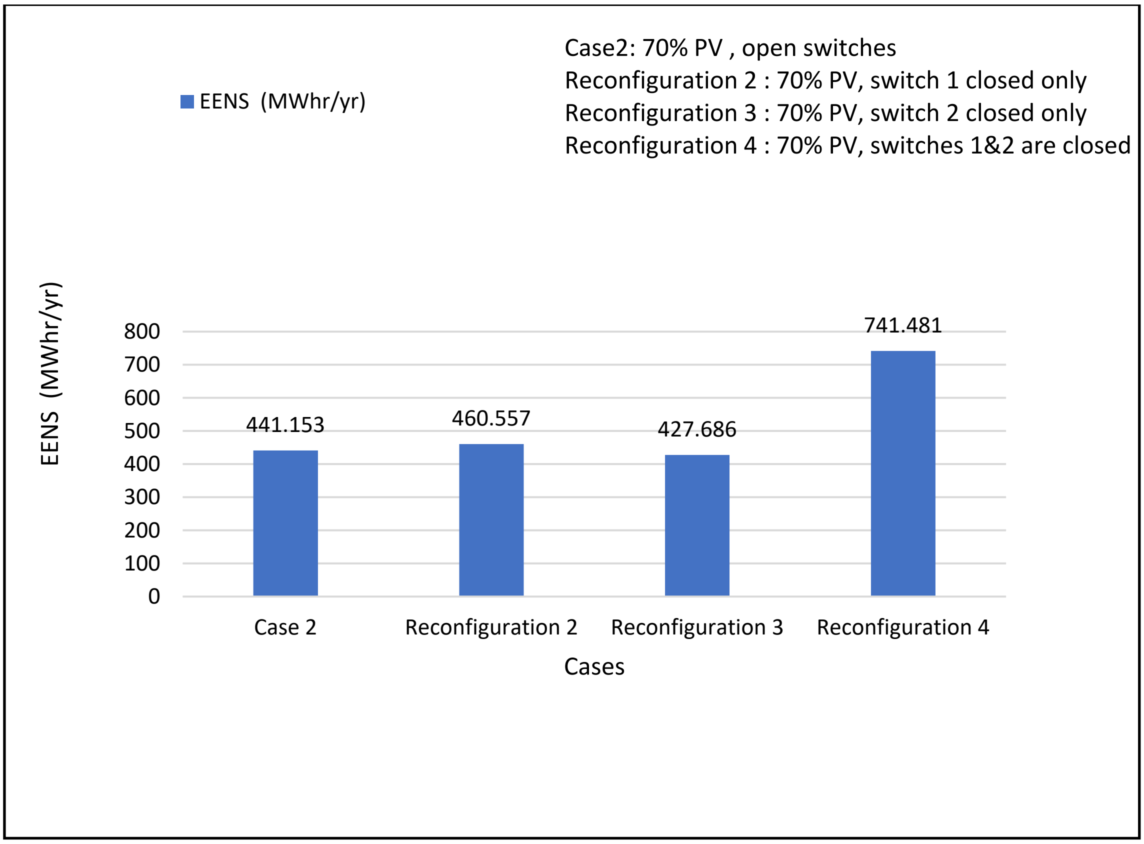


Figure B 22

Average Interruption Rate of Case 2 and Reconfigurations 2, 3, and 4

