Contingency Analysis and Voltage Profile Enhancement of High-Voltage Transmission Lines Using Artificial Neural Network

A Case Study: On the Ethiopian Power System

Dessalegn Diriba Tesema

A Thesis Submitted to the Department of Electrical Power and Control Engineering

College of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Power System Engineering

Office of Graduate Studies
Adama Science and Technology University

May, 2025
Adama, Ethiopia

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DECLARATION

I hereby declare that this Master's Thesis entitled **"Contingency Analysis and Voltage Profile Enhancement of High-Voltage Transmission Lines Using Artificial Neural Network: A Case Study on the Ethiopian Power System"** is my original work. That is, it has not been submitted for the award of any academic degree, diploma, or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Dessalegn Diriba Tesema	____________________	________________
Name of the student	Signature	Date

RECOMMENDATION

I, the advisor of this thesis, hereby certify that we have read the revised version of the thesis entitled **"Contingency Analysis and Voltage Profile Enhancement of High-Voltage Transmission Lines Using Artificial Neural Network: A Case Study on the Ethiopian Power System"** prepared under my guidance by Dessalegn Diriba submitted in partial fulfillment of the requirements for the degree of Mater's of Science in Power System Engineering.

Therefore, I recommend the submission of revised version of the thesis to the department following the applicable procedures.

Dr. C.S. Reddy	____________	10/06/2025
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APPROVAL PAGE

I, the advisor of the thesis entitled **"Contingency Analysis and Voltage Profile Enhancement of High-Voltage Transmission Lines Using Artificial Neural Network: A Case Study on the Ethiopian Power System"** and developed by Dessalegn Diriba, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Dr. C.S. Reddy	____________	10/06/2025
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We, the undersigned, members of the Board of Examiners of the thesis by **Dessalegn Diriba** Tesema, have read and evaluated the thesis entitled **"Contingency Analysis and Voltage Profile Enhancement of High-Voltage Transmission Lines Using Artificial Neural Network: A Case Study on the Ethiopian Power System"** and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the degree requirement of the Master of Science in Power System Engineering.

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ACKNOWLEDGMENT

First of all, I shall praise and thank the Almighty Lord for helping me through this difficult but very inspiring work and for providing me with the ideas and patience necessary for the successful completion of this thesis. I am thankful for the gift of life itself, and for the strength he provided me to conduct this research. His blessing and guidance throughout this journey have been instrumental in making this research a reality.

Then, I would like to express my deepest gratitude and appreciation to my adviser, **Dr. C.S. Reddy**, for his invaluable guidance and encouragement through this journey of growth and discovery. His patience and support have enabled me to achieve my highest potential in both academic and professional work.

I would also like to extend my sincere appreciation to my co-adviser, **Dr. Shimeles Demissie (PhD).** His expertise and constructive criticism have been immensely helpful in refining my research and ensuring its clarity. **Dr. Shimeles Demissie (PhD)** dedication to his student start from proposal to thesis final is unforgettable and deeply valuable especially on his timely response.

I am deeply indebted to **Dr. Endalew Ayenew** for his invaluable support and mentorship. His constant encouragement, insightful feedback, and meticulous guidance have been instrumental in shaping this research project by checking documents originality.

I am grateful to all Adama Science and Technology University's Electrical and Computer Engineering department members. I would like to thank all my friends and fellow students. Thank you for sharing your pleasure and need for knowledge with me and for always being willing to assist me in working through the occasional threatening problems.

Thanks to all EEP operator staff who helped provide the data used in this thesis. I appreciate their cooperation in providing all the necessary data to complete this thesis. Finally, I would like to thank Adama Science and Technology University for giving me this glorious chance to study my master’s degree at one of the Prestigious Universities in Ethiopia.

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LIST OF ACRONYMS AND ABBREVIATIONS

ANN	Artificial Neural Network
CA	Contingency Analysis
EEP	Ethiopian Electric Power
EEU	Ethiopian Electric Utility
EHV	Extra High Voltage
EMS	Energy Management System
ETAP	Electrical Transient Analysis Program
HPP	Hydro Power Plant
KVAR	Kilo Volt Ampere Reactive
MVA	Mega Volt Ampere
MVAR	Mega Volt Ampere Reactive
MW	Mega Watt
NR	Newton Raphson
NLDC	National Load Dispatch Center
OCP	Optimal Capacitor Placement
PI	Performance Index
Pu	per unit
RBFNN	Radial Basis Function Neural Network
SCP	Security Contingency Plan

ABSTRACT

The power system is an extensive and very sensitive to damage and failures network, especially in the period of outage of transmission lines as well as power-generating units. There has to be a contingency analysis because the sensitivity demands it; a check on the security of the power system upon any outage to ensure the operation remains within safe limits. Unsafe operating conditions may arise from unscheduled outages of lines in interconnected power systems that can propagate throughout the rest of the network. In addition, these types of outages can also further initiate cascading failures that eventually could develop into a total blackout. This paper presents detailed contingency analysis and simulation results for Ethiopian high-voltage transmission networks with Power World Simulator, which gives a deep evaluation on how well the power system performs under different scenarios.

The thesis starts with a case that represents normal system conditions, meaning all transmission lines, transformers, and generators are functioning. It then considers three critical line outage cases: the Gefersa to D/Markos line, the Sebeta to Gefersa line, and the Wolkite to Sebeta line. In each of these scenarios, major voltage drops and very bad overloading conditions are exhibited; in particular, when the Sebeta to Gefersa transmission line is outaged, the loading levels reach extremely high levels plus there is a very bad risk of cascading failures. Also, this thesis looks at the inclusion of Distributed Flexible AC Transmission Systems (D-FACTS), which are seen to greatly improve voltage profiles plus stabilize networks. Bus ranking severity: comparison via numerical analysis and Artificial Neural Network (ANN). The voltage profile after insertion of D-FACTS lies within its acceptable range (0.95-1.05p.u. Overall, the findings underscore the urgent need for robust contingency planning and infrastructure improvements to ensure the reliability and safety of the Ethiopian power system.

Keywords: *Contingency analysis, ranking level, Power World Simulator, Voltage profile enhancement, Line outage, ANN*

CHAPTER ONE

1. INTRODUCTION

1.1 Background of the Study

The electric power system is evolving into a new environment of deregulation, which forces modern electric utilities to run their systems under very stressed conditions near to security limits. Therefore, system operators must develop quicker and more precise methods for contingency severity and violation analysis to maintain safe operating limits. Contingency is defined as the failure of any power system equipment in the network due to an emergency. In the field of static security assessment of power systems, important was the role of contingency analysis, which was discussed in this thesis.

Power system steady-state security is another of the very vital issues in power systems. Contingency evaluation is a facet of the assessment of the security of the power system. Some cases in that set could cause either an overload on a transmission line or a bus voltage limit violation during operations of the power system. That severity must be identified as quickly as possible to enable further detailed assessment. The determination, therefore, of these critical contingencies is called contingency selection, and it uses basically a full AC load flow program considering the outage of every line and generator.

The possibility examination gives the security state of the control framework beneath a possibility. A few stack stream strategies, such as the Gauss-Seidel, Newton-Raphson, and quick decoupled strategies, were utilized to perform the possibility investigation. These strategies get the stack stream arrangements beneath the possibility conditions, which makes a difference in computing the framework seriousness. The AC stack stream strategy isn't attainable to perform online, since of the computational burden to assess the constrain infringement. To overcome this computational boundary, different inexact strategies have been created. There accessible two strategies known as the express and the verifiable strategies. The unequivocal strategies were talked about in (T.A.Mikolinnas & B.F.Wollenberg). These ranking techniques use a scalar performance index (PI), which gauges system stress, to rank the contingencies according to their severity. In contrast, implicit methods were covered in (G. D. Irisarri & A. M. Sasson, 1981), where higher severity is ranked first and lowest severity is ranked last. This technique uses network solutions to rank the severity of different outages and identify system violations. In order to implement corrective control measures, large power systems need to have all plausible contingencies in a short amount of time.

Contingency refers to the failure of any power system component due to unforeseen events or emergencies. One common consequence of such failures is transmission line congestion, which can result in parts of the network becoming either overloaded or under-loaded. Contingency analysis plays a vital role in ensuring the effective and stable operation of the power system. Without prompt corrective action, major power system disturbances can escalate rapidly, leading to significant damage. The Ethiopian electric power transmission network, characterized by its centralized grid interconnection, is particularly vulnerable, where the loss of a single transmission line can adversely affect the entire system. As a result, there is a critical need for modern autonomous control and protection systems on key transmission lines to enhance system security.

Power flow control refers to the regulation of electrical power distribution across transmission lines by adjusting their reactance. This control is essential for the efficient utilization of the existing power system, especially during contingencies such as transmission line outages. Electronic devices capable of injecting variable reactance, either inductive or capacitive, can facilitate this control.

Distributed Flexible AC Transmission System (D-FACTS) devices represent a modern solution for such scenarios. Among these, the Distributed Static Series Compensator (DSSC) is particularly effective in dynamically injecting reactance based on real-time system needs. These compact, cost-effective, and efficient devices enhance power flow control, redistribute loads during line outages, and contribute significantly to maintaining power system reliability and security.

1.1.1 Background of Ethiopian Power System

Electricity was introduced in Ethiopia as early as the 1950s. The establishment of Ethiopian Electric Power (EEP) was formalized through Council of Ministers Regulation No. 302/2013 (EEP, n.d.) EEP is tasked with overseeing the development, operation, maintenance, and administration of power generation facilities and transmission networks operating at voltage levels above 66 kV. At present, the Ethiopian transmission system includes primary voltage levels of 400 kV, 230 kV, and 132 kV, while 66 kV and 45 kV lines serve as sub-transmission systems. Recently, a 500 kV extra high voltage (EHV) transmission line has been completed, though it is not yet fully integrated into the grid. This line links the Grand Ethiopian Renaissance Dam (GERD) to the national grid via Dedessa and Holeta with 500 kV lines, and extends from Holeta to Sebeta-II through a 400 kV line. EEP is also mandated for the bulk sale of electricity to the Ethiopian Electric Utility (EEU) and neighboring countries like Kenya, South Sudan, Sudan, and Djibouti. The EEP manages 22 power-generating stations, with 16 being hydroelectric, generating a total of 5220.30 MW, as of 2025.

Whereas, EEU is responsible for the construction, operation, maintenance, and management of the sub-transmission part of the system at 66kV and 45kV voltage levels, the Primary distribution system at 33kV, 15kV voltage levels, and the retail of electricity.

Ethiopian Electric Power (EEP) and Ethiopian Electric Utility (EEU), which are in charge of power generation and distribution, respectively, oversee Ethiopia's transmission and distribution network. With the goal of achieving nearly universal access by 2030, the Universal Electrification Program has been extending the national grid to rural areas. Notwithstanding these advancements, the Ethiopian power system still has problems with system losses, power outages, inadequate grid infrastructure, and little involvement from the private sector. But Ethiopia is headed toward a more resilient and sustainable energy future with sustained infrastructure investment, regional ties (like power exports to Sudan, Kenya, and Djibouti), and policy changes. The existing power plants with their installed capacity are given in Table 1.1.

Table 1.1: Existing Ethiopian power plants (https://www.eep.com.et/?page_id=1033)

No.	Power Plant Name	No. of Units	Installed Capacity[MW]	Type
1	GERD	13	5150 (Upon completion)	Hydro
2	Genale Dawa III	3	254	Hydro
3	Gilgel Gibe III	10	1870	Hydro
4	Beles	4	460	Hydro
5	Gilgel Gibe II	4	420	Hydro
6	Tekeze	4	300	Hydro
7	Gilgel Gibe I	3	184	Hydro
8	Melka Wakena	4	153	Hydro
9	Finchaa	4	134	Hydro
11	Amerti Neshe	2	95	Hydro
12	Tis Abay II	2	72	Hydro
13	Koka	3	43.2	Hydro
14	Awash II	2	32	Hydro
15	Awash III	2	32	Hydro
16	Tis Abay I	3	14.4	Hydro
17	Aysha 1	80	120	Wind
18	Adama II	102	153	Wind
19	Ashegoda	120	120	Wind
20	Adama I	34	51	Wind
21	Reppie	2	50	Thermal
22	Aluto Langano	1	7.3	Geothermal

1.2 Statement of the Problem

In an interconnected power system unscheduled line outage due to a fault causes an overloading effect on the rest of the network. Furthermore more it led the system to a cascaded outage, then to a total blackout. The Ethiopian electric power system has been suffering from blackouts. As obtained from the NLDC archive, a frequent blackout has been recorded, and transmission line fault was one of the initiating events for blackouts (Ethiopia National Load Dispatch Centre, 2013-2015 G.C).

Reliable power delivery is essential for both profitability and customer satisfaction. However, in Ethiopia, frequent power interruptions have become a daily issue. In some cases, outages occur multiple times a day, not only in low-voltage networks but also in medium-voltage distribution systems. One major contributing factor is the complexity of Ethiopia's electric power transmission network, which is characterized by a large, interconnected system of geographically dispersed generators and loads linked by long transmission lines. This structure increases the likelihood of disturbances, affecting service reliability for customers. The failure of a single transmission line can lead to cascading disruptions across the network. As a result, transmission systems often become overloaded, and substation voltages deviate from acceptable ranges, increasing the risk of partial or total blackouts during both minor and major disturbances. To mitigate the aforementioned problems, this thesis focused on the transmission line contingency analysis and voltage profile improvement, considering different line outage conditions using Power World Simulator. ANN was carried out to predict the severity of the buses in the system and compared with the numerical method for the performance index of PIv. ANN is suggested for its strong capability to model complex, nonlinear relationships and learn from historical data without requiring an explicit mathematical of the system modeling. Traditional power flow methods such as Newton-Raphson, Fast Decouple load flow and others, while accurate, are computationally intensive and less adaptive under multiple or uncertain contingencies. ANN, on the other hand, offer fast, real time prediction and classification of voltage profiles and system stability, making it especially suitable for large and evolving networks like Ethiopia's, where data availability is growing and system dynamics are become more complex with the new generation and transmission projects.

1.3 Objectives

1.3.1 General Objective

The main objective of this thesis is to conduct the contingency analysis for the Ethiopian power network on 230kV voltage level transmission lines by using Power World Simulator software and Enhancement of Voltage Profiles because 230KV represents the backbone of Ethiopian high-voltage transmission network, offering a balance between regional interconnection and bulk power transfer rather than other voltage levels.

