ENHANCING STABILITY AND POWER RESTORATION OF SMART GRID THROUGH DISTRIBUTED ENERGY RESOURCES

by

MKHUTAZI MDITSHWA

Dissertation submitted in partial fulfillment of the requirements for the degree

Master of Engineering: Energy

in the Faculty of Engineering and the Built Environment

at the Cape Peninsula University of Technology

Supervisor: **Dr. Ali-Mustafa-Ali Almaktoof**
Co-supervisor: **Dr. Yohan Darcy Mfoumboulou**

Bellville Campus

Date submitted: July 2023

DECLARATION

I, Mkhutazi Mditshwa, declare that the contents of this dissertation/thesis represent my own unaided work, and that the dissertation/thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

02/05/2023

Signed **Date**

ABSTRACT

The power system network is exposed to several disturbances, from planned to unplanned events. The power system grid is expected to remain stable during these events. The power system grid is also anticipated to be flexible enough to accommodate various types of loads and smoothly integrate multiple energy resources.

The high penetration of distributed energy resources (DER) increases the level of complexity of the power system; however, their contribution to enhancing power system stability is also noticed. Some of these energy resources utilized are highly dependent on weather conditions. These include wind energy as well as solar energy. These energy resources are coupled to the grid through a power electronics interface. However, their integration configuration does not enable them to participate in active power dispatching based on system dynamics. The utilization of battery energy storage systems in parallel with DER has drawn attention word-wide to eliminate the dispatching capability issues of distributed energy resources.

The dissertation explores integrating these energy resources to enable them to participate in active and reactive power dispatching. Their vigorous participation has been observed to immensely enhance smart grid stability and improve service restoration. Various case studies have been performed, such as the impact of load demand increase, generation loss, and line tripping. These energy resources' contribution to improving the smart grid stability was possible through additional control loops in the system. The case studies were performed before and after implementing the proposed control system. The efficacy of the proposed control system was analyzed, and the implementation of this control system showed a significant improvement in smart grid stability and service restoration.

The standard IEEE 33 bus network was modified and modelled using PowerFactory DIgSILENT software. All the case studies and contingencies were performed using the same simulation tool, and the results were recorded.

Keywords: Service restoration, power dispatching, power system stability, distributed energy resources, battery energy storage.

ACKNOWLEDGEMENTS

I wish to thank:

- My supervisors, for guidance and advice
- My best friend Oyena Bongekile Masiko for her continued support throughout the journey of my studies.
- The CPUT Library management and staff for their support and willingness to provide me with the information needed for this study.
- Parents, friends, colleagues, more especially in Eskom - CPM Protection, etc

TABLE OF CONTENTS

GLOSSARY

Power restoration: refers to the process of bringing services to customers following an outage.

A smart-grid: refers to an electrical power system grid with advanced technology, fully automated, with the latest information technology communication protocol where power flow from generation is monitored in real-time to the point of consumption.

Micro-grid: refers to a small-scale power system grid that can be decentralized and operate in islanded mode with its distributed energy system integrated. It can be interconnected to the primary power system grid.

Power-voltage curve: is the relationship between the active power to the load and the voltage at the load busbar or terminal.

Power-voltage curve: is the relationship between reactive power and the voltage at the load busbar terminals.

Power system reliability: refers to the ability of the power system to balance load and the generation supply through controlling the variation in real-time, this include adjusting generation supply and flexible loads.

Power system stability: refers to the ability of the power system to remain stable following disturbance

Service Restoration (SR): process undertaken to bring back electrical supply to customers flowing a planned or unplanned power outage.

LIST OF ABBREVIATIONS

PV	Photovoltaic
DER	Distributed Energy Resource
ESS	Energy Storage System
DG	Distributed Generator
IPP	Independent Power Producer
DC	Direct Current
CST	Concentrating Solar Thermal
SHC	Solar Heating and Cooling
BEMCS	Battery Energy Management Control System (BEMCS)
LV	Low Voltage
MV	Medium Voltage
IEEE	Institute of Electrical and Electronics Engineers
AMI	Advanced metering infrastructure
BES	Battery Energy Storage
RES	Renewable Energy System
VRLA	Valve-regulated lead acid
NiCad	Nickel-cadmium
NiMH)	Nickel-metal-hydride
RMS	Root-Mean Square
P-V	Active Power-Voltage
Q-V	Reactive Power - Voltage
ZIP	Constant-Impendence, Constant -Current, Constant - Power
DIgSILENT	DIgital SImuLation and Electrical NeTwork
MATLAB	Matrix Laboratory
RSCAD	Rea-time Simulator Computer Aided Design
ETAP	Electrical Transient and Analysis Program
RTDS	Real-Time Digital Simulator
PI	Proportional and Integral
IED	Intelligent Electronic Device
SR	Service Restoration
EV	Electric-Vehicle
MILP	Mixed-integer linear program
ROI	Return on Investment
RDN	Radial-Distribution Network

CHAPTER ONE

INTRODUCTION

1.1 Introduction

There is a significant social and economic impact on power system outages or blackouts. Therefore, power system outages must be restored quickly to prevent revenue loss. However, due to the complexity of the power system, the restoration process is becoming an extremely challenging task (Feng & Peijie, 2017).

The aging equipment failures mainly cause unplanned power outages at the power station. In the South African context, many generators supposed to have been decommissioned are still in service (Fabricius et al., 2020). As a result, power system outages were recorded high in South Africa to a maximum of 1352 GWh (Jarrad & Joanne, 2020). Furthermore, the record of load shed in 2019 surpasses the high register of 1325 GWh in 2015. Therefore, in observing the current state of the power system in South Africa as indicated in Figure 1.1, it can be forecasted that beyond the year 2020 amount of load to be shared will surpass record obtained 1352 GWh recorded in year 2019.

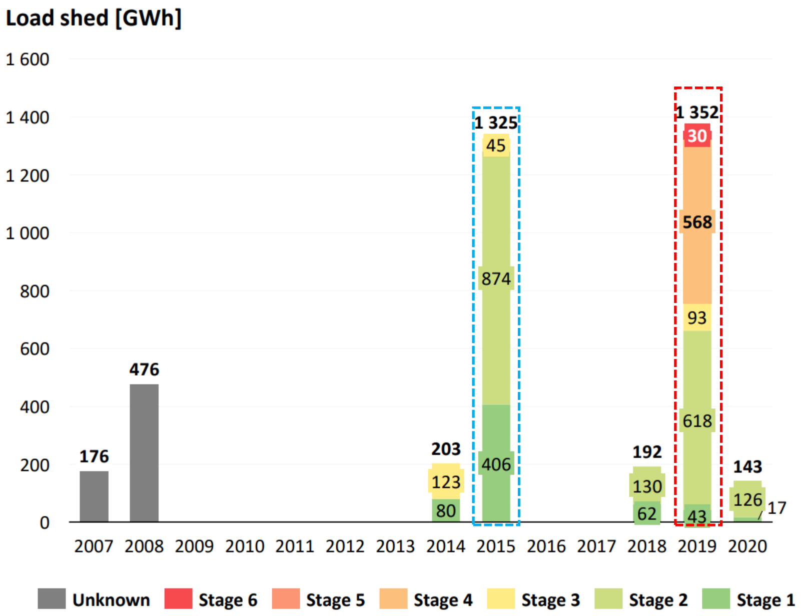
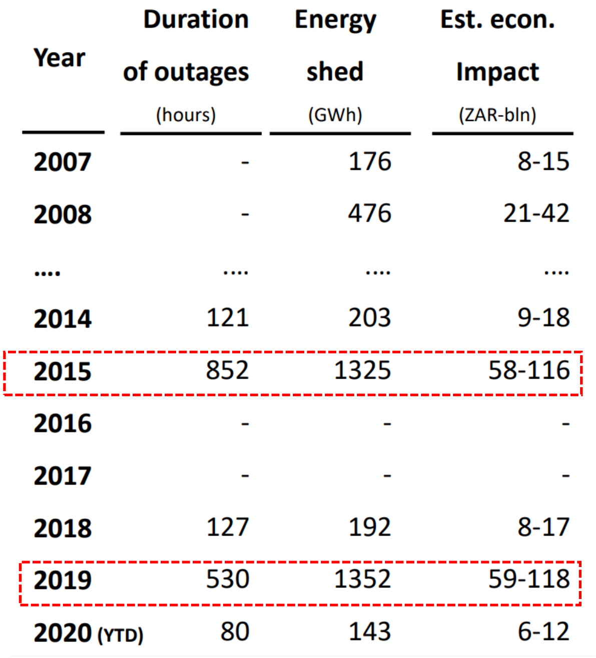


Figure 1.1: **South African load-shedding between 2007 and the beginning of 2020 according to stages** (Jarrad & Joanne, 2020)

The load-shedding has cause an immensely high disruption in its economic activities as most industrial and commercial activities are dependent on electricity. The revenue loss incurred due to the load-shedding between 2007 and the beginning of 2020 is illustrated in Table 1.1. In 2019, the revenue loss recorded is estimated to be between

R58-R116 billion as recorded year 2015. In 2019, the situation worsened, the revenue loss was estimated between R59-118 billion. It can be seen that the highest total time lost due to power outages was 530 hours for the year 2019, which was less than the outage duration of 2015 with record of 852 hours (Jarrad & Joanne, 2020).

Table 1.1: The outage duration and economic impact between 2007 and the beginning of 2020 (Jarrad & Joanne, 2020)



Year	Duration of outages (hours)	Energy shed (GWh)	Est. econ. Impact (ZAR-bln)
2007	-	176	8-15
2008	-	476	21-42
....	....	....	....
2014	121	203	9-18
2015	852	1325	58-116
2016	-	-	-
2017	-	-	-
2018	127	192	8-17
2019	530	1352	59-118
2020 (YTD)	80	143	6-12

After extended power outages due to planned and unplanned events, the restoration period is lengthened, as multiple steps must be followed to restore the power system. In addition, it will take time to achieve a self-healing power system due to the system's inherent complexity (Liu et al., 2016).

There are critical loads such as internet data centres that use large amounts of electricity, and these data centres include Google and Facebook. They heavily rely on electricity for the operation and cooling system, and power interruption could badly impact the world economy (Liu et al., 2019). Hospitals are also regarded as essential loads; therefore, power interruptions should be minimized.

Modern power systems eliminate conventional fossil-based generators as they present a high risk to the global climate and environment (Alireza et al., 2016).However, there are still some uncertainties about using renewable energy resources such as wind and solar due to their intermittent power output (Adrees & Milanović, 2019). However, they are clean energy sources. Another factor is improper integration into the power system grid, which risks triggering cascaded tripping, leading to more severe blackouts (Liu et al., 2016).

The introduction presents the foundation of the research study; however, to give a clear overview of the research, Section 1.2 covers the awareness of the research problem, and Section 1.3 highlights the research statement; the aims and objectives of the research are highlighted in Section 1.4. Then, the research question is indicated in Section 1.5; Section 1.6 focuses on the hypothesis, Section 1.7 describes the delimitation of the research. Section 1.8 presents the motivation of the research, and the assumptions are noted in Section 1.9. In Section 1.10, the research methodology is discussed, then Section 1.11 concludes the chapter.

1.2 Awareness of the Research Problem

The current power system model is based on fossil fuel as the primary energy resource of a conventional generation system. However, as decarbonization of the power system is the crucial focus globally, high penetration of renewable energy resources is noticed worldwide (Apfel et al., 2021; Mukoro et al., 2021; Sovacool, 2021; Maestre et al., 2021). Moreover, the intermittent nature of these energy resources results in less reliance; instead, fossil-fuel-based can be regarded as a reliable energy source as they have been proven to be dispatchable. On the other hand, wind and solar Photovoltaic (PV) energy are considered non-dispatchable energy resources, which means these resources generate power based on the resources, and they cannot be contracted to participate in any control structure of the power system (Contreras et al., 2019) and (Murray et al., 2021).

Due to control and dispatch capability limitations, energy resources such as wind and solar PV cannot be deployed in power outages. Therefore, it is necessary to consider other means of advancing these energy resources to enable different functions deemed essential in power systems for smooth smart grid operation. Therefore, a comprehensive study was required to be performed on how these resources can be configured to achieve other crucial functions for smart grid operations.

1.3 Statement of the Research Problem

The power system grid is becoming modernized and complex. Therefore, it is crucial and critical to investigate how distributed energy resources can be dispatched in the distribution system to improve the power system's reliability, stability, and service restoration. This proposed research studies the integration of distributed energy resources (DERs) and control configuration to achieve a reliable smart grid system.

1.4 Research Objective

The main objective of the study is to investigate grid integration methods of DERs in a smart grid and develop a control scheme that enables an optimal power dispatching to enhance power system stability and restoration.

To achieve the objective stated above, the following tasks were undertaken:

a. To write a literature review on:
    - Current distribution system model
    - Impacts of disturbance on power system stability considering load demand increase, generator trip, and excess power generation
    - Integration of DERs to enhance power system stability

b. To model the power system network and analyze its steady-state behaviour using DIgSILENT PowerFactory.

c. To apply DERs for smart grid stability enhancement and power restoration.

d. To develop an algorithm for the integration of DERs

e. To model and simulate the case study network in DIgSILENT PowerFactory software environment.

f. To develop a control scheme to enable the participation of DERs in smart grid stability and power restoration.

g. To investigate the algorithm's performance for various operating conditions in smart grids.

1.5 Research Questions

a. Can distributed energy resources be dispatched to optimize distribution grid stability?

b. How can distributed generators be configured to allow a smooth transition of active power flow following power system disturbances?

c. How can these energy resources be placed to minimize power loss in the power transmission process?

d. Can integrating distributed energy resources improve the restoration of distribution services following a power outage?

1.6 Hypothesis

The development of the additional control loop is expected to enable smooth, active power dispatching when the system experiences severe pressure and improves power restoration to the consumer. Industrial companies can utilize the proposed control loop where small-scale embedded generation is used. Independent power producers (IPPs) and utility companies can also enable their DERs to participate in active power deployment while maintaining system stability.

1.7 Delimitation of Research

The proposed research focused on active power dispatching and service restoration for distribution system applications. First, an analysis of the conventional distribution network system was performed. Then, the distributed energy resources was integrated, and the performance analysis was done after the integration; the development of an active power dispatching algorithm was considered. Finally, the distribution network was modeled using DIgSILENT Powerfactory simulation software, and various case studies were performed.

The case studies performed include:

- Distribution network under steady-state condition.
- Introduction of contingency and analysis of the distribution network under a dynamic state.
- Development of the control loop and assessment of its efficacy through a contingency analysis case study.

1.8 Motivation for the Research Study

It is required that a power system should be stable, supply electrical energy at the desired quality, maintain its stability following a disturbance, and be flexible enough to accommodate various energy technologies. However, it is a dynamic system (Eid et al., 2016) and (Bayat et al., 2016).

Introducing Distributed Energy Resources has resulted in more complex power system networks (Huang et al., 2021). In addition, these energy resources are much more dynamic than conventional generation systems. They quickly respond to power system changes due to their small-time constant reducing the overall moment of inertia (Bevrani, 2014) and (Zhang et al., 2011).

The most significant concern globally is the reliability of the network and its resilience when the fossil-fuel-based synchronous generation system is replaced with a renewable-based generation system. In addition, the quality of supply and the power system stability under dynamic and abnormal conditions are also of concern (Bello & Carter-Brown, 2010).

This study can pave a way for utility companies to utilize their DERs for power dispatch and service restoration to enhance the power system's reliance and stability. This will also encourage power producers to upscale renewable-based distributed energy resources integration to ensure that the load demand increase is supplied, and more energy reserves are secured, enabling more decarbonization of the power system grid.

1.9 Assumptions

In the study, the IEEE 33-bus distribution network was used as the power system model. The network was modified accordingly to achieve the objectives of the research. The network modeling and simulation were performed using the DIgSILENT PowerFactory simulation platform.

1.10 Research Methodology

The primary objective of the study was to develop a control loop that can enable the dispatching of active power from the Distributed Energy Resource to enhance the power system stability and improve service restoration. To achieve the objectives of the study, the IEEE 33-bus modified distribution network has been modeled using DIgSILENT. Figure 1.2 represent the configuration of IEEE 33-bus modified distribution network. The modified IEEE 33-bus network distribution network illustrated in Figure 1.2 consists of 34 busbars and 32 loads. The network modification was done by (Jelena Ponoćko, 2020) to incorporate the external grid supply by adding busbar 34. Moreover, the line connecting busbar 2 to busbar 19 on the conventional IEEE 33-bus network was rerouted from bus 2 to bus 34. Line 34 to 19 was also added, which presents the same parameters as the line between 2 and 34 (Jelena Ponoćko, 2020).

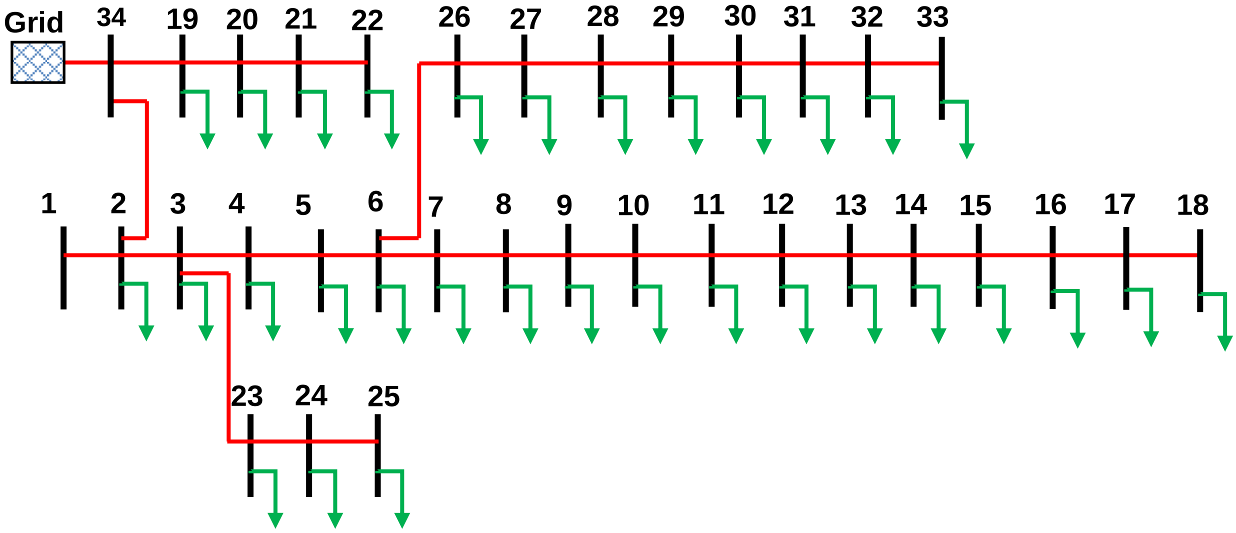


Figure 1.2: **Modified IEEE 33-Bus Network** (Jelena Ponoćko, 2020)

The methodology applied in this research follows the breakdown structure illustrated in the flow chart in Figure 1.3. The study workflow was first initiated through data collection. Then, the data collected needed to be analyzed and checked for suitability for the research's application. In the case of the proposed research study, validated data from previous literature and research work were considered, such as the data for the IEEE 33 bus distribution network. After that, network modeling was performed. The simulation of the steady-state and dynamic state was performed. The next was to consider the optimal placement of distributed energy resources and the integration methodology. Then the development of the control loop to enable the distributed energy resources to participate in active power dispatching was done. The results of the application of various case studies to validate the efficacy of the developed control loop were analysed, and conclusions and recommendations were drawn.

The modeling and simulations for the methodology shown in Figure 1.3 were performed using DIgSILENT powerfactory, including the control scheme development.

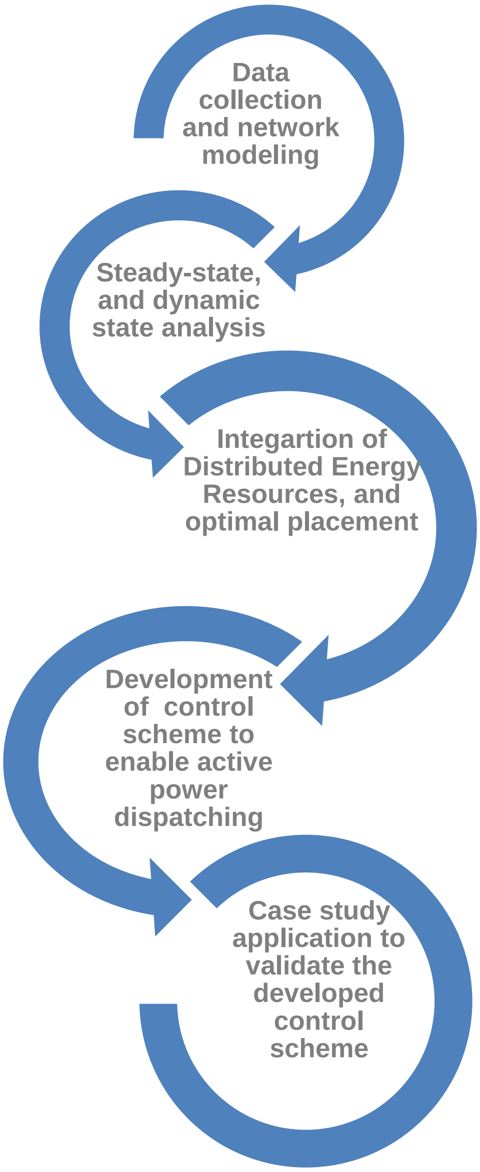


Figure 1.3: Research methodology flowchart

1.11 Dissertation Chapters

The structure of the dissertation has a composition of seven chapters; the details of what each chapter entails are as follows:

1.11.1 Chapter One

This chapter is the overall introduction of the research , where the study's background is described, highlighting the purpose, the aim and objective, and the whole dissertation structure.

1.11.2 Chapter Two

This chapter entails the literature reviewed concerning this study, the latest development, and the research gaps identified relating to this research.

1.11.3 Chapter Three

The third chapter presents the theory applicable to the research study to achieve the research objectives through the methodology proposed in chapter one.

1.11.4 Chapter Four

This chapter covered the modeling of the distribution grid network. First, steady-state simulation and the dynamic state are performed to state the network operation under these conditions. The distribution instability was observed when load demand increased, line trip disturbances were introduced, and analysis was made

1.11.5 Chapter Five

This chapter entails a systematic approach to improving distribution stability following the introduction of contingencies outlined in chapter four. The system includes determining the placement of distributed energy resources for optimal power dispatching to enhance grid stability. When energy resources are introduced, the dynamic contingencies applied in chapter four are repeated to analyze the contribution of these energy resources focusing on stability enhancement. Finally, a control scheme is developed to enable energy resource participation in intelligent distribution grid stability enhancement.

1.11.6 Chapter Six

The last objective of the research study is to improve the distribution grid service restoration. The approach to this objective is highlighted in chapter six using integrated energy resources. Using the same control scheme developed in chapter five, in this chapter, the restoration of the service approach is outlined

1.11.7 Chapter Seven

This chapter covers the conclusion and recommendations of the whole research. Achievements are noted within this chapter, and future research focuses are also covered.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

The global distribution grid is modernized through technological innovation and improved conventional systems. However, the modernization of the traditional distribution system has brought complexity to the distribution grid. Although the distribution system is modernized, power system faults are still occurring. Due to the complexity of the grid, fault finding and service restoration is being lengthened (Ganganath et al., 2017). Although the distribution network is being modernized, it is also anticipated that it can positively position the network to have adequate generation capacity by integrating other energy resources (Weijia & Fei, 2021). The configuration of the conventional distribution grid and the future grid needs a broad understanding to allocate resources for a more efficient system.

The main objective of this chapter is to provide a general overview for readers who are interested in DERs. The literature review entails the work conducted in line with the subject of concern: the utilization of distributed energy resources to enhance smart grid stability while improving service restoration. The power system grid is divided into generation, transmission, and distribution. These components consist of various apparatus integrated to form a functioning grid; however, the proposed study focuses on the distribution system. It is, therefore, necessary to outline the sub-sections to be covered.

Section 2.1.1 is the overview of the distribution system network, followed by section 2.1.2, which highlights the power outages and restoration methods in the distribution grid. Section 2.1.3 provides information on the optimal placement of Distributed Energy Resources in the distribution System. Section 2.1.4 covers the control techniques for power dispatching. The comparative analysis and discussion of the developments in the existing literature are indicated in Section 2.2 and finally, Section 2.3 is the conclusion of the literature review.

2.2 Overview of Distribution System Network

A distribution system network is a complex network of electrical components that delivers electrical power to end-users. It is a crucial part of the power grid and plays a vital role in ensuring that electricity is delivered reliably and efficiently to homes, businesses, and other facilities. A distribution system is also regarded as a tool for allocating electrical energy to end-users at the desired supply quality. It consists of the primary substation, switching station, and customer substation. The primary substation converts the high voltage (35-230kV) from transmission or sub-transmission to medium voltage (1-35kV) and sends it to the switching station. The switching station sends the electrical energy to the customer substation (mini-substation) to step down the voltage from the MV to low voltage (100-1000V). Finally, the power gets distributed to the end-user on the LV side for household consumption (Koutsoukis et al., 2021). Distribution can be either alternating current or direct current nature.

The distribution system consists of various components such as transformers, distribution lines, underground distribution cables, load, shunt capacitors, and voltage regulators for adequate power delivery to customers. The transformers convert voltage from a high to a lower level and vice versa. Distribution lines and cables perform the same function of enabling electric power delivery to customers at the desired voltage. Loads consume the power generated while shunt capacitors compensate reactive current through varying shunt impedance to maintain the distribution line voltage and improve the system power factor (Mondal et al., 2020). Voltage regulators also ensure that the voltage in the distribution system is maintained at its acceptable range (within 10% tolerance). This automatic voltage regulator setting is punched on a line-drop-compensator device in the voltage regulator control panel (Gönen, 2005). The current distribution system is vertically configured, meaning that the source of supply is from the generation system. It gets supplied to the distribution system through transmission infrastructure, as shown in Figure 2.1.

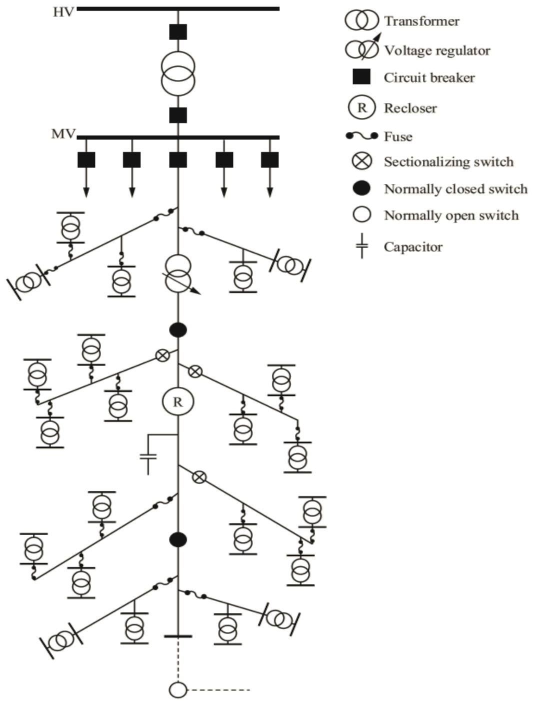


Figure 2.1: **Typical distribution network system** (Koutsoukis et al., 2021)

Meters are used to measure the amount of electricity consumed by end-users and are typically installed at the service drop or at the point of connection to the distribution system network.

The evolution of the distribution infrastructure has led to a modernized distribution network called a smart distribution grid. A smart distribution grid is an advanced electrical grid that uses modern digital communication and automation technologies to enhance the electricity distribution system's reliability, efficiency, and safety. It is a crucial part of the modernization of the power grid, which is necessary to meet the growing electricity demand, integrate renewable energy sources, and reduce carbon emissions.

A smart distribution grid can collect and analyze data from various sources, such as smart meters, sensors, and other devices, to optimize energy management, improve power quality, and reduce outage times. It can also support bidirectional power flows and enable the integration of distributed energy resources, such as solar panels, wind turbines, and energy storage systems.

Some of the key features of a smart distribution grid as indicated by (Kim et al., 2019), include:

- Advanced metering infrastructure (AMI) - Smart meters and other devices provide real-time energy consumption and production data.
- Distribution automation - The use of sensors, control systems, and other technologies to monitor and control the flow of electricity in the distribution network.
- Demand response - The ability to adjust energy usage in response to changing supply and demand conditions.
- Integration of distributed energy resources - The ability to manage and optimize renewable energy sources and energy storage systems.
- Cybersecurity - Robust security measures to protect the grid from cyber threats.

By implementing a smart distribution grid, utilities can improve operational efficiency, reduce costs, and enhance their ability to respond to emergencies and outages (Aman et al., 2022; Awad et al., 2015; Khasanov et al., 2020). As a result, consumers can also benefit from improved energy management, increased reliability, and lower energy bills.

The integration of distributed energy resources in the distribution system has sought advancement in grid stability; however, the complexity of the grid is on the rise. The modern distribution system with distributed generators is shown in Figure 2.2. This advancement also motivates micro-grid development to lower the dependence on the traditional power system grid.

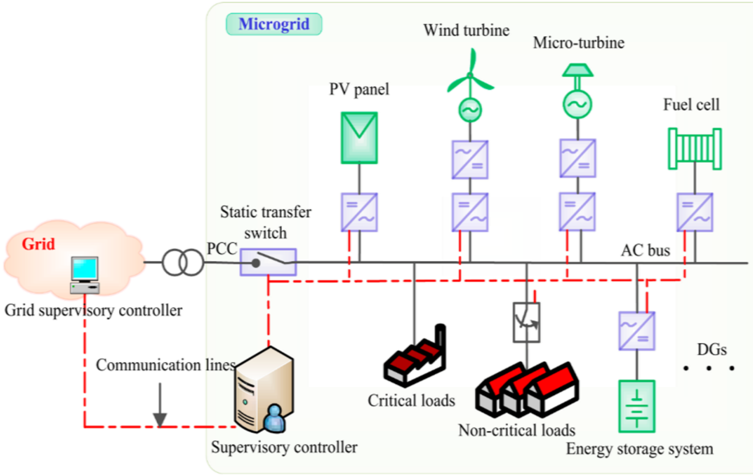


Figure 2.2: **Smart grid concept** (Hossain et al., 2019)

However, distribution networks are prone to various disturbances because no power system is completely reliable (Viawan & Banktavakoli, 2018), and the severity of these disturbances varies. However, disruptions can lead to power outages.

2.3 Power outages and restoration methods in the distribution grid

Power outages in the distribution grid can occur due to various reasons, such as severe weather conditions, equipment failures, maintenance activities, and other unforeseen circumstances. When power outages occur, it is essential to have a strategy to restore power as quickly and safely as possible. Here are some standard restoration methods used in the distribution grid:

- Fault Detection and Isolation: The first step in restoring power after an outage is to detect the location of the fault or the cause of the outage. This can be done using fault detection and isolation techniques such as remote monitoring, circuit breakers, and other sensing equipment.
- Power Restoration: Once the location of the fault has been identified, power restoration can begin. This typically involves rerouting power to the affected area through alternate routes or switching operations. This may also include repairing or replacing damaged equipment, such as transformers or power lines.
- Load Shedding: In some cases, the electricity demand may be too high for the available supply. In such situations, load shedding can be implemented to temporarily reduce the demand by shutting off power to non-critical loads.
- Backup Power: In some critical facilities, backup power sources such as generators or battery systems can provide temporary power during an outage.