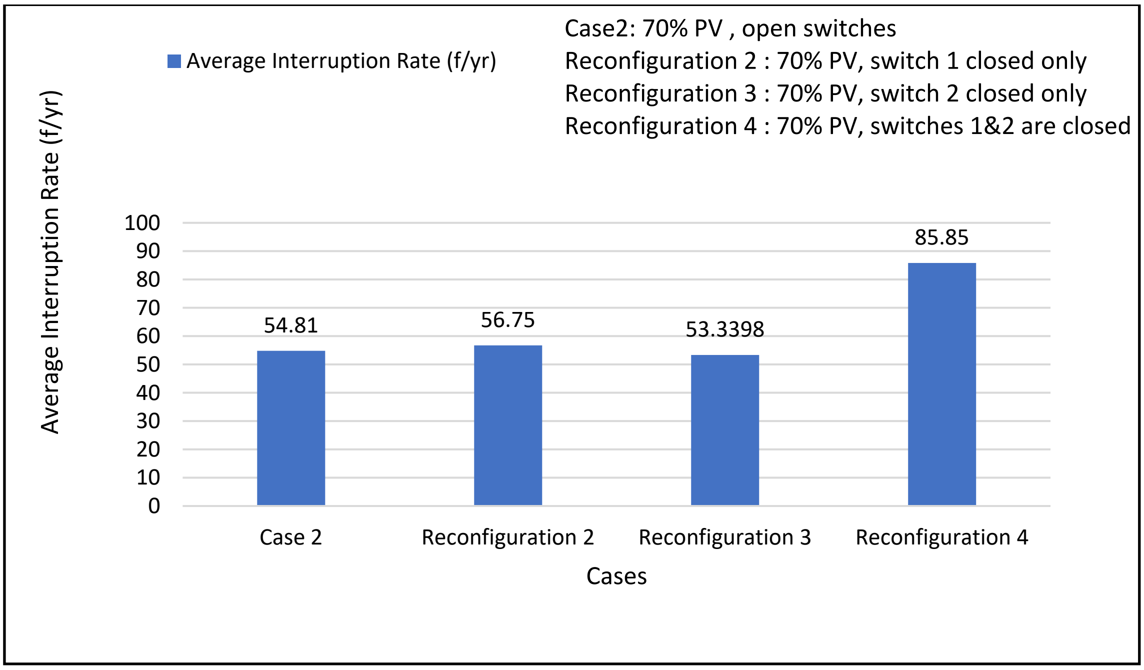


Figure B 23

Case 1: Failure Rate and Average Outage Duration

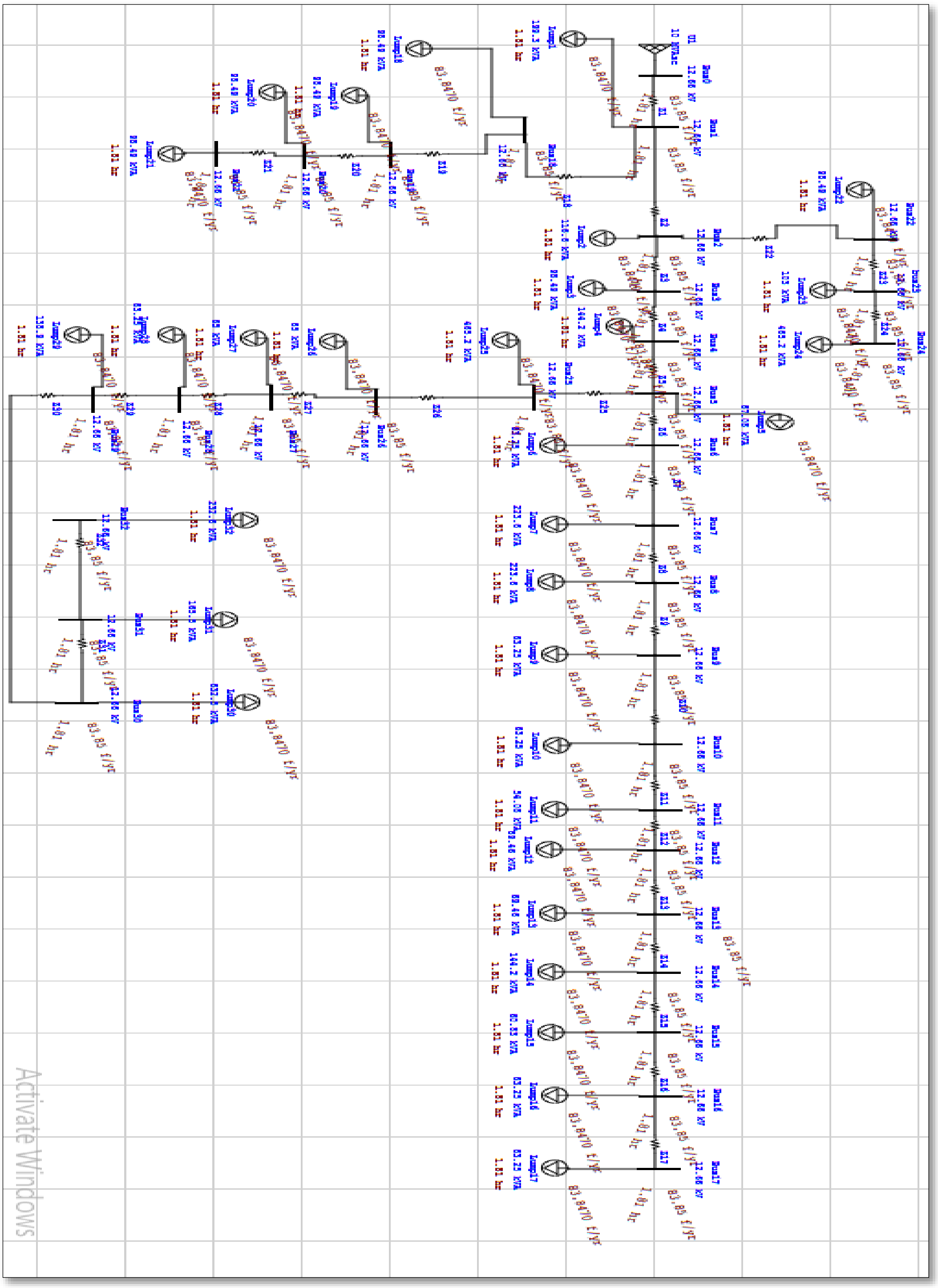