1.3.2 Specific Objectives

- To perform AC load flow and identify the most critical line outages.
- To analyze the steady-state power flow of Ethiopian 230 kV transmission lines.
- To perform and evaluate the loading of lines under different N-1 outages and ensure enhancement of Voltage Profiles.
- To compare the voltage profile of the buses under the base case and during contingency conditions.
- To compare the results of the performance index PIv for ranking the severity of buses in the system with numerical methods and ANN.
- To provide recommendations for the findings of this research.

1.4 Significance of the Study

Ensuring the security of the Ethiopian power system is a fundamental objective in modern power system planning and operation. Maintaining voltage levels within acceptable limits is essential not only for the stability of the grid but also for the proper functioning of sensitive equipment. Enhancing the overall reliability of the Ethiopian power system minimizes the risk of blackouts and reduces the frequency of service interruptions. Furthermore, preventing power interruptions can lead to substantial cost savings by avoiding the economic losses typically incurred during outages. Operating electrical equipment within permissible limits during contingencies also promotes optimal performance and extends equipment lifespan, thereby improving operational efficiency and reducing maintenance costs.

1.5 Scope of the Study

The main focus of my thesis is conducting AC load flow analysis based on the Ethiopian High Voltage Transmission network, contingency analysis with Power World Simulator in different line outages of the power system, and then ranking based on the severity of the line or the buses, depending on the Performance Index. This paper considers only some of the 230kV Ethiopian transmission line and is validated by software simulations rather than experimental implementation, because the software that I used could only draw 13 buses. ANN is manipulated to determine the voltage performance index PIv to identify the most severe buses in the system.

1.6 Methodology

A sequence of major steps used to tackle the problem and achieve the objective is as follows.

Data collection: The following data have been collected from NLDC and the kinds of literature

- ✓ Transmission line & generator parameters
- ✓ Shunt reactors and capacitors
- ✓ The Load at each substation at peak total demand on the grid
- ✓ Load curve of the EEP grid
- ✓ Generation Dispatch log sheet
- ✓ General network diagram

Data analysis: The raw data, which have been obtained from NLDC, were analyzed to model the EEP grid on Power World Simulator simulation software.

Design and modeling: The high-voltage EEP grid has been modeled on Power World Simulator software.

Simulation: Base case load flow and Contingency analysis using the AC load flow NR method for the system being subjected to different line outages have been performed, and the voltage profile was calculated.

Result discussion and conclusion: The simulation result has been discussed, and a conclusion was drawn.

1.7 Organization of the Thesis

This thesis has been organized into five chapters. The chapter's descriptions are presented as shown below:

Chapter One: is about the introduction part, which consists of the background of the study, statement of the problem, general and specific objectives, significance of the study, and the methodology used to achieve the work.

Chapter Two: is about reviewing different literature that has been done related to this work.

Chapter Three: discusses power system security, which consists of power system security levels, power system contingency analysis overview, contingency analysis procedure, and methods of contingency analysis.

Chapter Four: presents the Ethiopian power network model in the ETAP software simulation tool. And the simulation result & discussion of the base case and under line outage condition of Ethiopian power network is discussed. For some of 230kv line outage contingency with each case scenario of voltage profile is presented carefully. ANN is carried out to predict PIv.

Chapter Five: consists of the conclusion and recommendations and future work.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 Basic Theories and Overview

An essential component of evaluating the security of a power system is contingency analysis. It entails assessing the system's capacity to sustain suitable operating conditions after one or more system components, such as generators, transformers, or transmission lines, go out. Making sure the power system stays stable, within thermal and voltage bounds, and able to provide consumers with continuous power under a variety of fault scenarios is the main objective.

There are two primary types of contingency analysis:

- **N-1 Contingency Analysis:** Considers the loss of a single element, such as one transmission line, transformer, breakers, or generator units.
- **N-k Contingency Analysis:** Participate in the simultaneous loss of multiple elements at the same time, and is more computationally intensive.

Contingency analysis is supported by several theoretical foundations:

- **Power Flow Analysis:** Evaluates the steady-state operation of the system using methods such as Newton-Raphson or Fast Decoupled Load Flow (FDLF).
- **Linear Sensitivity Analysis:** Approximates post-contingency states using Jacobian-based sensitivity factors (e.g., Line Outage Distribution Factors - LODFs).
- **Optimization Theory:** Used for security-constrained optimal power flow (SCOPF) in corrective actions post-contingency.
- **Stability Theory:** Ensures rotor angle, frequency, and voltage stability are maintained after disturbances.

These theories are typically implemented in energy management systems (EMS) for real-time or offline security assessment.

2.2 Literature Review on Previous Works

Much research has been conducted regarding power system contingency analysis. Some of the related papers are presented as follows.

Woldemariam Wolde-Ghiorgis et al, conducted a simulation-based study using DigSILENT software to investigate technical power loss reductions in selected outgoing feeders connecting 15kV distribution lines to transformers at the Sebeta Substation. The analysis focused on routes where all transformers were operating at 60% of their rated capacity. The study evaluated total nominal power losses in both the feeders and transformers and explored alternative technical approaches for minimizing power losses under various loading conditions.

Wubante Getachew et al. presented a study aimed at minimizing bulk power transmission losses in the high-voltage grid network of the Ethiopian Electric Power (EEP) system, using the ETAP PowerStation software. The research focused on enhancing grid efficiency through various loss reduction strategies. One approach involved upgrading selected transmission lines, targeting 55% of 45 kV lines, 40% of 66 kV lines, and 30% of 132 kV lines, which collectively reduced transmission losses from 42.67 MW to 33.18 MW. Another strategy applied was voltage uprating, where all 45 kV lines were proposed to be upgraded to 66 kV, and key 132 kV lines within the grid's main loops were selected for uprating to 230 kV, resulting in a reduced loss of 35.42 MW. Additionally, reactive power compensation was implemented at selected buses, achieving a further loss reduction of 10.33 MW.

Kingsley Bediako Owusu et al. investigated the underlying causes of high transmission technical losses within Ghana’s interconnected power network. Their study combined a literature review with field interactions to support their findings. Using a power system simulation software package, the authors modeled the entire grid to identify sections violating predefined system parameters. Simulation results revealed widespread low-voltage conditions, particularly in the northern part of the network. To address this, an optimal capacitor allocation strategy was applied to critical buses in the affected area, determining the appropriate level of reactive power compensation needed. Following the compensation, significant improvements were observed in the voltage profiles of the targeted areas. The authors concluded by recommending the integration of distributed generation and the adoption of smart grid technologies to enhance voltage stability across the network in the future.

Sekhar P. and Mohanty S. (Sekhar P. & Mohanty S., 2013) In 2013 proposed the performance index-based contingency ranking based on the active power and voltage performance index. Applied the Newton-Raphson load flow approach to rank the power system contingency for the line outage. The active power performance index and voltage power performance index were determined afterwards by utilizing the data from the NR technique. To assess the severity of the contingency, the one with the highest total performance index is placed first and is arranged in descending order. A standard IEEE 5 bus was used as a test system. Here identify severe line outage using PI save time to execute load flow and see the result for all possible outage, but rather than using NR for performance index calculation it would be better to use other quicker way, because the purpose of performance index calculation is to identify relatively critical outage and then to do the detail analysis on it.

E. F. Dela Cruz et al. In 2016 used the Fast Decoupled Load Flow method for the load flow analysis of the system for each outage event. The researchers employed Performance Indices, notably the Voltage-Reactive Performance index, to assess each outage's severity and determine whether it was critical or not. A standard IEEE 5 bus was used as a test system. Here, the researchers used the FD load flow method to identify critical outages based on the Voltage-reactive performance index, which is quicker than the NR method, but after selecting the critical outage, the NR load flow method has to be used for detailed contingency analysis for better accuracy for that critical outage.

Rajendra Singh and Laxmi Srivastava. In 2007, in this paper, a cascade neural network-based approach has been proposed for fast line flow contingency screening and ranking. The developed cascade neural network was a combination of a filter module (ANN1) and a ranking module (ANN2) with a feed-forward architecture. A filter module was designed for a classification task so that contingencies were classified either in the critical class or the non-critical class, while the second module was designed for ranking. The proposed method only considers the severity of contingency on the load ability of the line, but equal emphasis has to be given to voltage limit violations due to contingency.

Kusum Verma and Niazi K.R. (Kusum Verma & Niazi K.R, 2012) used a supervised learning approach for quick and accurate contingency analysis of power systems. The artificial neural network Feed-Forward (FFNN) was used in this work, and two FFNNs were used to predict the contingency performance index: one for the line MVA performance index and the other for the voltage-reactive power performance index. The suggested method was tested on the New England IEEE-39 bus, which has 46 transmission lines, 10 generators, and 12 transformers. The accuracy of the approach was tested for unknown patterns, demonstrating its applicability for online applications at the Energy Management Center. FFNN with a gradient-based algorithm has the problem of local minima, and as the number of neural networks required is large, it may not apply to a practical power system.

Lekshmi M. et al. (Lekshmi M. et al, 2014) In 2014, in this paper, the Multi-Layer Feed-Forward Artificial Neural Network (MLFFN) and the Radial Basis Function Network (RBFN) were applied to realize an online static power system security assessment module. Comparison of the accuracy and computational speed of the MLFFN and RBFN models with the Newton-Raphson load flow analysis model shows that the model is effective and dependable in the quick evaluation of the security level of electrical systems. The suggested approach has been tested on an IEEE 118 bus test system to show its efficacy in assessing the online static security of the power system. This paper pointed out that RBFN takes less computation time. Input features for the RBFN model should be carefully considered, this is because RBFN with high input dimensional functional space could very quickly require huge memory storage and computational effort, and also have an impact on network performance.

Florian Schafer et al. (Dr.M. S. Nagaraj & Sowmya Lekshni M., 2018) In 2018, used a multilayer perceptron (MLP) architecture. ANN has been used for the contingency analysis to achieve a single contingency policy or N-1 criteria. The network was trained to predict power flow results for fast and accurate SCP analysis. The current flow through each branch and the voltage at each bus were predicted by the ANN for a given input of real power and reactive power injections. The proposed method has been tested on a real German 110 kV sub-transmission grid located in Karlsruhe, the IEEE 57 bus system, and the CIGRE 15 bus medium voltage grid. The paper pointed out that for each test, prediction errors were extremely low (0.5 %) in comparison to the Line outage distribution factor (LODF) method (18.6 %), and Prediction times were significantly less compared to AC power flow calculations. Since the performance of the MLP architecture is highly affected by the output dimension, care should have been given in selecting the network architecture. Also, the proposed method did not say anything about the severity level of the contingency.

Sudha and Manjula S. (Sudha & Manjula S., 2019) In 2019. In this paper, the artificial neural network Feed-Forward (FFNN) was used, which uses the pattern recognition approach to predict the post-contingency state of the power system. The loading and contingency conditions were used as input to the ANN, while each bus voltage magnitude and angle were considered as targeted outputs. The proposed method has been tested on a 4-bus sample system. The proposed method predicts the post contingency bus voltage magnitude and angle at each bus, which could be time-consuming and require computational effort as the size of the power system increases. And also, did not give any information about the severity of each contingency to line loading.

2.3 Research Gaps Identified and Recommendations

- Lack of comprehensive "Contingency Analysis" studies specific to the Ethiopian transmission grid using both numerical and ANN-based optimization techniques.
- Limited integration of real-time data and machine learning models in predictive contingency analysis.
- Minimal validation of theoretical models with actual operational data from EEP or load dispatch centers.
- They are use other STATCOM which is centralized at substation or bus rather than D-FACTS which distributed on transmission lines to control power flows at low cost in form of modular and easy to deploy.
- **Recommendation**: Using ANN method of improvement and D-FACTS device insertion in each Transmission line within calculated distance.

CHAPTER THREE

3. MATERIALS AND METHODS

3.1 Methodology

The methodology of this study begins with problem identification and an extensive review of relevant literature, including books, articles, and web pages. The primary issue addressed is the occurrence of blackouts, sudden load changes, oscillations, loss of synchronism, and system faults

in the power grid of Ethiopia, resulting in frequent power system breakdowns and momentary instability. Power system security refers to the methods employed to ensure continuous system operation even in the event of component failures. When a single failure triggers a sequence of subsequent failures, it is known as a cascading failure, which can ultimately cause a total system blackout (P. Venkatesh et al, 2012), (D P Kothari & I J Nagrath, 2011). There is an inherent trade-off between economic operation and the security of the Energy Management System (EMS); increasing the reliability of the power supply generally raises operational costs. Therefore, power systems are typically managed to minimize costs while maintaining an acceptable level of supply security. This level of security helps prevent and manage emergency situations (T. K. Nagsarkar & M. S. Sukhija, 2014).

According to D P Kothari and I J Nagrath (2011), system security is made up of three main tasks performed in an energy control center.

I. System observation
II. . Analysis of contingencies
III. Analysis of corrective action.

I. System monitoring gives power system operators relevant, current information about the state of the power system. In general, it is the most significant of the three functions. The efficient functioning of the system necessitated the measurement of critical quantities and the transmission of measurement values to a central location as soon as utilities moved beyond systems of a single unit supplying a collection of loads. These measurement and data transmission systems, also known as telemetry systems, have developed into schemes that are able to keep an eye on power flows, voltages, currents, and the condition of switches and circuit breakers in each substation within a power system transmission network. Furthermore, it is possible to telemeter other crucial data, including frequency, generator unit outputs, and transformer tap locations. It would be impossible for a human operator to check all of the telemetered data at once in a reasonable amount of time. Digital computers are usually installed in operation control centers to gather the telemetered data, process it, and store it in a database for operators to view on large display monitors. More significantly, the computer can alert the operators in the event of an overload or out-of-limit voltage by comparing incoming data to pre-stored limits. In these kinds of systems, state estimation is typically used to aggregate telemetered data and provide the best statistical estimate of the current "state" or system condition. These systems frequently cooperate with supervisory control systems to enable operators to operate switches, taps, and circuit breakers remotely. According to D P Kothari and I J Nagrath (2011), these systems collectively are referred to as SCADA (supervisory control and data acquisition) systems.

II. Contingency analysis serves as the second critical function in ensuring system security. The insights gained from this analysis enable power systems to be managed in a preventive manner. Many issues in power systems can escalate so quickly that operators may not have sufficient time to respond effectively this is especially true in the case of cascading failures. To address this challenge, modern operational computers are equipped with contingency analysis tools that simulate potential disturbances before they actually occur. These tools rely on a model of the power system and are used to examine outage scenarios, helping to alert operators to possible equipment overloads or voltage violations.