- Communication and Coordination: Effective communication and coordination among utilities, emergency responders, and customers are essential during power outages. This helps to ensure that everyone is informed about the status of the restoration efforts and any safety precautions that need to be taken.

Overall, effective planning, monitoring, and communication are key to restoring power in the distribution grid after an outage. By using a combination of these methods, utilities can minimize the duration and impact of power outages and ensure a safe and reliable supply of electricity.

Power disruptions continue to be witnessed across the globe, and the causes of these power outages are different. One of the significant causes of these power outages is severe weather conditions (Chen et al., 2017; Sun et al., 2019). Faults in the power system network also contribute to power outages (Shen et al., 2020). Some of the power outages are human-made; this includes theft of the power network infrastructure. (Patsakis et al., 2018) highlighted the significant contributors to power system blackouts, including human error in power system operation and natural phenomena, as highlighted before, which could be extreme weather events (hurricanes) and earthquakes. Most recently, the power system network has been prone to cyber-attacks, and there is research work in progress on network strengthening and prevention measures for cyber-attacks (Patsakis et al., 2018; Liu et al., 2016).

When measures to prevent power system supply disruptions have failed, it is crucial to find optimal ways of restoring the services to consumers as quickly as possible to avoid hostile attacks (Saxena & Bhatia, 2021). The security will be compromised due to the unavailability of services. (Liu & Ding, 2021) demonstrated that distributed energy resources (DERs) can be quickly used in supply recovery post-outage. In addition, distributed energy resources are being integrated into the power system grid to boost network stability and reliability. Therefore, the concern is how they can be optimally deployed to improve grid stability while enhancing the restoration of services. It is also essential to find a suitable position for the placement of DERs.

The summary of the literature reviewed is covered in Table 2.1. The summary highlighted covers the author's name, the aim of the study, methods used, challenges, the power system model utilized, and the simulation of real-time implementation of the proposed method.

Table 2.1: Summary of the reviewed literature for power outages and restoration methods in the distribution grid

Author(s)	Aim	Methods	Drawbacks	Power System Model	Simulations
(Xiaoyu et al., 2014)	Establishment of a restoration model based on grid actual situation, which is more realistic for the active distribution network (ADN)	The genetic algorithm as the recovery scheme	No evidence of the simulation to the results presented. No simulation software indicate where results were validated	IEEE 33 nodes system	Not specified
(Pavana & Triveni, 2015)	Enhancing restoration through Mst-kruskal's (minimum spanning tree) algorithm method	Mst-kruskal's algorithm (spamming tree)	The applied method's significance is only on losses reduction; however, the improvement in restoration time is not covered	IEEE 3 FEEDER, 16 BUS AND 1 FEEDER, 33 bus distribution system	MATLAB software.
(Chen et al., 2015)	An adjustable robust restoration optimization model with a two-stage (recovery of outage power and the worst-case fluctuation scenarios)	the uncertainty budget	No power system simulation system was utilized to test the efficacy of the proposed model.	PG&E 69-bus system and a modified 246-bus system	Monte-carlo simulations
(Shen & Wu, 2018)	Review on methods for service restoration (SR) in distribution networks, which can be categorized into two types, centralized and decentralized methods, according to their implementation.	Focusing on centralized and decentralized methods (a review)	The methodology only focuses on two methods; no evaluation validation is conducted regarding the simulation model.	No simulations conducted	No simulations conducted
(Papasani et al., 2021)	To automatically restore the load swiftly and reliably after a blackout. The comprehensive approach for CLPU, Inrush currents, load priority, and load variation are considered to achieve smooth and successful operation.	The bottom-up approach, with help, from intelligent electronic devices (IED).	The traditional method was used. The impact of the integration of distributed energy resources was not considered	A sample industrial system	Power world simulation
(Satinge & Jawadekar, 2021)	The power restoration plan relies on coordinating distributed control across relays, load switches, voltage source converters, and the autonomous operation of a multi-terminal DC system. The plan also involves stabilizing the DC system with a virtual impedance method to mitigate potential oscillations arising from constant power load terminals.	Utilization of Direct current (DC) stabilizing control	There is too much system conversion, which can affect the operation of the distribution protection system.	A four-terminal DC network is	MATLAB Simulation

Author(s)	**Aim**	**Methods**	**Drawbacks**	**Power System Model**	**Simulations**
(Poudel & Dubey, 2021)	A new two-stage restoration framework is introduced for generating a restoration solution through a sequence of control actions. In the first stage, the framework produces a restoration plan that enables traditional service restoration through feeder reconfiguration and intentional islanding using grid-forming distributed generation. In the second stage, an optimal switching operation sequence is generated to restore the system to its final configuration rapidly.	Mixed-integer linear program (MILP)	This work does not cover the propagation of distribution system congestion that may result from using a distributed generator to restore services to loads that were not covered in both stages	4-feeder 1069-bus distribution test system	Not specified
(Wen et al., 2022)	Using a hierarchical approach, developing a service restoration mechanism for distribution networks with distributed generations and multiple faults.	Hierarchical approach	The absence of consideration for load demand uncertainties and the assumption of an active remote control system are noteworthy omissions. Additionally, if the remote control system is inactive, the return on investment (ROI) for installing those control switches is also left unaddressed.	IEEE 33 and 69 bus systems	MATLAB R2021
(Zietsman et al., 2022)	A multi-objective analytical approach is utilized to evaluate wind power projects' technical and economic viability by conducting a financial analysis of the costs and benefits associated with the optimal integration of wind power into distribution networks. This assessment aims to determine the profitability of such integration.	Quantitative approach and various optimization algorithms for financial viability	The system assessment focuses on a single fault, and multiple faults are not considered.	1 Feede and 5 bus system	Digsilent PowerFactory
(Yuan et al., 2022)	the decision-making of transmission system restoration control, decision-making of distribution system restoration control, decision-making of transmission and distribution coordinated restoration control	Umbrella review or overview	The information is derived from literature and lacks specific details regarding a topology or experimental results.	No simulations conducted	No simulations conducted
(Swapna, Ganapaneni Srinivasa Varma et al., 2022)	a new approach to a service restoration method for a low-voltage distribution network at the time of a power outage using existing electric-vehicles (EVs) available in a parking place	linear optimization model	When load demand exceeds the predicted EV’s total power output, load shedding must be implemented.	Not specified	MATLAB

2.4 Optimal Placement of Distributed Energy Resources in the Distribution System

The optimal placement of Distributed Energy Resources (DERs) in a distribution system depends on a variety of factors, including the system's load profile, voltage profile, and the types and capacities of the DERs under consideration. However, several general principles can guide the placement of DERs in a distribution system.

- Load profile (Basu et al., 2010; Bogno et al., 2014; Gupta et al., 2021): The location of DERs should be based on the load profile of the distribution system. The DERs should be placed in areas with high electricity demand, so they can be used to offset the load and reduce the need for power from the grid.
- Voltage profile (Lasmari et al., 2020): DERs can also be used to improve the voltage profile of the distribution system. For example, if there are areas in the system where the voltage is low, DERs can be placed in those areas to help boost the voltage.
- Location of renewable resources: If the DERs under consideration are renewable resources, such as solar or wind, they should be placed in areas with high renewable energy potential. For example, solar panels should be placed in areas with high levels of sunlight, while wind turbines should be placed in areas with consistent wind patterns.
- Location of energy storage: If energy storage is considered a DER, it should be placed where it can be most effective. For example, if there are areas in the distribution system with frequent power outages, energy storage systems can be placed to provide backup power.
- Cost-effectiveness: The placement of DERs should also take into account the cost-effectiveness of each option. DERs that can provide the most benefits at the lowest cost should be given priority.

Overall, the optimal placement of DERs in a distribution system is a complex problem that requires careful consideration of various factors. However, by taking into account the load profile, voltage profile, renewable energy potential, location of energy storage, and cost-effectiveness of each option, it is possible to identify the optimal placement of DERs to improve the distribution system's performance.

The composition of distributed energy resources in the power system is worth noting. Distributed energy resources include energy storage systems (ESSs) and distributed generators (DGs). Furthermore, the DGs can comprise small units of photovoltaic, wind turbines, and diesel generators (Ahmadi et al., 2020).

The placement of DERs and size determination is crucial in cost minimization and technical losses incurred during the generation's tenure. (Sharma & Singh, 2020) indicated that optimal placement of DERs can be performed through various techniques, including numerical and mathematical methods. According to the same authors, the numerical method is more straightforward in implementation but lacks combined cumulative results and planning. Although there are still issues with results affected by many iterations, the mathematical method is highly recommended.

Table 2.2 is the summary of the some of the paper reviewed focusing on optimal power dispatching of distributed energy resources in the distribution system. The elements reviewed articles include the purpose of the paper, the methods or techniques used in optimal power dispatching in the presence of DERs, the drawbacks of the study, network model utilized to evaluate the proposed concepts of techniques, and lastly, the simulation platform used for concept evaluation and validation

Table 2.2: Summary of the reviewed literature for optimal power dispatching of Distributed Energy Resources in the Distribution System

Author(s)	Aim	Method / Technique	Drawbacks	Power System Model	Simulations
(Zima & Ledva, 2013)	This emphasizes the EU FP7 ADDRESS proposal, which aims to establish a self-dispatch market for active demand. The proposal involves a market clearing process followed by matching with distribution network constraints to validate cleared products.	centralized dispatch-based approach	The potential for reducing power losses and balancing supply and load demand is not addressed.	Physical network model of Carperone (500 nodes)	MATLAB software
(Limouchi et al., 2016)	The proposal is centered on implementing active and reactive power dispatching strategies for active generators within microgrids.	Droop control	The topic of variability in power output from PV systems is not addressed, and the power generated by such systems cannot be dispatched.	11 kV, 50 Hz grid with three short-distance distribution lines	MATLAB/Simulink
(Jobanputra & Kotwal, 2018)	The proposal suggests assigning the active power generation schedule among the generating stations while considering system constraints to minimize the total cost of power generation.	Particle swarm optimization	Renewable energy resources are not addressed in optimal power dispatching, and their potential role in the existing grid topology is also absent.	IEEE 39 Bus test system	Not specified
(T. Xu et al., 2019)	The research introduces an asynchronous distributed approach to economic dispatch in active distribution networks (ADNs).	Alternating direction method of multipliers (ADMM) algorithm	The study did not address demand response or scenarios with more intricate communication delays. In addition to not covering the impact of renewables on economic dispatching participation	IEEE 33-bus and 69-bus systems	MATLAB, YALMIP, and CPLEX
(Lu et al., 2019)	The focus of this study is on developing a distributed economic dispatch (ED) strategy for advanced distribution networks (ADNs) that have multiple virtual power plants (VPPs) using an alternating direction method of multipliers (ADMM).	An alternating direction method of multipliers (ADMM)-based Distributed Algorithm	The impact of virtual power plants on commercial applications and energy markets has been overlooked.	IEEE 33-bus incorporated with four VPPs Fig. including a 69-bus system for further testing	MATLAB simulation software
(Jian et al., 2019)	The focus of this study is to present a framework for active distribution network dispatch that is coordinated and interactive, which is structured hierarchically and divisionally.	Hybrid Particle swarm 0ptimization (HPSO) algorithm	The model's role in reducing power losses during power dispatching is not addressed in the study	14-bus active distribution network	Not specified
(Yuan et al., 2020)	This study presents a novel approach for determining the optimal allocation and sizing of a lithium-ion battery energy storage system (BESS) with the primary objective of minimizing total loss reduction in the distribution system.	Cayote Optimization Algorithm (COA). The technique was further compared to Firefly Algorithm (FA), Whale Optimization Algorithm (WOA), and Particle Swarm Optimization (PSO)	While the study concentrates on reducing losses in the distribution network by determining the location and size of BESS and PV, the optimal power dispatching process is not comprehensively addressed.	48 buses distribution system	Not specified

Author(s)	Aim	Method / Technique	Drawbacks	Power System Model	Simulations
(Zhou et al., 2021)	The proposed study suggests using a primal-dual gradient algorithm to solve an optimization problem that jointly addresses both Transmission and Distribution systems. Furthermore, a distributed (T&D) market-based equivalent of the gradient algorithm is proposed to be used for practical implementation purposes.	Primal-dual gradient algorithm	The simulation results do not demonstrate how the system frequency is affected when one of the generators, specifically generator 7, is removed.	IEEE 39-Bus system connected with 7 different distribution networks	MATPOWER
(Mulleriyawage & Shen, 2021)	The focus of this study is to explore methods for enhancing the economic viability of Battery Energy Storage Systems (BESS) through Demand Side Management (DSM) of residential loads.	BESS power dispatching, capacity sizing considering Demand Side Management (DSM)	The study utilized data from a single year, which may limit its ability to capture long-term trends. Additionally, it did not account for the potential impact of future load growth, nor did it examine the effects of different load composites.	A grid-connected residential DC microgrid	Not specified
(Gill et al., 2022)	The aim of this study is to optimize the placement of distributed energy resources (DER) in the radial distribution network (RDN) in order to reduce power loss, enhance voltage profile, and mitigate issues such as system islanding, relay tripping, and reverse power flow.	ANFIS, EPSO and GA techniques	The study does not address the role of distributed energy resources (DERs) in improving frequency stability or the effect of losing a distribution network line.	IEEE 33 bus radial distribution network	Not specified
(Kumar et al., 2022)	The study provides a comprehensive literature review and critical analysis of the state of the art in optimal multi-objective planning of distributed generation installation in power networks, taking into account various factors such as objective functions, constraints, optimization techniques, DG types, distribution models, DG variables, mathematical formulations, and international participation. The paper aims to identify research gaps and make future recommendations for robust optimal planning of DGs, considering various objectives and algorithms, as well as uncertainties and testing on large and complex distribution networks.	systematic literature review.	The authors did not review papers that highlight the contribution of distributed energy resources to frequency stability. The focus of the review was solely on voltage stability, although frequency stability is also a crucial aspect of power system stability.	As this is a literature review, no simulations were conducted.	As this is a literature review, no simulations were conducted.
(Gafari Abiola et al., 2023)	The aim of this study is to utilize Particle Swarm Optimization (PSO) to optimize the placement and sizing of Distributed Generation (DG) units in the distribution system, with the objective of minimizing the total power loss in the network.	Particle Swarm Optimization technique to reduce power losses.	The study solely focuses on mitigating losses and voltage issues in DG integration, without considering the overall improvement in grid stability that DGs could provide. Moreover, the study does not address reliability indexes enhancement after the integration of DGs.	Nigeria Distribution network 11 kV 34-bus Ayepe feeder of the Ibadan Electricity Distribution Company (IBEDC)	A MATLAB simulation program

2.5 The control techniques for power dispatching using Distributed Energy Resources in the distribution grid

Distributed Energy Resources (DERs) are small-scale power generation technologies located near or within the electricity consumers' premises. Examples of DERs include solar panels, wind turbines, small hydroelectric generators, and energy storage systems. DERs are becoming increasingly popular due to their ability to provide local energy solutions, improve the grid's resilience, and reduce greenhouse gas emissions. Control techniques for power dispatching are essential to integrate DERs into the distribution grid effectively. Here are some of the control techniques used for power dispatching using DERs in the distribution grid:

- Demand response (Bayat et al., 2016; Short et al., 2007; Lee et al., 2018; Zhu et al., 2021): Demand response involves controlling consumers' energy usage during peak hours. It helps reduce the demand for energy during peak periods, reducing the need for additional generation capacity. DERs such as energy storage systems and smart thermostats can be used to implement demand response.
- Dynamic pricing (Althaher et al., 2022; Bielecki et al., 2022; Gupta et al., 2022): Dynamic pricing involves charging consumers different prices for electricity at different times. It helps to encourage consumers to reduce their energy usage during peak periods when prices are high. DERs such as smart meters can be used to implement dynamic pricing.
- Forecasting and scheduling (Worral et al., 2016; Kabiri-Renani et al., 2022; Konstantin O, 2021; Anaadumba et al., 2021): DERs can be scheduled to operate during periods of high demand or low supply to optimize their usage. Forecasting techniques can be used to predict energy demand and supply, which can help in scheduling the operation of DERs.
- Voltage regulation (Roy et al., 2012; Bhusal et al., 2021; Khunkitti et al., 2022): DERs such as solar panels and wind turbines can cause voltage fluctuations in the distribution grid. Voltage regulation techniques can be used to control the grid's voltage levels and ensure the system's stability.
- Load balancing (Boyle et al., 2018; Moreno Jaramillo et al., 2021; Silva et al., 2021; Rodrigues & Garcia, 2023): Load balancing involves balancing the energy supply and demand in the distribution grid. DERs, such as energy storage systems and electric vehicles, can balance the load and ensure the grid's stability.
- Islanding detection and control: Islanding occurs when a small section of the grid continues to operate even when the rest of the grid is disconnected. This

can be dangerous for utility workers trying to repair the grid. DERs can be used to detect islanding and control the operation of the grid to prevent islanding.

Overall, the control techniques for power dispatching using DERs in the distribution grid involve using advanced monitoring and control systems to manage the energy supply and demand in the system. These techniques help to ensure the stability and reliability of the distribution grid while maximizing the benefits of DERs.

The utilization of DERs for power dispatching starts with the classification of the types of DG that can be used for this function. According to (Shaaban et al., 2013), the DGs can be divided into two categories: synchronous generator-based, such as diesel and natural gas, and inverter-based, such as fuel cells mini-turbine generators. (Xu et al., 2021) indicate that the power generated through dispatchable DGs can be adjusted; however, wind and solar power are intermittent, and fluctuation is expected as they are climate-dependent. These energy resources are regarded as non-dispatchable, and their modeling is based on probability density. The control techniques in enabling DERs to be dispatchable not only assist in power restoration; their dispatchable capability also helps stabilize the power system grid as they seek to balance the load demand of the power being generated. The wind power plant is used in (Dai et al., 2019) and (Mditshwa et al., 2021) for participation in primary frequency control. (Bragantini, 2019) indicates that the battery energy storage system has the potential to assist in frequency regulation. According to the assessment (Muhammad et al., 2021), the wind power plant can also help improve voltage stability. The voltage stability index improvement was further validated by (Radvar et al., 2020). Solar PV can also be utilized, according to (Alramlawi et al., 2019) and (Lusis et al., 2019), but a vigorous control scheme to deal with active and reactive power will be needed. In their proposed models, a battery energy storage system is incorporated to assist in dealing with system frequency issues by dispatching active power management when required.

Table 2.3 summarises some of the papers reviewed about control techniques for power dispatching using Distributed Energy. The elements reviewed articles include the purpose of the paper, the methods or power dispatching control techniques used in power system dominated with distributed energy resource, the drawbacks of the study were highlighted, network model utilized to evaluate the proposed concepts of power dispatching control techniques, and the simulation platform used for concept evaluation and validation

Table 2.3: Summary of the reviewed literature for the control techniques for power dispatching using Distributed Energy

Author(s)	Aim	Methods	Drawbacks	Power System Model	Simulations
(Onar & Demirbas, 2022)	Implemented a survey for the provision of smooth transition between operation modes in PV-BESS Microgrid	a survey aimed at facilitating a smooth transition between different operating modes in a PV-BESS Microgrid.	Possible control techniques or methods to be used in dispatching power from distributed energy resources are not emphasized by the authors.	A survey – no simulation network modelled	A survey – No simulation tools utilized
(Stanojev et al., 2022)	Introduction of a novel centralized MPC-based controller that enables the concurrent provision of voltage support and primary and secondary frequency control by adjusting the setpoints of a heterogeneous group of DERs in active distribution grids	Multirate model predictive control using centralized MPC algorithm	The authors did not take into account the effect that switching may have on the total distribution losses. Additionally, there was no consideration given to the potential consequences for the distribution grid in the event of a main line failure.	Modified IEEE 33-bus system, with the DER	YALIMP – Matlab
(Panda et al., 2022)	A review into the Integration of Distributed Energy Resources and Energy Storage Systems with Smart Distribution Networks Using Demand-Side Management highlighting gaps in the research and possible prospects	A systematic review	The study focuses on the challenges of frequency regulation in a power system that is integrated with DERs, which are intermittent in nature. However, the study does not review any existing control schemes that could potentially overcome these challenges. Additionally, the available power dispatching mechanisms are not addresse	A review – no simulation network modelled	A review – No simulation tools utilized
(Sharma & Mishra, 2022)	Development of a virtual power plant (VPP) model for the 11 kV distribution networks, which assists the utility in flattening its demand profile and permits high integration of grid-connected DER in a secure manner	Virtual power plant (VPP) integration	The analysis is limited to dynamic models with durations ranging from seconds to hours, and does not take into account grid stability control. While the study shows that deploying DERs can significantly improve feeder loading by reducing peaks, it does not address losses.	Physical network model-11 kV distribution networks	DER-CAM
(Mondal et al., 2022)	Design of a brownfield microgrid and the control framework to manage diesel generators and renewable sources as well as demand and storage assets	microgrid controller with	The study has a broad scope focusing on brownfield microgrids, and it does not delve into the specific composition of the microgrid controller or provide mathematical models. However, it does identify the variables that are being controlled within the microgrid.	Not specified	Not specified
(Patel et al., 2022)	Development of distributed control architecture for distributed energy resources (DERs) that include photovoltaics (PVs) and battery energy storage systems (BESSs). The control architecture is based on the virtual clustering of DERs to provide power balance (minimizing the net load (generation load) in each cluster) considering the BESS's state of charge.	Distributed control architecture cluster for distributed energy resources (DERs) that include photo- voltaics (PVs) and battery energy storage systems (BESSs)	The model analysis does not take into account frequency stability or service restoration after a disturbance in the grid.	IEEE123-bus system and theIEEE 8500-bus system	OpenDSS simulator

2.6 Comparative analysis and discussion on the developments in the existing literature

The literature reveals that there has been immense workaround utilization of DERs for improving the power system stability and service restoration. Various methodologies for DERs placement and sizing are also proposed. Multiple algorithms are proposed to find the best place for DERs in the power grid. Possible techniques to be used in dispatching power from DERs are highlighted. However, there needs to be more evidence to deploy these DERs. These techniques are primarily theoretical and lack practical implementation to prove their validity.

From the literature reviewed, no specific consolidated scheme is developed to enable the optimal power dispatching of DERs to enhance grid stability while improving the service restoration to the loads. In addition, wind power plants and solar energy penetrate at a high rate in the power grid, and their intermittent nature limits their participation in service restoration and stability. However, the proposed work seeks to address the issue of the utilization of energy resources in all activities in the power system on the grid to enhance reliability, restoration, and stability with a battery energy storage system. Furthermore, using a battery energy system will also help maintain the service when these energy resources cannot produce power in the event of primary resource unavailability (wind and sunlight). Moreover, DIgSILENT Powerfactory is one of the industrial-based software that helps in concepts and techniques validating in the research and development process; however, the utilization of this software has yet to be used in the literature being reviewed. Therefore, to prove the validity of techniques, methodology, and algorithms performed, software like DIgSILENT can be used to perform such studies.

2.7 Summary

The literature review showed a gap in developing and implementing the control scheme on various power system simulation platforms to validate proposed philosophies. The proposed research study aimed to develop a control scheme that can enable the smooth dispatching of power to ensure grid stability and improve service restoration. Furthermore, it has been noted in the literature reviewed that there needs to be more work on control development studies using DIgSILENT PowerFactory simulation platforms. Most of the research work conducted was done using MATLAB simulation platform. DIgSILENT simulation platform offers an interactive network simulation to observe the dynamics found in power system. Therefore, this research study will also contribute immensely to the utilization of PowerFactory simulation platforms in developing control schemes.

CHAPTER THREE

DISTRIBUTION NETWORK MODELING AND OPERATION ANALYSIS

3.1 Introduction

The distribution network configuration is traditionally configured in a vertical structure. In the vertically configured power system, the power flow is uni-directional, meaning that it only flows in one direction, from the generation on top through the transmission system to distribution for consumption, as indicated in Figure 3.1. Since the power delivered at the distribution system is transported from a generation located far away, losses during transmission are encountered. However, the quality of supply needs to be satisfactory. Therefore, the power quality variables that are constantly monitored are the system frequency and voltage.

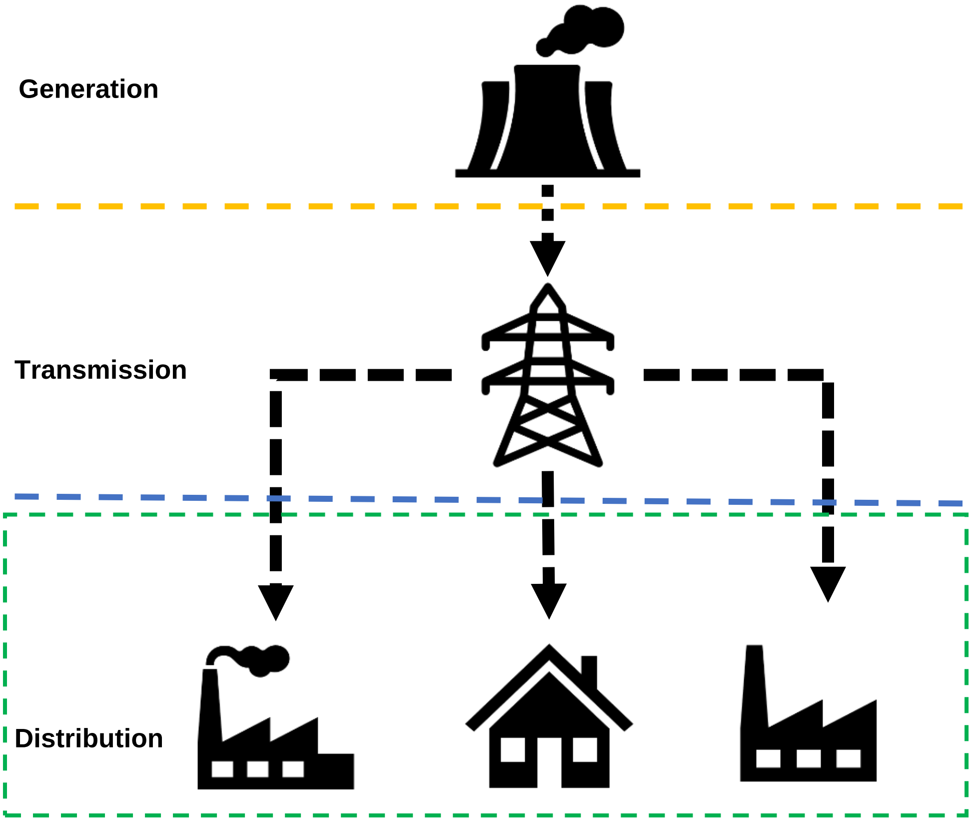


Figure 3.1: **Vertically configurated conventional Power system configuration with power flow**

The impact of inadequate supply quality is realized at the distribution level by consumers, where their equipment can be operated below or over the rated voltage and frequency levels.

Therefore, it is essential for the power system planners first to model the system and study its behavior under various conditions to which the power system can be subjected. The distribution network analysis needs to be evaluated under the steady-state condition and dynamic state to understand its response broadly under multiple conditions aiming at determining the power flow and the overall system loading (Georgilakis et al., 2021).

The chapter's structure can be summarized as follows: Section 3.1 serves as an introduction to the topic at hand, while section 3.2 provides an overview of the distribution network modeling approach. Section 3.3 delves into power flow analysis, and section 3.4 discusses the optimal placement of Distributed Energy Resources. In section 3.5, the modeling approach for different types of distributed energy resources is covered. The chapter concludes with section 3.6, which provides a summary of the key points discussed in the chapter.

3.2 Distribution network modeling approach

The modeling approach for the distribution system starts with representing all the system components in a single-line diagram to understand their mathematical modeling and operation.

3.2.1 Load modeling

Load modeling represents the mathematical relationship between the power and the voltage in the load bus of concern. There are various load types, and their behavior and configuration are different. The load composition varies; some loads are purely resistive, others are more inductive, and some are more capacitive. The dominating component within the load configuration influences the dynamic response behavior to system changes (Stork & Mayer, 2017), (Abo-Al-Ez et al., 2012).

The modelling of the distribution network requires all load types to be configured to ensure that they can smoothly operate under various conditions, considering the dynamicity that these load types bring to the network. (Arif et al., 2018) provided a well-coordinated load model configuration, which can be used to analyze the distribution network operation. It is essential to note that the categories of the distribution network operations are of dynamic and static natures. The application of the load is critical when evaluating the dynamicity of the network. For this research, the static load model is used as it can be used to study both steady-state and dynamic-state network behavior.

3.2.1.1 Static load model

The static load types include the exponential, constant-impedance, constant-current, and constant-power (ZIP) load model, and frequency-dependent models. In addition, there is an interlink between these three models, which are static based and mainly used for steady-state and dynamic studies (Georgilakis et al., 2021).

- ZIP model mathematical representation:

$$P = P_0\left[a_1\left(\frac{V}{V_0}\right)^2 + a_2\left(\frac{V}{V_0}\right) + a_3\right] \quad \textbf{(3.1)}$$

$$Q = Q_0\left[a_4\left(\frac{V}{V_0}\right)^2 + a_5\left(\frac{V}{V_0}\right) + a_6\right]$$

$\boldsymbol{a_1}$ - $\boldsymbol{a_6}$ are the polynomial coefficients, $\boldsymbol{V}$ represents the actual voltage magnitude, while $\boldsymbol{V_0}$, $\boldsymbol{P_0}$, and $\boldsymbol{Q_0}$ present nominal voltage, active power, and reactive power, respectively.

The model presented by Equation (3.1) is a polynomial zip model, and the other models can be developed using the same equation. For example, the co-efficiencies are disregarded in the exponential model, while on frequency-dependant types, the load model is multiplied by the frequency factor. The frequency factor is given by:

$$Factor = \left[1 + a_f(f - f_0)\right] \quad \textbf{(3.2)}$$

$\boldsymbol{f}$ represents the system frequency measured on the busbar, $\boldsymbol{f_0}$ is for nominal frequency, while $\boldsymbol{a_f}$, represents the frequency-sensitivity parameter.

The load model can still be extended by incorporating all the model types, meaning integrating the exponential and frequency dependant features within the polynomial ZIP model.

3.2.2 Line and cable modeling

Other critical components of the distribution are the distribution conductors. These components ensure that the power is delivered to the customer by enabling the power flow to the load. They can be configured as overhead lines or underground cables (Pavana & Triveni, 2015). Overhead lines are separated and are running in parallel to one another. Each phase has its dedicated conductor on overhead lines; while underground, all phases can be grouped in one cable and separated through the insulation.

Overhead lines are cheaper than underground lines on the initial cost and installation; however, underground cables have much more advantages than overhead lines. These advantages are the following:

- No maintenance required
- Less susceptible to outages
- Environmental preferred in urban areas

The conductor used for overhead lines and underground cables can be copper or aluminum. The overhead line model is similar to the transformer series impedance equivalent circuit, except that shunt capacitance is not considered for overhead lines

(Mditshwa, 2021). On the other hand, the nominal $\boldsymbol{\pi}$ model is used for underground cables, and the shunt capacitance is considered.