Figure B 24

Case 2: Failure Rate and Average Outage Duration

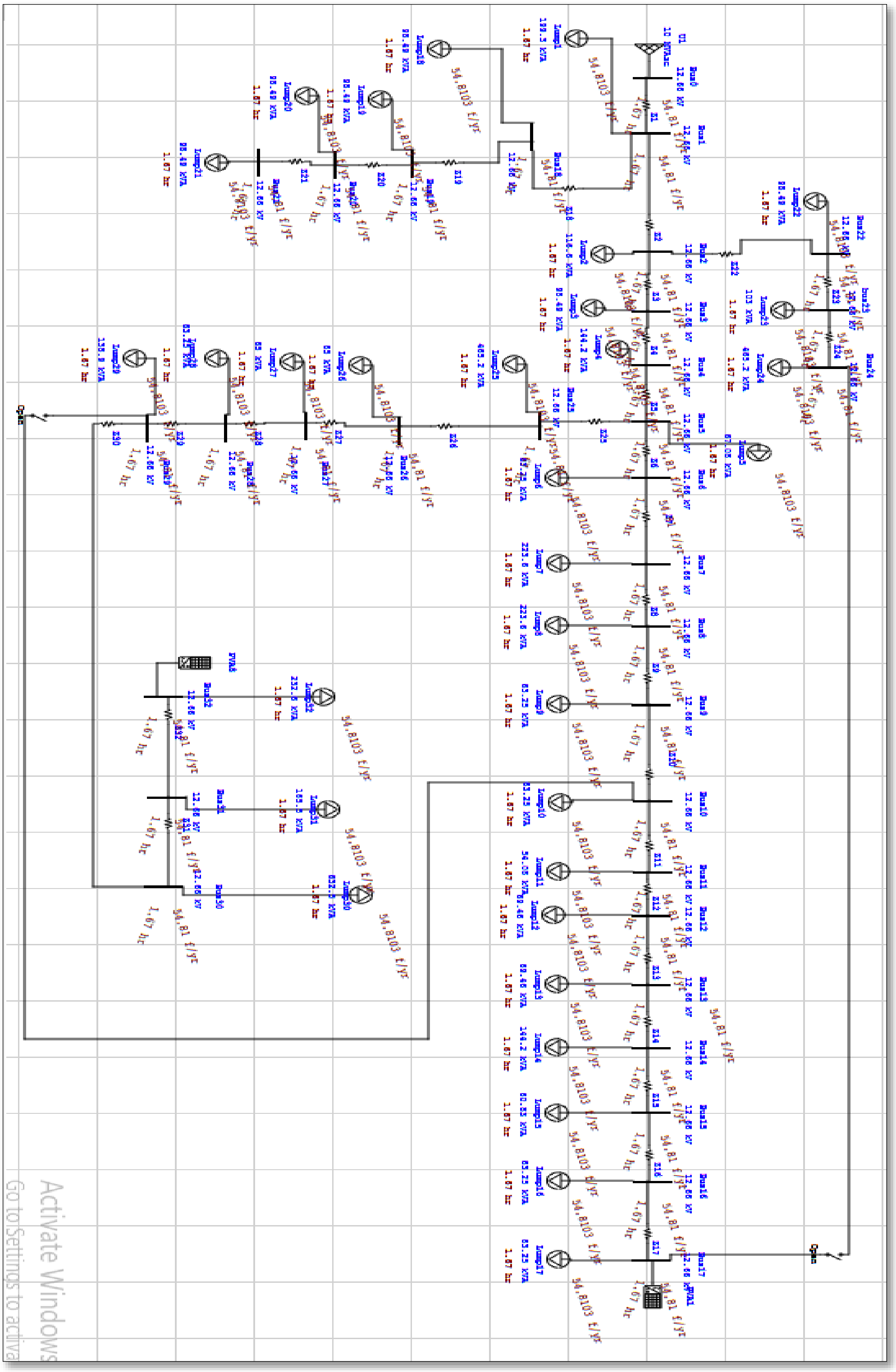
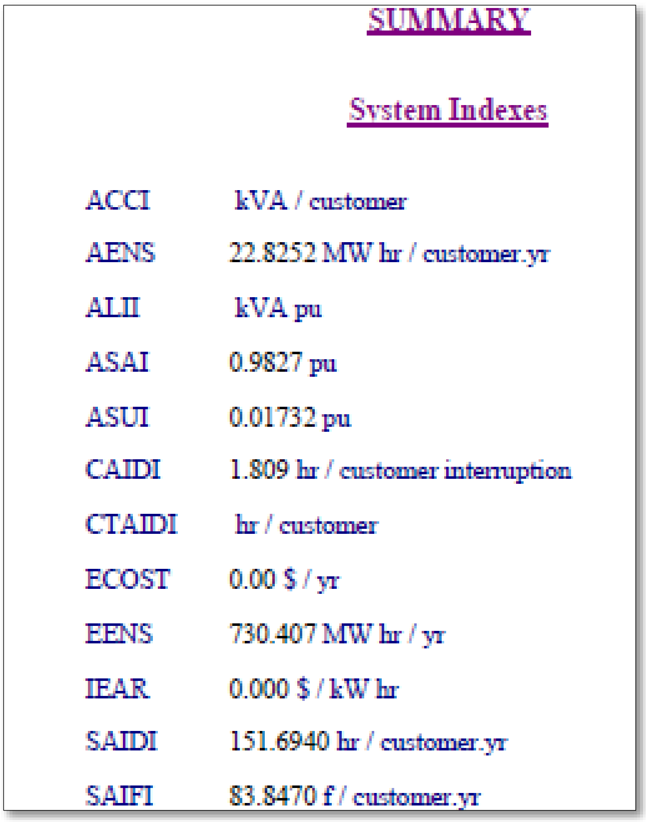