The most basic type of contingency analysis can be implemented using a conventional load flow program, combined with methods to configure the load flow data for each specific outage scenario under examination. This approach helps system operators identify secure operating conditions where no single contingency would result in equipment overloads or voltage deviations.

III. The third key function in maintaining power system security is corrective action analysis. This function allows operators to modify system operations if the contingency analysis indicates that a particular outage could lead to significant problems. In this way, it supports both preventive and post-contingency control strategies. A basic example of a corrective action is rescheduling generation, which can alter power flow patterns and shift the loading on lines that were previously overloaded. This function integrates contingency analysis with optimal power flow techniques to adjust generation dispatch and other parameters, ensuring that security assessments show no violations under any considered contingency.

3.1.1. Need for Contingency Analysis

1. Enhancing System Reliability

In many developing countries, frequent load shedding is a persistent issue. Despite numerous reforms in the power sector, desired improvements have not been realized. Moreover, system components such as transformers and generators are often damaged due to overloads, security breaches, or voltage deviations beyond permissible limits. Without proper maintenance of generation units and the network, significant infrastructure losses may occur. Contingency analysis plays a crucial role in this context, as it helps prioritize system components based on vulnerability, enabling the estimation of potential losses associated with faults in buses, generators, transformers, or transmission lines. Proactively identifying and addressing these issues before they escalate is essential for reliable operation.

2. Ensuring Secure Operation

Contingency analysis aids in the early detection of high-risk components that may fail shortly. By identifying these vulnerable parts of the network in advance, maintenance strategies can be implemented to mitigate the risk of failure. This ensures safer and more effective operation of the power system.

3. Planning for Future Expansion

When a transmission line fails, the load is redistributed across the remaining lines, increasing their stress. Conducting a contingency analysis allows planners to identify these bottlenecks and design parallel transmission paths to prevent overloading. This approach supports efficient expansion of the transmission network and enhances the long-term reliability of the power system.

3.1.2. Power System Reliability and Security

The main objective of a power system is to deliver electrical energy to consumers in a cost-effective manner while ensuring continuity and acceptable quality. To meet this goal, reliability is key, and it is typically evaluated in terms of how often, how long, and how severely service interruptions occur.

Electric system reliability consists of two key components:

1 Adequacy: The system's ability to supply the total electricity demand within operational limits, accounting for both planned and unexpected outages.

2 Security: The system's capacity to endure sudden disturbances, such as the unplanned loss of key components. Power system security specifically refers to the system's ability to remain stable and operational in the face of a predefined set of credible disturbances or contingencies.

Security Assessment (SA) evaluates whether the system can withstand disturbances without major operational issues. It classifies the system state as either secure or alert:

A secure state implies that all demands are met and no violations are expected, even if unforeseen outages occur. An alert state suggests that limits are being exceeded or that demands are unmet, requiring corrective measures to restore secure conditions.

3.1.3. States of Power System Security

a. Preventive State: This is the normal operating condition, where all equipment functions within defined limits and all system variables are stable. The system should remain stable even if contingencies occur. Operators should anticipate these events and take preventive actions, balancing security and economic operation.

b. Emergency State: Occurs when operational limits are breached, e.g., components overload or frequency drops. The objective here is to relieve system stress through emergency control actions.

c. Restorative State: In this state, parts of the system or the entire grid may be down. The focus is on restoring power and returning the system to normal operating conditions. Security studies place significant emphasis on how well the system can recover from such disturbances.

A system state is considered secure only about specific contingency scenarios and based on defined monitoring metrics. In well-managed systems, the network is typically operated to ensure that no single contingency leads to severe overloading elsewhere, thereby avoiding cascading failures.

Why These Levels Matter: Understanding and managing these security levels is crucial for:

- ► Preventing blackouts
- ► Protecting equipment
- ► Keeping the lights on for everyone from homes to hospitals

Power system operators use real-time data, simulations, and automated controls to keep the system in a secure state as much as possible and respond quickly when things go wrong.

3.2 Power System Security Levels

Power system security is divided into various tiers. In order to define pertinent EMS functions, Dy Liacco initially proposed a formal classification of power system security levels, which Fink and Carlsen later further illustrated. By including correctly secure (security level 2) and correctable emergency (security level 4), Stott et al. have also provided a more useful static security level diagram. Figure 3.1 provides a summary of the power system security level.

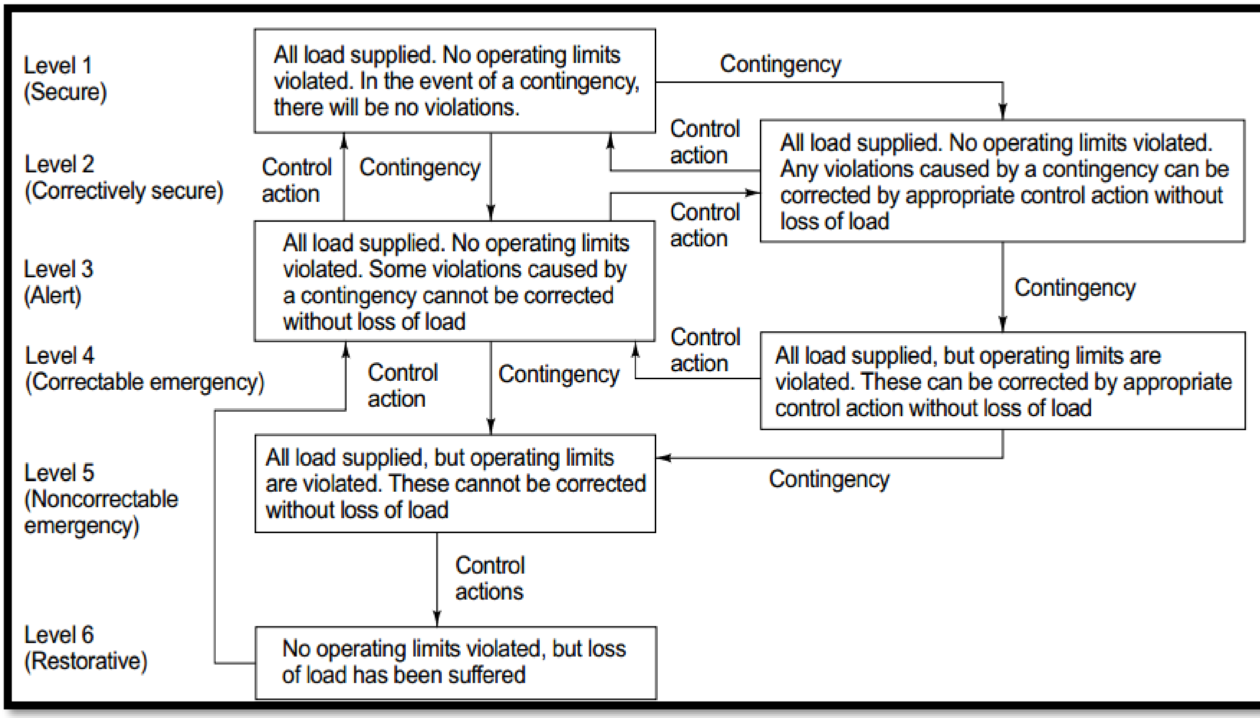


Figure 3.1: Power system static security level

3.3 Power System Contingency Analysis

3.3.1 Power System Contingency Analysis Overview

Because it depends on time and the system's resilience to impending disruptions, power system steady-state security is a condition that exists instantly. Every aspect of human development is based on a stable and sound energy supply regime, as the past century has shown. The aging infrastructure of the transmission and distribution networks is one of the elements endangering the network's dependability. Careful monitoring, automation, and information management are some ways to guarantee a dependable and secure power network. A contingency analysis is one such tool that can be used to perform a power system analysis in this context.

The study of transmission line, transformer, and generator outages and their impact on line power flows in the remaining system network components is known as contingency analysis. Studying the impact of contingencies is particularly useful during the planning and operation phases. Contingencies are disruptions, such as transmission element or generator failures, that could result in abrupt and significant changes to the system's state and configuration. They frequently cause serious operating constraints to be broken and frequently result in power outages.

The goal of steady state contingency analysis is to evaluate the risk that specific situations could present to an electrical. This allows operators to be better prepared to react to outages by using pre-planned recovery scenarios. During contingency analysis, it should be noted that:

- ✓ The system's resilience to equipment failure determines its level of security.
- ✓ Those that exhibit overloads in the emergency situations are considered weak elements.
- ✓ Performing a single (N-1) contingency analysis simulation is the conventional method.

When an electrical network experiences anomalous conditions, contingency analysis stresses the entire system or just a portion of it. It happens because of:

- ✓ The transmission line suddenly opened,
- ✓ The generator tripping,
- ✓ The generation suddenly changing, or
- ✓ The load suddenly changing

3.3.2 Power System Contingency Analysis Procedure

In the above section causes of contingency or the causes that force the power system to operate under stress, here procedures to perform contingency analysis are presented. Consider that N power system components are there in a power system, and if contingency analysis is done following the failure of one component, i.e., one generator or one transmission line, then this is called single or N-1 contingency analysis. Whereas contingency analysis following the failures of two components, i.e., two generators or transmission lines, is called N-2 contingency analysis. Contingency analysis in a power system is a critical process used to assess the impact of potential failures, as mentioned before, on the stability and operation of the system. It helps in ensuring system security and planning for corrective actions. Here is a step-by-step procedure for CAs.

Data Collection: Gather real-time or forecasted system data such as network topology (buses, lines, and transformers), generation and load data, lines and transformers limits, and generator capabilities (Real and reactive power).

Base Case Load Flow Analysis: Perform a power flow analysis using methods like Newton-Raphson or Gauss-Seidel and ensure the base case is within operational limits of voltages and power flows.

Contingency Selection: Identify credible contingencies typically as

- ► N-1 Contingency: Which is considered a single element outage, like a transmission line or generator units
- ► N-2 Contingency: Which means multiple contingencies that occur less frequently but are possible
- ► Consider Both Planned and Unplanned events to predict incidents

Simulate Each Contingency: For each contingency selected:

- ➢ Remove the element from the system on simulation by making an open circuit
- ➢ Re-run power flow analysis to observe system response in percentage of overloading

Evaluate System Performance: Check the system for the case summary and monitoring limits as:

- ❖ Voltage violation: Check voltage outage of 0.95-1.05p.u range
- ❖ Line over loads: That means if it exceeds thermal limits
- ❖ Generator limits violations
- ❖ Islanding or system separations

Rank Contingencies

- ✓ Use severity indices or performance indices as of line loading index and the voltage deviations index.
- ✓ Rank based on the level of risk or impact to prioritize action.

Take Corrective Actions: If violations are detected,

- ► Generation rescheduling
- ► Load Shedding
- ► Switching operations
- ► D-FACTS device deployment
- ► Reactive power compensation

The contingency analysis procedure is given with a flow chart as shown in Figure 3.2

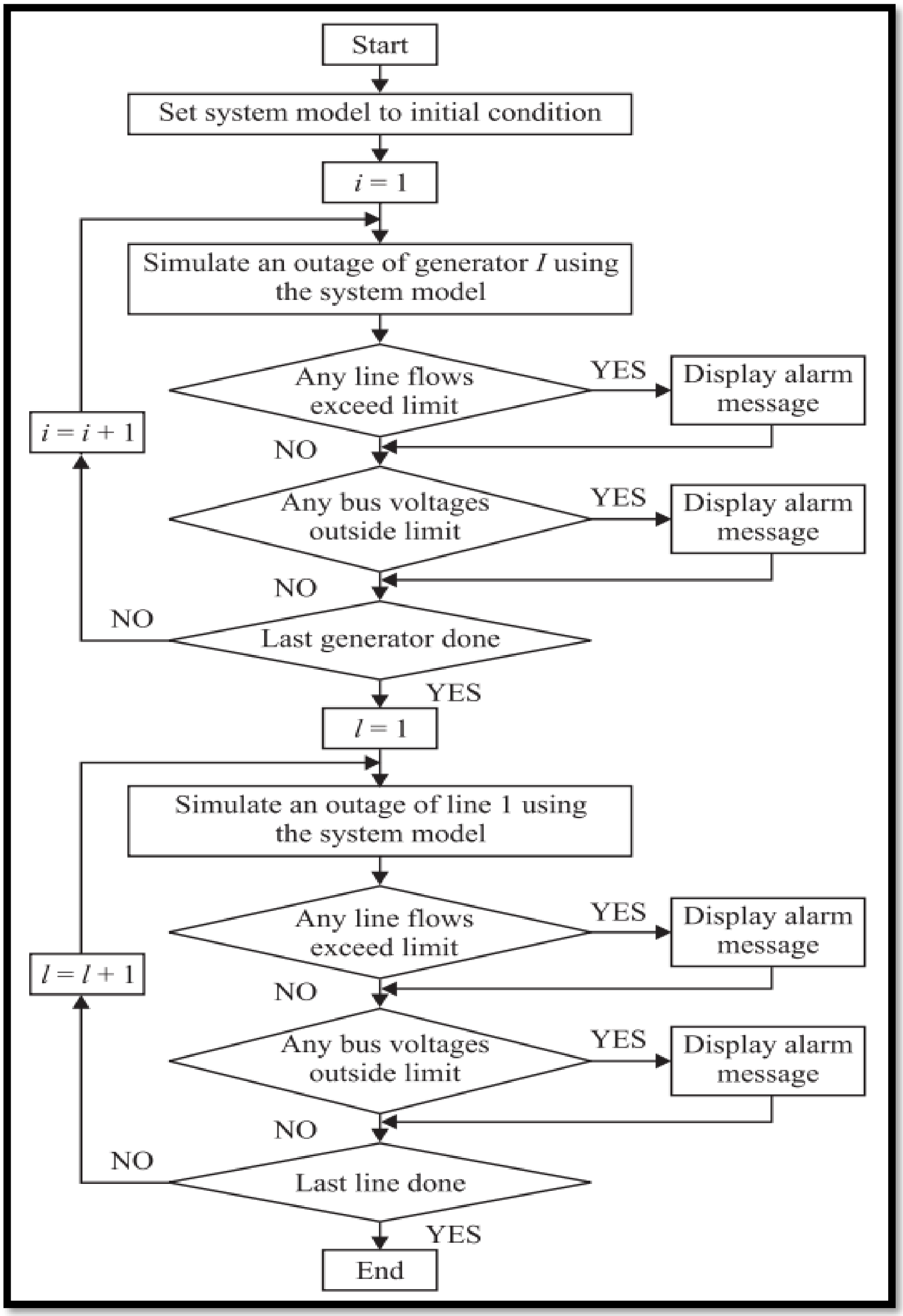


Figure 3.2: Power System Contingency Analysis Procedure

Contingency analysis consists of the following major components or steps (Pudi Sekhar & Prof. Sanjeeb Mohanty, 2013)

I. **Contingency Definition:** It is the initial stage of the contingency analysis. It is the list of all possible contingency in the system.