The conductor selection to be used in distribution depends on various characteristics. According to (Georgilakis et al., 2021), the following factors need to be considered:

- The conductor type; is either an overhead line or an underground cable
- The material of the conductor and its crossectional area
- The series impedance per unit length
- Current carrying capacity
- The nominal operating voltage.

3.2.3 Transformer modeling

Power transformers are found in power generation, transmission, and distribution systems to transfer voltage from one level to another through electromagnetic induction (Georgilakis et al., 2021). For the distribution application, they step down the primary voltage to a lower level at the secondary voltage. The equivalent transformer circuit is presented in Figure 3.2 as a series impedance. These distribution transformers have less reactance and are more resistive due to their rated power capacity. This is why the power losses are considerably low.

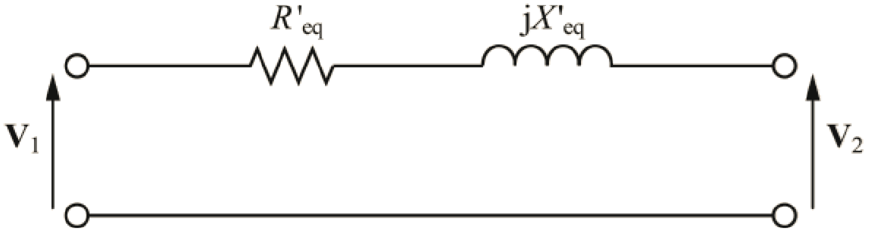


Figure 3.2: **Transformer equivalent circuit** (Koutsoukis et al., 2021)

The equivalent circuit impedance Z'_{eq} for the distribution transformer can be determined using Equations (3.3) to (3.6) (Georgilakis et al., 2021):

$$Z'_{eq} = R'_{eq} + jX'_{eq} \tag{3.3}$$

$$R'_{eq} = R_1 + R'_1 = R_1 + a^2 R_2 \tag{3.4}$$

$$X'_{eq} = X_1 + X'_1 = X_1 + a^2 X_2 \tag{3.5}$$

$$a = \frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{I_2}{I_1} \tag{3.6}$$

R_1 and R_2 denote the primary and secondary resistance, respectively, while reactance for primary and secondary are represented by X_1 and X_2 respectively. a is the turns ratio of the transformer.

3.3 Power flow analysis

After the distribution network modeling, the power flow simulation needs to be executed. The aim of performing this simulation is to determine the operation of the network during steady-state. Therefore, the network loading, such as line loading, transformer loading, and bus voltage constraints, can only be analyzed after the power flow is executed.

Various methods of performing power flow analyis exist. However, most are limited by network complexity. The most prominent used methods are the Gauss-Seidel and Newton-Raphson Iterative methods.

3.3.1 Gauss-Seidel iterative technique

The gauss-seidel iterative method is developed to provide solutions to non-linear algebraic equations. In this method, the value of voltages is guessed to calculate the value of a particular variable, such as current, real, or reactive power (Adejumobi & Hamzat, 2013). Then, the value of the voltage that has been guessed is set to the initial calculations. These calculations are recurring until iteration convergence is achieved. Finally, the new value of the voltage is calculated using Equation (3.7).

$$V_i^{(k+1)} = \frac{\frac{P_i^{sch} - jQ_i^{sch}}{V_i^*} + \sum Y_{ij} V_i^k}{\sum Y_{ij}} \tag{3.7}$$

where, $j \neq i$.

Gauss-Seidel iterative technique uses Kirchoff's current law. At the sending end, it can be assumed that the current flowing into the bus is positive, also P_i^{sch} and Q_i^{sch} which represent the active and reactive power, respectively. But at the receiving end, the active and the reactive will have a negative polarity due to the flow direction. The active and reactive power can be determined using Equations (3.8) and (3.9).

$$P_i^{(k+1)} = \text{Real}\left[V_i^{*(k)}\left\{\sum_{i=0}^{n} y_{ij} - \sum_{ji}^{n} V_i^{(k)}\right\}\right] \tag{3.8}$$

$$Q_i^{(k+1)} = \text{Imaginary}\left[V_i^{*(k)}\left\{\sum_{j=1}^{n} y_{ij} - \sum_{ji}^{n} V_i^{(k)}\right\}\right] \tag{3.9}$$

where, $j \neq i$.

The power flow can also be presented using a bus admittance matrix, which can be diagonal and non-diagonal configured. For example, Equation (3.10) is the equation to calculate the voltage using bus admittance matrix elements.

$$V_I^{(k+1)} = \frac{\frac{P_i^{sch} - jQ_i^{sch}}{V_i^*} - \sum Y_{ij} V_j^k}{Y_{ii}} \tag{3.10}$$

where, $j \neq i$.

To further simplify the equation, the rectangular form of complex numbers presents other elements of the bus admittance matrix. The real and imaginary powers are shown in Equations (3.11) and (3.12)

$$P_i^{(k+1)} = \text{Real}\left[V_i^{*(k)}\left\{V_i^{*(k)} Y_{ii} + \sum\nolimits_{i=1, j=1}^{n} y_{ij} V_j^{(k)}\right\}\right] \tag{3.11}$$

$$Q_i^{(k+1)} = \text{Imaginary}\left[V_i^{*(k)}\left\{V_i^{*(k)} Y_{ii} + \sum\nolimits_{i=1, j=1}^{n} y_{ij} V_j^{(k)}\right\}\right] \tag{3.12}$$

where, $j \neq i$.

3.3.2 Newton-Raphson iterative technique

This iterative power flow method uses a non-linear equation approximated to linear equations through Taylor series expansion. This method is more effective in convergence analysis compared to other iterative techniques. In addition, this method is more reliable because it can solve events resulting in divergence. With this method, power flow results are populated quickly, provided that the acceptable values are close enough, making it more reliable than others (Adejumobi & Hamzat, 2013) and (Jegatheesan et al., 2008). However, its disadvantage is that if values obtain through iteration are not as close; it can take a long time to finish the computation. This iterative method uses non-linear equations, and the bus admittance matrix approach can be used to solve the power flow. The current flow at bus i of the system can be calculated using Equation (3.13), which is in polar form.

$$I_i = \sum\nolimits_{j=1}^{n} \left|Y_{ij}\right| \left|V_i\right| \angle\theta_{ij} + \delta_j \tag{3.13}$$

The real and reactive power can then be determined with I_i, substituted as expressed in Equations (3.14) and (3.15). The real power is:

$$P_i = \sum\nolimits_{j=1}^{n} \left|V_i\right| \left|V_j\right| \left|Y_{ij}\right| \cos\left(\theta_{ij} - \delta_i + \delta_j\right) \tag{3.14}$$

And the reactive power is given as:

$$Q_i = \sum\nolimits_{j=1}^{n} \left|V_i\right| \left|V_j\right| \left|Y_{ij}\right| \sin\left(\theta_{ij} - \delta_i + \delta_j\right) \tag{3.15}$$

Equations (3.14) and (3.15) above are non-linear and algebraic equations expressed in terms of voltage per unit and δ is expressed in radians. However, these two equations can be expanded further through the Taylor series to form a linear equation.

The distribution network is prone to disturbances ranging from natural to human-made. Therefore, developing innovative models that will enable the power system to remain stable following these disturbances is essential. Development concerning distributed energy resources is at a fast rate. Distribution planners must develop fundamentally innovative funds to deal with this high penetration of renewable energy. Their remarkable contribution to distribution enhancement is acknowledged; however, their placement is crucial in ensuring they optimally deliver power to the grid (Sadeghi & Abasi, 2021; Gautam et al., 2020; Georgilakis & Hatziargyriou, 2013; Selim et al., 2020).

3.4 Optimal placement of Distributed Energy Resources

The placement of Distributed Energy Resources depends on the primary purpose set by the distribution planner. The advantage of these energy resources is that they can be integrated closer to the load, which limits the power loss due to distribution to a more extended range of distances and reduces the infrastructure required for power distribution, such as distribution lines and underground (Xiaoyu et al., 2014) and (Georgilakis & Hatziargyriou, 2013).

Various methods exist to determine the placement of distributed energy resources. One effective tool to assess the place of the energy resource is the static approach using QV and PV curves (Manjul, 2018), by identifying the weakest bus in the network (Roy et al., 2012). This method is effective primarily in studies relating to voltage and frequency stability.

3.4.1 QV curve approach for placement of Distributed Energy Resources

The QV curve approach is performed by ramping the load until the power flow cannot converge, and then the system continues to yield toward the voltage collapse point (Aziz et al., 2010). It should be noted that when the load demand increases, it negatively affects the sensitivity factor, $\frac{dQ}{dV}$, of reactive power concerning bus voltage and it can decrease to voltage limit point as indictated in Figure 3.3. Finally, at the voltage instability point, the sensitivity $\frac{dQ}{dV}$ is zero, indicating the critical point of operation, and if the load demand increases further, the system will collapse (Huang et al., 2007). The distance between the minimum threshold of the reactive power and the voltage is known as the reactive power margin.

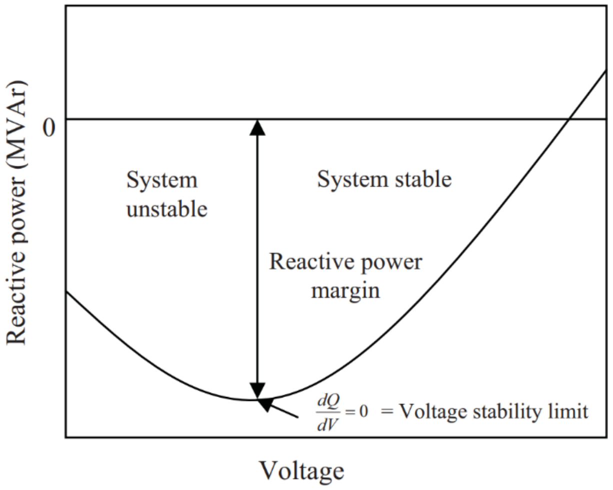


Figure 3.3: Reactive power and voltage (QV) curve (Roy et al., 2012)

3.4.2 PV curve approach for placement of Distributed Energy Resources

The PV curve also follows the QV curve approach, except that on the PV curve, the active part of the load increases until the Pload which refers to the power demand reaches the Pmax, and at Pmax is the stability point. If the load continues to grow, the system will become unstable. It should be noted that, as soon as the voltage surpasses the critical voltage ($V_{critical}$), the power system will be unable to recover its stability and slow down load equipment operation. Figure 3.4 shows the relationship between power and voltage as load increases.

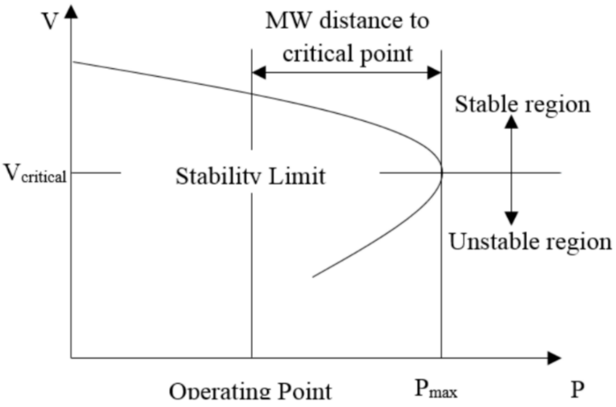


Figure 3.4: Active power and Voltage (PV) curve (Rahman et al., 2013)

Utilizing both approaches to identify the most vulnerable bus in the distribution network can help to adequately allocate the distributed energy resources to assist to strengthen distribution grid stability.

3.5 Modeling of Distributed Energy Resources

The distributed energy resources are mostly renewable energy based. It is worth knowing how we define Renewable Energy in a simplified version. It is a source of environmentally friendly electrical energy that has less impact on climate change, and its power is not depleted when used. This energy is mainly generated through natural resources such as wind, sun, rain, and tides. Figure 3.5 illustrate the distributed energy resource, such as wind and solar energy system with substation where they can be integrated.

Figure 3.5: **Solar and Wind energy** (Donald & Anning, 2021)

The benefit of renewable energy is that this technology is sustainable, and the power generated through these energy resources will never be depleted as long as the sun and wind are available. Renewable energy facilities generally require less maintenance than traditional generators. Renewable energy technologies are often composed of clean energy sources with less environmental impacts than fossil-fuel-based conventional energy technologies. Renewable energy resources produce little to no waste products such as carbon dioxide or other chemical pollutants and are cost-effective.

The disadvantages of renewable energies are related to the challenges to generate quantities of power that are as large as those produced by conventional fossil fuel generators. In addition, renewable energies are often climate-based reliant for their power source, meaning that no wind, sun, or water means no power. This is true for wind, solar, hydro, and geothermal energy except for the Bioenergy and Waste to Energy technologies.

Wind and Solar are the most prominent energy resources currently used worldwide. The technology is at its maturity stage, and primary resources such as the sun and wind are available worldwide. It is, therefore, pivotal to understand their basic modeling and operation.

3.5.1 Wind energy system modeling

Wind energy is described as the kinetic energy of wind used to drive wind turbines and generate electricity (Pérez-denicia et al., 2017). Wind turbines produce electricity through an aerodynamic rotor which is mutually connected to an electric generator (Pérez-denicia et al., 2017). A gearbox is used to vary the speed of the turbine rotor. Most recent wind turbine designs have three blades rotating on a horizontal axis; however, they are also available in two blades (Pérez-denicia et al., 2017). Figure 3.6 below illustrates the gearbox model and the parts of the whole wind turbine system.

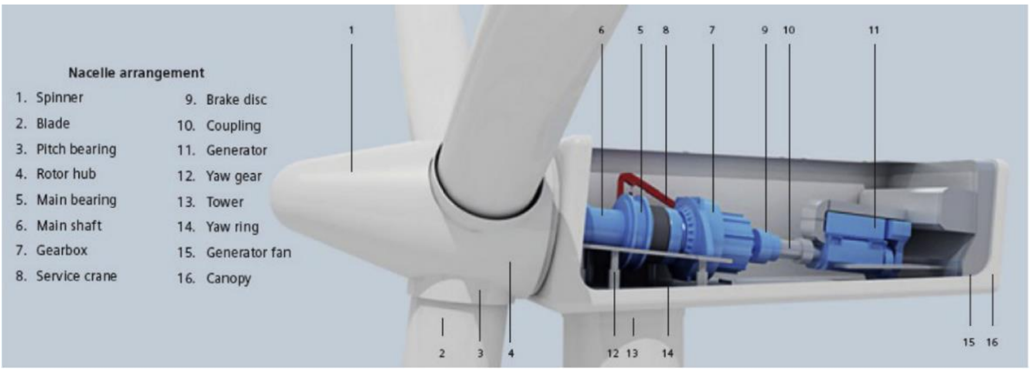


Figure 3.6: **Wind turbine generator gearbox drive-train illustration (Lacal-ar, 2015)**

Wind energy can be generated through land-based wind turbines (onshore) or offshore wind turbines. Both configurations have a low environmental impact compared with other generation systems such as gas and coal-fired (Pérez-denicia et al., 2017).

Wind turbine-generated power output $P_{wt}(t)$ can be mathematically expressed as follows (Singh et al., 2016):

$$P_{wt}(t) = \begin{cases} 0 & V(t) \leq V_{cin} or\ V(t) \geq V_{cout} \\ P_r^w & V_{rat} \leq V(t) \leq V_{cout} \\ P_r^w \dfrac{V(t) - V_{cin}}{V_{rat} - V_{cin}} & \leq V(t) \leq V_{rat} \end{cases} \tag{3.16}$$

From Equation (3.16), P_r^w is the rated power out of a single wind turbine, V_{cin} is the cut in rated speed, V_{rat} represents the rated wind speed, while V_{cout} is the furling speed and $V(t)$ represent the wind speed at the desired height. The wind speed at the hub height depends upon the geographical location, which also differs from the reference height. Further, it is expressed as (Singh et al., 2016):

$$V(t) = V_r(t) \left(\frac{H_{WT}}{H_r}\right)^{\gamma} \tag{3.17}$$

Where $V(t)$ represent the wind speed at height H_{WT}, $V_r(t)$ is wind speed considering friction while H_r is the reference height, and γ is the friction coefficient. The typical friction coefficient γ is 1/7 for low roughness, surface, and well-exposed site.

Onshore energy illustrated in Figure 3.7 below denotes the power generated by turbines installed on land. In contrast, offshore energy refers to the power generated by wind turbines installed in the ocean (Pérez-denicia et al., 2017).

Figure 3.7: **Onshore and Offshore Wind Energy System** (Okedu & Okedu, 2018)

The mechanical output power of the wind turbine generator can be calculated using Equation (3.18).

$$P_m = \frac{1}{2}\rho A C_p U^3 \tag{3.18}$$

Where P_m is the mechanical power output of the wind turbine, C_p, is the power coefficient, U, is the wind speed, ρ is the air density, and A, represents the blade sept area which can be calculated using equation 3.19, where is the rotor radius.

$$A = \pi \times R^2 \tag{3.19}$$

The integration of distributed energy resources requires the incorporation feasibility study based on the energy markets to verify whether the investment is implementable. The return on investment is also essential to consider so that their implementation is not at a loss.

3.5.1.1 Cost of production

The Levelized cost of electricity is an important economic indicator to compare the cost of different production types of electricity calculated in terms of the price per unit of electricity output (R/MWh), and It also includes carbon, fuel, capital, and other sources of cost (Mohsin et al., 2018). The Levelized cost of electricity can be measured by the annual cost of energy production divided by energy production annually (Mohsin et al., 2018). By increasing wind resources, the total cost remains constant, but the price per unit of energy will decrease. The annual fixed charge rate transfers the lump-sum investment into an annual payment.

3.5.2 Solar energy system modeling

Solar energy is extracted from sunlight radiation and converted to electrical power, which can be utilized to meet the energy requirement (Pérez-denicia et al., 2017). Sunlight can be captured by three types of technologies of solar energy, which are as follows (Pérez-denicia et al., 2017): photovoltaic (PV), concentrated solar thermal (CST), and solar heating and cooling (SHC). Power gets generated through sunlight rays that strike a semiconductor, the PV cell, and solar energy is produced into direct current (DC) electricity through the photoelectric effect. CST generates electricity by capturing sunlight heat and gets channeled to collectors that focus the heat to boil the liquid, creating a steam that drives a turbine that generates electricity. Finally, the Solar Heat and Cooling system is based on thermal energy produced from the sun eating the solar hydrocubes, usually placed on roof top to heat water, and with the heat captured, space heating is also achieved, or pool heating. Additionally, these technologies can also reach air-conditioning needs using two techniques called thermally driven chillers and desiccant cooling systems. Figure 3.9 shows these three solar energy technologies.

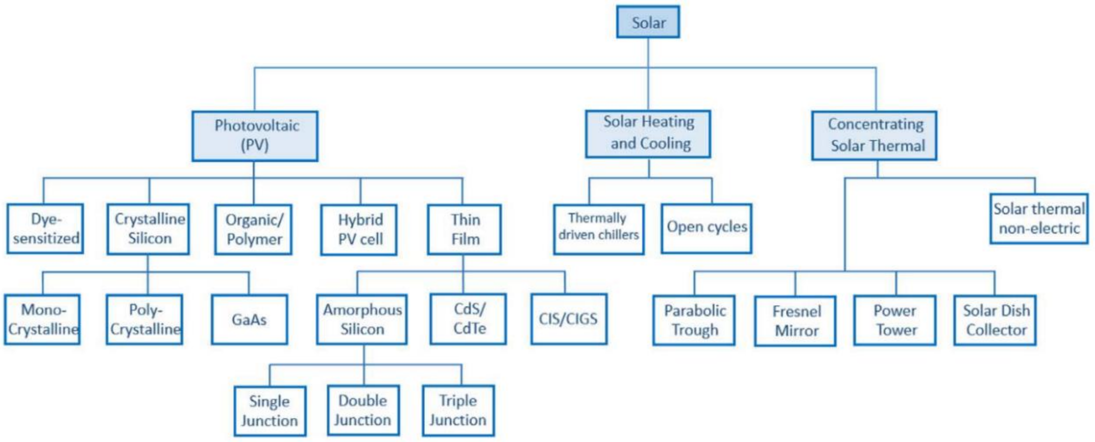


Figure 3.8: Technologies of solar energy (Pérez-denicia et al., 2017)

The power output of a solar PV panel F_{loss} depends on solar radiation, and it can be specified as follows (Singh et al., 2016):

$$P_{sol}(t) = P_r^s \times F_{loss} \times \frac{G_h(t)}{G_s} \tag{3.20}$$

Where P_r^s represents the rated power output of the solar PV panel, F_{loss} is loss factor of the solar PV panel due to shadow, dirt, temperature etc, $G_h(t)$ is the solar radiation incident captured hourly at the surface of the solar PV panel (W/m^2) and G_s is the base value of incident radiation (1000 W/m^2).

The variability of renewable-based energy results in these energy resources being unreliable to be utilized as a base load supply, as is the case with fossil-fuel-based generation systems. Therefore, it is necessary to consider an alternative to strengthen and enhance the renewable energy system's reliability, security, and supply quality. The energy storage system is considered the best option to incorporate these variable energy resources. Therefore, battery energy storage has been widely used as a suitable energy storage technology.

3.5.3 Battery energy storage system modeling

Energy storage technology can play a prominent role in the complete chain from generation, transmission, and distribution to end users (Rohit & Rangnekar, 2017). This technology can help increase energy access, including availability in distance areas, and improve quality, reliability, energy security, and performance.

Energy storage may reduce standby fossil fuel generators for peak demand and reduce carbon emissions and pollution. In addition, energy storage can help utilities better manage and mitigate possible load shedding. These technologies integrated with solar PV can smooth the output, reduce intermittency, and help maintain grid stability (Rohit & Rangnekar, 2017).

Various energy storage systems are available, but the main focus is on the battery type. Battery energy storage (BES) in power systems refers to the secondary batteries cells comprising a pair of opposite electrodes dipped in an electrolyte. They can store and provide energy through reversible electrochemical reactions (Nikolaidis & Poullikkas, 2018). BES systems are divided into lead-acid, alkaline, metal-air, high-temperature, and lithium-ion (Nikolaidis & Poullikkas, 2018). Since the invention of valve-regulated lead acid (VRLA) batteries, banks of up to 36 MW are already being utilized for power generation from RES, as they achieve higher than that of flooded-type specific energy and depths of discharge with negligible maintenance requirements (Nikolaidis & Poullikkas, 2018).

Lead toxicity and sulfuric acid are still the main concerns and may restrict this battery type from being indefinitely used. Nickel-cadmium (NiCad) and nickel-metal-hydride (NiMH) represent the main alkaline batteries (Nikolaidis & Poullikkas, 2018). On the other hand, nickel-cadmium batteries are widely used in portable and stationary applications providing higher specific energy and longer cycle life (1500–3000 cycles) compared to lead-acid (Nikolaidis & Poullikkas, 2018).On the contrary, except for the higher cost, its maximum capacity and whole life are subjected to the memory effect. They thus cannot be repeatedly recharged after being partially discharged (Nikolaidis & Poullikkas, 2018).

Metal-air batteries are expensive, and a concern is probable fire due to the high reactivity with humid air. Furthermore, it is challenging to be recharged and offers a limited cycling capability of a few hundred cycles, along with a pretty low efficiency of relatively 50% (Nikolaidis & Poullikkas, 2018).
The other type of battery storage technology is *lithium-ion;* its high cost and the prohibitive for their lifetime deep discharging are the main drawbacks of lithium-ion batteries that restrict their use in large-scale applications (Nikolaidis & Poullikkas, 2018). In addition, the disadvantage of battery energy storage systems is their sensitivity to high temperatures. Hence they are equipped with the Battery Energy Management Control System (BEMCS) to facilitate protection against overvoltage, temperature, and over-current (Nikolaidis & Poullikkas, 2018).

However, with the production and domination of product usage, its direct cost decrease as the technology evolves and becomes affordable. This is true for lithium-ion batteries, as outlined by (Khunkitti et al., 2022). Battery energy storage operation depends on two factors: the state of charge and the state of health. These two factors are significant in maximizing the battery life span. Therefore, the battery sizing and its life span determination are important before considering integrating them into the grid. The battery size and life of the battery can be calculated using Equations (3.21) to (3.23), respectively (Khunkitti et al., 2022).

$$BESS_{size(kWh)} = \frac{E_B^{max} - E_B^{min}}{DOD_{max}} \tag{3.21}$$

$\boldsymbol{E_B^{max}}$ represents the maximum value for BESS, $\boldsymbol{E_B^{min}}$ is the minimum value for BESS while $\boldsymbol{DOD_{max}}$ present is the depth of discharge of BESS. This is usually about 80% of the rated capacity to avoid high temperatures during the charging and discharging of the battery (Khunkitti et al., 2022).

Battery life can be calculated using cycles, which are the indicators of its performance.

$$Cycle = \frac{1}{2}\ \frac{\sum_{t=1}^{T} |E_B - E_B(t-1)|}{DOD_{max} \cdot BESS_{size(kWh)}} \tag{3.22}$$

The battery life in years is then calculated using Equation (3.23). The cycle of the battery is 3221, while D, which indicates days of operation throughout the year, is 365 days.

$$BESS_{Life(years)} = \frac{Cycle\ life}{(cycle \cdot D)} \qquad \textbf{(3.23}$$

Battery Energy Storage Systems are used worldwide to deal with the intermittence of electrical power generated through renewable energy resources. And they also offer ancillary services such as frequency and voltage support, peak-shaving, energy arbitrage, etc (Moyo, 2018). Moreover, their dispatchable capability helps maintain the power system on its stability margin.

3.6 Summary

To begin modeling a functional system, the first step involves examining the existing literature, which provides the necessary theoretical information for the modeling process. This chapter provides an overview of the theory required for modeling a distribution system, along with the available equipment models. Additionally, the chapter discusses the theory behind various types of distributed energy resources such as wind power, solar PV systems, and energy storage systems like battery energy storage, along with their corresponding mathematical models. The chapter also explores the criteria for determining the placement of distributed energy resources.

CHAPTER FOUR

NETWORK MODELING, STEADY-STATE AND DYNAMIC STUDY SIMULATION ANALYSIS

4.1 Introduction

The distribution system network needs to be modeled and simulated to study its operation under different conditions. This study aims to validate the equipment performance and the entire grid operation to ensure that, when practically implemented, they can achieve their functions as anticipated. Various simulation tools or software are available to model and analyze the network operation. This software includes ETAP, MATLAB, Powerfactory DIgSILENT, RSCAD FX and RTDS simulator, Powerworld Simulator, etc. Each software has its advantages and disadvantage.

Digsilent simulation software has been well used in industrial network simulation for its robustness and user friendly. Various tools exist to perform multiple analyses. In addition, there are specific simulation tools precisely for distribution and transmission applications. Two particular tools are used, time-based, to analyze the network behavior under dynamic conditions. One of them is the quasi-dynamic simulation. This simulation tool is used to analyze the network behavior for a long time. In quasi-dynamic simulation tools, the load profile needs to be known and is based on probabilistic analysis. However, to study network behavior dynamicity for a short period, Root-Mean Square (RMS) simulation is used. These tools help to perform network analysis for both steady-state and dynamic states (Rueda et al., 2014; DIgSILENT, 2020; Mditshwa et al., 2021). This tool (DIgSILENT) was adopted to analyze distribution under various contingencies in this research study. The analysis of this research study is performed using a modified IEEE 33 bus distribution network (Ponoćko, 2020).

This chapter is structured as follows: section 4.1 is the introduction of the chapter, section 4.2 covers the distribution network modeling. Section 4.3 is the steady-state analysis to investigate the network operation before any disturbances are introduced, section 4.4 covers the dynamic state, where load demand increase is introduced, and results are recorded and analyzed. Finally, section 4.5 is the conclusion of the chapter.

4.2 Distribution network modeling

The decision to select the modified IEEE 33 bus distribution network was based on its ability to closely resemble a real distribution network that is configured in a radial manner. By utilizing this network in the DIgSILENT simulation software, it is possible to assess the impact of various line types, distances between substations, and load models on the behavior of the distribution network in real time. Therefore, the selection of this network is essential for accurately studying and understanding the dynamics of a real-world distribution network.

The load data is shown in Table 4.1 with its associated busbar. In addition, a synchronous machine (generator) is included as a modification to the existing IEEE network. The aim of introducing the synchronous machine is to ensure that the general characteristics of a conventional distribution system are emulated.

Table 4.1: **IEEE-33 Bus network Load data (Jelena Ponoćko, 2020)**

Terminal	Name	Act.Pow.	React.Pow.	App.Pow.
Busbar	**Load**	**MW**	**Mvar**	**MVA**
10	L10	0.06	0.02	0.06324555
11	L11	0.045	0.03	0.05408327
12	L12	0.06	0.035	0.06946222
13	L13	0.06	0.035	0.06946222
14	L14	0.12	0.08	0.1442221
15	L15	0.06	0.01	0.06082762
16	L16	0.06	0.02	0.06324555
17	L17	0.06	0.02	0.06324555
18	L18	0.09	0.04	0.09848858
19	L19	0.09	0.04	0.09848858
2	L2	0.1	0.06	0.116619
20	L20	0.09	0.04	0.09848858
21	L21	0.09	0.04	0.09848858
22	L22	0.09	0.04	0.09848858
23	L23	0.09	0.05	0.1029563
24	L24	0.42	0.2	0.4651881
25	L25	0.42	0.2	0.4651881
26	L26	0.06	0.025	0.065
27	L27	0.06	0.025	0.065
28	L28	0.06	0.02	0.06324555
29	L29	0.12	0.07	0.1389244
3	L3	0.09	0.04	0.09848858
30	L30	0.2	0.1	0.2236068
31	L31	0.15	0.07	0.1655295
32	L32	0.21	0.1	0.2325941
33	L33	0.06	0.04	0.07211103
4	L4	0.12	0.08	0.1442221
5	L5	0.06	0.03	0.06708204
6	L6	0.06	0.02	0.06324555
7	L7	0.2	0.1	0.2236068
8	L8	0.2	0.1	0.2236068
9	L9	0.06	0.02	0.06324555

The line data is illustrated in Table 4.2. The data shown include the line’s impedance, resistance, and reactance.