Figure B 25

Case 1: Reliability Indices as Shown in ETAP



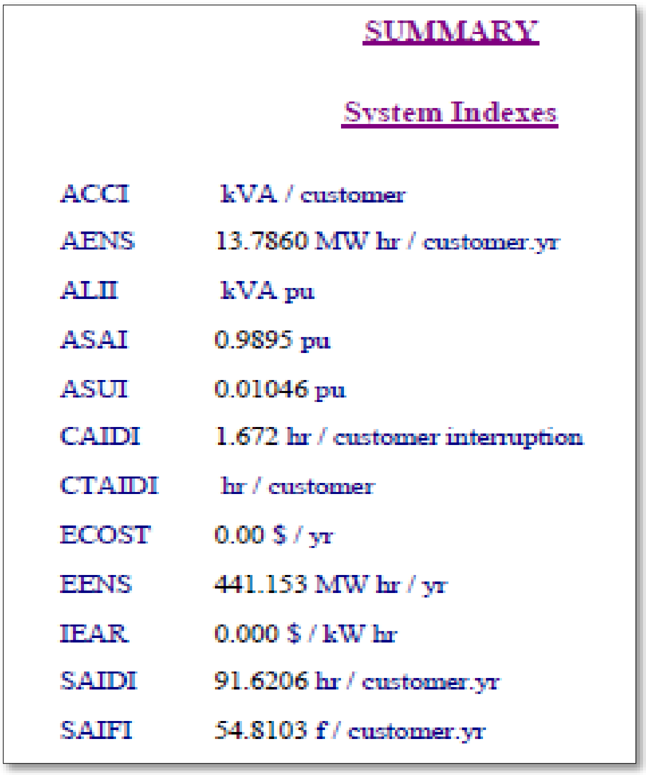
SUMMARY

System Indexes

ACCI	kVA / customer
AENS	22.8252 MW hr / customer.yr
ALII	kVA pu
ASAI	0.9827 pu
ASUI	0.01732 pu
CAIDI	1.809 hr / customer interruption
CTAIDI	hr / customer
ECOST	0.00 $ / yr
EENS	730.407 MW hr / yr
IEAR	0.000 $ / kW hr
SAIDI	151.6940 hr / customer.yr
SAIFI	83.8470 f / customer.yr