II. **Contingency Selection:** It is the second stage in contingency analysis. All possible contingencies may not able to cause power system security limit violation. Therefore, the process of selecting the contingency which can cause security limit violation is said contingency selection. Index calculations are used to select severe contingencies.

III. **Contingency Evaluation:** It is the final and significant stage. It consists of all the necessary control actions used to reduce or mitigate the effects of severe contingencies.

3.3.3 Methods of Power System Contingency Analysis

AC Load Flow Method: A Newton-Raphson or a decoupled power flow is used by the majority of operations control centers that employ an AC power flow program for contingency analysis. These algorithms are employed because they solve problems quickly and have a fair amount of convergence reliability in challenging situations. Another benefit of the decoupled load flow is that it can be used to simulate transmission line outages without reversing the system Jacobian matrix at each iteration by incorporating a matrix alteration formula. A typical ith bus of a power system is depicted in Figure 3.3: By applying KCL to this bus, the relationship between voltage and current is determined. Applying KCL to this bus yields the relationship between voltage and current.

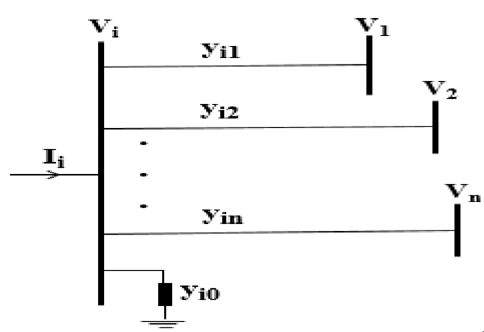


Figure 3.3: A typical bus of a power system

$$I_i = Y_{ii}V_i + \sum_{\substack{j=1 \\ j\neq i}}^{n} Y_{ij}V_j \tag{3.1}$$

where, $Y_{ij} = -y_{ij}$, $Y_{ii} = y_{io} + y_{i1} + y_{i2} + ... + y_{in}$

The real and reactive power at bus *i* is given by

$$P_i - jQ_i = V_i{}^*.I_i \tag{3.2}$$

$$I_i = \frac{P_i - jQ_i}{V_i{}^*} \tag{3.3}$$

From equations (3.1) and (3.3)

$$\frac{P_i - jQ_i}{V_i{}^*} = Y_{ii}V_i + \sum_{\substack{k=1 \\ k\neq i}}^{n} Y_{ik}V_k \tag{3.4}$$

Where I_i = current at bus i.

Y_{ij} = mutual admittance between buses i and j.

V_i and V_j are the calculated voltages of buses i and j.

θ_{ij} = phase angle at bus i and j.

P_i = active and reactive power at bus i.

Equation (3.4) is used to formulate a power flow problem, which leads to a set of nonlinear equations that are solved iteratively using methods like the Newton-Raphson method. The Newton-Raphson method's quadratic convergence nature has minimal divergence characteristics and is computationally superior. Accordingly, the NR approach is utilized for contingency analysis and is found to be more effective and feasible for large power systems.

From equation (3.4), the net injected power at bus i is given by

$$P_i - jQ_i = V_i^* \left[Y_{ii} V_i + \sum_{\substack{j=1 \\ j \neq i}}^{n} Y_{ij} V_j \right]$$

(3.5)

Converting equation (3.5) into polar form

$$P_i - jQ_i = |V_i|^2 |Y_{ii}| \underline{|\theta_{ii}} + \sum_{\substack{j=1 \\ j \neq i}}^{n} |Y_{ij}||V_i||V_j| \underline{|\theta_{ij} + \delta_j - \delta_i} \tag{3.6}$$

Converting equation (3.6) into rectangular form and separating real & imaginary parts

$$P_i = \sum_{\substack{j=1 \\ j \neq i}}^{n} |Y_{ij}||V_i||V_j| \cos(\theta_{ij} + \delta_j - \delta_i) \tag{3.7}$$

$$Q_i = -\sum_{\substack{j=1 \\ j \neq i}}^{n} |Y_{ij}||V_i||V_j| \sin(\theta_{ij} + \delta_j - \delta_i) \tag{3.8}$$

A collection of nonlinear algebraic equations in terms of independent variables is formed by equations (3.7) and (3.8). Here, equation (3.7) provides one equation for each voltage-controlled bus, and equations (3.7) and (3.8) provide two equations for each load bus. The following set of linear equations is produced by expanding equations (3.7) and (3.8) in Taylor's series.

$$
\begin{bmatrix} \Delta P_2^{(k)} \\ \vdots \\ \Delta P_n^{(k)} \\ \Delta Q_2^{(k)} \\ \vdots \\ \Delta Q_n^{(k)} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_2^{(k)}}{\partial \delta_2^{(k)}} & \cdots & \frac{\partial P_2^{(k)}}{\partial \delta_n^{(k)}} & \frac{\partial P_2^{(k)}}{\partial |V_2|^{(k)}} & \cdots & \frac{\partial P_2^{(k)}}{\partial |V_n|^{(k)}} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial \delta_2^{(k)}} & \cdots & \frac{\partial P_n^{(k)}}{\partial \delta_2^{(k)}} & \frac{\partial P_n^{(k)}}{\partial |V_2|^{(k)}} & \cdots & \frac{\partial P_n^{(k)}}{\partial |V_n|^{(k)}} \\ \frac{\partial Q_2^{(k)}}{\partial \delta_2^{(k)}} & \cdots & \frac{\partial Q_2^{(k)}}{\partial \delta_n^{(k)}} & \frac{\partial Q_2^{(k)}}{\partial |V_2|^{(k)}} & \cdots & \frac{\partial Q_2^{(k)}}{\partial |V_2|^{(k)}} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial \delta_2^{(k)}} & \cdots & \frac{\partial Q_n^{(k)}}{\partial \delta_n^{(k)}} & \frac{\partial Q_n^{(k)}}{\partial |V_2|^{(k)}} & \cdots & \frac{\partial Q_n^{(k)}}{\partial |V_n|^{(k)}} \end{bmatrix} \begin{bmatrix} \Delta \delta_2 \\ \vdots \\ \Delta \delta_n \\ \Delta |V_2^{(k)}| \\ \vdots \\ \Delta |V_n^{(k)}| \end{bmatrix} \tag{3.9}
$$

The Jacobian matrix gives the linearized relationship between small changes in the voltage angle. And voltage magnitude with the small changes in real $\Delta P_i^{(k)}$ and reactive power $\Delta Q_i^{(k)}$. The equation (3.9) can be written in short form as

$$
\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \tag{3.10}
$$

The diagonal and the off-diagonal elements of J_1 are

$$
\frac{\partial P_i}{\partial \delta_i} = \sum_{j \neq i}^{n} |Y_{ij}||V_i||V_j| \sin(\theta_{ij} - \delta_i + \delta_j) \tag{3.11}
$$

$$
\frac{\partial P_i}{\partial \delta_j} = -|Y_{ij}||V_i||V_j| \sin(\theta_{ij} - \delta_i + \delta_j) \quad j \neq i \tag{3.12}
$$

The diagonal and the off-diagonal elements of J_2 are

$$
\frac{\partial P_i}{\partial |V_i|} = 2|Y_{ii}||V_i| \cos\theta_{ii} + \sum_{j \# i}^{n} |Y_{ij}||V_j| \cos(\theta_{ij} - \delta_i + \delta_j) \tag{3.13}
$$

$$
\frac{\partial P_i}{\partial |V_j|} = |Y_{ij}||V_i| \cos(\theta_{ij} - \delta_i + \delta_j) \quad j \neq i \tag{3.14}
$$

The diagonal and the off-diagonal elements of J_3 are

$$\frac{\partial Q_i}{\partial \delta_i} = \sum_{j \neq i}^{n} |Y_{ij}||V_i||V_j| \cos(\theta_{ij} - \delta_i + \delta_j) \tag{3.15}$$

$$\frac{\partial Q_i}{\partial \delta_j} = -|Y_{ij}||V_i||V_j| \cos(\theta_{ij} - \delta_i + \delta_j) \quad j \neq i \tag{3.16}$$

The diagonal and off-diagonal elements of J_4 are

$$\frac{\partial Q_i}{\partial |V_i|} = -2|Y_{ii}||V_i| \sin(\theta_{ii}) - \sum_{j \neq i}^{n} |Y_{ij}||V_j| \sin(\theta_{ij} - \delta_i + \delta_j) \tag{3.17}$$

$$\frac{\partial Q_i}{\partial |V_j|} = -|Y_{ij}||V_i| \sin(\theta_{ij} - \delta_i + \delta_j) \quad j \neq i \tag{3.18}$$

$\Delta P_i^{(k)}$ And what is the difference between the scheduled and calculated values, known as power residuals or power mismatch, which is given by

$$\Delta P_i^{(k)} = P_i^{(sch)} - P_i^{(k)} \tag{3.19}$$

$$\Delta Q_i^{(k)} = Q_i^{(sch)} - Q_i^{(k)} \tag{3.20}$$

The new estimates for bus voltages are

$$\delta_i^{(k+1)} = \delta^{(k)} + \Delta \delta_i^{(k)} \tag{3.21}$$

$$|V_i^{(k+1)}| = |V_i^{(k)}| + \Delta |V_i^{(k)}| \tag{3.22}$$

Where,

$\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$ = difference in calculated and scheduled values.

$P_i{}^{sch}$ and $Q_i{}^{sch}$ are scheduled real and reactive power at bus i.

$P_i{}^{(k)}$ and $Q_i{}^{(k)}$ = calculated real and reactive power at bus i.

$\delta_i{}^{(k)}$ = calculated angle.

$\Delta\delta_i{}^{(k)}$ = change in calculated angle.

$|V_i{}^{(k+1)}|$ = the difference between the voltage value at bus i.

$|V_i{}^{(k)}|$ = most recently voltage bus value.

K and (k+1) denote previous and next iteration respectively and process is repeated until a stopping condition is met.

The process keeps repeating until the power residuals reach an acceptable level until then, it won't stop, even if it's taking a while. When using AC power flow analysis to examine each contingency scenario, two things matter most: how many scenarios there are and how fast you can get results. It's important to remember that contingency alerts are practically useless if they come too late for operators to actually do something about them.

As shown in Figure 3.2, the most straightforward way to run an AC security analysis is by carrying out a full AC power flow study for every possible failure whether it's a transformer, transmission line, or generator going out. This method is very accurate and can clearly flag overloads or voltage issues within the defined limits.

But there's a big downside time. Running this kind of analysis takes a lot of it. If you're dealing with thousands of potential outages, the time needed to process all of them could be way too long to be practical.

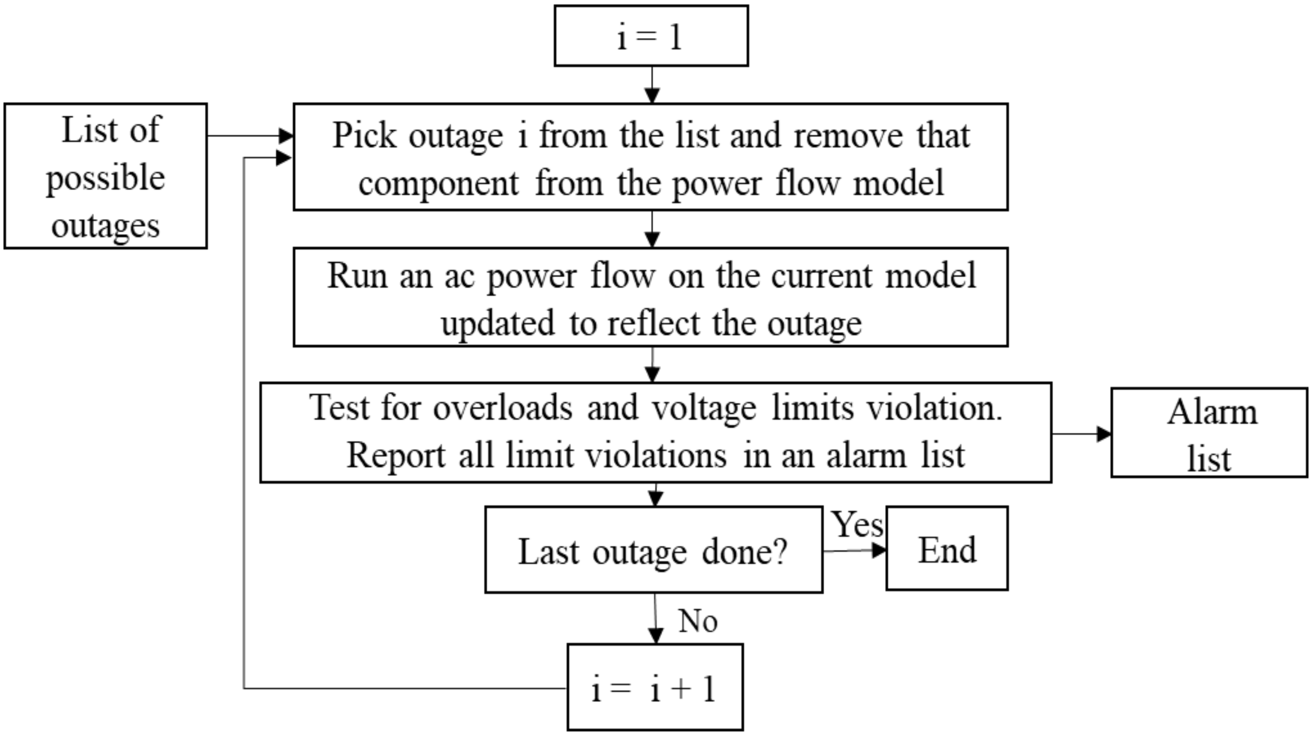


Figure 3.4: General AC Power Flow for Contingency Analysis flow chart.