Table 4.2: **IEEE-33 Bus network line data (Jelena Ponoćko, 2020)**

Bus	To Bus	Name	Z1	phiz1	R1	X1
		Line	**ohm**	**degree**	**ohm**	**ohm**
1	2	L1-2	0.064568	27.01071	0.057525	0.029324
2	3	L2-3	0.345195	26.9912	0.307595	0.156668
3	4	L3-4	0.256266	26.9894	0.228356	0.1163
6	5	L5-6	0.675054	40.80231	0.510995	0.441115
8	7	L7-8	0.46747	18.28747	0.44386	0.146685
7	6	L6-7	0.403365	73.16844	0.116798	0.386085
11	12	L11-12	0.246036	18.29717	0.233597	0.077242

Bus	To Bus	Name	Z1	phiz1	R1	X1
9	10	L9-10	0.798414	35.3295	0.651378	0.461705
10	11	L10-11	0.129193	18.29499	0.122663	0.040555
14	13	L13-14	0.558598	52.77562	0.337917	0.444796
16	15	L15-16	0.576578	36.13951	0.465635	0.340039
15	14	L14-15	0.493633	41.66971	0.368739	0.328185
17	18	L17-18	0.580384	38.10188	0.456713	0.358133
21	22	L21-22	0.73323	52.89904	0.4423	0.584805
19	20	L19-20	1.26331	42.02129	0.938508	0.845668
20	21	L20-21	0.392903	49.43725	0.255497	0.298486
28	29	L28-29	0.665461	41.06165	0.50176	0.437122
27	28	L27-28	0.880879	41.40204	0.660736	0.582559
26	27	L26-27	0.19898	26.98293	0.177319	0.090282
32	33	L32-33	0.393317	57.25281	0.212758	0.330805
31	32	L31-32	0.297516	49.37151	0.193728	0.225799
30	31	L30-31	0.85476	44.6629	0.607952	0.60084
29	30	L29-30	0.355352	26.99251	0.316642	0.161285
2	34	L2-34	0.064568	27.01071	0.057525	0.029324
6	26	L6-26	0.14214	26.99265	0.126656	0.064514
24	25	L24-25	0.709839	38.04239	0.559037	0.437434
23	24	L23-24	0.713903	38.29618	0.560284	0.442425
8	9	L8-9	0.791304	35.69525	0.642643	0.461705
12	13	L12-13	1.16543	38.19515	0.915922	0.720634
16	17	L16-17	1.341564	53.16742	0.804239	1.073775
4	5	L4-5	0.266842	26.99045	0.237778	0.121104
3	23	L3-23	0.340957	34.34435	0.281515	0.192356
34	19	L19-34	1.26331	42.02129	0.938508	0.845668

The general power system characteristics influence the behavior of the distribution network on system disturbance. The most influential component is the generation system. The fault level, transient response, and general disturbances such as line fault and generator trip differ from system to system based on the dominating generation machines. Therefore, the synchronous machine replaced the external grid representing the distribution source to emulate the power system characteristics. Table 4.3 indicates the data for the synchronous generator used as the source of the modified IEEE-33 bus network.

Table 4.3: **Grid source data**

Name	Terminal	Act.Pow.	React.Pow.	App.Pow.	App.Pow.	Voltage	Pow.Fact.
	Busbar	MW	Mvar	MVA	MVA	p.u.	
G1	1	1.851	0	1.851	10	1	1

The modeled modified IEEE 33 bus network is illustrated in Figure 4.1. The distribution network topology is radially configured. The network diagram was modelled using DIgSILENT. The modeled network needs to be evaluated for its operation under steady-state first. This analysis considers the loading of the lines, busbar voltages, transformer, and generator loading. The aim of stead-state simuation is to assess the network performance, and its contrainst before any introduction of disturbances

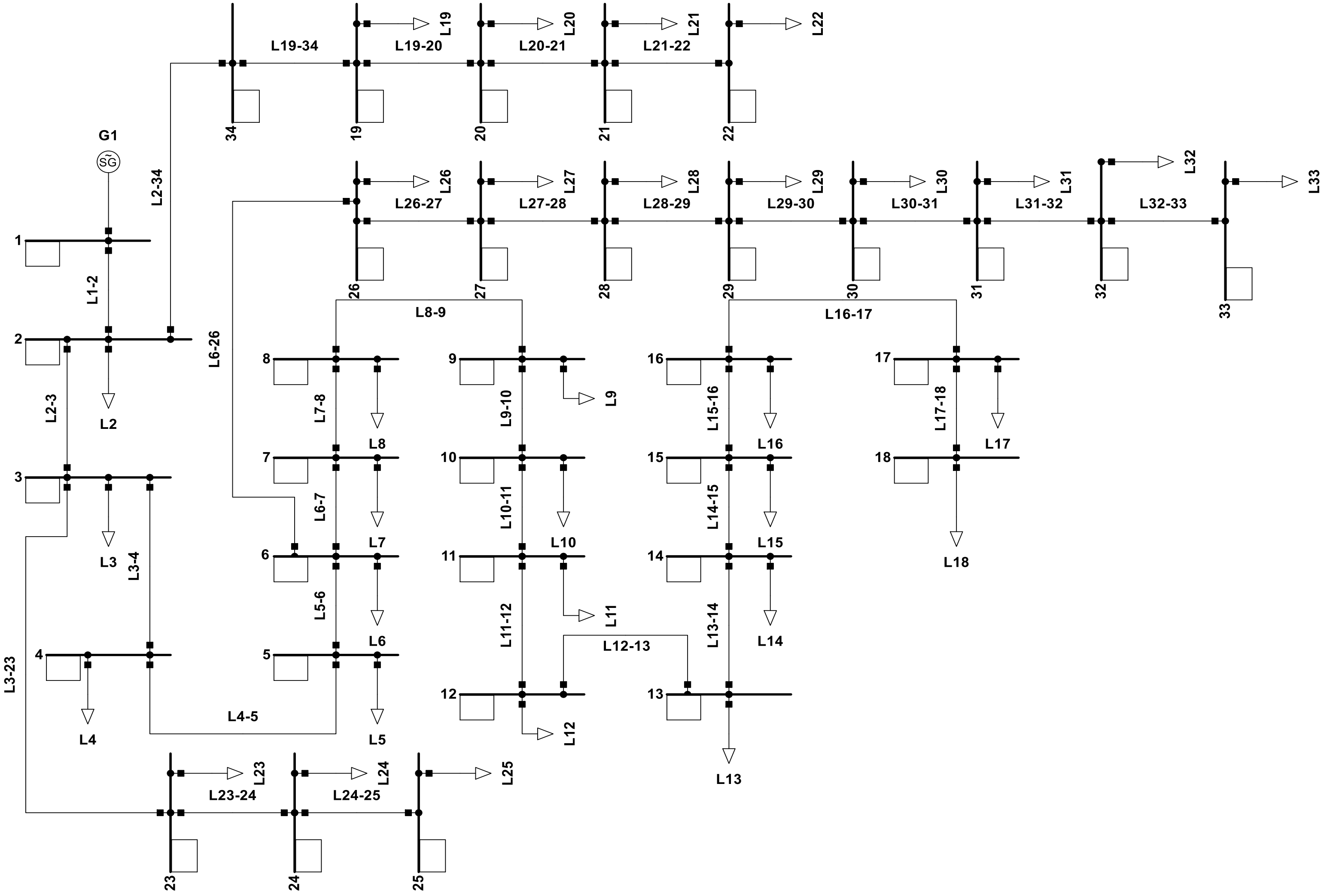


Figure 4.1: Modified IEEE-33 Bus network modeled using DIgSILENT

4.3 Power-flow and steady-state analysis of the distribution network

The steady-state simulation was performed to analyze the network behavior. The simulation results obtained indicate the distribution network operating within acceptable operating limits. Conformance with the distribution grid code is essential; for example, the busbar voltage in the power system needs to be maintained within ± 10% of its nominal value (NERSA, 2019). This means the distribution voltage needs to be kept within 0.95 and 1.05 pu. Figure 4.2 is the distribution network simulation under steady-state. It can be noted that from bus 14 to bus 18, the system voltage is at a critical operating point, and 0.95 pu is the lowest acceptable operating voltage according to the grid codes, as indicated in Figure 4.2. Other essential features to be noted are the legend block and heatmap illustration, where the system loading limit is displayed in Figure 4.2. For example, the lower voltage is shown as 0.9 pu, which is blue, while for higher, it is shown as 1.1 pu, which is red. The equipment's loading can only be indicated when operating.

The busbar voltage was further illustrated in Figure 4.3, where the busbars that has the lowest voltage were noted. All these busbars are the weakest in the system, but they are still within the operating limit, with busbar 18 being the lowest. Busbars 1, 2, 19, 34, etc are the highest in the system, but they are not more than 1pu.

Additional results obtained during steady-state simulation analysis are shown. Figure 4.4 (a) is the total system load, while (b) illustrates the bus voltages for both busbar 3 and 18. Figure 4.4(c) is the system frequency and (d) indicates the current grid losses during steady-state analysis.

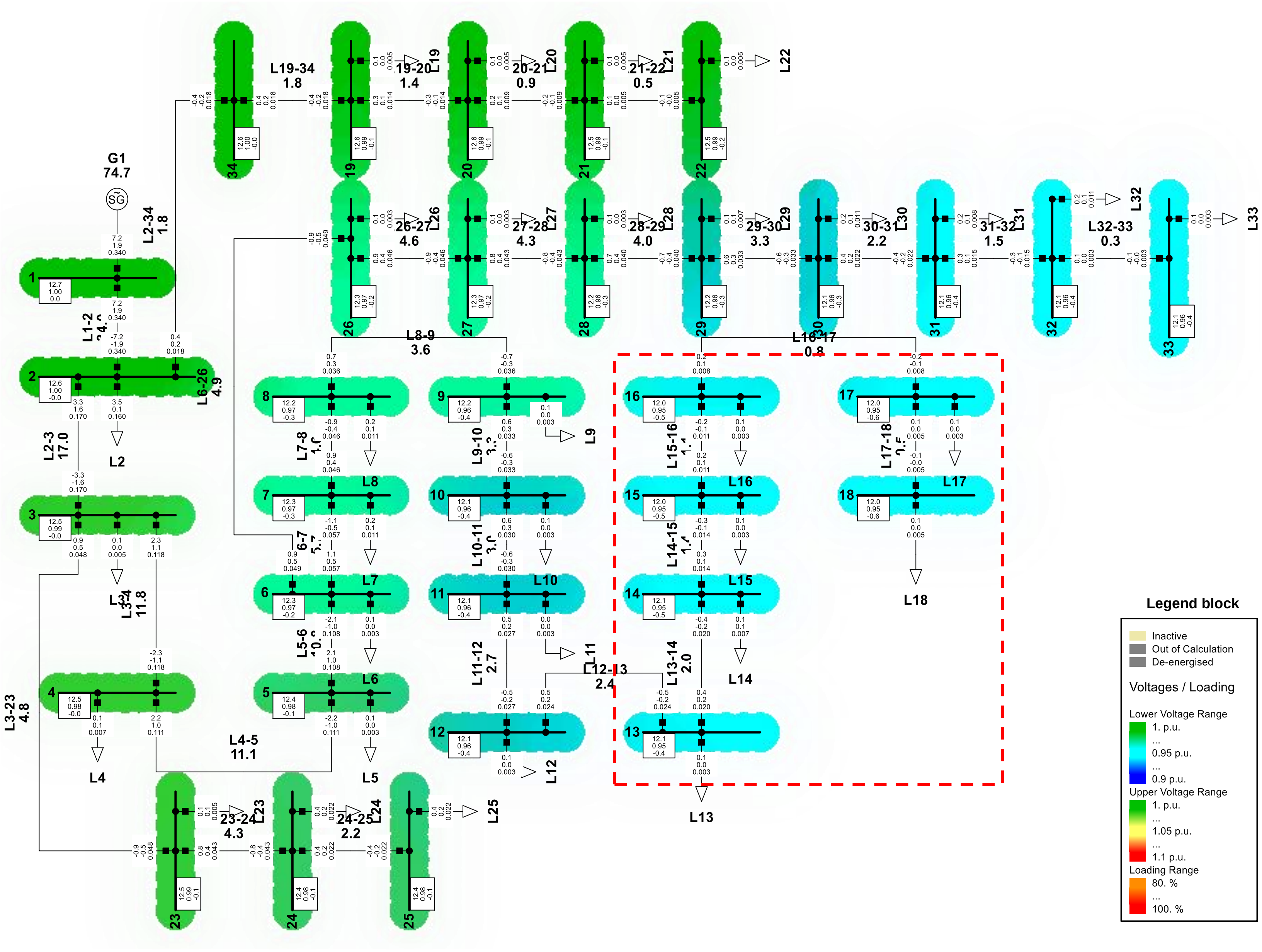


Figure 4.2: Distribution network under steady-state simulation

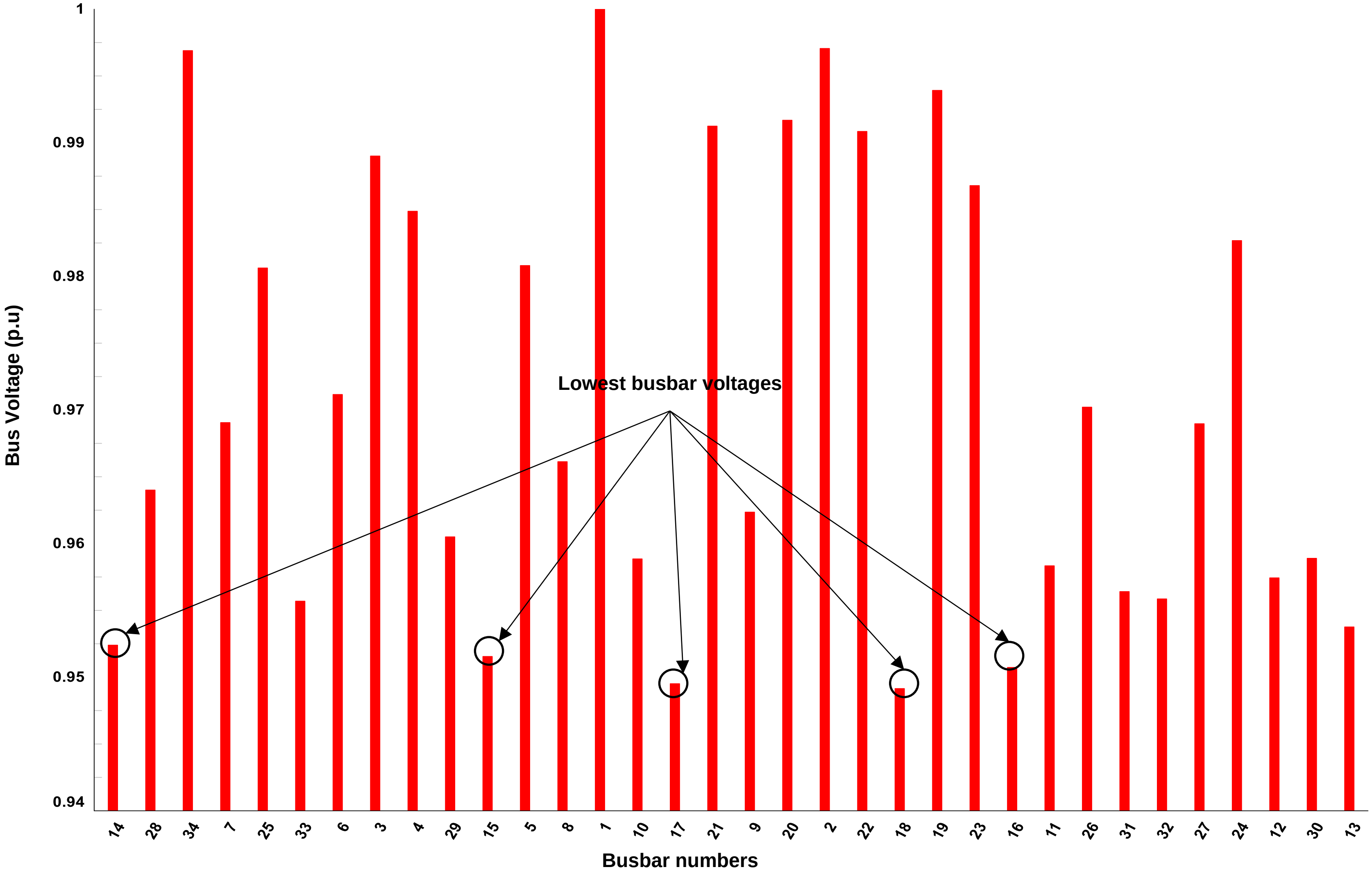
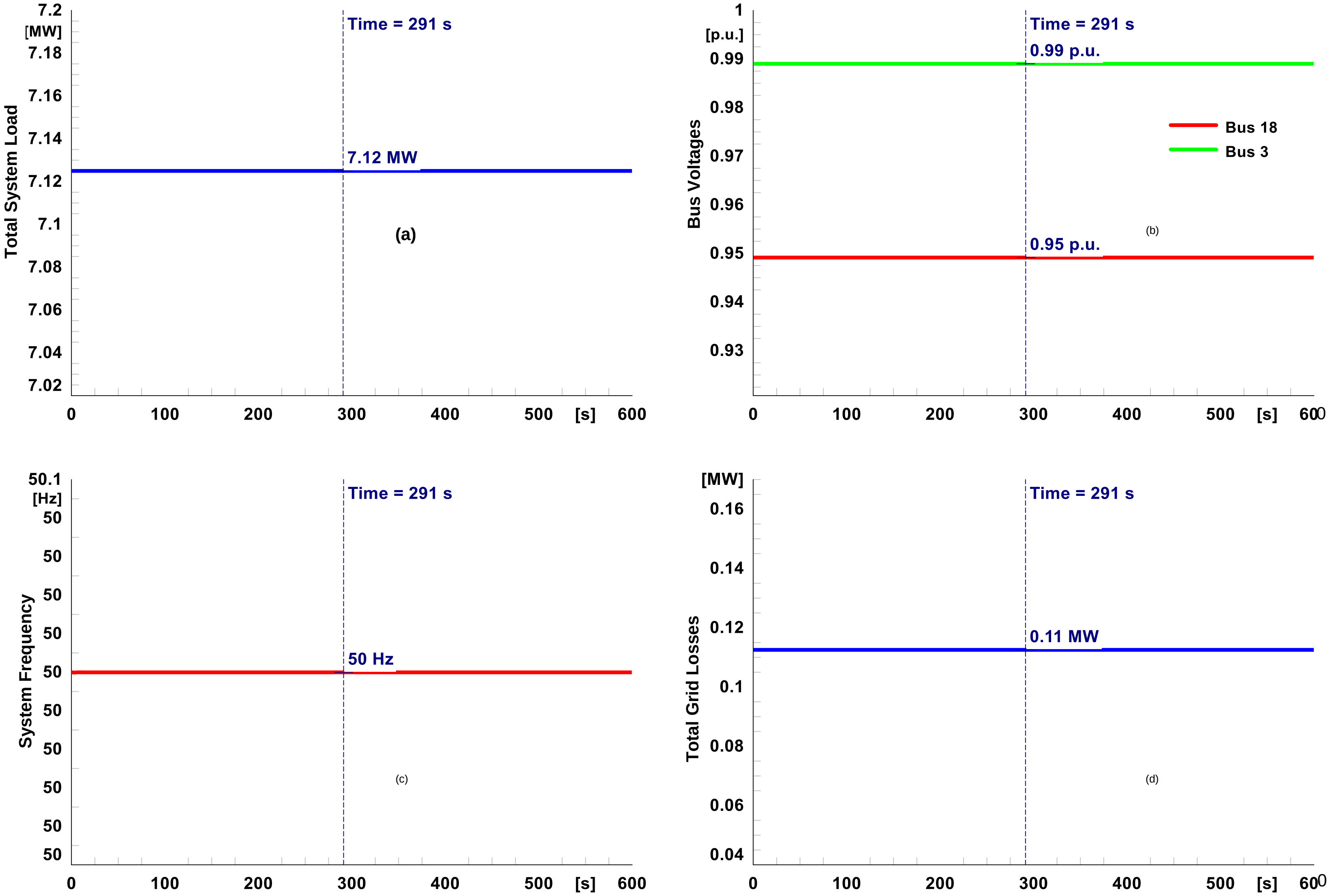


Figure 4.3: Bus voltages under steady-state condition



aa

Figure 4.4: System behaviour during steady-state operating condition - (a) Total system load, (b) Bus 3 and 18 voltages, (c) System Frequency, and (d) Total Grid losses in a steady-state condition

4.4 Dynamic-state analysis of the distribution network

The dynamicity of the distribution network needs to be evaluated to ensure that appropriate measures to safeguard the network instability phenomenon can be taken. Most of the contingencies that occur in the distribution network include line outages and load and load demand increases (Papasani et al., 2021). The line outages can be a result of a plan event or unplanned event (Y. Xu et al., 2019). The planned events have periodic maintenance of distribution infrastructure. However, the unplanned outage is a consequence of a fault event.

4.4.1 Load demand increase case study

Various case studies were used in the distribution system to study its behavior to significant disturbances such as a load demand increase and line outage. For example, case study 1 is the load demand increase, aiming to evaluate the network behavior under this condition. The load demand increase is applied to all loads in the system. 1% active and reactive power is spread throughout the load, and the ramp interval is used per load increase stage. Fifteen stages have been used based on long-term system evaluation, and the 15 steps can be presumed as in years, assuming an occurrence of a 1% load demand increase per year.

Table 4.4: Load event case study

Name (years)	Start	Stage Interval	Ramp Duration	Active Power	Reactive Power
	s	s	s	%	%
Stage 1 to 15	10	30	5	1	1

The load demand increase event was implemented, and the results in Figure 4.5 illustrated the system response to the disturbance. Figure 4.5 (a) represents the total system load under a dynamic state. Initially, the load demand was ramped from 7.12 MW and reached 8.24 MW before the system collapsed at T=341s. The load demand increase negatively affects the bus voltage, as indicated in Figure 4.5 (b). The system voltage drastically decreased as the load demand kept on increasing. The system frequency decay is also shown in (c); at T=257s, it is the point of system collapse considering the system frequency. At this point, load-shedding implementation can be initiated. Load shedding is the last defense mechanism in ensuring that the power system is kept stable at its acceptable operating level (Rudez et al., 2015; Sigrist et al., 2012; Mditshwa, 2021). Moreover, the grid losses have risen from 0.11MW to 0.15MW, as indicated in Figure 4.5 (d)

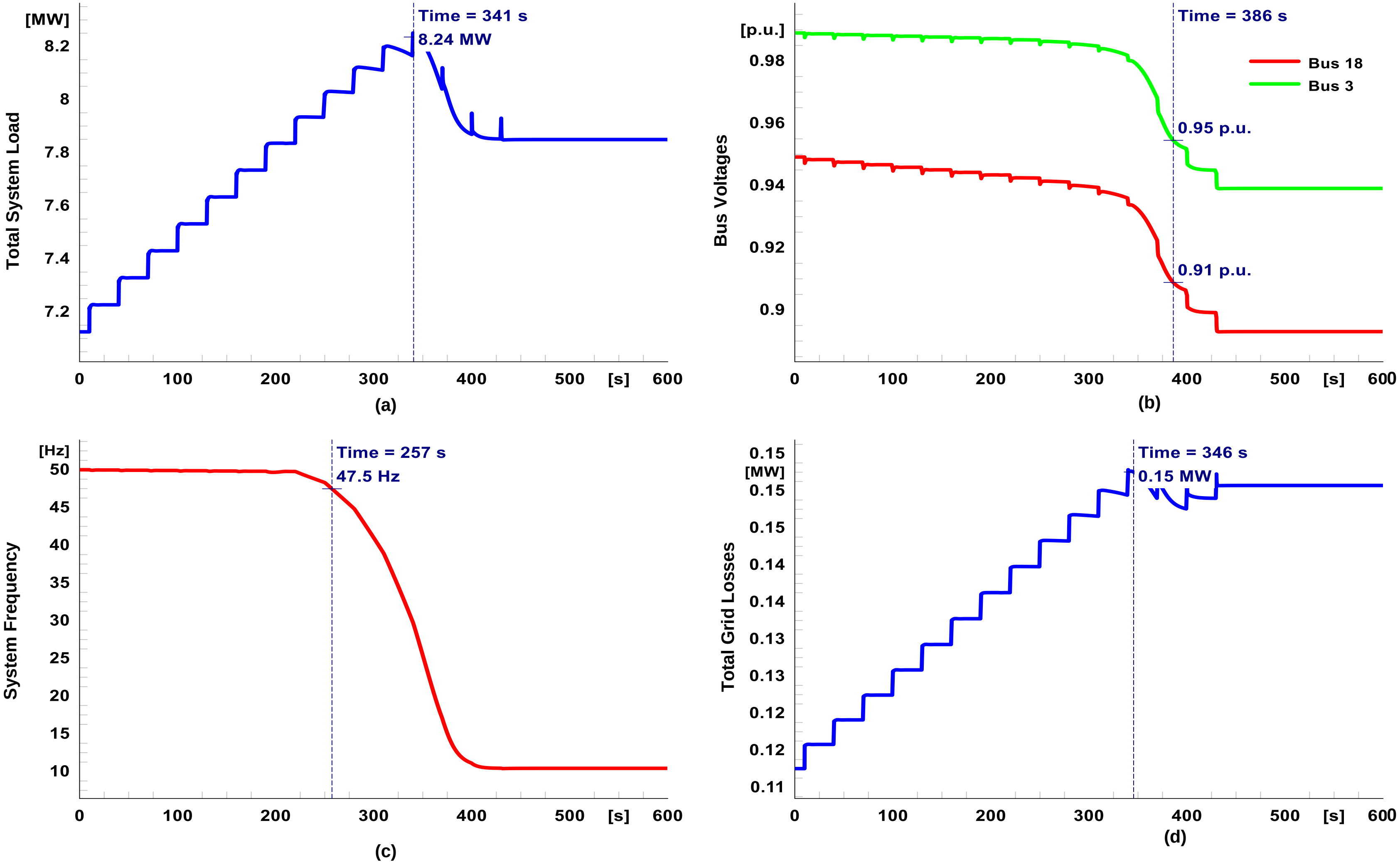


Figure 4.5: System dynamic-response following 15% load demand increase - (a) Total system load, (b) Bus 3 and 18 voltages, (c) System Frequency, and (d) Total Grid losses

4.5 Summary

The distribution system requires a more technical approach to enhance its reliability and supply security. The current network operation is in radial topology, and there is no alternative supply point if the n-1 contingency can be required. Therefore, an improvement in the system voltage is needed. The lowest operating voltage on steady-state conditions is 0.95 pu at bus 18. There is also a need to improve the overall system stability as more active and reactive power is required to keep the system stable. Distributing distributed energy resources has more advantages than static var compensators. The static var compensator can also improve the system voltage; however, the distributed energy resource with an energy storage system can facilitate both active and reactive components to the grid. The system improvement approach to enhance the distribution system stability is covered in Chapter 5.

CHAPTER FIVE

PLACEMENT OF DISTRIBUTED ENERGY RESOURCES, AND SIMULATION ANALYSIS

5.1 Introduction

Introducing the renewable energy system to traditional power systems has brought more system complexity in operation and control; however, their significant contribution to enhancing grid stability is also released. The contribution of these energy resources can be realized when they have been adequately integrated into the grid. Distributing energy resource placement is critical for optimal power dispatching (Meriem et al., 2021).

The proper siting of the distributed energy resources can improve the system's performance and decrease overall power losses. Another critical aspect that needs to be evaluated is the sizing of these energy resources. When additional power is injected into the grid, over-voltage and over-frequency can take place. Therefore, the energy resource that needs to be integrated into the grid must improve the distribution grid on the following attributes: reliability, security, and resilience. The distribution grid must be reliable enough to maintain the power system when a disturbance occurs. In terms of security, when the system experience power outages due to a planned or unplanned event, an alternative supply route needs to be established and service restoration must happen as quickly as possible. Moreover, when it comes to resilience, the grid needs to remain stable post-disturbance.

The structure of this chapter is as follows: section 5.1 is the chapter's introduction, section 5.2 covers the strategy of placing distributed energy resources using the static approach, and section 5.3 covers the development of the control scheme enabling the participation of distributed energy resources in power dispatching and voltage improvement while section 5.4 covers the evaluation of the control scheme under dynamic state events. Lastly, section 5.5 is the conclusion of the chapter.

5.2 Placement of distributed energy resources strategy using a static approach

The sequence of distributed energy resources can be approached in various alternatives. Usually, the siting of these energy resources is algorithmically based. Though these energy resources are algorithmic-based, conventional methods are still applied.

PV and QV curves are the most widely used approaches to determine the weakest busbar in the system. This method is robust and efficient in determining the most vulnerable busbar, which helps to find a suitable and sustainable solution to enhance the system's reliability and resilience. (Siyanda Mnguni, 2020), used the PV curve method to find the critical operating point of system voltage before it reached the instability point. Therefore, this method was also adopted to determine the system's most vulnerable busbar in the grid. The most strained busbar was found in the distribution network using the flowchart presented in Figure 5.1.

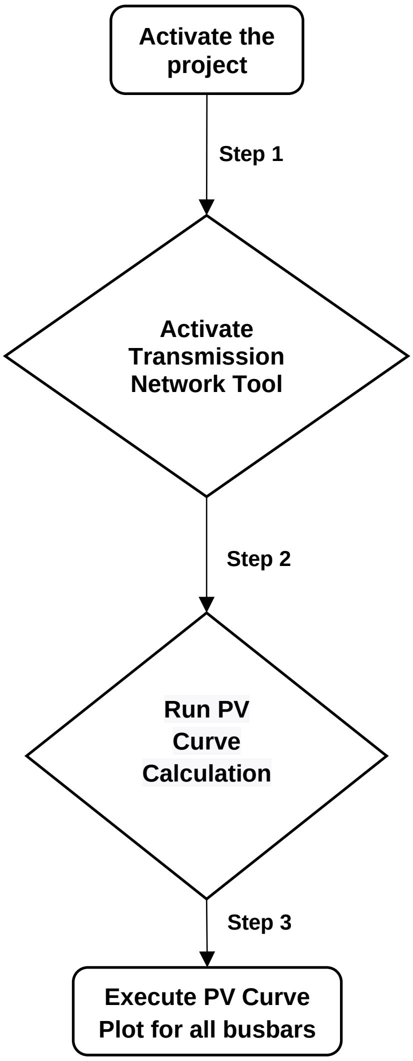


Figure 5.1: PV Curve execution flowchart

The most susceptible busbar was selected based on the results obtained through the PV Curve method, which is performed by ramping the active power transfer in the grid. By doing so, the busbar voltages decreased as the active power transfer increased. The most affected busbar was then selected. As a result, bus 18 was identified as the weakest busbar in the distribution network, as illustrated in Figure 5.2. Within Figure 5.2, the initial voltages before the active power transfer increase took place are shown. When the active power transfer was executed, the voltage at bus 18 decreased to a collapse point of 0.3753605 pu.