Figure B 26

Case 2: Reliability Indices as Shown in ETAP



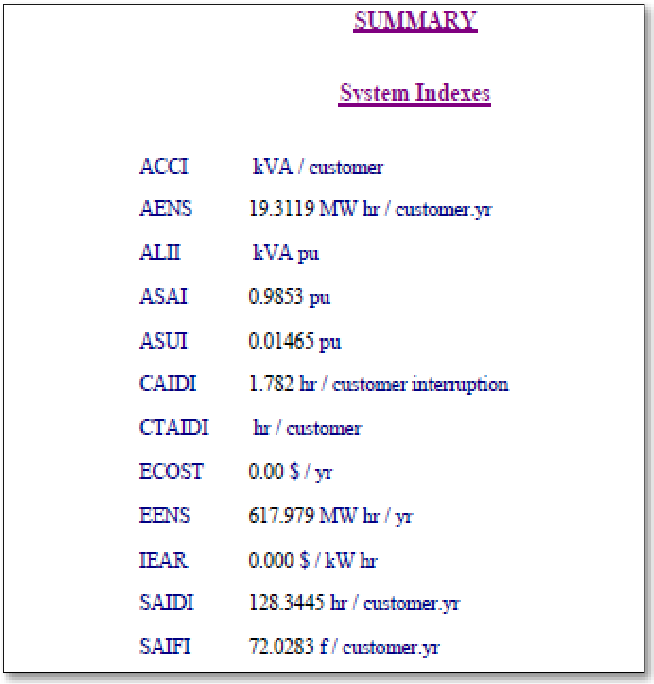
SUMMARY

System Indexes

ACCI	kVA / customer
AENS	13.7860 MW hr / customer.yr
ALII	kVA pu
ASAI	0.9895 pu
ASUI	0.01046 pu
CAIDI	1.672 hr / customer interruption
CTAIDI	hr / customer
ECOST	0.00 $ / yr
EENS	441.153 MW hr / yr
IEAR	0.000 $ / kW hr
SAIDI	91.6206 hr / customer.yr
SAIFI	54.8103 f / customer.yr

Figure B 27

Reconfiguration 1: Reliability Indices as Shown in ETAP



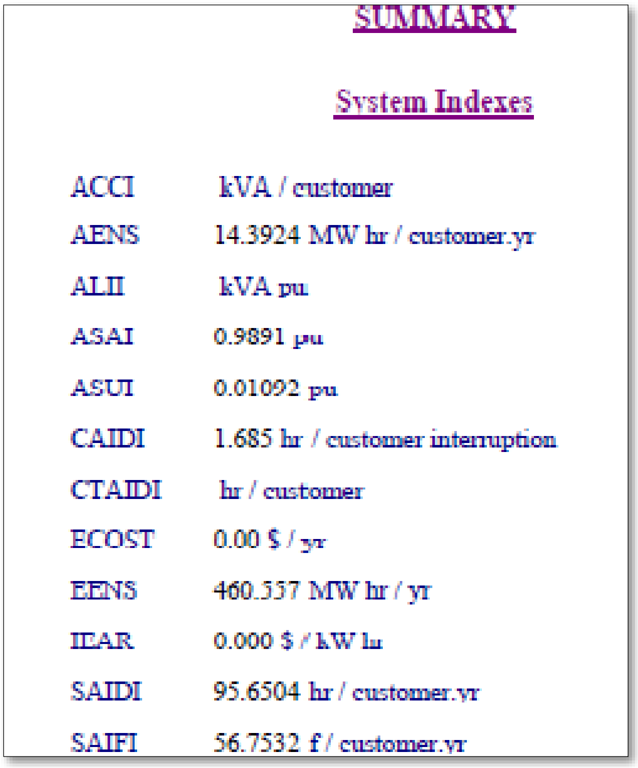
SUMMARY

System Indexes

ACCI	kVA / customer
AENS	19.3119 MW hr / customer.yr
ALII	kVA pu
ASAI	0.9853 pu
ASUI	0.01465 pu
CAIDI	1.782 hr / customer interruption
CTAIDI	hr / customer
ECOST	0.00 $ / yr
EENS	617.979 MW hr / yr
IEAR	0.000 $ / kW hr
SAIDI	128.3445 hr / customer.yr
SAIFI	72.0283 f / customer.yr