Power Flow Algorithm of Newton-Raphson

This section presents the Newton-Raphson load flow solution procedure, while the flowchart is depicted in Figure 3-5.

- For load buses, the voltage magnitudes and angles are set equal to 1.0 and 0.0.
- Equation (3-7) and (3-8) compute $Pi^{(k)}$ and $Qi^{(k)}$ for load buses and Equation (3- 19) and (3-20) compute $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$.
- Equation (3-7) and (3-19) compute $P_i^{(k)}$ and $\Delta P_i^{(k)}$ for voltage controlled-buses.
- Calculate the Jacobian matrix elements J1, J_2, J_3, and J_4.
- The simultaneous Equation (3-7) is solved using triangular factorization and Gaussian elimination methods.
- Equation (3-21) and (3-22) calculate the updated voltage values and angles from.
- The process continues till the $\Delta Q_i^{(k)}$ and $\Delta P_i^{(k)}$ are smaller than the tolerance.

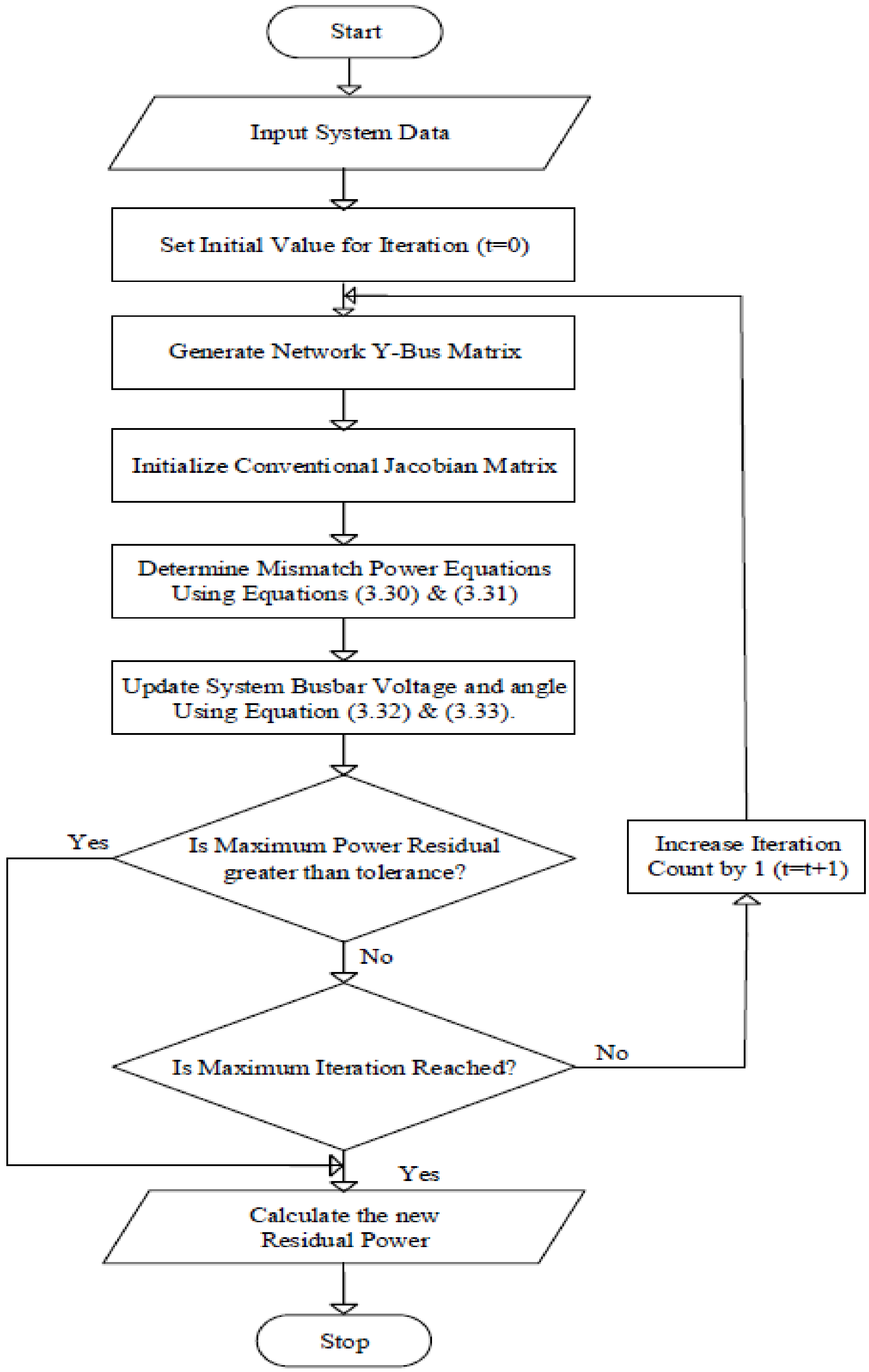


Figure 3.5: Newton Raphson Load Flow

Approximate Method

Using an approximate model of the power system is one way to increase the speed of solution in a contingency analysis procedure, as the AC load flow method's speed is limited by its longer computation time. The application of DC load flow models offers sufficient capability for a large number of systems. In these systems, the DC load flow offers adequate accuracy in relation to the megawatt flows, and the voltage magnitudes might not be a major concern. Full AC load flow analysis is necessary for other systems where voltage is an issue. When thousands of cases need to be reviewed, this becomes extremely challenging.

Using network linear sensitivity factors is one of the easiest ways to quickly calculate potential overloads. These variables can be computed from the DC load flow and provide an approximate change in line flows for variations in system generation. According to John J. Grainger and W. D. Stevenson (1994), they primarily fall into two categories: generation shift factor and line outage distribution factor.

Generation shift factors**:**

The generation shift factors, $\alpha_{li,}$ are defined as:

$$a_{li} = \frac{\Delta f_l}{\Delta P_{Gi}} \tag{3.23}$$

Where, Δf_l is a change in megawatt power flow on line l when a change in generation ΔP_{Gi} occur at bus i, ΔP_{Gi} is the change in the generation at bus i. It is assumed that ΔP_{Gi} is fully compensated by an equal and opposite change in generation at the slack bus, with all other generators remaining fixed at their original power generations. The factor a_{li} then gives the sensitivity of the lth line flow to a change in generation at the ith bus. Let us now study the outage of a large generating unit and assume that all the lost generation $-P_{Gi}^{o}$ would be supplied by the slack bus generation.

$$\Delta P_{Gi} = -P_{Gi}^{o} \tag{3.24}$$

Then, and the new power flow on each line could be calculated using a pre calculated set of 'α' factors as given below.

$$f_l = f_l^o + \alpha_{li} \Delta P_{Gi} \text{ , for all lines} \quad (3.25)$$

Where, f_l is the power flow on the lth line after the failure of i^{th} generator, f_l^o is power flow on l^{th} line before the failure. Values of line flow can be compared to their limits, and those that are higher can be reported to the operator so that the proper control measures can be implemented. The generation shift sensitivity factors are linear estimates of the change in line flow with a change in power at a bus. Consequently, the effects of concurrent changes on a given number of generating buses can be computed using the superposition principle.

Line outage distribution factors

Similarly, the line outage distribution factors can be used to check if the line overloads when some of the lines are lost. The line outage distribution factor is defined as:

$$d_{l,k} = \frac{\Delta f_l}{f_k^o} \quad (3.26)$$

Where, $d_{l,k}$ is the line outage distribution factor when monitoring the l^{th} line after an outage of the k^{th} line, Δf_l is the change in MW flow on l^{th} line, f_k^o is the pre-outage line flow on k^{th} line. If pre-outage line flows on lines l and k, the power flow on line l with line k out can be found by employing 'd' factors.

$$f_l = f_l^o + d_{l,k} f_k^o \quad (3.27)$$

Where, f_l^o and f_k^o pre-outage flows on lines l and k, respectively, f_l is power flow on l^{th} line with k^{th} line outage. As a result, by pre-calculating "d" factors for each line, it is possible to quickly check for overloading in the event of a specific line outage. One by one, this can be done for each line outage, and by comparing $f_{l\max}$, overloads can be identified so that corrective action can be taken.

3.3.4 Power System Contingency Selection Based on Performance Indices

It's true that not every situation has the potential to violate operating limits. Consequently, it is necessary to carefully choose and research the situations that have the potential to result in operating limit violations. To determine the level of a network's security, a number of techniques have been employed in the past. They are ranked according to the performance index (PI), which determines the severity of each case by calculating its PI value. The screening method is an additional contingency ranking algorithm. To remove those non-critical contingencies, this specific approach relies on approximate load flow solutions. Indices of system performance are not unique and take different forms. The most common form of system PI gives a measure of the deviation from rated values of system variables such as power flows, bus voltage.

The performance indices used in this thesis is voltage power performance index (PIv) which shows the relative severity of the outage in terms of bus voltage limit violation. The other performance index used in this thesis is line flow performance index (PI_{MVA}) which shows the relative severity of the outage in terms of overloading effect on the rest of the system components.

Voltage power performance index (PIv): This index shows the relative severity of the outage in terms of bus voltage limit violation and is given as:

$$PI_V = \sum_{i=1}^{n}\left[\left(\frac{W}{2z}\right)\left(\frac{\left(|V_i| - |V_i^{sp}|\right)}{\Delta V_i^{\lim}}\right)^{2z}\right] \tag{3.28}$$

Where, $|V_i|$ is the voltage magnitude at bus i, $|V_i^{sp}|$ is the specified voltage magnitude at bus i, $\Delta V_i^{\lim}$ is the voltage deviation limit, z is exponent of the penalty function, n is the number of buses in the given power system, W is the real non negative weighting factor. In some software divide the result by number of buses.

Line flow performance index (PI_{MVA}): which shows the relative severity of the outage in terms of overloading effect on the rest of the system components given as:

$$PI_{MVA} = \sum_{i=1}^{N_L} \left[\left(\frac{W_{Li}}{M} \right) \left(\frac{S_i^{post}}{S_i^{\max}} \right)^M \right] \tag{3.29}$$

Where, S_i^{post} is the post contingency MVA flow of line i, S_i^{max} is the MVA rating of the line i, N_L is the number of lines in the system, W_{Li} is the real non-negative weighting factor, M=2n is the order of the exponent for the penalty function. Performance indices are a number and have no unit. Therefore, we can add different indices. PI can be ordered from the largest value to the least, then the top severe candidate can be chosen for further analysis.

3.4 Functions of D-FACTS Devices in Power Systems

D-FACTS (Distributed Flexible AC Transmission System) devices are a class of power electronics-based controllers used to improve power flow control, system stability, and transmission efficiency in power systems. They are part of the broader family of FACTS (Flexible AC Transmission Systems), but with a distributed and modular design, making them more flexible and cost-effective in certain applications. D-FACTS devices are crucial in contingency analysis because they allow for proactive mitigation of power system issues caused by outages or other disturbances, enhancing system security and reliability. They offer flexible control over power flow, voltage, and other parameters, enabling operators to maintain stability and prevent cascading failures. A transmission line failure might cause a surge in power flow on nearby lines. D-FACTS devices strategically placed on those lines can help manage the flow, preventing them from overloading and causing further issues. The main functions of D-FACTS are as follows:

Real-Time Power Flow Control: - The main function of the D-FACTS device is to adjust the impedance of a transmission line in real-time. By dynamically changing line reactance, D-FACTS devices redistribute power flow across parallel transmission lines and helps to relieve overloaded lines and maximize system capacity.

Congestion Management: - D-FACTS can alleviate transmission congestion by diverting power flows away from heavily loaded lines. This improves the system's ability to carry more power without costly infrastructure upgrades.

Enhanced Voltage Stability: - Some D-FACTS devices can support voltage regulation by injecting or absorbing reactive power locally. This stabilizes voltage profiles, especially under varying load or contingency conditions.

Improved System Reliability: - D-FACTS help to mitigate the impact of line outages or other disturbances by rerouting power flow intelligently. Accordingly, it enhances the system's ability to withstand contingencies (N-1 or N-2 reliability).

Increased Transmission Efficiency: - By optimizing power flow paths, D-FACTS reduce transmission losses and improves overall system efficiency. They also allow better utilization of existing infrastructure without the need for new lines.

Support for Renewable Integration: - Helps to manage variability and uncertainty associated with renewable energy sources, enables flexible and dynamic re-routing of power to accommodate fluctuating generation.

3.5 Artificial Neural Network for PI prediction

Artificial Neural Network Basics

Artificial Neural Networks (ANNs) are computational models inspired by the structure and function of the human brain, where interconnected nodes simulate neurons and their synaptic interactions. During training, the network adjusts its connection weights through repeated exposure to input-output pairs, gradually learning to produce desired outputs, much like how the brain learns from experience. ANNs operate as parallel, distributed systems capable of modeling intricate and nonlinear relationships between input features and output responses. They have shown outstanding performance across various domains, particularly in tasks such as classification, prediction, and function approximation.

The Architecture of a Neuron: Neurons serve as the fundamental processing elements in an artificial neural network, characterized by their nonlinear behavior. A basic mathematical model of a neuron, illustrating its simplified structure and function, is depicted in Figure 5.1.

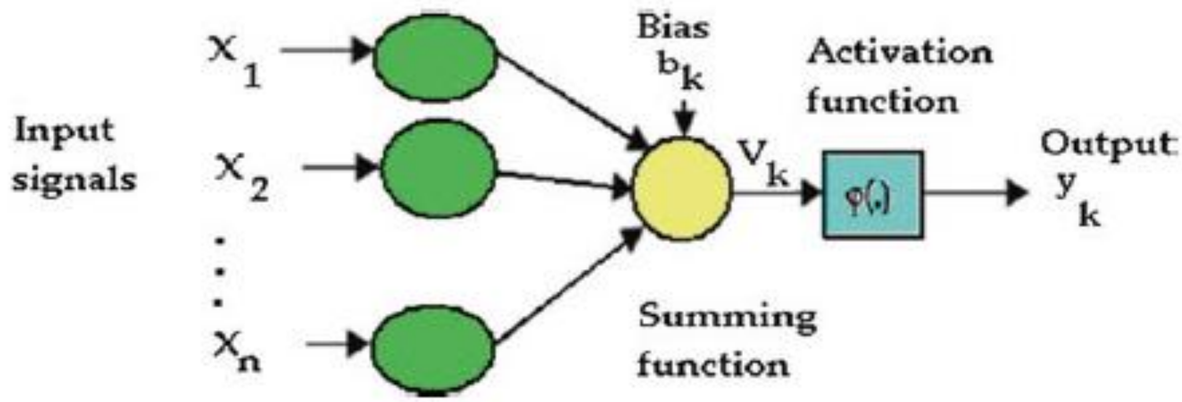


Figure 3.6: Simplified mathematical representation of a neuron

A neuron in an artificial neural network is composed of several key elements that enable it to process information effectively. Synapses serve as the connecting pathways between neurons, each carrying a specific weight that determines the strength of the connection. The summing function aggregates all the weighted inputs received via these synapses. The activation function then processes this aggregated input to produce the neuron's output, with various types such as threshold, linear, sigmoid, logistic, hyperbolic tangent, and radial basis functions, depending on the application. Additionally, a bias term is included to adjust the net input, helping the model learn more effectively by shifting the activation function's threshold. Collectively, these elements form the foundational structure of a neuron, and in a broader sense, contribute to the eight core components commonly found in artificial neural networks.