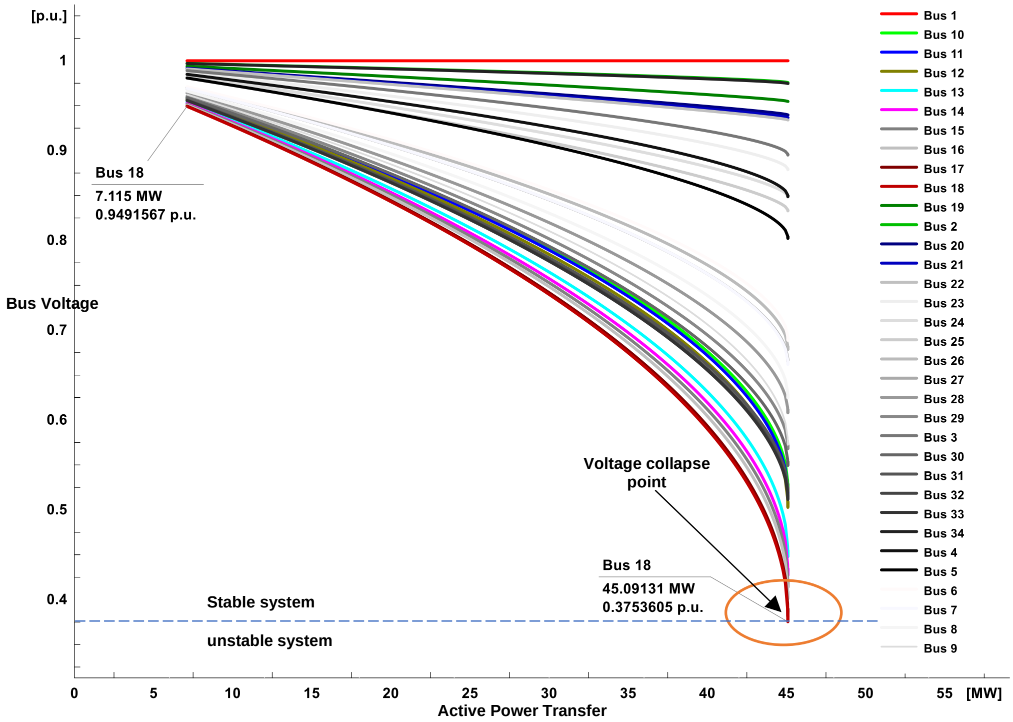


Figure 5.2: Modified IEEE 33 Bus PV Curve characteristic

The QV curve was also applied to determine the voltage collapse point based on the reactive power transfer function for the same busbar. Figure 5.3 indicates the flowchart used to determine the critical operating point of the system when the reactive power transfer was increased.

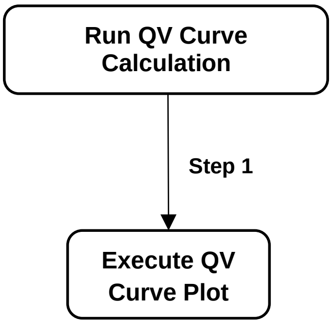


Figure 5.3: QV curve flowchart

As a result, it was observed that the voltage collapse point based on reactive-power transfer was 0.529 pu, as indicated in Figure 5.4, and the regions of operation, such as stable and unstable regions, are also shown. The turning point of the curve is when the system reaches an unstable region, and there is no more convergency.

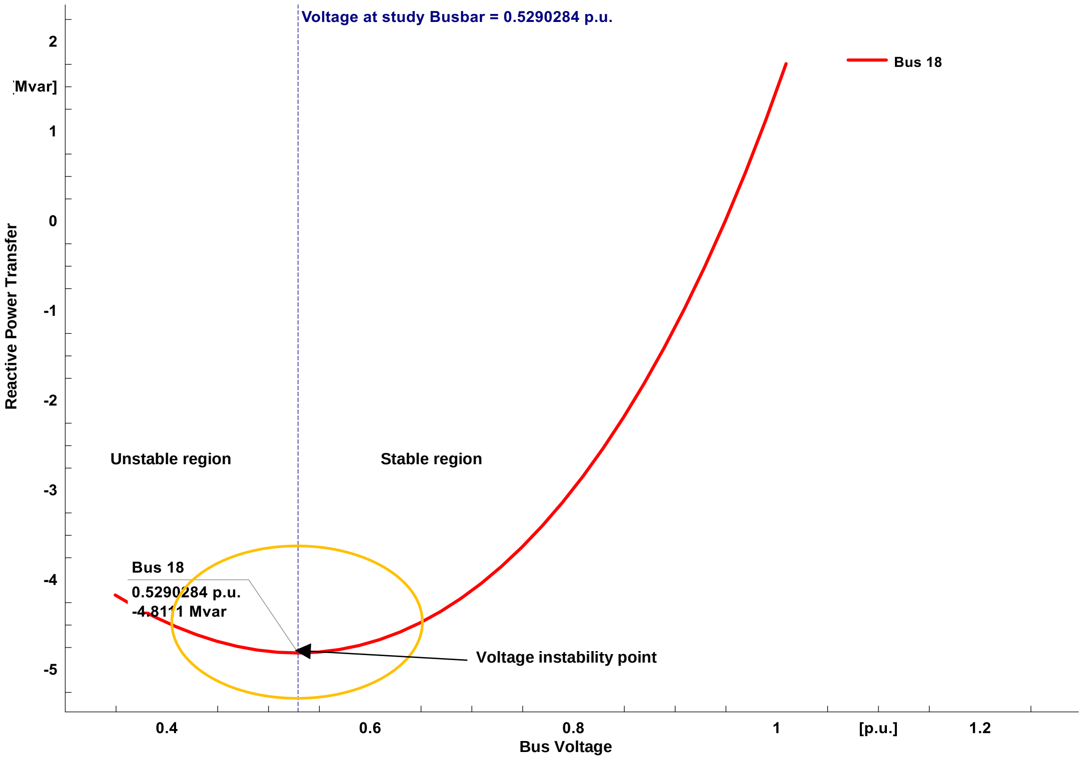


Figure 5.4: QV Curve characteristic for Bus 18

The PV and QV curves have been used to identify the distribution's weakest busbar and optimally integrate the distributed energy resources. As a result, PV and battery energy storage systems were selected as suitable distribution and energy storage systems, respectively. The model is demonstrated in Figure 5.5, where the PV system shares the busbar with BESS at low voltage. The voltage is further increased using the PVD1 transformer, as shown in the figure.

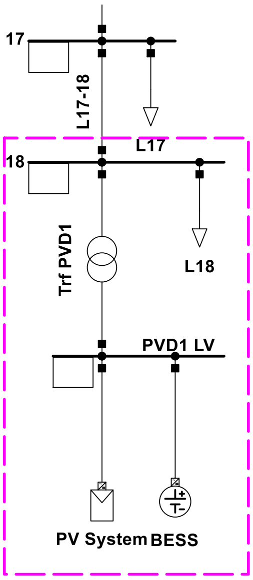


Figure 5.5: Integrated PV and BESS on modified IEEE 33 Bus Distribution Network

Furthermore, the integration of the energy system has brought an improvement in power system reliability and stability. The system voltage was improved, as indicated in Figure 5.6. All the bus bar voltages are above the minimum acceptable level of 0.95pu.

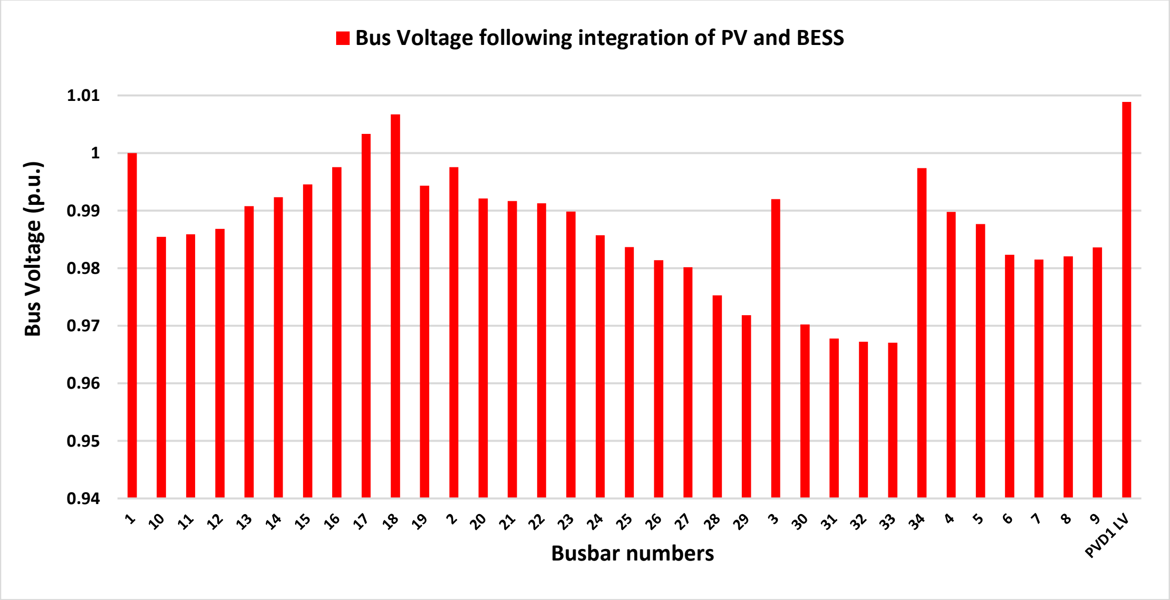


Figure 5.6: Bus voltage after integrating the PV and BESS

The bus voltage results presented in Figure 5.6 indicate the PV system's contribution to the distribution grid. BESS is, however, utilized to provide ancillary service when a disturbance occurs. Under the steady-state condition, the BESS is not expected to deliver any power to the grid. The load flow results are shown in Figure 5.7.

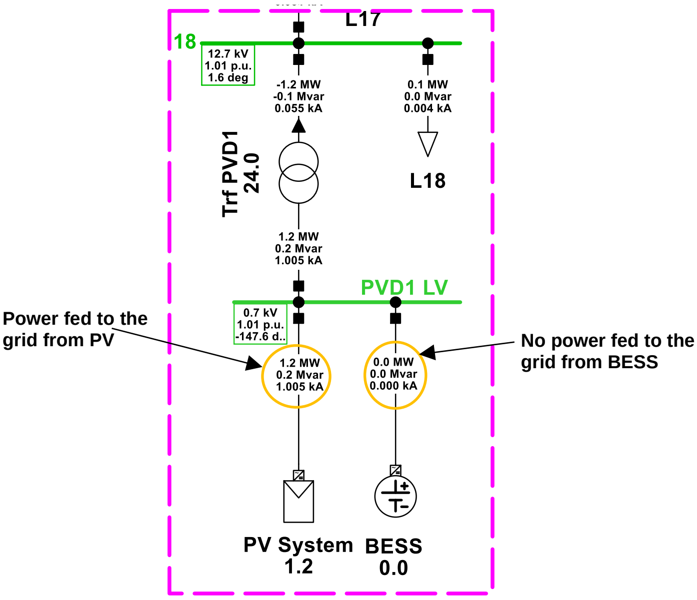


Figure 5.7: PV and BESS under steady-state simulation

Ideally, distributed energy resources are primarily climate-based and intermittent by nature. These energy resources are widely used only to provide energy when it is available. Their participation in ancillary service is also limited due to their configuration and operation. It is, therefore, pivotal to consider other alternatives to facilitate the function of ancillary services, such as voltage and frequency support.

5.3 Development of the control scheme for power dispatching and voltage support

The need to develop a control system that will enable the dispatchable distributed energy resource to participate in grid ancillary services is of uttermost importance. As indicated in Figure 5.7, the BESS is integrated into the grid to support the system to always maintain its stability; however, this system requires an additional control loop to provide the expected services fully. Therefore, a control scheme is proposed to enable power dispatching from the BESS for distribution grid support. The control scheme is developed using DIgSILENT simulation software, and control signals fed to it include the system frequency and the bus voltage at the critical busbar.

Using DIgSILENT simulation software, the control frame to map the inputs to the control scheme was modeled. Furthermore, the block function was used to develop the control logic. Finally, the main control scheme uses the proportional and integral (PI) function control to eliminate the control error. The developed control scheme operates as follows: when a disturbance affects the system frequency and voltage, the error signal is sent to the PI control, reducing the difference between the input and the output signals while improving the system stability. This is done for both voltage and frequency. Therefore, the control scheme is divided into two parts: the first is for frequency control, and the second is for voltage support.

Figure 5.8 is the control frame demonstrating the input signals mapping to the control scheme. The system frequency is the same throughout the network; hence there is only one signal fed for frequency; however, the bus voltage is different through the network, and bus voltage from the far end of the radial was selected as the control signal. These busbars include 18, 33, and 22.

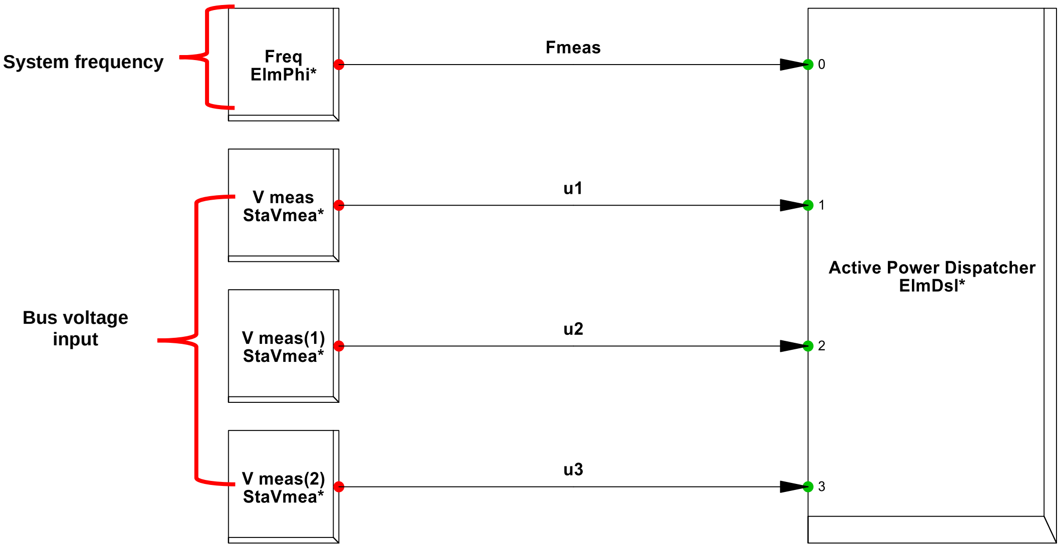


Figure 5.8: Input signals to the control scheme

The input signals indicated in Figure 5.8 are sent to the primary control scheme; the mathematical operation of the system is shown in Equations (5.1) and (5.2).

$$\Delta f = f_{ref} - f \tag{5.1}$$

$$\Delta V = V_{nominal} - V_{measured} \tag{5.2}$$

Where f_{ref} , is the nominal system frequency (50Hz), and f is the measured system frequency. $V_{nominal}$, is the nominal voltage, while $V_{measured}$, is the measured voltage at the busbar. The PI control mathematical model is expressed in Equations (5.3) and (5.4).

$$yo = [K_p\left(f_{ref} - f\right) + \int_0^t (f_{ref} - f)\, dt] \times \frac{1}{(1 + sT)} \tag{5.3}$$

$$yo1 = [K_p(V_{nominal} - V_{measured}) + \int_0^t (V_{nominal} - V_{measured})\, dt] \times \frac{1}{(1 + sT1)} \tag{5.4}$$

In Equation (5.3), yo is the output control signal for frequency, while $yo1$ is the control output signal for the voltage. The frequency and voltage control output signals are further processed through a low-pass filter. The control scheme modeled on DIgsilent block functions is shown in Figure 5.9, which also represents the control scheme's mathematical model from Equations (5.1) to (5.4).

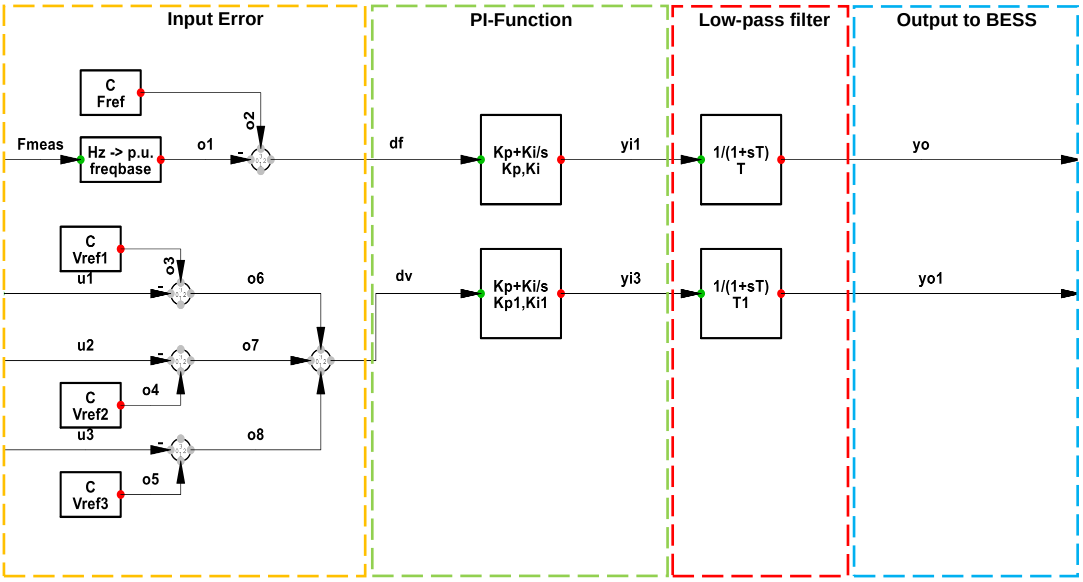


Figure 5.9: **Active power dispatching and voltage support control scheme function block diagram**

The developed control scheme working principle is summarized in the flowchart diagram illustrated in Figure 5.10. The voltage and the frequency are the variables of the control scheme. The control scheme aims to keep both frequency and voltage within acceptable operating limits and prevent the distribution grid from collapsing when it is subjected to a disturbance. The last step of the flowchart shows that the control action only ends when the controlled variable reaches a steady state. At this stage, the system frequency is equal to its reference value and the same with bus voltages, as they need to be equal to their nominal or reference value.

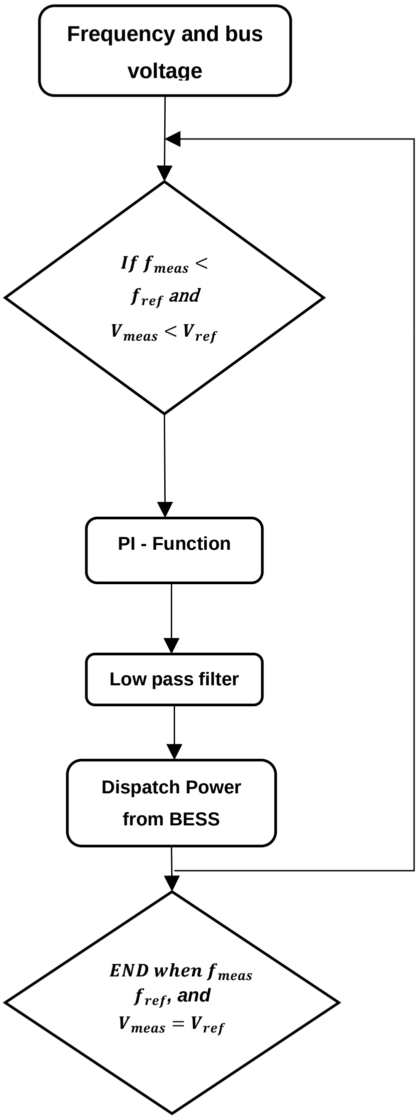


Figure 5.10: Control scheme functional flowchart

The efficacy of the developed control scheme needs to be tested under various system conditions. This analysis is essential to assess the robustness of the developed scheme and check its shortcomings or setbacks.

5.4 Control scheme evaluation under various disturbance events

The functionality of the proposed control scheme needs to be evaluated mainly under a dynamic state because, during steady-state, the BESS is not supplying power to the grid, whereby a disturbance is introduced. This is done to prove its efficacy, reliability, and robustness. During load flow simulation, when the PV and BESS were integrated, the results showed some improvement compared to the results presented in Section 4.3 through Figure 4.2. The heatmap is shown in Figure 5.11, which shows the system loading. The generator loading is also decreased by the power provided by the Solar PV plant.

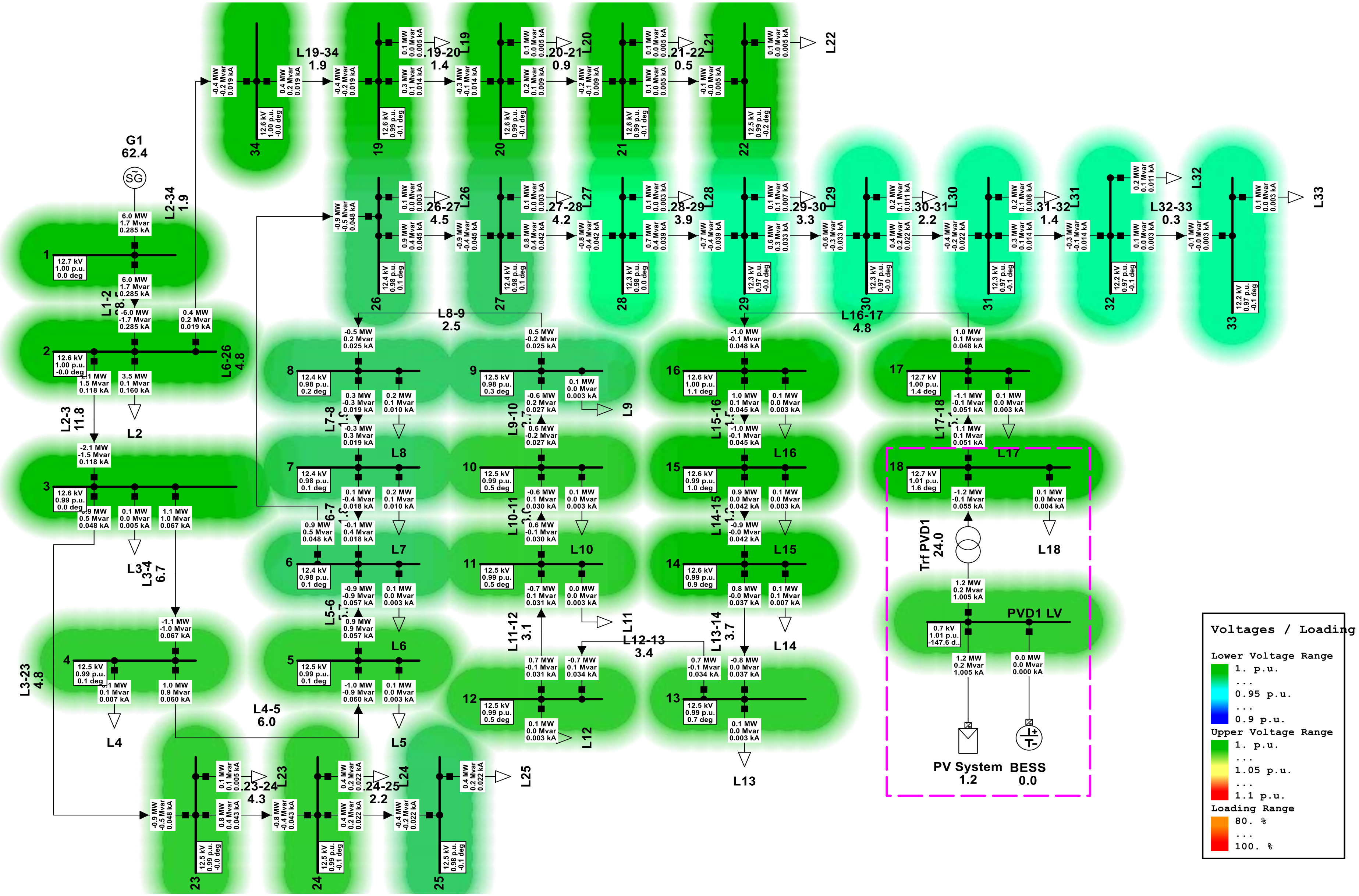


Figure 5.11: Distribution network heatmap understeady-state condition with PV system and BESS intergrated

The case study executed in Section 5.4.1 for load incremental is used to analyze the behavior of the distribution integrated with the PV system and BESS.

5.4.1 Load demand increment event analysis when PV and BESS are integrated

The total grid load demand is increased by 15%, and the results obtained are analyzed. Considering Figure 5.12 (a), when the load demand was increased, the BESS responded to the disturbance by dispatching the active power required, as shown in Figure 5.12 (b). the demand increase led to a change in system voltage; however, with support from the PV system and BESS, the voltage fluctuation was stabilized and controlled. Nevertheless, due to the increase in power demand, and the distance to the load, which requires additional supply capacity, for example, load 2 is the biggest in the system; therefore, when the demand increases, more power is needed to be supplied to it. Hence the losses increase from 0.14MW to 0.4MW, as indicated in Figure 5.12(d).

Thus, the placement of the bulk load needs to be closer to the supply point to eliminate power losses during power transfer. Moreover, the system frequency was brought to its initial state following a 15% load demand increase to the entire distribution grid. Therefore, system frequency is also forming part of the controlled variables of the control scheme for power dispatching. As a result, the control scheme maintained the system frequency between 50Hz and 49.9Hz, as shown in Figure 5.12 (c).

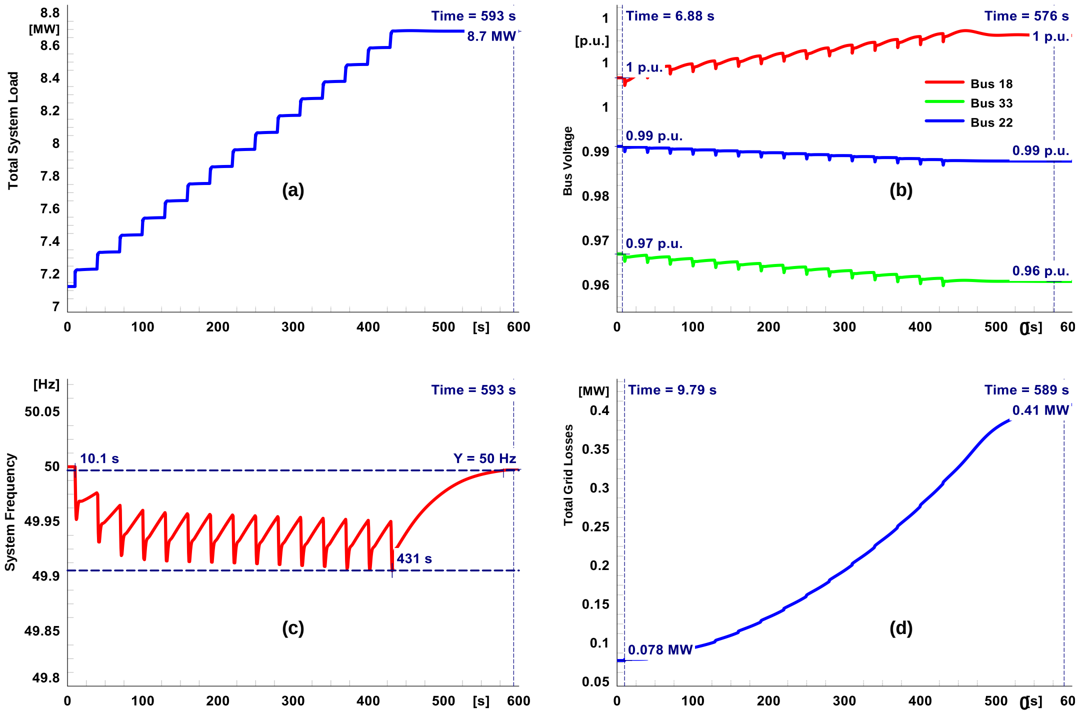


Figure 5.12: System behavior following 15% load demand increase - (a) Total system load, (b) Bus 3 and 18 voltages, (c) System Frequency, and (d) Total Grid losses

As the load demand increased, the BESS started to dispatch power to support the grid on its ancillary services, such as frequency and voltage. As indicated in Figure 5.13 (a), the active power dispatching started to increase as the load demand continued to increase. As a result, the total active power dispatched reached 1.86MW. On the other hand, the BESS initially provided a reactive power component for a short period and suddenly dropped as the bus voltages reached their steady-state level.

Figure 5.13(b) illustrates the contribution of the PV system during the dynamic-state event analysis. The PV system, as indicated earlier, provides power to the grid when sunlight is present. However, the intensity of solar radiation is intermittent and climate dependent; hence, under these dynamic conditions, the PV system continues to supply a constant amount of power to the grid for both active and reactive power.

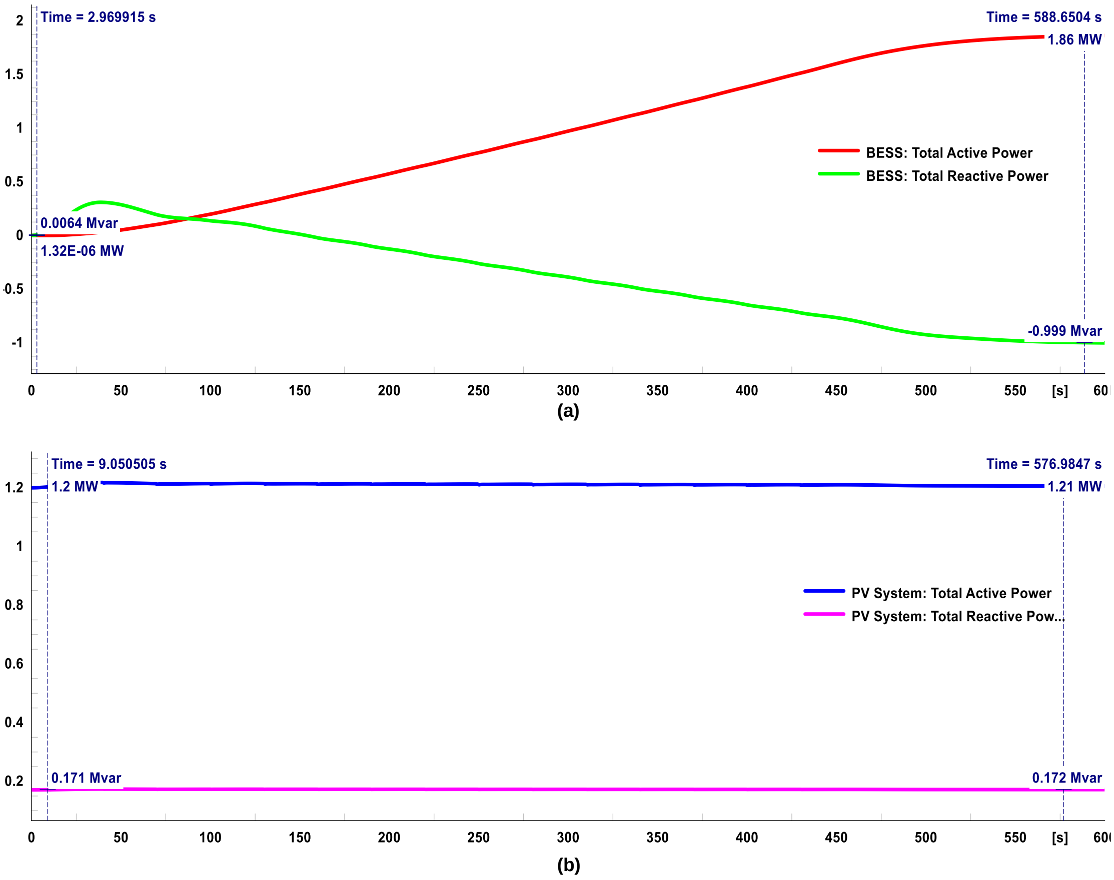


Figure 5.13: System behavior following 15% load demand increase - (a) BESS Active and Reactive Power, (b) PV System Active and Reactive Power in a dynamic-state condition

The BESS is only configured to support the power system with ancillary services. Hence it only provides power to the grid when there is a disturbance. This configuration aims to overcome the issues of distribution grid voltage and frequency instabilities. The contribution of both the PV system and BESS to the distribution network when it is subjected to load demand increase disturbance is illustrated in Figure 5.14.