Figure B 28

Reconfiguration 2: Reliability Indices as Shown in ETAP



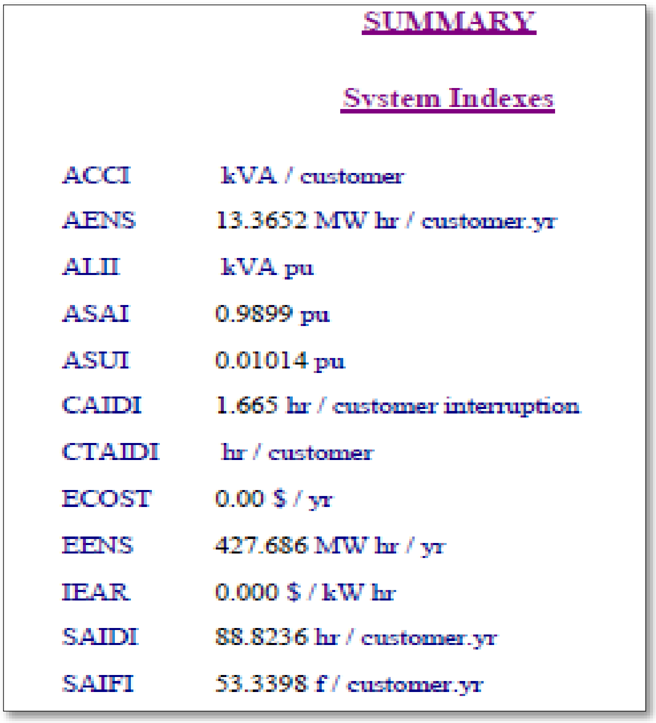
SUMMARY

System Indexes

ACCI	kVA / customer
AENS	14.3924 MW hr / customer.yr
ALII	kVA pu
ASAI	0.9891 pu
ASUI	0.01092 pu
CAIDI	1.685 hr / customer interruption
CTAIDI	hr / customer
ECOST	0.00 $ / yr
EENS	460.337 MW hr / yr
IEAR	0.000 $ / kW hr
SAIDI	95.6504 hr / customer.yr
SAIFI	56.7532 f / customer.yr

Figure B 29

Reconfiguration 3: Reliability Indices as Shown in ETAP



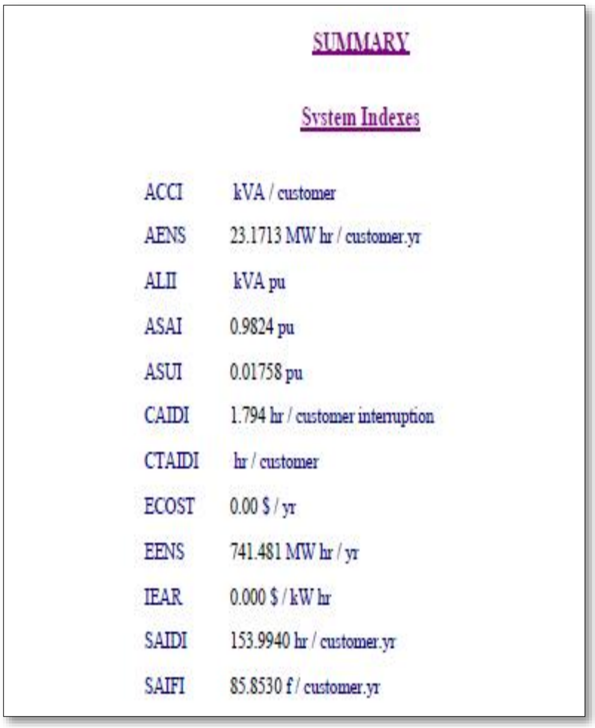
SUMMARY

System Indexes

ACCI	kVA / customer
AENS	13.3652 MW hr / customer.yr
ALII	kVA pu
ASAI	0.9899 pu
ASUI	0.01014 pu
CAIDI	1.665 hr / customer interruption
CTAIDI	hr / customer
ECOST	0.00 $ / yr
EENS	427.686 MW hr / yr
IEAR	0.000 $ / kW hr
SAIDI	88.8236 hr / customer.yr
SAIFI	53.3398 f / customer.yr