In its simplest form, a Radial Basis Function (RBF) network is a feedforward neural model with three layers. The input features are represented by the first layer, the hidden layer is made up of neurons that are activated by radial basis functions, and the final output is generated by the third layer based on the hidden layer's responses.

The architecture of the RBF neural network is shown in Figure 3.6, which can be considered as a mapping $R^r \rightarrow R^s$

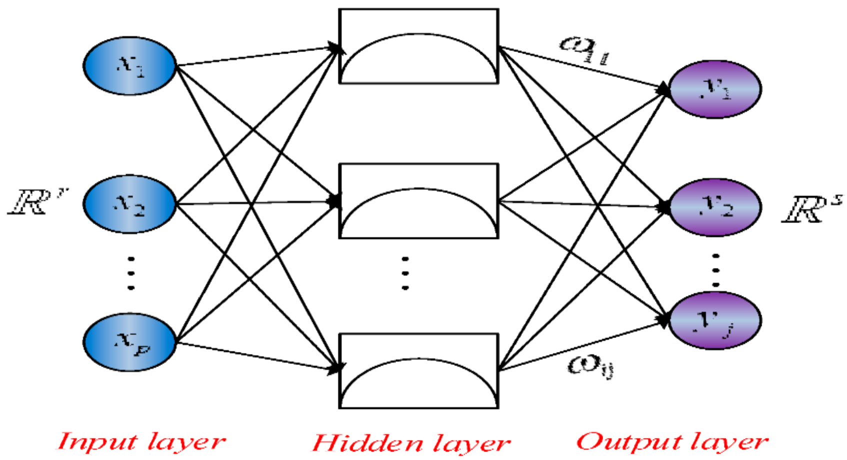


Figure 3. 7: The architecture of the RBF neural network

Every input in the network is connected to every neuron in the hidden layer, which uses a radial basis function most commonly the Gaussian function as the activation mechanism. The Gaussian function is a popular choice due to its smooth and localized response properties, as the norm is usually determined using the Euclidean distance. As one gets farther away from the radial basis function center, the level of neuronal activation diminishes. Let $x_p \in Rr$ be the input vectors; the radial basis function is given by:

$$R\left(x_p - c_i\right) = \exp\left(-\frac{1}{2\sigma^2}\left\|x_p - c_i\right\|^2\right) \qquad (3.30)$$

Where, P is the total number of samples, $x_p = (x_1^p, x_2^p, ..., x_m^p)^T$ is pth input sample; $\left\|x_p - c_i\right\|$ represents Euclidean norm; c_i is the center of the Gaussian function, σ is the width (spread) of the Gaussian function. Then the output of the network is denoted as:

$$y_j = \sum_{i=1}^{h} \omega_{ij} \exp\left(-\frac{1}{2\sigma^2}\left\|x_p - c_i\right\|^2\right), j = 1, 2, \ldots, n. \qquad (3.31)$$

Where, ω_{ij} is the link weight from the hidden layer to the output layer; i = 1, 2, 3,…, h is the number of neurons in the hidden layer; y_j is the network's actual output of the j^{th} node corresponding to the input sample.

Once the architecture of the Artificial Neural Network (ANN) is chosen, the next step is to define what goes into the network (inputs) and what we want it to predict (outputs or targets). In this case, we're using a Radial Basis Function Neural Network (RBFNN), as discussed earlier. Now it's time to decide on the input features and target values. The inputs are the features we feed into the neural network so it can learn to predict the correct output—in this case, the severity or performance index (PIv) of buses under a specific loading condition. So, the output or target we want the network to predict is the voltage performance index (PIv).

This prediction is based on the power system's state before any outage happens. That pre-outage state can be described using variables like bus voltages, power injections at buses, and line power flows. However, using all of these variables as inputs would make the network too complex and harder to train effectively. That's because, as the number of input features grows, the number of basis functions in the hidden layer also grows—often exponentially—which can lead to poor performance.

To keep things efficient, only selected variables are used as inputs: voltage (V), real power injection (P), and reactive power injection (Q) from chosen buses. These form the input vector X for the RBFNN. This relationship can be expressed as:

$$X_{input} = [V_1, P_1, Q_1, \ldots..V_N, P_N, Q_N]$$

$$Y_{output} = [PIv]$$

Where, N is a number of buses, and PIv is voltage performance index of the buses.

CHAPTER FOUR

4. SIMULATION RESULTS AND DISCUSSIONS

4.1. Contingency Analysis and Simulation Results

All of the service's components should be operational in the base case, which is when the power system is operating normally and steadily. Every substation load has power, and the transmission line, transformers, and generators, all components of the power system, are operational.

4.2. Single Line Diagram and Assumptions

Several assumptions were made to simplify the complex single-line diagram into a more manageable and clear representation of a 230kV grid. This simplification was necessary due to the software's limitation, which only allows for about 13 bus bars. As a result, the 230kV transmission grid was chosen, even though not all 230kV bus bars are utilized, as there are around twenty available. To meet the 13-bus bar limitation, a mechanism was employed to shift serial bus bars to other locations.

Parameters of the System

- ► Nominal Voltage Level: 230 kV (line-to-line RMS)
- ► System Frequency: 50 Hz
- ► Voltage Limits: ±5% to ±10% (acceptable operating voltage: ~218.5 kV to 241.5 kV)
- ► Line Model: Pi model for long lines (above 80 km), with R, X, and shunt capacitance
- ► Transformer Ratings: Typically 230/132 kV and 230/15 kV, with impedance ~8–15%
- ► Load Modeling: Static ZIP model or constant power
- ► Generator Modeling: Voltage-controlled buses (PV) or slack bus for large hydropower stations

Apart from the 230kV transmission grid, the rest of the system is considered a load to be supplied by the 230kV network, and the single line diagram is drawn in Figure 4.1.

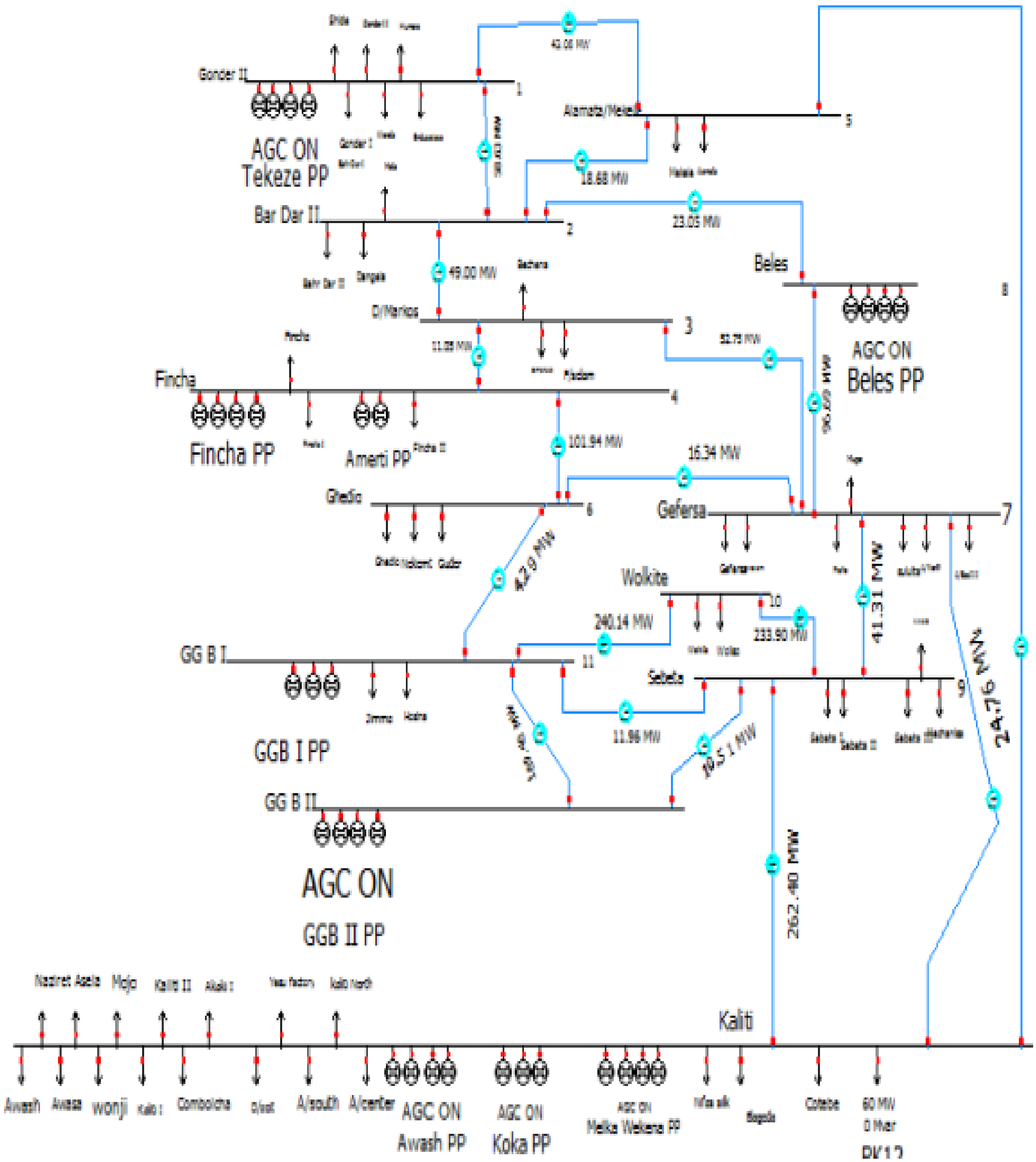


Figure 4. 1: Single line diagram of 230KV grid

4.3. Case Studies Analysis

The case has been conducted on different line outages and carried out using power world simulator software. The study considered five cases for further investigation of the line outage effect analysis. The case study is comprised in to five cases as shown the following in which the simulation is done independently.

Case 1: Base case (without contingency)

Case 2: Line outage of Gefersa to D/Markos

Case 3: Line outage of Sebeta to Gefersa

Case 4: Line outage of Wolkite to Sebeta

Case 5: With Insertion of D-FACTS

Case 1: Base Case Contingency Analysis and Simulation Results

As per the collected data from the Dispatch Center, most of the time, an outage of a single transmission line on the network has effects on others. The simulation is shown in Figure 4.2.

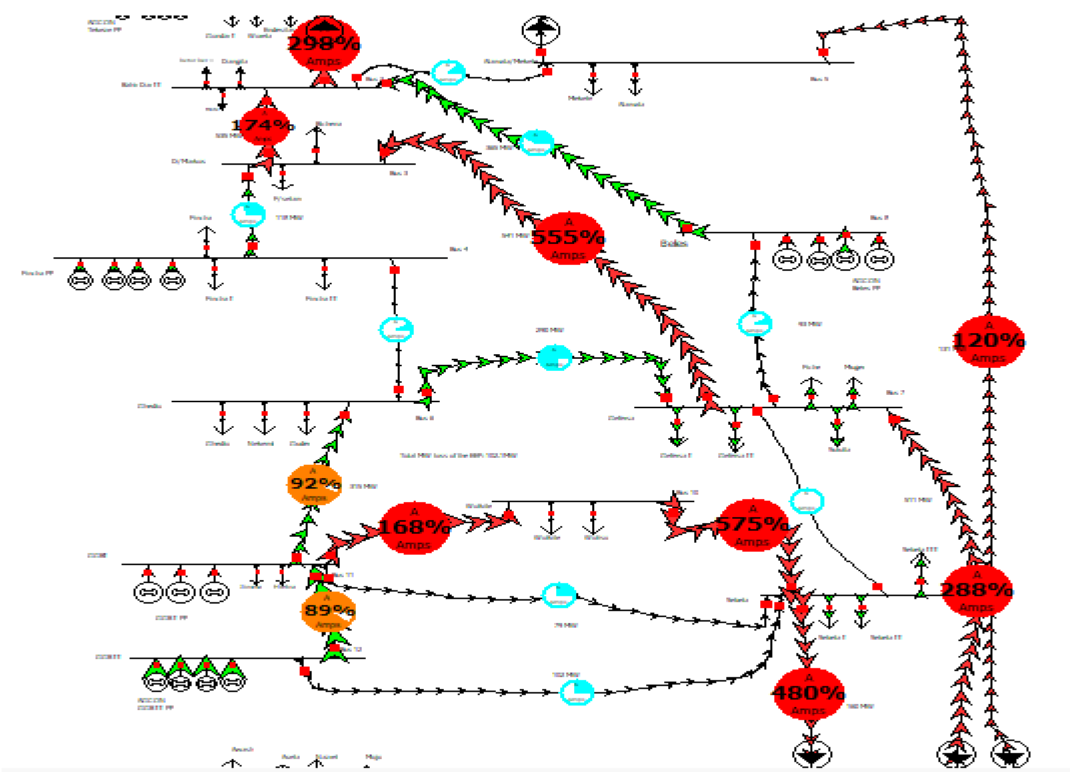


Figure 4. 2: Base case simulations of EEP 230KV Existing Grid network

As indicated from the simulation most of the transmission lines are working on overloading which will lead the network to a partial blackout. The lines are even overloaded (red colors) under normal condition as shown in the Figure 4.2 above.