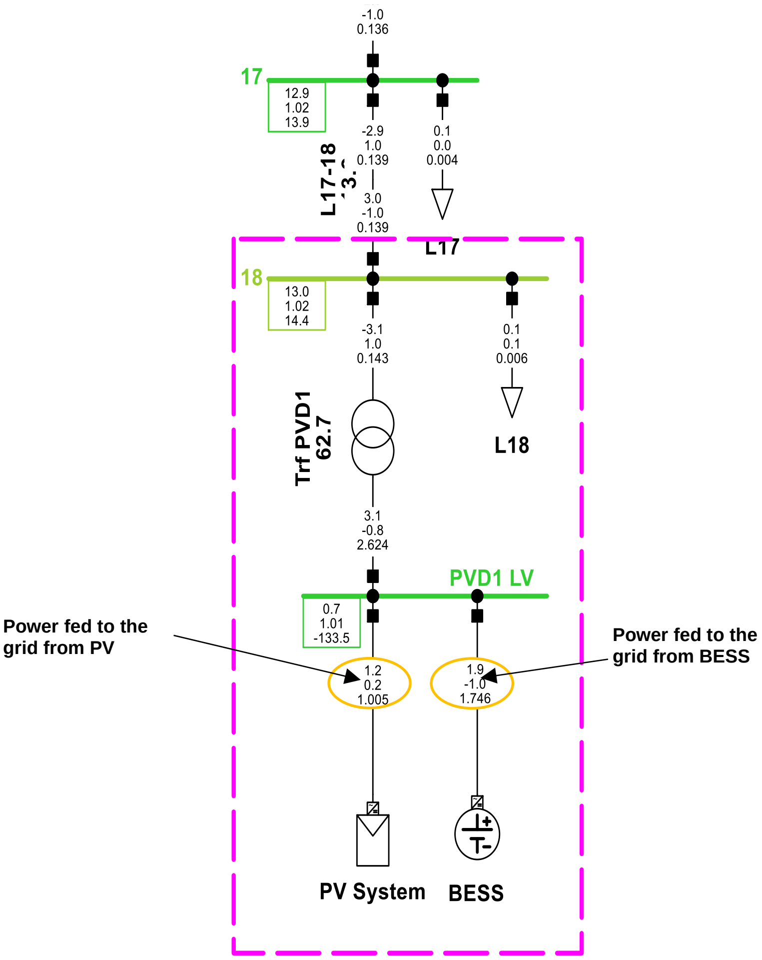


Figure 5.14: Power output of PV system BESS following 15% load demand increase

5.5 Summary

Maintaining distribution grid stability is a crucial aspect that requires constant monitoring to ensure reliable and uninterrupted power supply. When the distribution grid experiences any disturbance or interruption, it must be resilient enough to overcome the disruption and restore its stability. To achieve this, a thorough evaluation of the system's robustness must be carried out, taking into account all possible disturbances and contingencies.

In this chapter, the focus was on studying the contribution of distributed energy resources in enhancing the stability and reliability of the distribution system. The results of the study demonstrated that the control scheme developed to enable power dispatching from battery energy storage systems (BESS) significantly improved the distribution network's stability and reliability.

To ensure the distribution network's reliability, it is essential to assess its performance under contingency scenarios. This evaluation helps strengthen the network's ability to restore services and recover from any disturbance efficiently. The reliability analysis involves determining how long it takes to restore services after a disturbance and how frequently the network experiences disruptions. This analysis enables us to understand how the network operates when one of its components is out of service, whether due to a fault or planned maintenance, and provides a basis for improving the distribution service restoration process.

In summary, maintaining distribution grid stability is critical to ensuring reliable and uninterrupted power supply, and a thorough evaluation of the system's robustness is necessary to achieve this. The use of distributed energy resources, such as BESS, can enhance the distribution system's stability and reliability. Finally, assessing the distribution network's reliability under contingency scenarios is crucial to improve the service restoration process and strengthen the network's resilience to disruptions.

CHAPTER SIX

DISTRIBUTION SYSTEM SERVICE RESTORATION ENHANCEMENT APPROACH THROUGH NETWORK RECONFIGURATION

6.1 Introduction

Distribution stability is one of the prominent features that the distribution grid needs to possess (Wang et al., 2022). This feature was discussed in Chapter 5, and various methods were applied to prove the efficacy of the proposed control strategy applicable to enhance the distribution system stability. However, when the network experiences heavy disturbance, the control measures are exhausted, and eventually, power outages and service restoration need to be executed as quickly as possible.

Service restoration is the mechanism to restore the electrical energy supply to the customers following a power outage resulting from a planned or unplanned event. The distribution possesses this attribute, resulting in the network being regarded as reliable. Therefore, evaluating and developing methods to enhance the distribution service restoration is essential.

This chapter covers the cutting-edge approach to enhance the distribution system service restoration. In improving service restoration, the network reconfiguration strategy is adopted as the first alternative mechanism, which is outlined in Section 6.2. Furthermore, the deployment of distributed energy resources to improve service restoration is also presented in Section 6.3. Section 6.4 covers the utilization of distributed energy resources in a reconfigured distribution network to enhance service restoration. Finally, Section 6.5 concludes the chapter.

6.2 Distribution network reconfiguration

Distribution network loads evolve with time, which should be the same as distribution network reconfiguration to accommodate new load compositions. The network reconfiguration requires the distribution system planners to develop a redundant system that can help in the event of an emergency, such as a power outage, to return the service to the customers. This approach requires more investment, and is defined as infrastructural development. Redundancy in the distribution network is meant to offer an alternative supply route if the one in service is inactive. The redundant system approach helps to improve the supply interruption frequency. Another critical aspect that motivates network reconfiguration is the supply outage duration. Network reconfiguration assists in enhancing supply restoration as the network is the equipment's typical open point which can be used to pick up customer while fault-finding and repairs are taking place (Wu et al., 2022).

When planning distribution network reconfiguration, distribution reliability indices such as the System Average Interruption Duration Index (SAIDI) and the System Average Interruption Frequency Index (SAIFI) need to be applied (Prettico et al., 2022). Another critical aspect to consider when using these indices is the history of the power outages. These are the outages that occurred in the past that need to be known. This will help to understand how much energy was lost, the time taken to return the system to the customers, and how frequently the power outage occurs. This classification will also help to determine the need to invest in network reconfiguration, considering how much revenue has been lost due to power outages (Agarwal et al., 2022).

The PV and QV curve static approach used in Chapter 5 to identify the most critical busbar in the system is also used to determine the common point of coupling the distribution line. Bus 18 is also selected as the common coupling point of all the distribution lines to form a ring network. The normal open points are also configured in Bus 18. Figure 6.1 illustrates the reconfigured network operating in a steady state where additional distribution lines are shown. The additional lines are highlighted in yellow graphic illustration.

The parameters of the selected additional distribution line, line A, line B, and line C are shown in Table 6.1.

Table 6.1: **Additional distribution line data (Line A, B, and C)**

Name	From Bus	To Bus	Z1	phiz1	R1	X1
			ohm	**degree**	**ohm**	**Ohm**
Line A	33	18	0.064568	27.01071	0.057525	0.029324
Line B	25	18	0.064568	27.01071	0.057525	0.029324
Line C	22	18	0.064568	27.01071	0.057525	0.029324

As indicated in Figure 6.1, the additional lines are active, but their circuit breakers are currently open at Bus 18. The aim of developing this configuration is to ensure that, when one line is on either part of the network, the customer supply can be re-routed using the normally open lines, which serve as a backup.

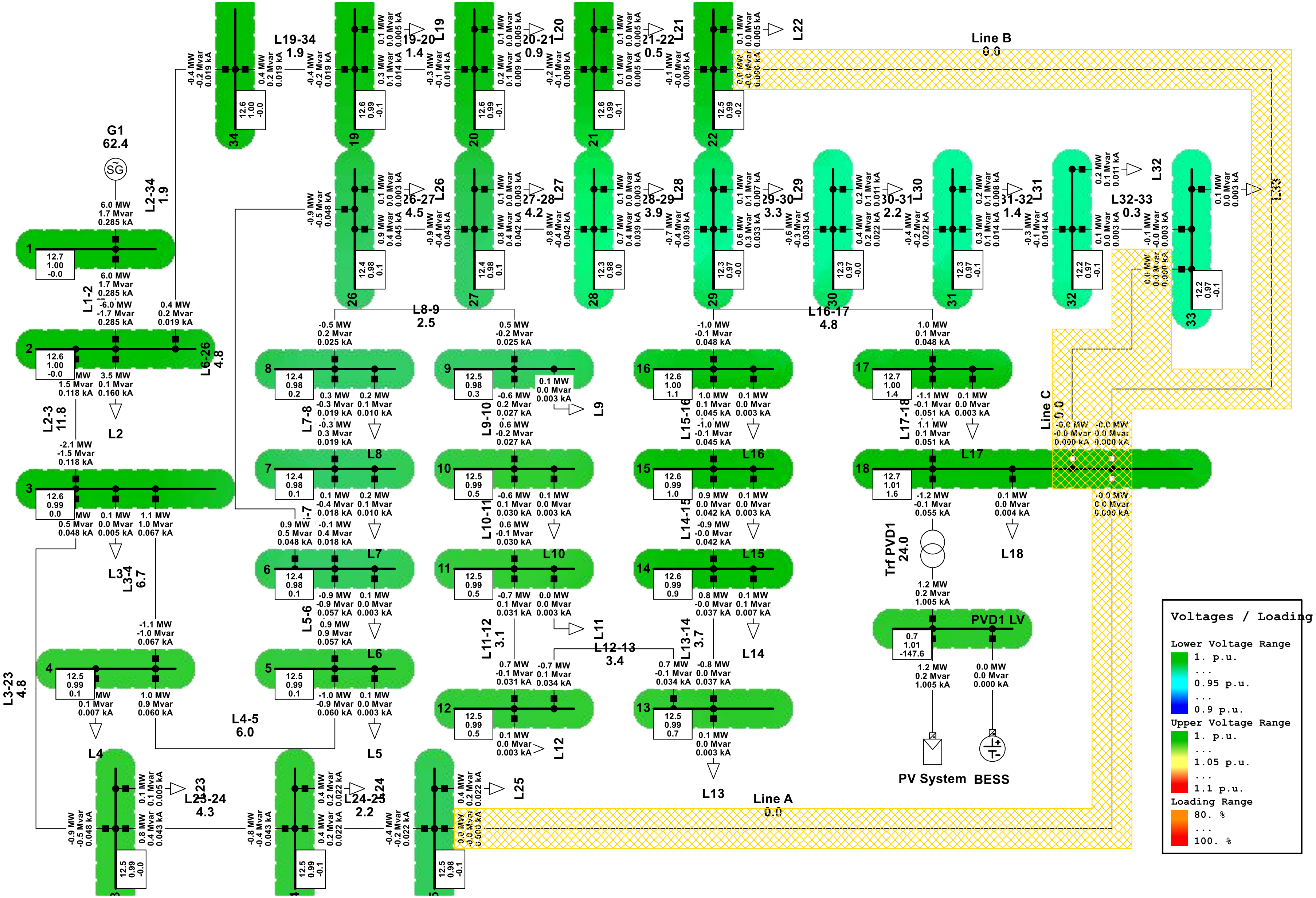


Figure 6.1: Reconfigure the Distribution network heatmap operating at steady-state

The normal open points were then closed to assess the system load flow when all the lines were in service and when the system was operating in a ring topology. Figure 6.2 shows the system voltage before and after the reconfiguration. During this analysis, the distributed energy resources were out of service, and the new additional distribution lines were implemented. As a result, the bus voltage improvement is observed. In addition, all the system busbars are now above the minimum of 0.95 pu, which is the requirement for the distribution grid code.

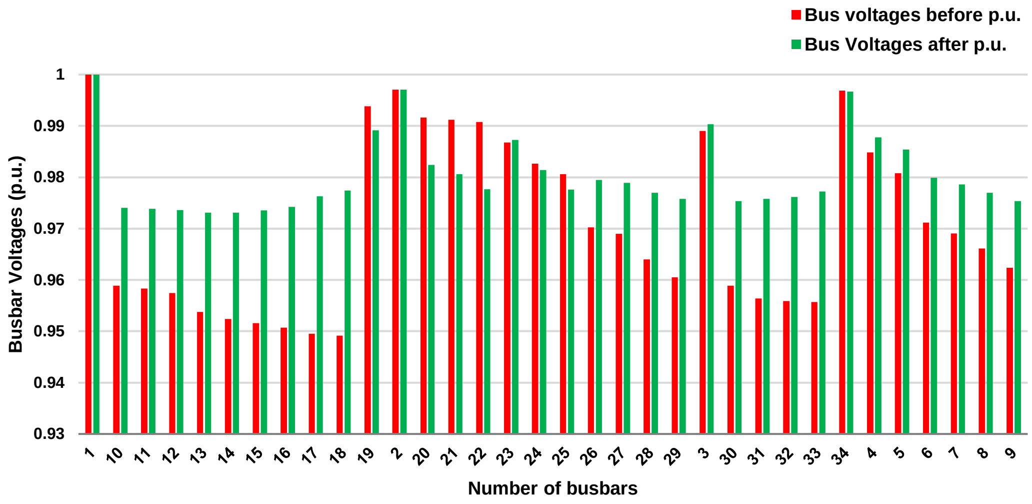


Figure 6.2: **System voltages when the grid was operating at steady-state with new additional lines**

The operation of the reconfigured distribution network needs to be evaluated on both steady-state and dynamic-state conditions. This is done to check if there is any improvement to the network. Therefore, the distribution network is analyzed first based on n-i contingency.

6.2.1 n-i dynamic simulation and analysis

The n-i contingency analysis is performed to assess the network reliability when one of the critical components is lost. The distribution system's critical components include lines, cables, and power transformers. The contingency can also be applied when a full distribution substation is out of service.

This analysis is performed by eliminating one component of the distribution system, in this case, the distribution line. Finally, the contingency analysis is performed following the sequence presented in Table 6.2, where the first trip condition is implemented on line 2-34 at t=10 s; after that, a close command is issued to close the circuit breaker for line B at Bus 18 at t=50 s. Next, at t=100 s, line 3-23 is taken, and following this event, restoration is also performed by closing line A. Finally, line 27-28 is tripped at t=200 s, and for supply to be restored to the affected customers, line C is closed at t=250 s.

Table 6.2: Switching events

Name	Breaker or Element	Time
		s
Trip 1	L2-34	10
Close 1	Line B	50
Trip 2	L3-23	100
Close 2	Line A	150
Trip 3	L27-28	200
Close 3	Line C	250

The system response to the switching event is indicated in Figure 6.3. The contingencies case shown in Table 6.2 is when the system operates without support from the distributed energy resource. The system voltage collapsed on the second trip, and the voltage collapsed to less than 0.95 pu. On the last event trip and close line C closing event, the system voltage could not be recovered, and the result of the voltage was recorded as 0.85 pu, as shown in Figure 6.3 (b). The disturbance introduced also influenced the grid losses, which rose from 0.11 pu to 0.35 pu after all the switching events. The system frequency also oscillated during the switching events; when the load was lost, the system frequency rose to 50.3Hz, with some switching transients which reached above 50.4Hz, and after the whole switching events, the frequency stabilized at 50.11Hz.

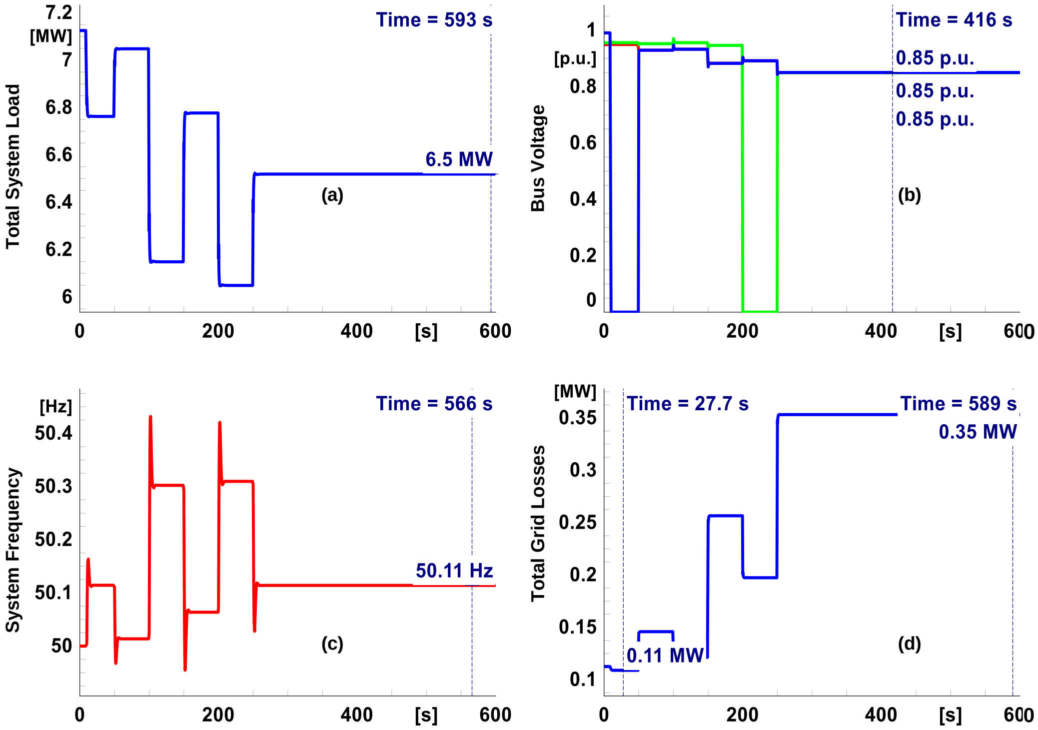


Figure 6.3: System response following switching events without BESS support- (a) Total system load, (b) Bus 3 and 18 voltages, (c) System Frequency, and (d) Total Grid losses

The voltage results for each busbar are shown in Figure 6.4, and it can be seen that the bus voltage before the contingency was operating within the acceptable range between 0.95 pu and 1.05 pu. However, after the switching event, most of the busbar voltage collapsed to a level that was too low, below 0.85 pu. At this point of the case study, it is challenging to recover the distribution network.

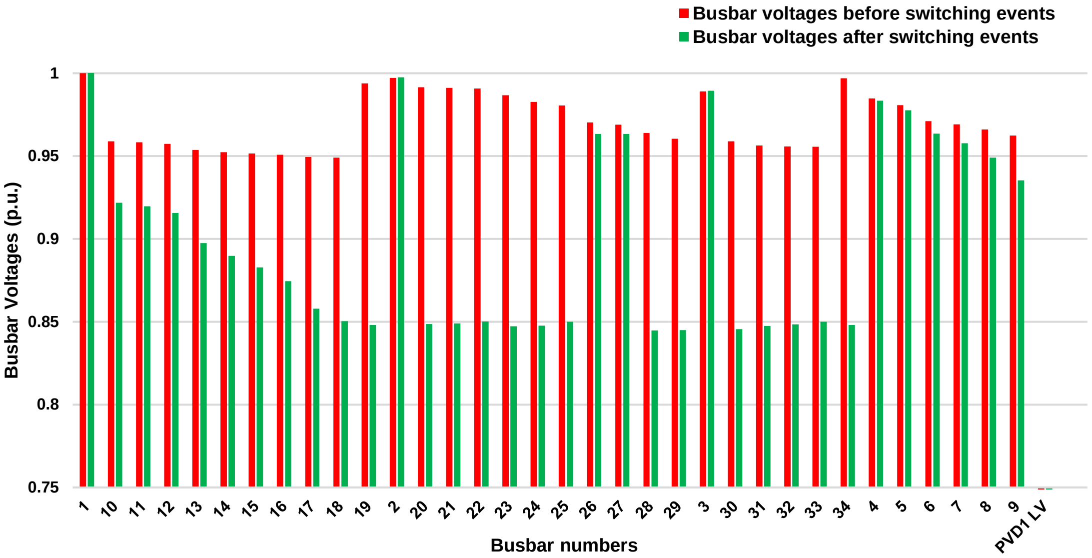


Figure 6.4: System voltages before and after the switching event following distribution grid reconfiguration

6.3 Deployment of distributed energy resources to improve service restoration before the distribution network reconfiguration

The event described in Table 6.2 is applied once the network returns to its radial configuration and the normally open point on busbar 18 is activated. This analysis aims to assess the impact of distributed energy resources on the restoration process. As shown in Figure 6.4, the voltage on busbars 18 to 24 and 28 to 34 dropped to 0.85 p.u. or less. Although the integration of the PV system improved the voltage from below 0.85 p.u to above 0.9 p.u, it remained below the acceptable minimum voltage of 0.95 p.u. as indicated in Figure 6.5. At this point, the BESS was integrated into the distribution grid, but its controller was not functioning, so the BESS did not contribute any power to the grid.

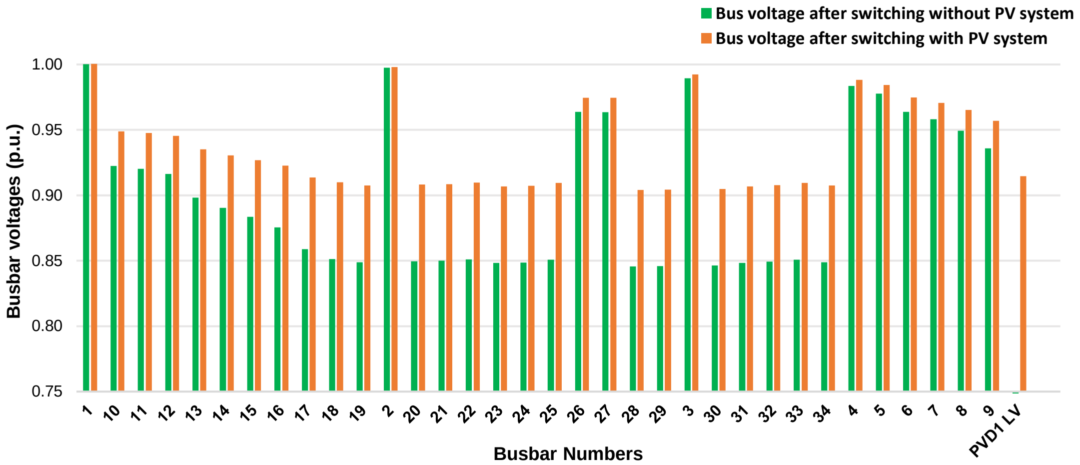


Figure 6.5: System voltages before and after the switching event with PV system support

The PV support for voltage stability is inadequate, as the system voltage is still very low. Therefore, the battery energy storage system (BESS) is needed to support the PV in stabilizing the distribution grid. The exploitation of BESS is based on voltage support and system frequency support.

6.4 Utilization of distributed energy resources enhancing reservice restoration on a reconfigured distribution network

Distributed energy resource has the advantage of being integrated into the load, enabling them to be dispatched as quickly as possible to quench any instability in the distribution system. It has been observed that the distributed energy resources that lack the capability of dispatching cannot assist in enhancing service restoration. These energy resources do not provide additional power required by the grid when a disturbance occurs; however, they can only offer electrical energy when available. Solar PV was evaluated, and its limitation in regards to power dispatch capability, and when it was used, the system voltage showed a small improvement.

Battery energy storage can store the excessive amount of power fed to the distribution grid, and this power can be used as the system operating conditions change. For more power capturing, it is recommended that the battery energy storage is placed close to the energy resource. For this study, BESS was placed close to the Solar PV system. This approach was implemented to capture the power from the PV when the system condition enables to reuse this power when the load demand changes.

The battery energy storage system has several operational advantages which help to ensure that the distribution is operated within its operating limits. First, the BESS addresses the low voltage event that the PV could not cover in Section 6.3. The same contingency applied in Section 6.3 is repeated to assess the contribution of the BESS.

After the control scheme was activated, the distribution system operating conditions were improved from those highlighted in Section 6.3. The system voltage was enhanced in all the busbars to 1pu. This is due to the reactive power support from the battery energy storage system. Figure 6.6 (a) illustrates the impact of the switching on the overall system load demand. Therefore by tripping L2-34, the overall demand decreases, and the system frequency increases as there is less demand, as indicated in Figure 6.6(c). As shown in figure 6.6 (d), the losses also dropped.

The system dynamics are changing as the switching events change. Figure 6.6(b) illustrates the impact of the switching events on bus voltages, and worth noting that after the switching events, the bus voltages were restored without the distribution network collapsing. The system frequency dropped from 50Hz to 49.79Hz, as indicated in Figure 6.6 (a), flowing the switching events as shown in Table 6.2, and this level of system frequency is still within the acceptable level in terms of the distribution code standard. Still, it is not fully recovered to its nominal value of 50Hz. The load reached a new steady state of 7.4MW compared to an initial value of 7.1MW. This is due to the load swing that occurred, and the load flow direction changed following the switching events after the network was reconfigured and strengthened by additional distribution lines.

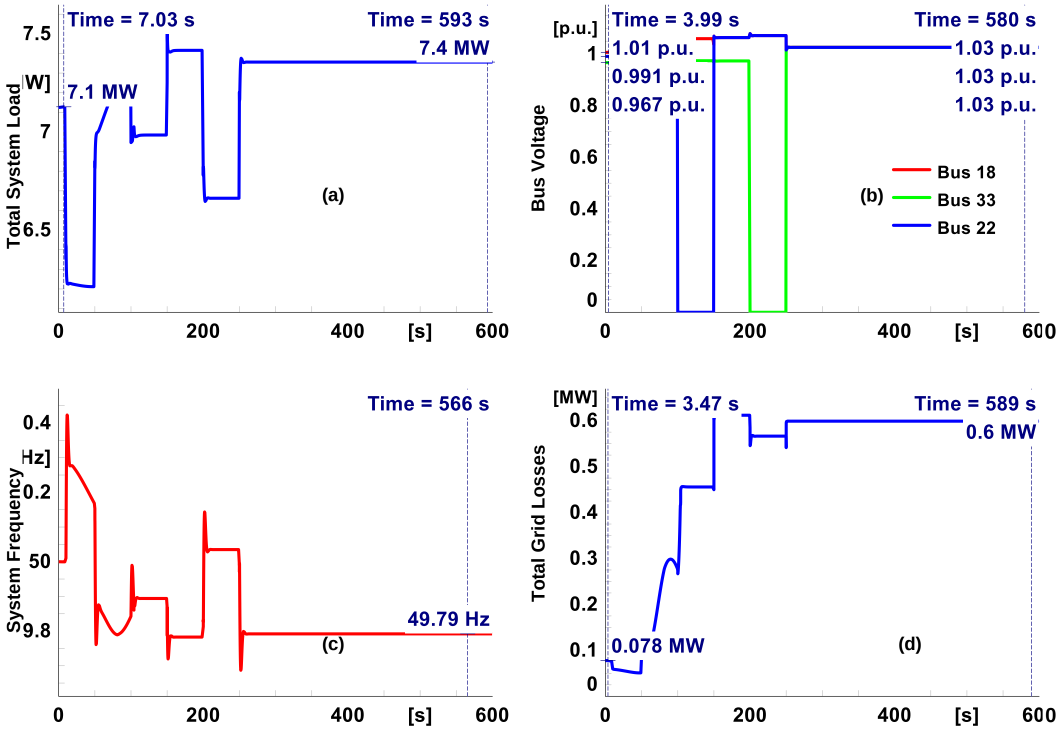


Figure 6.6: **System response following switching events with PV system support (a) Total system load, (b) Bus 3 and 18 voltages, (c) System Frequency, and (d) Total Grid losses**

The BESS's contribution to improve the system’s stability is illustrated in Figure 6.7 (a), where the reactive power contribution is shown. The PV provides constant power to the grid as indicated in Figure 6.7 (b).

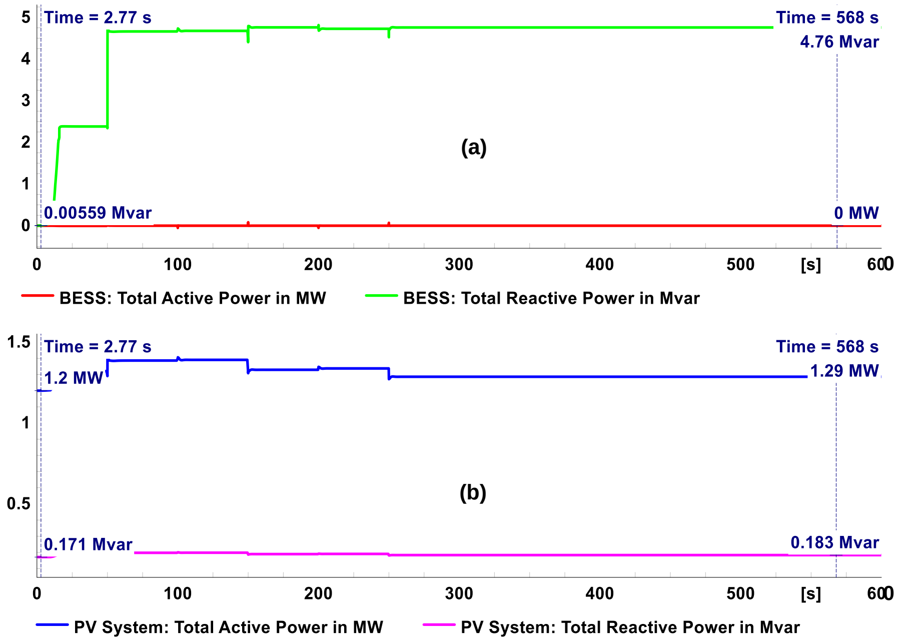


Figure 6.7: PV System and BESS without the control scheme following switching event

Figure 6.8 shows the distribution network after the switching event, and the heatmap indicates the system loading. The contribution of the BESS and PV system has significantly improved the distribution stability following switching events highlighted in Table 6.2. The analysis of figure 6.8 is done in conjunction with figure 6.6. Following the switching events, the bus voltage on busbabr 18 improved from 0.85.pu, as indicated in figure 6.3, to 1.03p.u, as shown in figure 6.6. In figure 6.8, the color legend is now more green and light orange since the bus voltage is above 1p.u, as indicated on the color legend in figure 6.8. The network remained stable after the switching events, leading to its new radial configuration by closing the normally open circuit breakers or switches positioned at busbar 18.