Figure B 30

Reconfiguration 4: Reliability Indices as Shown in ETAP



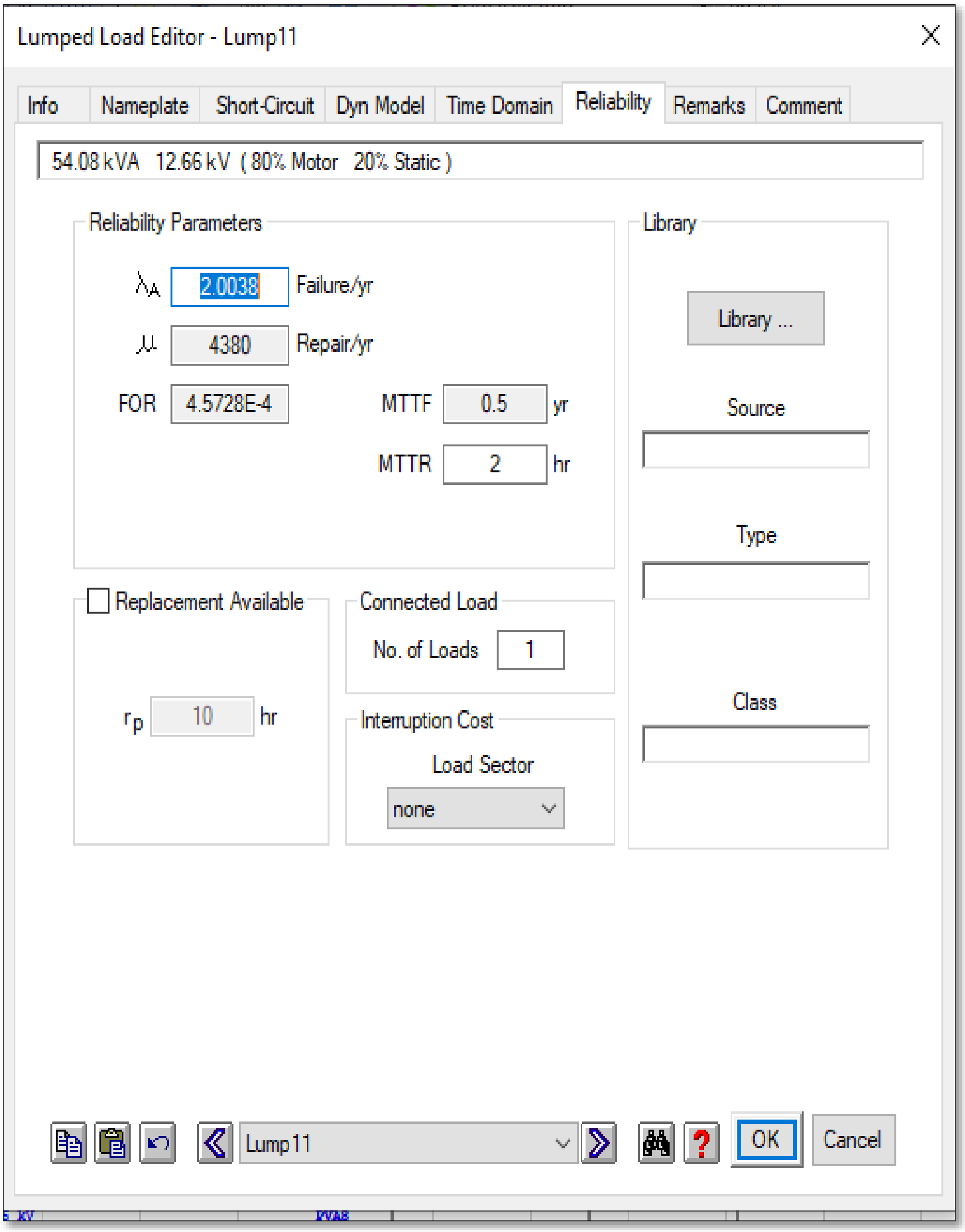
SUMMARY

System Indexes

ACCI	kVA / customer
AENS	23.1713 MW hr / customer.yr
ALII	kVA pu
ASAI	0.9824 pu
ASUI	0.01758 pu
CAIDI	1.794 hr / customer interruption
CTAIDI	hr / customer
ECOST	0.00 $ / yr
EENS	741.481 MW hr / yr
IEAR	0.000 $ / kW hr
SAIDI	153.9940 hr / customer.yr
SAIFI	85.8530 f / customer.yr

Figure B 31

Failure Rate and MTTR Settings of Load 11 as an Example



Lumped Load Editor - Lump11

54.08 kVA 12.66 kV (80% Motor 20% Static)