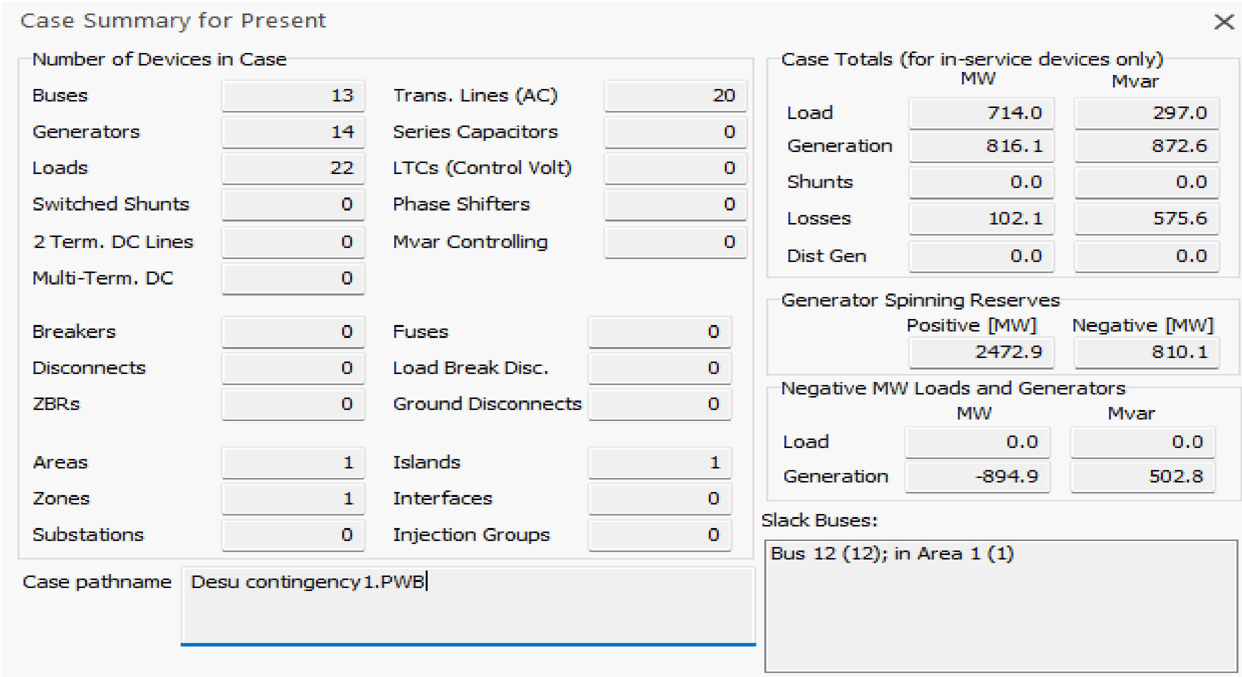


Figure 4. 3: Simulation result of total loss under base case condition

Figure 4.3 shows the EEP 230KV Existing Grid network base case simulations. In the base case, the system's actual power load is 102.1 MW, and its generators provide 816.1 MW of active power. The base case simulation has been run, and Figure 4.3 displays the simulation's outcome. Using Power World Simulator's run mode, the load flow analysis is performed to ascertain the bus voltage, real and reactive power flow, and line losses. The Power World simulator's base-case bus voltage results are shown in Table 4.1.

Table 4. 1: Bus voltage record of the network under base case simulation

Bus number	Name	V (p.u)
1	Gondar II	0.685
2	Bahir Dar II	0.6851
3	D/Markos	0.9597
4	Fincha	1.00
5	Alamata/Mekele	0.7304
6	Ghedio	0.9890
7	Gefersa	0.9833
8	Beles	1.00
9	Sebeta	0.9858
10	Wolkite	0.9892
11	GGB I	1.00
12	GGB II	1.00
13	Kaliti	1.00

Case 2: Simulation Result for Line Outage of Gefersa to D/Markos

In this scenario, contingency analysis is carried out for the line outage between Gefersa and D/Markos. During the event, the total line losses, voltage profile, and line loading conditions are recorded for evaluation.

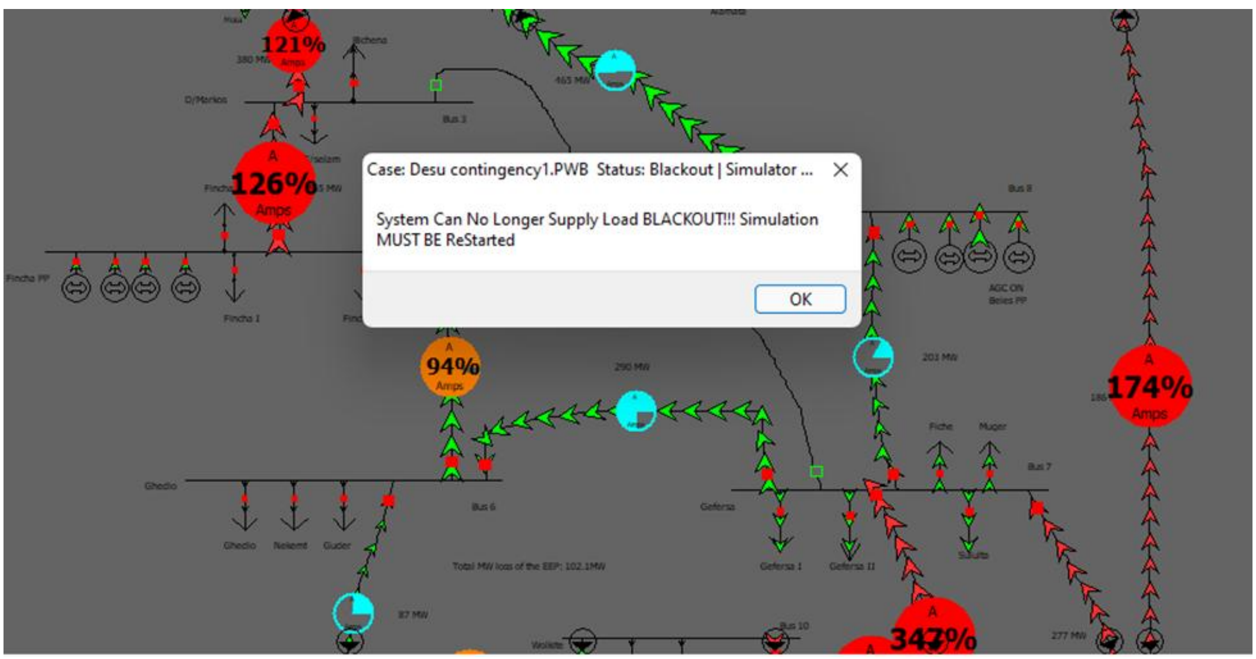


Figure 4. 4: Simulation Result during the Outage of the Gefersa to D/Markos Line

As shown in Figure 4.4, the line between Gefersa and D/Markos was disconnected from the system due to the operation of protective devices such as relays and circuit breakers. This disconnection triggered a cascading outage, which ultimately lead to a total system blackout.

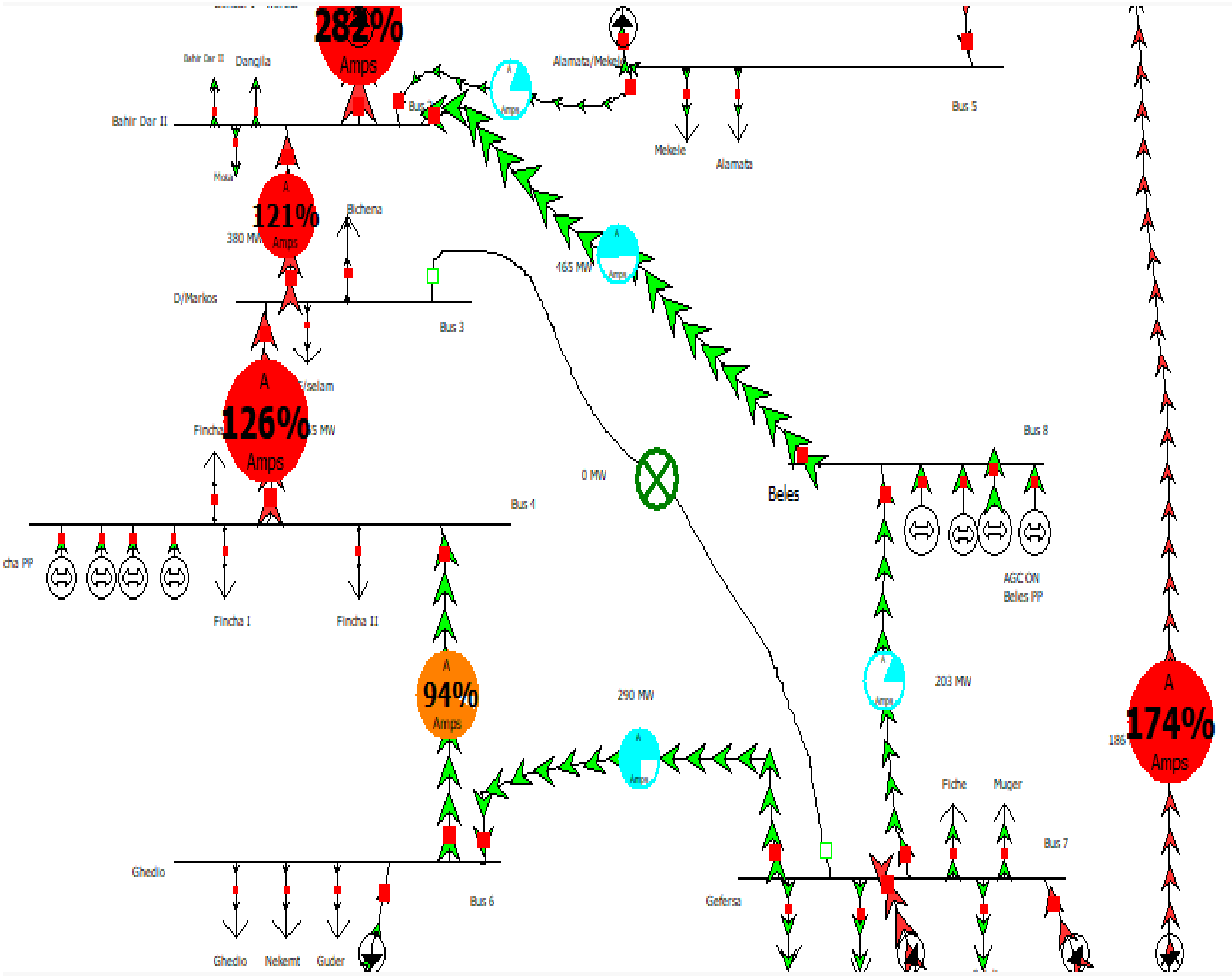


Figure 4. 5: Simulation result during the line outage of Gefersa to D/Markos

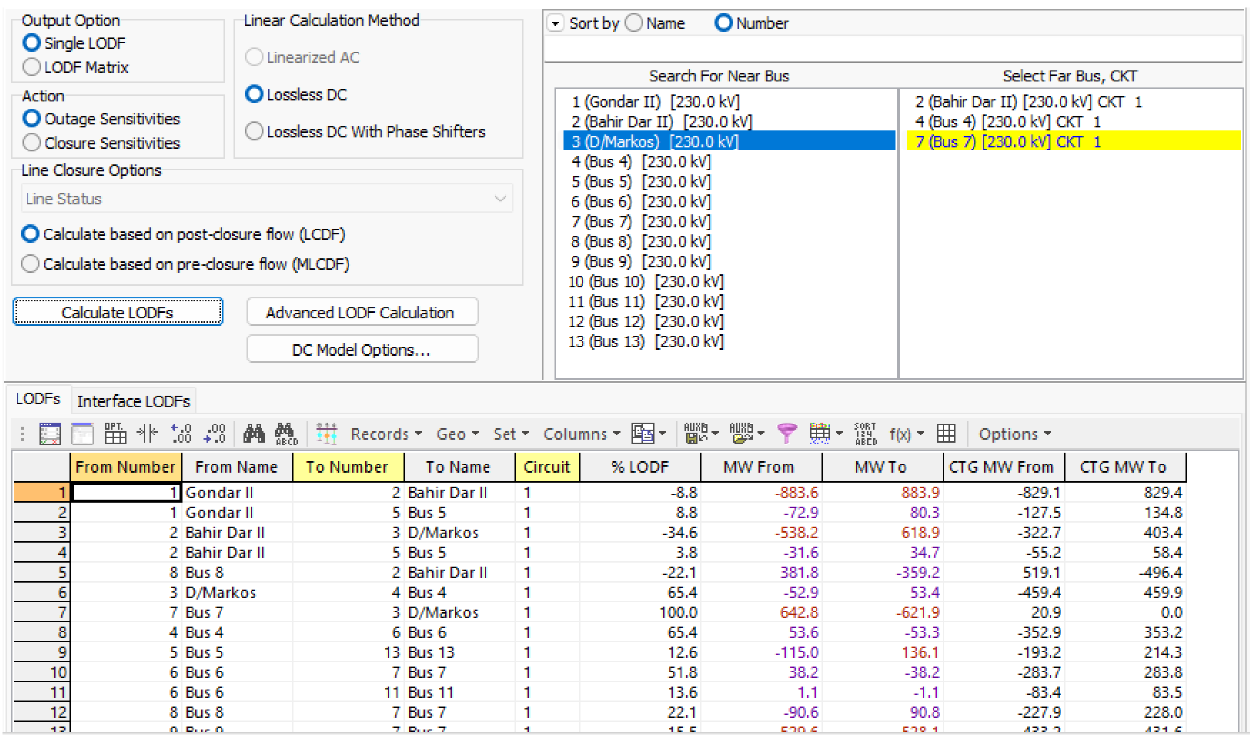
The blackout of the Gefersa to D/Markos line results in severe overloading of the Bahir Dar II to Gondar II line and the Sebeta to Alamata line, with loading levels reaching 282% and 174%, respectively, as illustrated in Figure 4.5. This indicates that both lines enter emergency and alert conditions due to operating well beyond their rated capacity.

As indicated in Table 4.2, the voltage profile was recorded after the outage of the Gefersa to D/Markos transmission line.