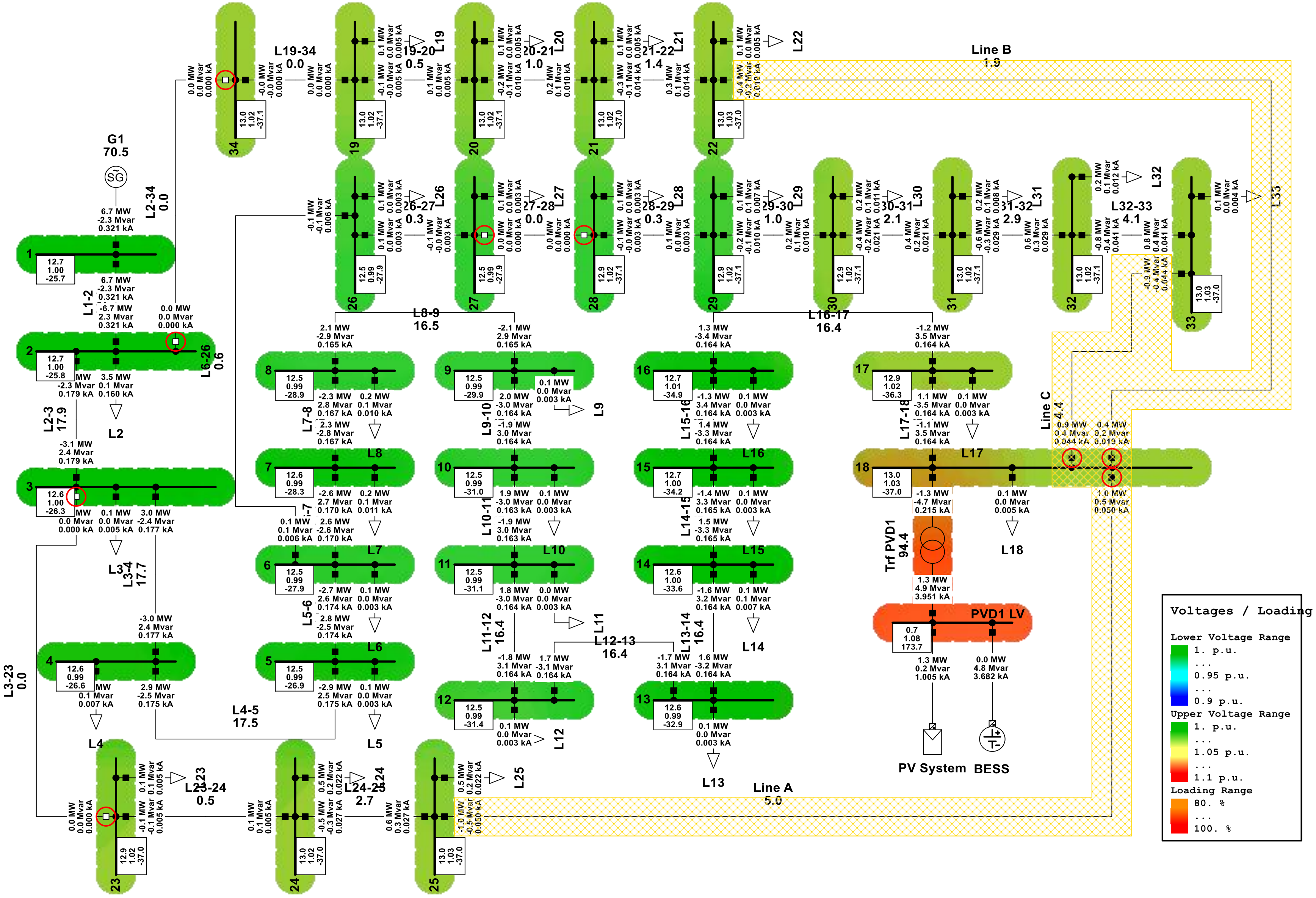


Figure 6.8: Distribution network following the switching and the contribution of PV System without the control scheme being activated

Automation in the distribution network needs to be exploited to enhance service restoration. The following case is considered for an intelligent distribution network with automation capability to improve the power outage duration and restoration. In Table 6.3, trip and close events are deemed to be co-occurring.

Table 6.3: **Switching events**

Name	Breaker or Element	Time
		s
Trip 1	L2-34	50
Close 1	Line B	50
Trip 2	L3-23	150
Close 2	Line A	150
Trip 3	L27-28	250
Close 3	Line C	250

The results shown in Figure 6.9 follow the automation sequence whereby line l2-34 tripped, and immediately, the normally open point for Line B at Bus 18 was closed. This event was followed by trip 2 at Line 3-23, and line A close instantaneously. Lastly is trip 3, which isolated Line 27-28, and close command was issued to Line C.

Figure 6.9 shows the network simulation results following the automation switching event indicated in Table 6.3. Figure 6.9(a) is the total load demand of the distribution network. Following the switching events, the load demand with some losses increase by 0.1MW from 7.1MW to 7.2MW. But these results are relatively low compared to those obtained when there was no contribution of DERs, and network configuration as indicated from previous chapters and in figures 6.3 and 6.6.

The DERs have also significantly contributed to voltage stability following the switching events, as figure 6.9(b) indicates. Before the switching event, the bus 18 voltage was 0.967p.u. After the switching event, this voltage improved to 0.991 p.u. Bus 22 and 33 remain stable as close as 1pu.

The system frequency remained stable before and after the switching event, as the BESS contributed additional active power to balance the supply and load demand, as indicated in figure 6.9(c); the amount of active power contributed to recover the system frequency is shown in figure 6.10 (a)

The system frequency remains stable for the duration of the series of events. This is true for the system voltage as well. However, the power losses increased from 0.078 MW to 0.22 MW, as Figure 6.9 (d) shows. These losses are relatively taking into account that these are the results following switching events; therefore, the contribution of DERs is also noticeable in this regard.

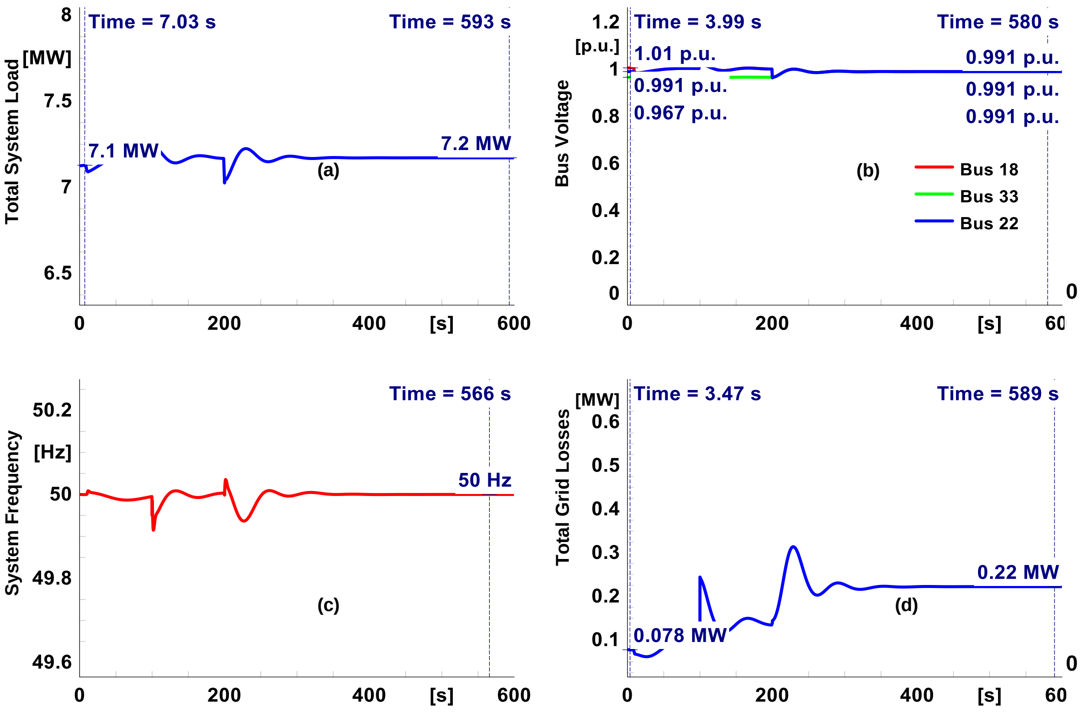


Figure 6.9: System dynamic-response following a switching event with control scheme activated - (a) Total system load, (b) Bus 18, 22 and 33 voltages, (c) System Frequency, and (d) Total Grid losses

Furthermore, Figure 6.10 demonstrates the contribution of the BESS in (a) and for the PV system in (b). The initial power output from BESS was 0 MW, which rose to 0.17 MW. The reactive power from BESS increased from 0 Mvar to 2.83 Mvar. At the same time, the PV remained constant in power dispatching.

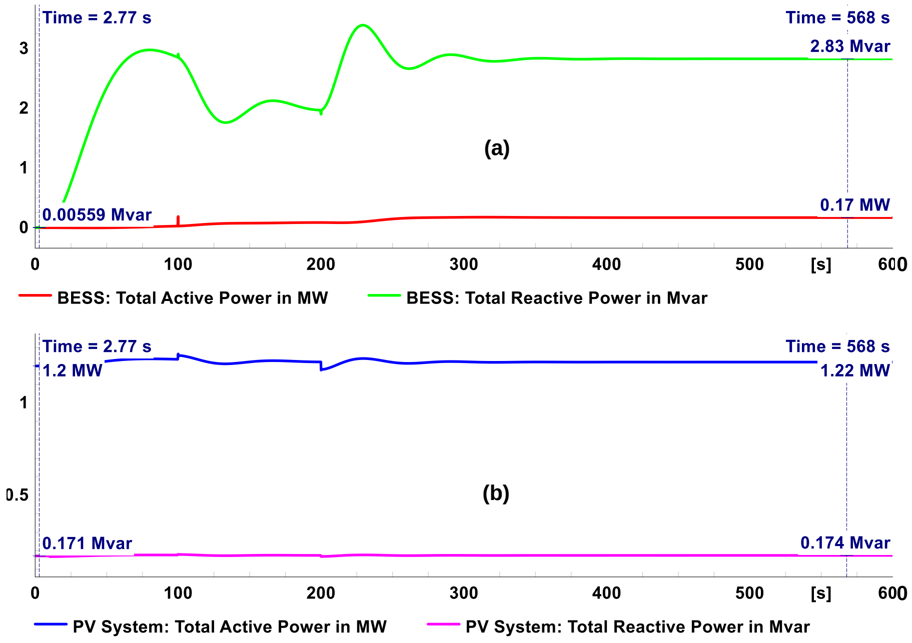


Figure 6.10: System dynamic-response following a switching event with control scheme activated - (a) BESS support and (b) PV System support

6.5 Robustness and reliability assessment

The system's robustness and reliability were analyzed using the composition of two different events over time. First, the line outages and the load demand increase were considered during the disturbance initiation. The aim is to assess the distribution network behaviour under a series of events. The vigorous assessment helps to analyze the efficacy of the developed control scheme under various contingencies.

Table 6.4: **Switching events**

Name	Breaker or Element	Time
		s
Load demand	**All loads**	**10-430**
Trip 1	L2-34	450
Close 1	Line B	450
Trip 2	L3-23	500
Close 2	Line A	500
Trip 3	L27-28	200
Close 3	Line C	200

As indicated in Figure 6.11, the 15 steps load events were initiated, and later, line outages with immediate restoration through the normally open point were also included in the simulation. As a result, the total load demand was increased from 7.1 MW to 8.8 MW. During load demand increase, the BESS supported the system frequency with the control scheme. After the whole series of events, the system frequency returned to its nominal state of 50Hz, as demonstrated in Figure 6.11 (c).

During the load demand increase, the bus voltages were maintained at their initial values after the line trip and service restoration. The voltage was improved to 0.99 pu on buses 18, 22, and 33, as indicated in Figure 6. 11 (b). The total grid load decreased from 0.078 MW to a new value of 0.059 MW, as shown in Figure 6.11 (d).

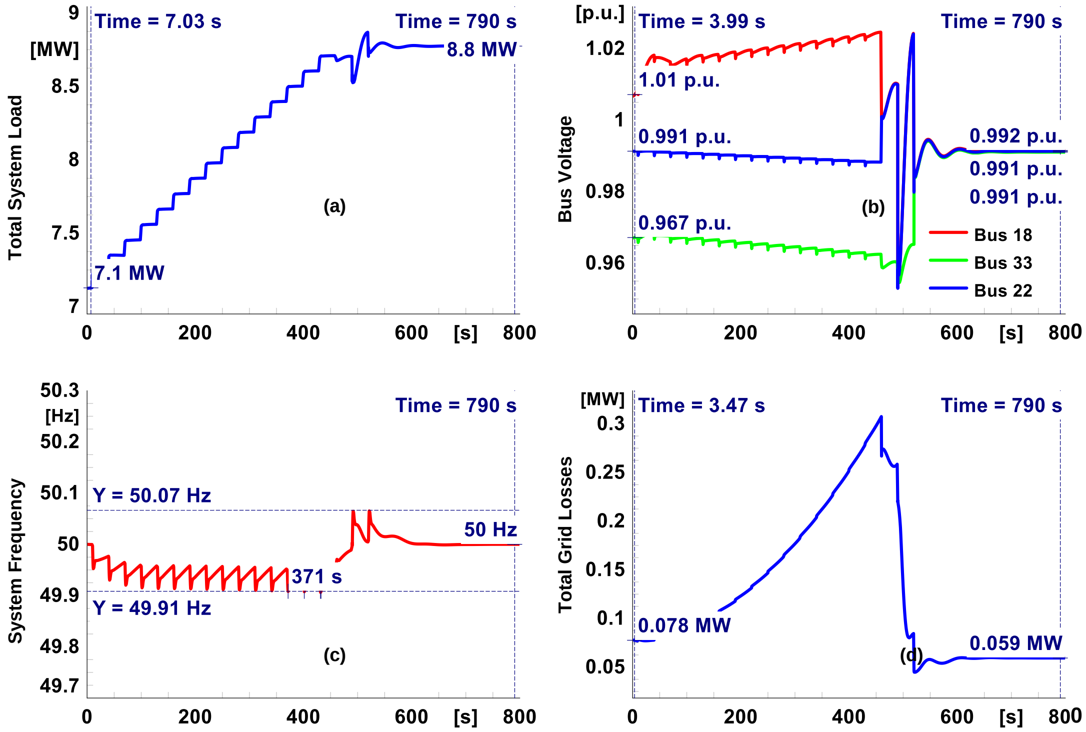


Figure 6.11: System behaviour following load demand increase and switching events - (a) Total system load, (b) Bus 18, 22, and 33 voltages, (c) System Frequency, and (d) Total Grid losses

Figure 6.12 depicts the distribution network following a rigorous assessment aimed at demonstrating the effectiveness of proposed methodologies in enhancing the network's robustness. The network's performance was evaluated extensively by gradually increasing the total load demand by 15% in increments of 1%. Subsequently, a switching event was carried out, and the distribution network remained stable. Notably, none of the network's parts experienced any thermal overload, and no busbars recorded low voltage readings.

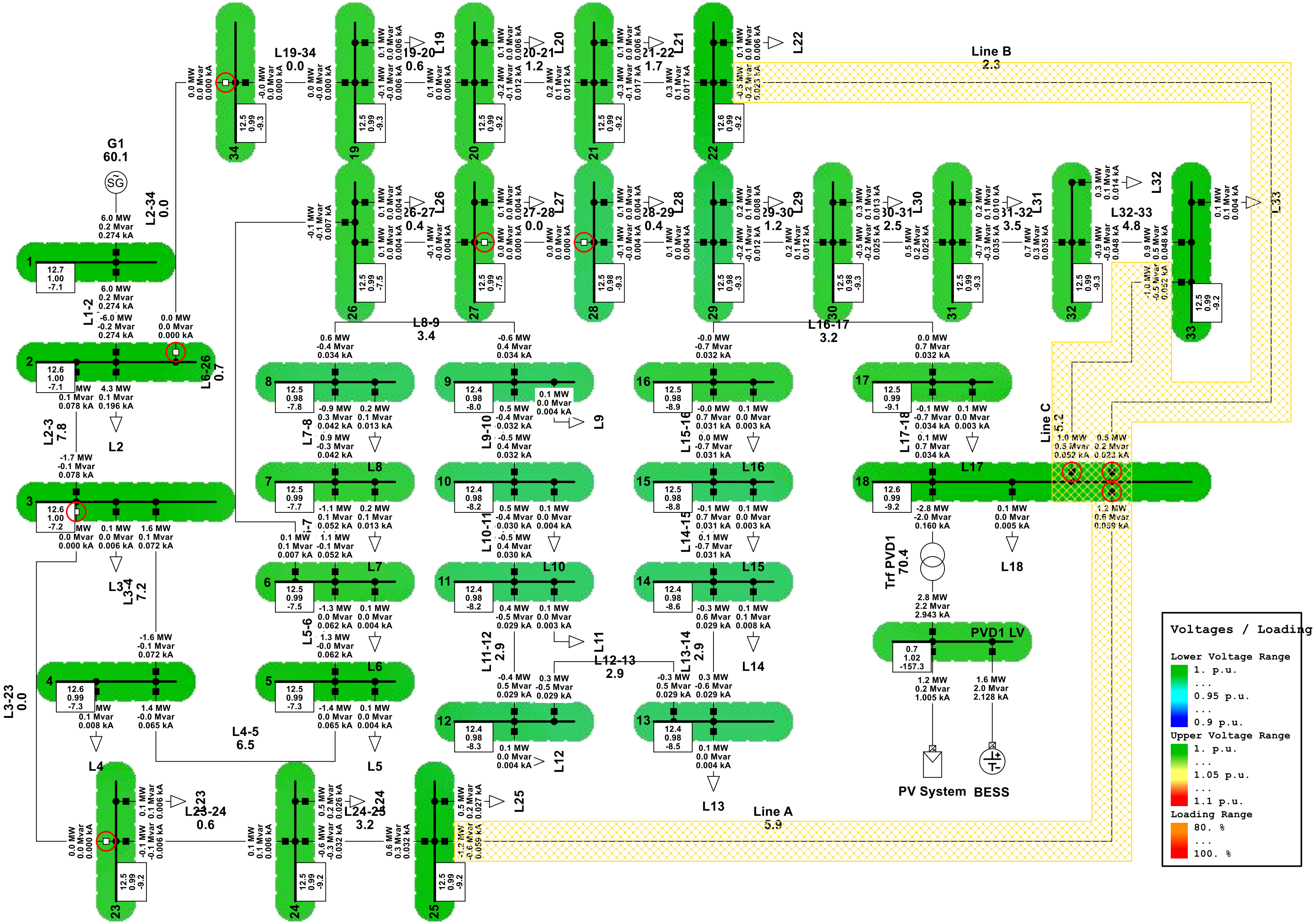


Figure 6.12: Distribution network robustness assessment following the switching and load demand increase.

The BESS's power output increase was triggered by the disturbances introduced on the grid, such as load demand increase first, followed by switching events adopted in Section 6.4, in Table 6.3. As a result, the BESS contributed to 1.62 MW and 2.02 Mvar to support both frequency and voltage, respectively, as shown in Figure 6.12 (a). The PV system continues to supply a constant active power of 1.2 MW while the reactive power was 0.17 Mvar as shown in Figure 6.12 (b).

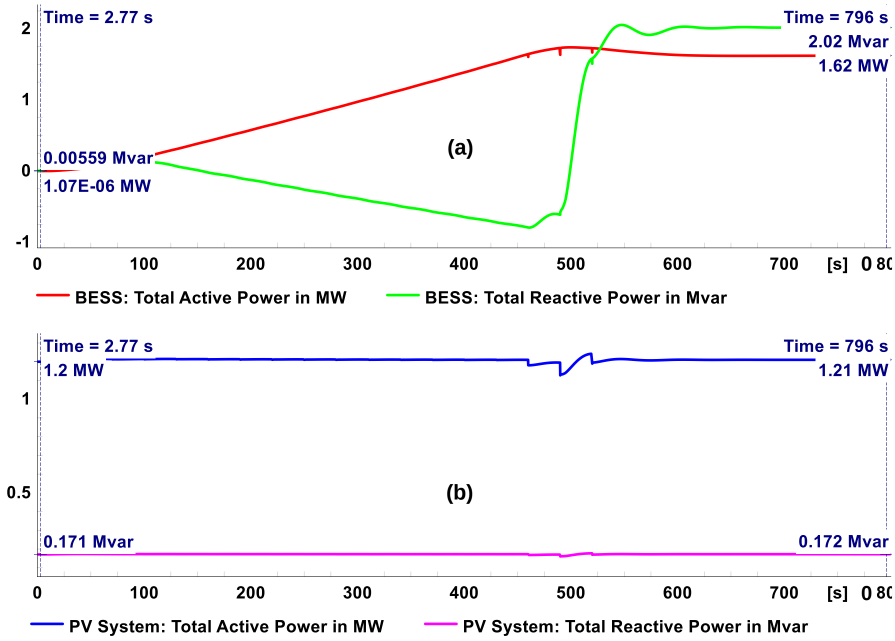


Figure 6.13: PV System and BESS active control scheme following load demand increase and switching event

6.6 Summary

This chapter covered the approach to enhance the service restoration in the distribution system following a power outage due to planned or unplanned events. First, the network reconfiguration was performed to ensure the N-I contingency was met. Next, reconfiguration alone was assessed to evaluate the grid stability and reliability following the switching event where certain distribution lines were out of service. It was discovered that the bus voltage is compromised when the restoration is performed by closing the normally open point.

PV system was integrated into the grid, and the same contingency was applied. However, the contribution of the PV system was limited as the power produced through this energy resource is not exporting supplementary power to compensate for system dynamics. Later, the BESS, with its active control scheme, was implemented. As a result, there was an impressive improvement in the distribution grid stability as the BESS dispatched the power required by the grid to maintain its stability criterion. Furthermore, robustness and reliability assessment were performed to assess the contribution of BESS under various contingencies. As a result, it was discovered that the system stability index was maintained post disturbances.

The efficacy of the developed control scheme covered in Chapter 5 can improve and maintain the distribution grid stability, enhancing supply security and reliability. However, to take advantage of the power generated through non-dispatchable distributed energy resources, BESS has to be a compulsory component of such integration to convert the system from a non-dispatchable to a dispatchable system.

CHAPTER SEVEN

CONCLUSION AND RECOMMENDATIONS

7.1 Introduction

Stability must be maintained at all times to provide quality of supply to the customers. Additional reliability assessment indices must be evaluated continuously to ensure that distribution can provide good supply quality now and in the foreseeable future. Load forecasting is the projection function to determine the relevance of the current distribution topology in the foreseeable future.

Utilizing distributed energy resources to improve distribution grid stability is a trending research interest. However, most of these energy resources lack the capability of power dispatching since their power output is primarily dependent on the availability of primary resources such as sun and wind for Solar PV systems and Wind energy, respectively.

This dissertation covers how distributed energy resources can enhance distribution grid stability while improving service restoration following power outages. A control scheme to enable the distributed energy resource to dispatch power to the grid when needed was developed using DIgSILENT Power factory simulation software. The efficacy of the developed control scheme was assessed using various disturbance contingencies. To enhance the distribution service restoration, there was a need to consider reconfiguration of the distribution network topology. After the reconfiguration, various contingencies were performed to assess distributed energy resources' contribution to service restoration. The results showed an improvement in both stability of the grid and service restoration.

This chapter is structured as follows: section 7.1 is the introduction of the chapter, followed by section 7.2, which covers the aim and objectives of the research study, and section 7.3 covers the overall deliverables of the dissertation in summarized form. Section 7.4 describes how the work covered in this dissertation can be utilized for academic and industrial advancement. Section 7.5 outlines the future work that can be conducted concerning this topic of interest and other elements that link up to work covered in this dissertation. And finally, section 7.6 covers the list of publications developed from the achievement of this dissertation output, as well as potential publications which can be considered in the future.

7.2 Aim and objectives

The research aimed to study and develop grid integration methods for Distributed Energy Resources (DERs) in a smart grid. The research objectives included conducting a literature review on current distribution system models, analyzing power system network behavior, applying DERs for smart grid stability enhancement and power restoration, developing an algorithm for DER integration, modeling and simulating a case study network, and investigating an algorithm performance for different operating conditions in smart grids. The ultimate goal was to develop a control scheme that optimized power dispatching and enhanced power system stability and restoration.

7.3 Dissertation deliverables

This section covers the summary of the work performed to achieve the aim and objectives of the research study.

7.3.1 Chapter 2: Literature review

The literature review shows a gap in developing and implementing the control scheme on various power system simulation platforms to validate proposed philosophies. The proposed research seeks to develop a control scheme that will enable the smooth dispatching of power to ensure grid stability and improve service restoration. Furthermore, it has been noted in the literature reviewed that there needs to be more work on control development studies using DISILENT powerfactory simulation platforms. Therefore, this research study will also contribute immensely to the utilization of PowerFactory simulation platforms in developing control schemes.

7.3.2 Chapter 3: Distribution network modelling and operation analysis

Examining the existing literature was the first step in beginning to model a functional system, which provided the necessary theoretical information for the modeling process. An overview of the theory required for modeling a distribution system, along with the available equipment models, was provided in this chapter. Additionally, various types of distributed energy resources, such as wind power, solar PV systems, and energy storage systems like battery energy storage, were discussed in detail, along with their corresponding mathematical models. The chapter also delved into the criteria for determining the placement of distributed energy resources. In chapter four, the equipment's performance analysis was carried out, which served to validate the theoretical aspects discussed in this chapter.

7.3.3 Chapter 4: Network modelling, steady-state and dynamic study simulation analysis

To enhance the reliability and supply security of the distribution system, a more technical approach was required. The network operation was in radial topology, meaning that there was no alternative supply point if the n-1 contingency occurred. Thus, it was necessary to improve the system voltage, with the lowest operating voltage being 0.95 pu at bus 18. Additionally, the system's overall stability needed improvement as more active and reactive power was required to keep it stable.

In comparison to static var compensators, distributing distributed energy resources had more advantages. Although static var compensators could improve the system voltage, distributed energy resources with an energy storage system facilitated both active and reactive components to the grid. Chapter 5 covered the approach to improving the distribution system's stability.

7.3.4 Chapter 5: Placement of distributed energy resources, and simulation analysis

Maintaining distribution grid stability is a crucial aspect that requires constant monitoring to ensure reliable and uninterrupted power supply. When the distribution grid experiences any disturbance or interruption, it must be resilient enough to overcome the disruption and restore its stability. To achieve this, a thorough evaluation of the system's robustness must be carried out, taking into account all possible disturbances and contingencies.

In this chapter, the focus was on studying the contribution of distributed energy resources in enhancing the stability and reliability of the distribution system. The results of the study demonstrated that the control scheme developed to enable power dispatching from battery energy storage systems (BESS) significantly improved the distribution network's stability and reliability.

To ensure the distribution network's reliability, it is essential to assess its performance under contingency scenarios. This evaluation helps strengthen the network's ability to restore services and recover from any disturbance efficiently. The reliability analysis involves determining how long it takes to restore services after a disturbance and how frequently the network experiences disruptions. This analysis enables us to understand how the network operates when one of its components is out of service, whether due to a fault or planned maintenance, and provides a basis for improving the distribution service restoration process.

In summary, maintaining distribution grid stability is critical to ensuring reliable and uninterrupted power supply, and a thorough evaluation of the system's robustness is necessary to achieve this. The use of distributed energy resources, such as BESS, can enhance the distribution system's stability and reliability. Finally, assessing the distribution network's reliability under contingency scenarios is crucial to improve the service restoration process and strengthen the network's resilience to disruptions.

7.3.5 Chapter 6: Distribution system service restoration enhancement approach through network reconfiguration

This chapter covered the approach to enhance the service restoration in the distribution system following a power outage due to planned or unplanned events.

First, the network reconfiguration was performed to ensure the N-I contingency was met. Next, reconfiguration alone was assessed to evaluate the grid stability and reliability following the switching event where certain distribution lines were out of service. It was discovered that the bus voltage is compromised when the restoration is performed by closing the normally open point.

PV system was integrated into the grid, and the same contingency was applied. However, the contribution of the PV system was limited as the power produced through this energy resource is not exporting supplementary power to compensate for system dynamics. Later, the BESS, with its active control scheme, was implemented. As a result, there was an impressive improvement in the distribution grid stability as the BESS dispatched the power required by the grid to maintain its stability criterion. Furthermore, robustness and reliability assessment were performed to assess the contribution of BESS under various contingencies. As a result, it was discovered that the system stability index was maintained post disturbances.

The efficacy of the developed control scheme covered in Chapter 5 can improve and maintain the distribution grid stability, enhancing supply security and reliability. However, to take advantage of the power generated through non-dispatchable distributed energy resources, BESS has to be a compulsory component of such integration to convert the system from a non-dispatchable to a dispatchable system.

7.4 Academic and industrial application

The knowledge presented in this dissertation will help the power system planners and operators from utility companies and private entities to make an informed decision about distribution grid reliability and the security of supply. The research study provides a detailed approach to enhancing distribution network stability and service restoration using distributed energy resources. The developed control scheme will also help utility companies to exploit as much power as possible from the distributed energy resource to enhance grid stability and reliability.

In the academic space, the knowledge presented in this dissertation can help to build a foundation for power system researchers to understand the current methods of stabilizing the distribution network; furthermore, this study can be used as a reference to further research studies.

7.5 Future work

In the future, hardware development of the proposed control scheme can be performed to assess the efficacy of the control scheme in real-time. Furthermore, the automation system for service restoration is also one of the gaps, and the proposed control scheme hardware can be integrated with the automatic service restoration control loop.

7.6 Publications

7.6.1 Journal Articles

- Mkhutazi Mditshwa, Ali-Mustafa-Ali- Almaktoof, Yohan Darcy Mfoumboulou (2023). "*Voltage Stability Enhancement in the distribution grid through network reconfiguration and strengthening*." (in progress)
- Mkhutazi Mditshwa, Ali-Mustafa-Ali- Almaktoof, Yohan Darcy Mfoumboulou (2023) "*Placement of Distributed Energy Resources for Optimal Power Dispatching in the Distribution System.*" (in progress)
- Mkhutazi Mditshwa, Ali-Mustafa-Ali- Almaktoof, Yohan Darcy Mfoumboulou (2023). "*Contribution of Distribution Energy Resources in Service Restoration.*"(in progress)

7.6.2 Conference Publications

- Mkhutazi Mditshwa, Ali-Mustafa-Ali- Almaktoof, Yohan Darcy Mfoumboulou (2023). "*Optimizing Service Restoration on the Eskom Distribution Grid System through Network Reconfiguration*." (submitted to 6th International Conference on Renewable Energy in Developing Countries REDEC 2023 in Lebanon)
- Mkhutazi Mditshwa, Ali-Mustafa-Ali- Almaktoof, Yohan Darcy Mfoumboulou (2023). "*Energy Efficiency and Management in South Africa: A case of resource availability*." (submitted to 6th International Conference on Renewable Energy in Developing Countries REDEC 2023 in Lebanon)

7.7 Summary

This chapter summarizes the objective and expected deliverables of the research study. Extensive and systematic literature reviews were conducted, and the theoretical aspects of the topic were also considered. Power Factory DIgSILENT simulation software was used to perform the model and simulations as described in the chapter. The academic and industrial contributions of the research work are highlighted, along with future considerations for advancing the work. Additionally, publications such as journals and conferences are mentioned, and a list of references consulted for this dissertation is included in this chapter.

BIBLIOGRAPHY/REFERENCES

Abo-Al-Ez, K.M., Xia, X. & Zhang, J. 2012. Smart interconnection of a PV/wind DG micro grid with the utility distribution network. *9th Int. Conf. Ind. Commer. Use Energy, ICUE 2012*, Stellenbos: 243–250. http://www.scopus.com/inward/record.url?eid=2-s2.0-84869384998&partnerID=40&md5=bb2d31baa79542b82601240a0dd9c54d.