Reliability Parameters

λ_A 2.0038 Failure/yr

μ 4380 Repair/yr

FOR 4.5728E-4

MTTF 0.5 yr

MTTR 2 hr

☐ Replacement Available

r_p 10 hr

Connected Load

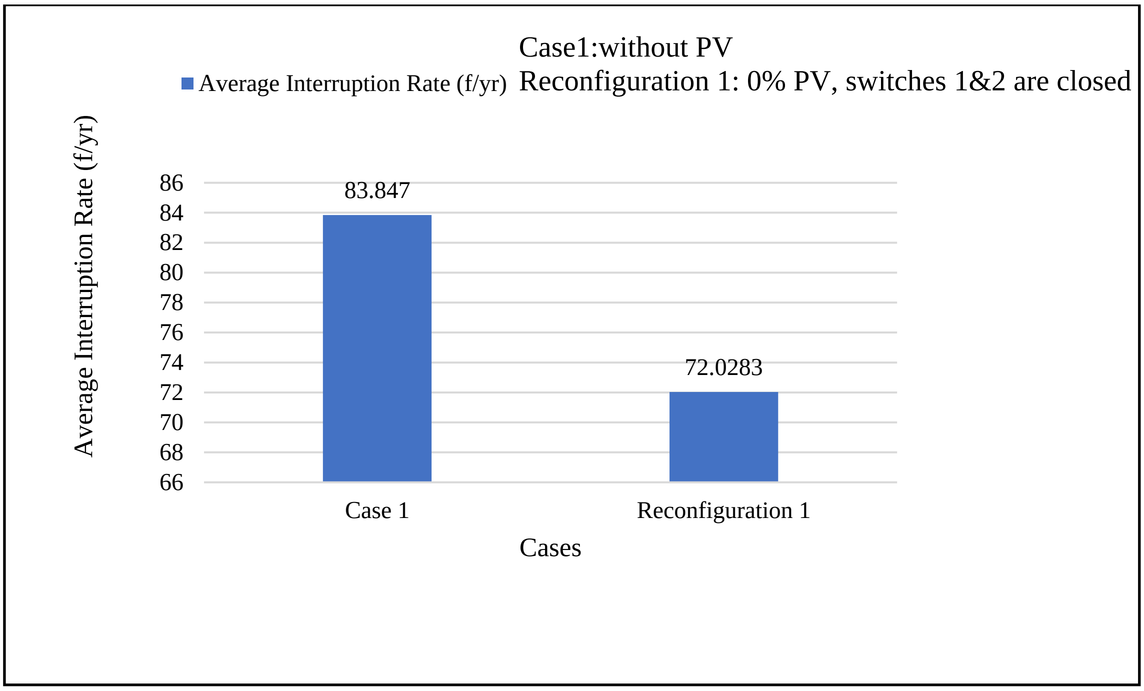
No. of Loads 1

Interruption Cost

Load Sector none

Figure B 32

Average Interruption Rate of Case 1 and Reconfiguration 1



جامعة النجاح الوطنية

كلية الدراسات العليا

إعادة هيكلة الشبكة الكهربائية لتحسين موثوقية نظام التوزيع المكون من مصادر الطاقة المتجددة

إعداد

تحرير "محمد داود" ذياب

إشراف

د. معين عمر

قدمت هذه الرسالة استكمالا لمتطلبات الحصول على درجة الماجستير في هندسة القوى الكهربائية، من كلية الدراسات العليا، في جامعة النجاح الوطنية، نابلس– فلسطين.

2024

تحسين موثوقية الشبكات الكهربائية التى تتضمن مصادر الطاقة المتجددة من خلال إعادة تشكيلها

إعداد

تحرير "محمد داود" ذياب

إشراف

د. معين عمر

الملخص

تناول هذه الأطروحة تأثيرات إضافة أنظمة الطاقة الشمسية (PV) إلى الشبكة الكهربائية. نظرًا لأن إنتاج الطاقة الشمسية متغير، فإنه يؤثر على موثوقية الشبكة نتيجة تقلبات الجهد الكهربائي، سواء في الانخفاض أو الارتفاع. حتى حد معين، يمكن أن تحسن الطاقة الشمسية من مؤشرات الموثوقية، ولكن عند مستويات اختراق عالية، تتدهور الموثوقية بسبب ارتفاع الجهد. لذلك، فإن إعادة تكوين الشبكة اعتمادًا على مستويات إنتاج الطاقة الشمسية، سواء كانت منخفضة أو عالية، يمكن أن يساعد في تحسين الموثوقية.

تم استخدام برنامج ETAP لمحاكاة نظام IEEE المعدل ذو الـ33 خطًا لتقييم تأثيرات ذلك على مؤشرات الموثوقية في سيناريوهات مختلفة. وأظهرت النتائج أن إعادة تكوين الشبكة تمثل حلاً لتحسين الموثوقية حتى مع الطبيعة المتقطعة للطاقة الشمسية عند مستويات اختراق عالية. على سبيل المثال، تحسنت مؤشرات الموثوقية مثل SAIDI، وSAIFI، وEENS بشكل ملحوظ بعد إعادة التكوين. ففي أحد السيناريوهات، انخفض SAIDI من 91.62 إلى 88.82 ساعة لكل عميل سنويًا، بينما انخفض SAIFI من 54.81 إلى 53.34 انقطاعًا لكل عميل سنويًا. كما انخفض مؤشر EENS من 441.15 ميجاواط/ساعة سنويًا إلى 427.69 ميجاواط/ساعة سنويًا، مما يبرز فعالية إعادة التكوين في تخفيف الآثار السلبية للاختراق العالي للطاقة الشمسية على الشبكة.

الكلمات المفتاحية: تقييم الموثوقية، إعادة تكوين الشبكة الكهربائية، نفاذية الطاقة الشمسية الكهروضوئية، مؤشرات الموثوقية، معدل الفشل.