Adejumobi, I.A. & Hamzat, A.G.A. 2013. Iterative Techniques for Load Flow Study: A Comparative Study for Nigerian 330kv Grid System as a Case Study. *International Journal of Engineering and Advanced Technology (IJEAT)*, (3): 2249–8958.

Adrees, A. & Milanović, J. 2019. Effect of load models on angular and frequency stability of low inertia power networks. *IET Generation, Transmission & Distribution*, 13(9): 1520–1526.

Agarwal, U., Jain, N. & Kumawat, M. 2022. Reliability enhancement of distribution networks with remote-controlled switches considering load growth under the effects of hidden failures and component aging. *AIMS Electronics and Electrical Engineering*, 6(3): 247–264.

Ahmadi, B., Ceylan, O. & Ozdemir, A. 2020. Impacts of Load and Generation Volatilities on the Voltage Profiles Improved by Distributed Energy Resources. *UPEC 2020 - 2020 55th International Universities Power Engineering Conference, Proceedings*.

Alireza, H.M., Escandon, A.S.A., Najafi, B., Shirazi, A. & Rinaldi, F. 2016. Techno-economic feasibility of photovoltaic, wind, diesel and hybrid electrification systems for off-grid rural electrification in Colombia. *Renewable Energy*, 97: 293–305.

Alramlawi, M., Mohagheghi, E. & Li, P. 2019. Predictive active-reactive optimal power dispatch in PV-battery-diesel microgrid considering reactive power and battery lifetime costs. *Solar Energy*, 193(July): 529–544.

Althaher, S.Z., Alnaser, S.W., Zhou, Y. & Long, C. 2022. Transactive Energy System for Distribution Network Management: Procuring Residential Flexibility Services Under Dynamic Pricing. *IEEE Access*, 10(August): 102019–102032.

Aman, M.A., Ren, X.C., Tareen, W.U.K., Khan, M.A., Anjum, M.R., Hashmi, A.M., Ali, H., Bari, I., Khan, J. & Ahmad, S. 2022. Optimal Siting of Distributed Generation Unit in Power Distribution System considering Voltage Profile and Power Losses. *Mathematical Problems in Engineering*, 2022.

Anaadumba, R., Liu, Q., Marah, B.D., Nakoty, F.M. & Liu, X. 2021. A renewable energy forecasting and control approach to secured edge-level efficiency in a distributed micro-grid. : 1–12.

Apfel, D., Haag, S. & Herbes, C. 2021. Research agendas on renewable energies in the Global

South: A systematic literature review. *Renewable and Sustainable Energy Reviews*, 148(June): 111228. https://doi.org/10.1016/j.rser.2021.111228.

Arif, A., Wang, Z., Wang, J., Mather, B., Bashualdo, H. & Zhao, D. 2018. Load modeling - A review. *IEEE Transactions on Smart Grid*, 9(6): 5986–5999.

Awad, A.S.A., El-Fouly, T.H.M. & Salama, M.M.A. 2015. Optimal ESS allocation for load management application. *IEEE Transactions on Power Systems*, 30(1): 327–336.

Aziz, T., Saha, T.K. & Mithulananthan, N. 2010. Distributed generators placement for loadability enhancement based on reactive power margin. *2010 9th International Power and Energy Conference, IPEC 2010*, (1): 740–745.

Basu, A.K., Chowdhury, S. & Chowdhury, S.P. 2010. Impact of strategic deployment of CHP-based DERs on microgrid reliability. *IEEE Transactions on Power Delivery*, 25(3): 1697–1705.

Bayat, M., Sheshyekani, K., Hamzeh, M. & Rezazadeh, A. 2016. Coordination of Distributed Energy Resources and Demand Response for Voltage and Frequency Support of MV Microgrids. *IEEE Transactions on Power Systems*, 31(2): 1506–1516.

Bello, M. & Carter-Brown, C. 2010. Impact of embedded generation on distribution networks. *Energize*: 32–34.

Bevrani, H. 2014. *Robust Power System Frequency Control (Power Electronics and Power Systems)*.

Bhusal, N., Gautam, M., Benidris, M. & Louis, S.J. 2021. Optimal Sizing and Siting of Multi-purpose Utility-scale Shared Energy Storage Systems. *2020 52nd North American Power Symposium, NAPS 2020*.

Bielecki, A., Gupta, N., Prusty, R., Alrumayh, O., Almutairi, A. & Alharbi, T. 2022. The Role of Transactive Energy in the Future Energy Industry: A Critical Review. *Energies 2022, Vol. 15, Page 8047*, 15(21): 8047. https://www.mdpi.com/1996-1073/15/21/8047/htm 16 December 2022.

Bogno, B., Sali, M. & Aillerie, M. 2014. Technical and economic analysis of a wind power generation system for rural electrification in subequatorial area of Africa. In *Energy Procedia*.

Boyle, J., Littler, T. & Foley, A. 2018. Review of frequency stability services for grid balancing with wind generation. *The Journal of Engineering*, 2018(15): 1061–1065.

Bragantini, A. 2019. *Investment Planning for Distribution Networks in Multi Carrier Energy Systems*. Swiss Federal Institute of Technology (ETH).

Bulat, H., Franković, D. & Vlahinić, S. 2021. Enhanced contingency analysis—a power system operator tool. *Energies*, 14(4).

Chen, C., Wang, J. & Ton, D. 2017. Modernizing Distribution System Restoration to Achieve Grid Resiliency Against Extreme Weather Events : An Integrated Solution. , 105(7).

Chen, X., Wu, W., Member, S. & Zhang, B. 2015. Robust Restoration Method for Active Distribution Networks. *IEEE Transactions on Power Systems*, 31(5): 4005–4015.

Dai, J., Tang, Y., Wang, Q. & Jiang, P. 2019. Aggregation frequency response modeling for wind power plants with primary frequency regulation service. *IEEE Access*, 7: 108561–108570.

DIgSILENT. 2020. PowerFactory 2020 User Manual. : 1–1253. https://www.digsilent.de.

Donald, V. & Anning, B. 2021. NEM connections, complexity, risk and tolerance: achieving a balanced approach to grid connection | Entura. *ETHURA*. https://www.entura.com.au/nem-connections-complexity-risk-and-tolerance-achieving-a-balanced-approach-to-grid-connection/ 25 November 2022.

Eid, B.M., Rahim, N.A., Selvaraj, J. & El Khateb, A.H. 2016. Control methods and objectives for electronically coupled distributed energy resources in microgrids: A review. *IEEE Systems Journal*, 10(2): 446–458.

Fabricius, C., Sigwebela, N., Damba, S. & Rambau, P. 2020. Medium-Term System Adequacy Outlook 2020. , (October): 24.

Feng, Q. & Peijie, L. 2017. An Integrated Approach for Power System Restoration Planning. , 105(7).

Gafari Abiola, A., Baruwa Abiodun, A., Sunday Adeleke, S. & Oladosu Jamiu, A. 2023. Optimal placement and sizing of distributed generation for power loss reduction using particle swarm optimization. *European Journal of Engineering and Technology Research*, 8(1): 19–23.

Ganganath, N., Cheng, C.T., Iu, H.H.C. & Fernando, T. 2017. Subsystem size optimization for efficient parallel restoration of power systems. *Proceedings - IEEE International Symposium on Circuits and Systems*.

Gautam, M., Bhusal, N., Benidris, M., Singh, C. & Mitra, J. 2020. A Sensitivity-based Approach for Optimal Siting of Distributed Energy Resources. *2020 International Conference on Probabilistic Methods Applied to Power Systems, PMAPS 2020 - Proceedings*.

Georgilakis, P.S. & Hatziargyriou, N.D. 2013. Optimal Distributed Generation Placement in Power Distribution Networks: Models, Methods, and Future Research. *IEEE Transactions on Power Systems*, 28(3): 3420–3428. http://ieeexplore.ieee.org/document/6418071/.

Georgilakis, P.S., Korres, G.N. & Hatziargyriou, N.D. 2021. Distribution System. In Springer: 1093–1129.

Gill, A., Singh, P., Jobanputra, J.H. & Kolhe, M.L. 2022. Placement analysis of combined renewable and conventional distributed energy resources within a radial distribution network. *AIMS Energy*, 10(6): 1216–1229.

Gönen, T. 2005. Power Distribution. *The Electrical Engineering Handbook*: 749–759.

Gupta, N., Prusty, B.R., Alrumayh, O., Almutairi, A. & Alharbi, T. 2022. The Role of Transactive Energy in the Future Energy Industry: A Critical Review. *Energies*, 15(21): 8047.

Gupta, Y., Doolla, S., Chatterjee, K. & Pal, B.C. 2021. Optimal DG Allocation and Volt-Var Dispatch for a Droop-Based Microgrid. *IEEE Transactions on Smart Grid*, 12(1): 169–181.

Hossain, M.A., Pota, H.R., Hossain, M.J. & Blaabjerg, F. 2019. Evolution of microgrids with converter-interfaced generations: Challenges and opportunities. *International Journal of Electrical Power & Energy Systems*, 109: 160–186.

Huang, Y., Wu, J., Ren, W., Tse, C.K. & Zheng, Z. 2021. Sequential Restorations of Complex Networks After Cascading Failures. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, 51(1): 400–411.

Huang, Z., Bao, L. & Xu, W. 2007. A method to measure QV curves and its applications in power systems. *International Journal of Electrical Power and Energy Systems*, 29(2): 147–154.

Jarrad, W. & Joanne, C. 2020. *Setting up for the 2020s Addressing South Africa ' s electricity crisis and getting ready for the next decade*. https://researchspace.csir.co.za/dspace/bitstream/handle/10204/11282/RS_Setting up for 2020.pdf version 1.1.pdf?sequence=3&isAllowed=y.

Jegatheesan, R., Nor, N.M. & Romlie, M.F. 2008. Newton-raphson power flow solution employing systematically constructed jacobian matrix. *PECon 2008 - 2008 IEEE 2nd International Power and Energy Conference*, (PECon 08): 180–185.

Jelena Ponoćko. 2020. *Data Analytics-Based Demand Profiling and Advanced Demand Side Management for Flexible Operation of Sustainable Power Networks*. Springer.

Jian, Z., Ning, Z., Lei, W., Hao, L. & Qian, S. 2019. Hierarchical and Divisional Optimal Dispatching Strategy for Active Distribution Network based on Hybrid Particle Swarm Optimization. *2019 IEEE PES Innovative Smart Grid Technologies Asia, ISGT 2019*: 1883–1888.

Jobanputra, J. & Kotwal, C. 2018. Optimal Power Dispatch using Particle Swarm Optimization. In *2018 International Conference on Smart Electric Drives & Power System Optimal*. IEEE: 157–161.

Kabiri-Renani, Y., Daneshvar, M. & Mohammadi-Ivatloo, B. 2022. Transactive energy revolution: Innovative leverage for reliable operation of modern energy networks—A critical review. *IET Renewable Power Generation*, 16(15): 3368–3383.

Khasanov, M., Kamel, S., Hasanien, H.M. & Al-Durra, A. 2020. Rider optimization algorithm for optimal DG allocation in radial distribution network. *2020 2nd International Conference on Smart Power and Internet Energy Systems, SPIES 2020*: 138–143.

Khunkitti, S., Boonluk, P. & Siritaratiwat, A. 2022. Optimal Location and Sizing of BESS for Performance Improvement of Distribution Systems with High DG Penetration. https://doi.org/10.1155/2022/6361243 25 November 2022.

Kim, S.C., Ray, P. & Reddy, S.S. 2019. Features of smart grid technologies: An overview. *ECTI Transactions on Electrical Engineering, Electronics, and Communications*, 17(2): 169–180.

Konstantin O, P. 2021. *Springer Handbook of Power Systems*. Singapore: Springer Nature Singapore Pte Ltd. https://doi.org/10.1007/978-981-32-9938-2.

Koutsoukis, N.C., Georgilakis, P.S., Korres, G.N. & Hatziargyriou, N.D. 2021. Distribution System. In *Springer Handbook of Power Systems*. 1093–1129. https://doi.org/10.1007/978-981-32-9938-2_15 1 May 2022.

Kumar, M., Soomro, A.M., Uddin, W. & Kumar, L. 2022. Optimal Multi-Objective Placement and Sizing of Distributed Generation in Distribution System: A Comprehensive Review. *Energies*, 15(21): 1–48.

Lacal-ar, R. 2015. Materials use in electricity generators in wind turbines – state-of-the-art and future specifications Materials use in electricity generators in wind turbines e state-of-the-art and future speci fi cations. , (January).

Lasmari, A., Zellagui, M., Hassan, H.A., Settoul, S., Abdelaziz, A.Y. & Chenni, R. 2020. Optimal Energy-Efficient Integration of Photovoltaic DG in Radial Distribution Systems for Various Load Models. *11th International Renewable Energy Congress, IREC 2020*, (Irec): 2–7.

Lee, J., Yoo, S., Kim, J., Song, D. & Jeong, H. 2018. Improvements to the customer baseline load (CBL) using standard energy consumption considering energy efficiency and demand response. *Energy*, 144: 1052–1063.

Limouchi, E., Taher, S.A. & Ganji, B. 2016. Active generators power dispatching control in smart grid. *21st Electrical Power Distribution Network Conference, EPDC 2016*, (May): 26–32.

Liu, W. & Ding, F. 2021. Hierarchical Distribution System Adaptive Restoration With Diverse Distributed Energy Resources. , 12(2): 1347–1359.

Liu, Y., Fan, R. & Terzija, V. 2016. Power system restoration : a literature review from 2006 to 2016. , 4: 332–341.

Liu, Y., Lei, S., Hou, Y. & Member, S. 2019. Restoration of Power Distribution Systems With Multiple Data Centers as Critical Loads. , 10(5): 5294–5307.

Lu, Q., Yang, Y., Zhu, Y., Xu, T., Wu, W. & Chen, J. 2019. Distributed Economic Dispatch for Active Distribution Networks with Virtual Power Plants. *2019 IEEE PES Innovative Smart Grid Technologies Asia, ISGT 2019*: 328–333.

Lusis, P., Andrew, L.L.H., Liebman, A., Tack, G. & Chakraborty, S. 2019. Reducing the unfairness of coordinated inverter dispatch in pv-rich distribution networks. *2019 IEEE Milan PowerTech, PowerTech 2019*: 1–6.

Maestre, V.M., Ortiz, A. & Ortiz, I. 2021. Challenges and prospects of renewable hydrogen-based strategies for full decarbonization of stationary power applications. *Renewable and Sustainable Energy Reviews*, 152: 111628. https://doi.org/10.1016/j.rser.2021.111628.

Manjul, N. 2018. PV / QV Curve based Optimal Placement of Static Var System in Power Network using DigSilent Power Factory.

Mditshwa, M. 2021. *THE ROLE OF DISTRIBUTED ENERGY RESOURCES (DERs) IN SMART GRID STABILITY*. Cape Peninsula University of Technology. https://etd.cput.ac.za/handle/20.500.11838/3411.

Mditshwa, M., Mnguni, M.E.S. & Ratshitanga, M. 2021. Integration of Wind Power Plant (WPP) for primary frequency regulation. *2021 IEEE PES/IAS PowerAfrica, PowerAfrica 2021*: 1–5.

Meriem, M., Rachid, B. & Ismail, E. 2021. Optimal siting and sizing of the Distributed Generation units to reduce power loss and improve the voltage profile by using an improved Chaotic Particle Swarm Optimization. *2021 3rd Global Power, Energy and Communication Conference (IEEE GPECOM2021)*: 132–141.

Mohsin, M., Rasheed, A.K. & Saidur, R. 2018. Economic viability and production capacity of wind generated renewable hydrogen. *International Journal of Hydrogen Energy*, 43(5): 2621–2630. https://doi.org/10.1016/j.ijhydene.2017.12.113.

Mondal, A., Chandra, S., Bhavaraju, V., Yang, Y. & Buck, E.F. 2022. Distributed Energy Resource Control and Utility Interconnection Management: Implementation in a Distributed Microgrid. *IEEE Industry Applications Magazine*, 28(5): 38–49.

Mondal, D., Chakrabarti, A. & Sengupta, A. 2020. Application of FACTS Controller. *Power System Small Signal Stability Analysis and Control*: 197–242.

Moreno Jaramillo, A.F., Laverty, D.M., Morrow, D.J., Martinez del Rincon, J. & Foley, A.M. 2021. Load modelling and non-intrusive load monitoring to integrate distributed energy resources in low and medium voltage networks. *Renewable Energy*, 179: 445–466. https://doi.org/10.1016/j.renene.2021.07.056.

Moyo, P. 2018. Eskom’s flagship battery energy storage systems (BESS) project. *EE Publishers*: 1–7. http://www.ee.co.za/article/eskoms-flagship-battery-energy-storage-systems-bess-project.html.

Mukoro, V., Gallego-Schmid, A. & Sharmina, M. 2021. Life cycle assessment of renewable energy in Africa. *Sustainable Production and Consumption*, 28: 1314–1332. https://doi.org/10.1016/j.spc.2021.08.006.

Mulleriyawage, U.G.K. & Shen, W.X. 2021. Impact of demand side management on optimal sizing of residential battery energy storage system. *Renewable Energy*, 172: 1250–1266. https://doi.org/10.1016/j.renene.2021.03.122.

NERSA. 2019. The South African Grid Code - System Operation Code. , 10(August): 24. http://www.nersa.org.za/.

Nikolaidis, P. & Poullikkas, A. 2018. Cost metrics of electrical energy storage technologies in potential power system operations. *Sustainable Energy Technologies and Assessments*, 25(December 2017): 43–59. https://doi.org/10.1016/j.seta.2017.12.001.

Okedu, K.E. & Okedu, K.E. 2018. Introductory Chapter: Stability Control and Reliable Performance of Wind Turbines. *Stability Control and Reliable Performance of Wind Turbines*. https://www.intechopen.com/state.item.id 25 November 2022.

Onar, B. & Demirbas, S.E. 2022. A Survey on the Provision of Smooth Transition between Operation Modes in PV-BESS Microgrid. *10th International Conference on Smart Grid, icSmartGrid 2022*: 203–207.

Panda, S., Mohanty, S., Rout, P.K., Sahu, B.K., Parida, S.M., Kotb, H., Flah, A., Tostado-Véliz, M., Abdul Samad, B. & Shouran, M. 2022. An Insight into the Integration of Distributed Energy Resources and Energy Storage Systems with Smart Distribution Networks Using Demand-Side Management. *Applied Sciences (Switzerland)*, 12(17).

Papasani, A., Zia, K. & Lee, W.J. 2021. Automatic Power System Restoration with Inrush Current Estimation for Industrial Facility. *Conference Record - Industrial and Commercial Power Systems Technical Conference*, 2021-April(July 2012): 1–8.

Patel, S., Murari, K. & Kamalasadan, S. 2022. Distributed Control of Distributed Energy Resources in Active Power Distribution System for Local Power Balance With Optimal Spectral Clustering. *IEEE Transactions on Industry Applications*, 58(4): 5395–5408.

Patsakis, G., Member, S., Rajan, D., Aravena, I., Member, S., Rios, J., Oren, S. & Fellow, L. 2018. Optimal Black Start Allocation for Power System Restoration. , 33(6): 6766–6776.

Pavana, D. & Triveni, M.T. 2015. POWER SYSTEM RESTORATION IN DISTRIBUTION NETWORK THROUGH RECONFIGURATION USING MST- KRUSKAL ' S ALGORITHM. *International Journal of Research in Engineering and Technology*, 04(07): 295–299.

Pérez-denicia, E., Fernández-luqueño, F., Vilariño-ayala, D., Manuel, L. & Maldonado-lópez, L.A. 2017. Renewable energy sources for electricity generation in Mexico : A review. *Renewable and Sustainable Energy Reviews*, 78(May): 597–613. http://dx.doi.org/10.1016/j.rser.2017.05.009.

Ponoćko, J. 2020. Data Analytics-Based Demand Profiling and Advanced Demand Side Management for Flexible Operation of Sustainable Power Networks. *Springer*: 191–197. http://link.springer.com/10.1007/978-3-030-39943-6.

Poudel, S. & Dubey, A. 2021. A two-stage service restoration method for electric power distribution systems. *IET Smart Grid*: stg2.12021. https://onlinelibrary.wiley.com/doi/10.1049/stg2.12021.

Prettico, G., Marinopoulos, A. & Vitiello, S. 2022. Guiding electricity distribution system investments to improve service quality: A European study. *Utilities Policy*, 77(May): 101381. https://doi.org/10.1016/j.jup.2022.101381.

Radvar, M.E., Yeung, S. & Arefifarm, S.A. 2020. Stability Analysis of a 100MW Wind Power Plant with Type 3 Wind Turbines-A Field Test Verification of Generic Dynamic Models. *Proceedings of the IEEE Power Engineering Society Transmission and Distribution Conference*, 2020-Octob: 3–7.

Rahman, M.M., Barua, S., Zohora, S.T., Hasan, K. & Aziz, T. 2013. Voltage sensitivity based site selection for PHEV charging station in commercial distribution system. *Asia-Pacific Power and Energy Engineering Conference, APPEEC*: 1–6.

Rodrigues, S.D. & Garcia, V.J. 2023. Transactive energy in microgrid communities: A systematic review. *Renewable and Sustainable Energy Reviews*, 171: 112999.

Rohit, A.K. & Rangnekar, S. 2017. An overview of energy storage and its importance in Indian renewable energy sector : Part II – energy storage applications , benefits and market potential. *Journal of Energy Storage*, 13: 447–456. https://doi.org/10.1016/j.est.2017.07.012.

Roy, N.K., Pota, H.R. & Anwar, A. 2012. A new approach for wind and solar type DG placement in power distribution networks to enhance systems stability. *2012 IEEE International Power Engineering and Optimization Conference, PEOCO 2012 - Conference Proceedings*, (June): 296–301.

Rudez, U., Bogovic, J. & Mihalic, R. 2015. Probability-based approach for parametrisation of traditional underfrequency load-shedding schemes. *IET Generation, Transmission & Distribution*, 9(16): 2625–2632.

Rueda, J.L., Korai, A.W., Cepeda, J.C., Erlich, I. & Gonzalez-Longatt, F.M. 2014. *Implementation of Simplified Models of DFIG-Based Wind Turbines for RMS-Type Simulation in DIgSILENT PowerFactory*.

Sadeghi, M. & Abasi, M. 2021. Optimal placement and sizing of hybrid superconducting fault current limiter for protection coordination restoration of the distribution networks in the presence of simultaneous distributed generation. *Electric Power Systems Research*, 201(August): 107541. https://doi.org/10.1016/j.epsr.2021.107541.

Satinge, P. & Jawadekar, U.A. 2021. Fast Restoration Technique for Distribution Power System with Multi-Terminal DC Links. *International Journal of Engineering Science and Computing*, 11(06): 28364–28367.

Saxena, S. & Bhatia, S. 2021. Cybersecurity Analysis of Load Frequency Control in Power Systems : A Survey. *Designs*, 5(3): 1–15. https://www.mdpi.com/2411-9660/5/3/52/htm.

Selim, A., Kamel, S., Alghamdi, A.S. & Jurado, F. 2020. Optimal Placement of DGs in Distribution System Using an Improved Harris Hawks Optimizer Based on Single- And Multi-Objective Approaches. *IEEE Access*, 8: 52815–52829.

Shaaban, M.F., Atwa, Y.M. & El-Saadany, E.F. 2013. DG allocation for benefit maximization in distribution networks. *IEEE Transactions on Power Systems*, 28(2): 639–649.

Sharma, D. & Singh, P. 2020. Optimal Planning of Distribute Energy Resources Sizing and Location Problem - A Review. *Proceedings of the 2nd International Conference on Inventive Research in Computing Applications, ICIRCA 2020*: 500–504.

Sharma, H. & Mishra, S. 2022. Optimization of Solar Grid-Based Virtual Power Plant Using Distributed Energy Resources Customer Adoption Model: A Case Study of Indian Power Sector. *Arabian Journal for Science and Engineering*, 47(3): 2943–2963. https://doi.org/10.1007/s13369-021-05975-z.

Shen, F. & Wu, Q. 2018. Review of Service Restoration Methods in Distribution Networks. In *2018 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*. 1–6.

Shen, F., Wu, Q. & Xue, Y. 2020. Review of Service Restoration for Distribution. , 8(1): 1–14.

Shi, Q., Li, F., Olama, M., Dong, J., Xue, Y., Starke, M., Winstead, C. & Kuruganti, T. 2021. Network reconfiguration and distributed energy resource scheduling for improved distribution system resilience. *International Journal of Electrical Power and Energy Systems*, 124: 1–28.

Short, J.A., Infield, D.G. & Freris, L.L. 2007. Stabilization of grid frequency through dynamic demand control. *IEEE Transactions on Power Systems*, 22(3): 1284–1293.

Sigrist, L., Egido, I. & Rouco, L. 2012. Performance analysis of UFLS schemes of small isolated power systems. *IEEE Transactions on Power Systems*, 27(3): 1673–1680.

Silva, J.G., Doekemeijer, B., Ferrari, R. & van Wingerden, J.-W. 2021. Active Power Control of Waked Wind Farms: Compensation of Turbine Saturation and Thrust Force Balance. http://arxiv.org/abs/2104.03894.

Singh, S., Singh, M. & Chandra, S. 2016. Feasibility study of an islanded microgrid in rural area consisting of PV , wind , biomass and battery energy storage system. *Energy Conversion and Management*, 128: 178–190. http://dx.doi.org/10.1016/j.enconman.2016.09.046.

Siyanda Mnguni, M.E. 2020. A Multi-Stage Under-Voltage Load Shedding Scheme using a DIgSILENT power factory software to stabilize the power system network. *International Journal of Engineering Research and Technology*, 13(6): 1475.

Sovacool, B.K. 2021. Clean, low-carbon but corrupt? Examining corruption risks and solutions for the renewable energy sector in Mexico, Malaysia, Kenya and South Africa. *Energy Strategy Reviews*, 38(November): 100723. https://doi.org/10.1016/j.esr.2021.100723.

Stanojev, O., Guo, Y., Aristidou, P. & Hug, G. 2022. Multiple Ancillary Services Provision by Distributed Energy Resources in Active Distribution Networks. In *11th Bulk Power Systems Dynamics and Control Symposium (IREP 2022)*. http://arxiv.org/abs/2202.09403.

Stork, M. & Mayer, D. 2017. Reactive power in circuits with sampled resistive load. *Journal of Electrical Engineering*, 68(5): 357–363.

Sun, L., Liu, W., Chung, C.Y., Ding, M., Bi, R. & Wang, L. 2019. Improving the Restorability of Bulk Power Systems With the Implementation of a WF-BESS System. , 34(3): 2366–2377.

Swapna, Ganapaneni Srinivasa Varma, P., Ch. Rami, R., Flah, A., Basem, A., Habib, K., 4, M.A. & 1. 2022. Distribution System Service Restoration Using Electric Vehicles. *Energies*, 15(3264): 1–15.

Viawan, F. & Banktavakoli, R. 2018. Power system restoration: Blackstart studies. *4th IEEE Conference on Power Engineering and Renewable Energy, ICPERE 2018 - Proceedings*.

Wang, H.J., Pan, J.S., Nguyen, T.T. & Weng, S. 2022. Distribution network reconfiguration with distributed generation based on parallel slime mould algorithm. *Energy*, 244: 123011. https://doi.org/10.1016/j.energy.2021.123011.

Weijia, L. & Fei, D. 2021. Collaborative Distribution System Restoration Planning and Real-Time Dispatch Considering Behind-the-Meter DERS. *IEEE Transactions on Power Systems*, 36(4): 3629–3644.

Wen, J., Qu, X., Jiang, L. & Lin, S. 2022. A Hierarchical Restoration Mechanism for Distribution Networks Considering Multiple Faults. *Hindawi Mathematical Problems in Engineering*, 2022.

Worral, J., Cazalet, E.G., Cox, W., Rajagopal, N., R Nudell, T. & Heitmann, P. 2016. Transactive Energy Challenge Energy Management in Microgrid Systems. *Transactive Systems Conference*: 1–5.

Wu, H., Xie, Y., Xu, Y., Wu, Q., Yu, C. & Sun, J. 2022. Robust coordination of repair and dispatch resources for post-disaster service restoration of the distribution system. *International Journal* *of Electrical Power and Energy Systems*, 136(October 2021): 107611. https://doi.org/10.1016/j.ijepes.2021.107611.

Xiaoyu, H., Mingchao, X. & Yinghui, H. 2014. A service restoration method for active distribution Network. *Energy Procedia*, 61: 339–344. http://dx.doi.org/10.1016/j.egypro.2014.11.1120.

Xu, T., Wu, W., Chen, J., Lu, Q. & Zhu, Y. 2019. Asynchronous Distributed Dynamic Economic Dispatch in Active Distribution Networks. *2019 IEEE PES Innovative Smart Grid Technologies Asia, ISGT 2019*: 318–322.

Xu, X., Xue, F., Wang, X., Lu, S., Jiang, L. & Gao, C. 2021. Upgrading Conventional Distribution Networks by Actively Planning Distributed Generation Based on Virtual Microgrids. *IEEE Systems Journal*, 15(2): 2607–2618.

Xu, Y., Wang, Y., He, J., Su, M. & Ni, P. 2019. Resilience-Oriented Distribution System Restoration Considering Mobile Emergency Resource Dispatch in Transportation System. *IEEE Access*, 7.

Yuan, G., Li, Z., Yuxin, Z., Fu, S., Zhihu, H. & Yu, C. 2022. A Review on Decision-making Methods for Restoration Control of Transmission and Distribution Systems A Review on Decision-making Methods for Restoration Control of Transmission and Distribution Systems. In *EPES 2021*.

Yuan, Z., Wang, W., Wang, H. & Yildizbasi, A. 2020. A new methodology for optimal location and sizing of battery energy storage system in distribution networks for loss reduction. *Journal of Energy Storage*, 29(January): 101368. https://doi.org/10.1016/j.est.2020.101368.

Zhang, Y.Y., Zhang, K.S., Sun, W.L. & Zhang, F. 2011. Control strategy of distributed generators in microgrid. *Proceedings 2011 International Conference on Mechatronic Science, Electric Engineering and Computer, MEC 2011*: 146–149.

Zhou, X., Chang, C., Bernstein, A., Zhao, C. & Chen, L. 2021. Resources : Co-Optimization of Transmission and Distribution Systems. *IEEE CONTROL SYSTEMS LETTERS*, 5(6): 1994–1999.

Zhu, Q., Wang, Y., Song, J., Jiang, L. & Li, Y. 2021. Coordinated Frequency Regulation of Smart Grid by Demand Side Response and Variable Speed Wind Turbines. *Frontiers in Energy Research*, 9(September): 1–8.

Zietsman, M., Adefarati, T., Bansal, R. & Naidoo, R. 2022. Cost-benefit analysis of wind power integration in distribution networks. *Journal of Energy in Southern Africa*, 33(1): 21–39.

Zima, M. & Ledva, G. 2013. Self-dispatch of central dispatch in active distribution grids? Test case EU-FP7 ADDRESS. *International Conference on the European Energy Market, EEM*.