Table 4. 2: Voltage Profile Following Contingency (Gefersa to D/Markos Line Outage)

	Number	Name	Area Name	Monitor	Limit Group	PU Volt	Volt (kV)
1	5	Bus 5	1	YES	Default	0.72516	166.786
2	1	Gondar II	1	YES	Default	0.76772	176.575
3	2	Bahir Dar II	1	YES	Default	0.76772	176.576
4	3	D/Markos	1	YES	Default	0.85791	197.320
5	6	Bus 6	1	YES	Default	0.98425	226.377
6	7	Bus 7	1	YES	Default	0.98851	227.358
7	9	Bus 9	1	YES	Default	0.99043	227.800
8	10	Bus 10	1	YES	Default	0.99294	228.377
9	12	Bus 12	1	YES	Default	1.00000	230.000
10	11	Bus 11	1	YES	Default	1.00000	230.000
11	13	Bus 13	1	YES	Default	1.00001	230.002
12	8	Bus 8	1	YES	Default	1.00104	230.238
13	4	Bus 4	1	YES	Default	1.00326	230.749

Table 4. 3: LODF for line outage



	From Number	From Name	To Number	To Name	Circuit	% LODF	MW From	MW To	CTG MW From	CTG MW To
1	1	Gondar II	2	Bahir Dar II	1	-8.8	-883.6	883.9	-829.1	829.4
2	1	Gondar II	5	Bus 5	1	8.8	-72.9	80.3	-127.5	134.8
3	2	Bahir Dar II	3	D/Markos	1	-34.6	-538.2	618.9	-322.7	403.4
4	2	Bahir Dar II	5	Bus 5	1	3.8	-31.6	34.7	-55.2	58.4
5	8	Bus 8	2	Bahir Dar II	1	-22.1	381.8	-359.2	519.1	-496.4
6	3	D/Markos	4	Bus 4	1	65.4	-52.9	53.4	-459.4	459.9
7	7	Bus 7	3	D/Markos	1	100.0	642.8	-621.9	20.9	0.0
8	4	Bus 4	6	Bus 6	1	65.4	53.6	-53.3	-352.9	353.2
9	5	Bus 5	13	Bus 13	1	12.6	-115.0	136.1	-193.2	214.3
10	6	Bus 6	7	Bus 7	1	51.8	38.2	-38.2	-283.7	283.8
11	6	Bus 6	11	Bus 11	1	13.6	1.1	-1.1	-83.4	83.5
12	8	Bus 8	7	Bus 7	1	22.1	-90.6	90.8	-227.9	228.0

Case 3: Simulation Result for Line Outage of Sebeta to Gefersa

In this scenario, the contingency analysis is carried out for the line outage between Sebeta and Gefersa. During the event, the total line losses, voltage profile, and line loading conditions are recorded for evaluation. The outage of the Sebeta to Gefersa line results in severe overloading of Wolkite to Sebeta line, with loading levels reaching 575% as illustrated in Figure 4.6. This indicates that the line enters emergency and alert conditions due to operating well beyond its rated capacity.

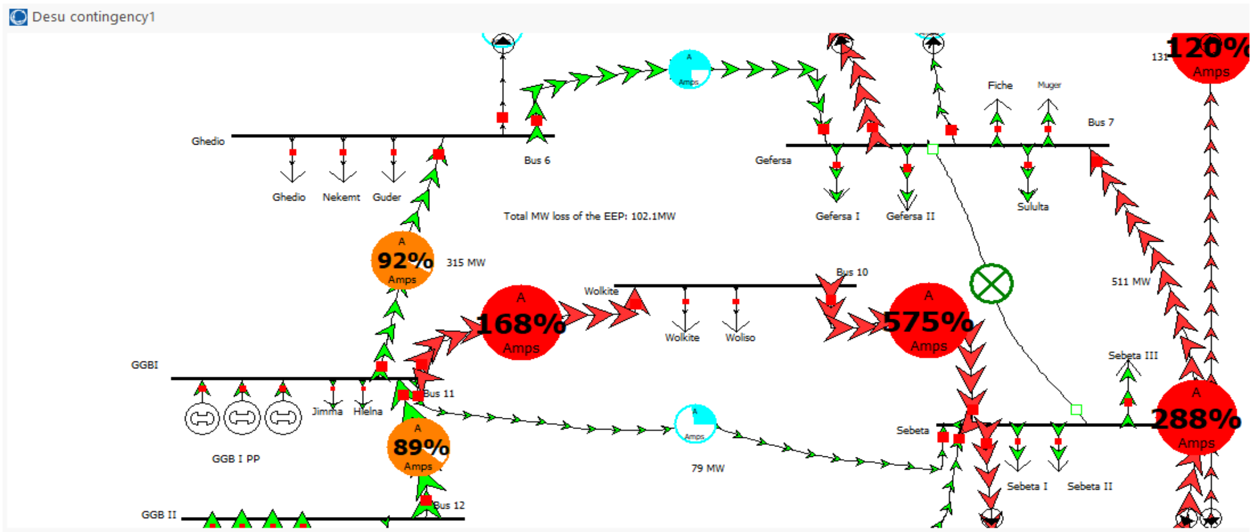


Figure 4. 6: Simulation result during line outage of Sebeta to Gefersa

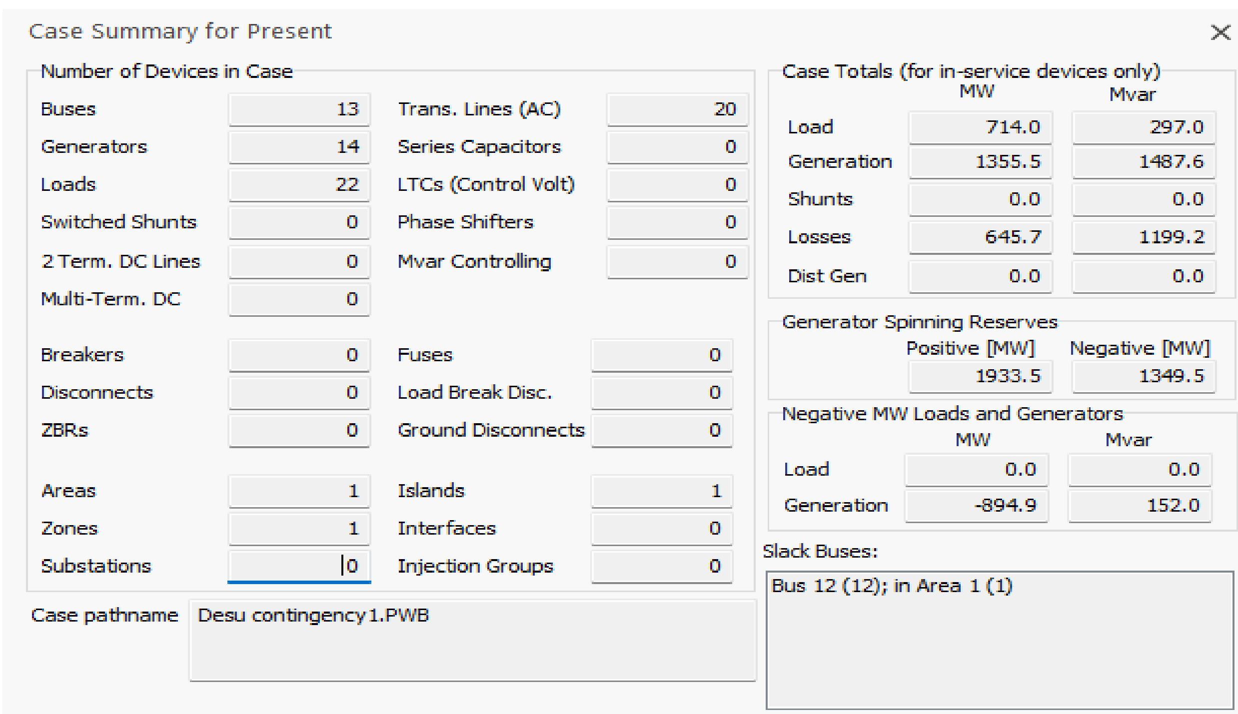


Figure 4. 7: Simulation result of total loss under Line outage of Sebeta to Gefersa

In this scenario, the total line loss is 645.7 MW, while the generators collectively supply 1355.5 MW of active power. The simulation for Case 3, involving the outage of the Sebeta to Gefersa line, is presented in Figure 4.7. Load flow analysis was performed using the run mode of Power World Simulator to assess bus voltages, real and reactive power flows, and line losses under this contingency condition. The Table 4.4 is the result of bus voltages at for case 3 which is record of in Power World simulator.

Table 4. 4: Voltage Profile Following Contingency (Sebeta to Gefersa to Line Outage)

Number	Name	Area Name	Monitor	Limit Group	PU Volt
1	Gondar II	1	YES	Default	0.75189
2	Bahir Dar II	1	YES	Default	0.75200
5	Bus 5	1	YES	Default	0.78571
3	D/Markos	1	YES	Default	0.95107
6	Bus 6	1	YES	Default	0.96551
7	Bus 7	1	YES	Default	0.97168
4	Bus 4	1	YES	Default	0.98344
12	Bus 12	1	YES	Default	1.00000
11	Bus 11	1	YES	Default	1.00000
13	Bus 13	1	YES	Default	1.00046
9	Bus 9	1	YES	Default	1.00408
10	Bus 10	1	YES	Default	1.00500
8	Bus 8	1	YES	Default	1.03252

Case 4: Simulation Result for Line Outage of Wolkite to Sebeta

In this scenario of case 4, the contingency analysis is carried out for the line outage between Wolkite and Sebeta. During the event, the total line losses, voltage profile, and line loading conditions are recorded for evaluation. The outage of the Wolkite to Sebeta line results in severe overloading of Sebeta to Gefersa line, with loading levels reaching 455% as illustrated in Figure 4.8. The other lines also exposed to overloading due to this line outage. This indicates that the line enters emergency and alert conditions due to operating well beyond its rated capacity.

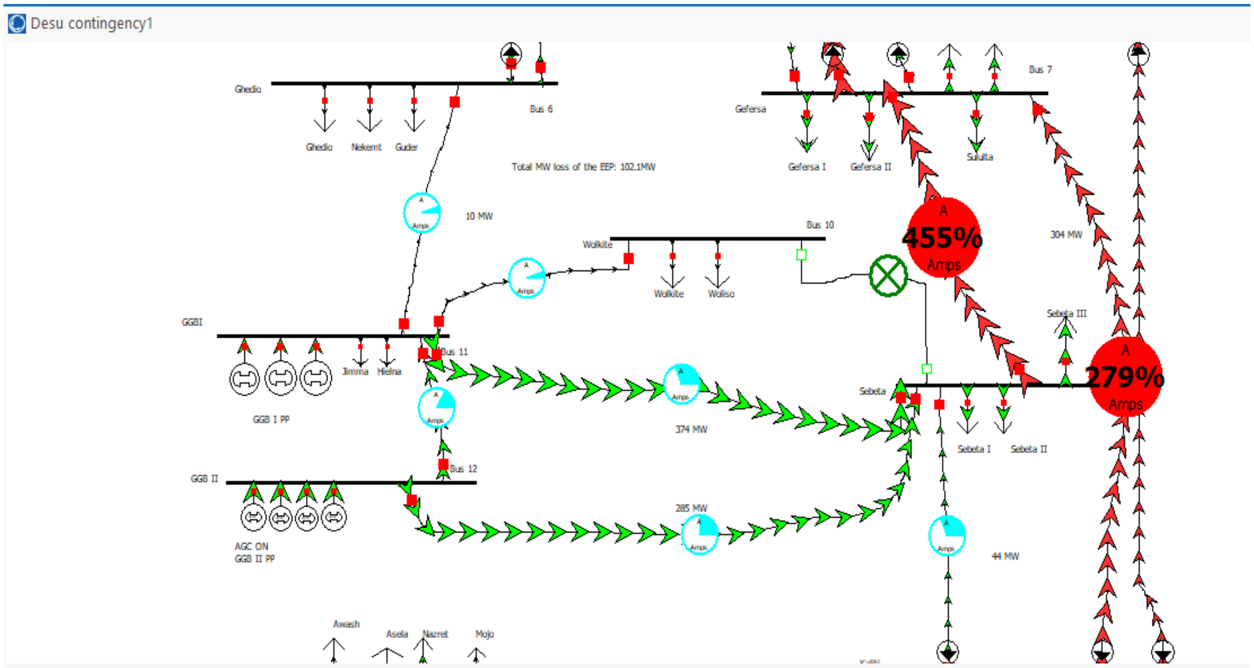


Figure 4. 8: Simulation result during line outage of Wolkite to Sebeta

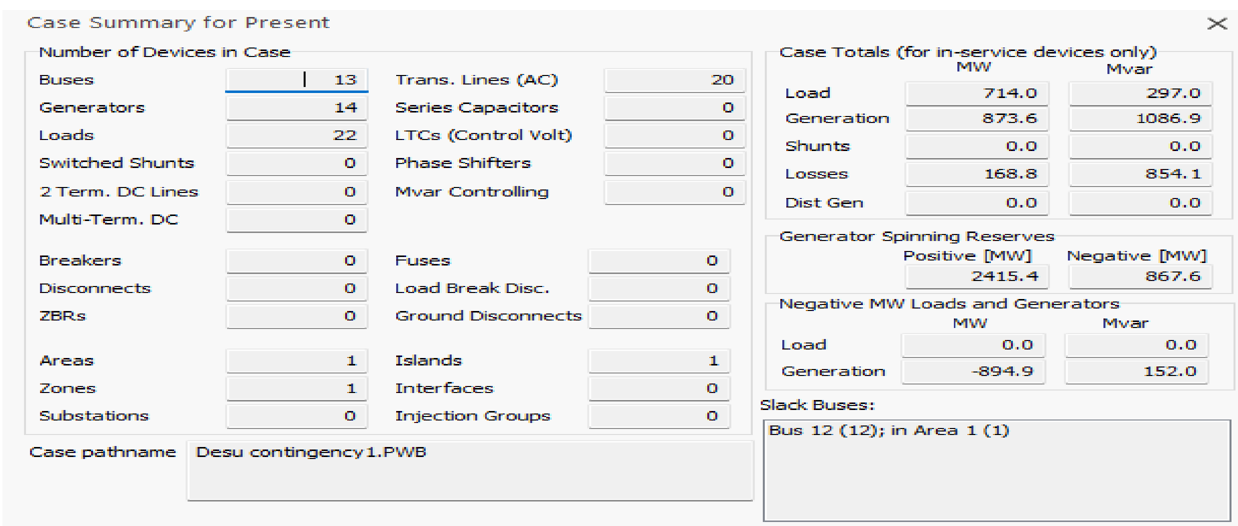


Figure 4. 9: Simulation result of total loss under Line outage of Wolkite to Sebeta

In this scenario, the total line loss amounts to 168.8 MW, with generators supplying a total of 873.6 MW of active power. Case 4 examines the outage of the Wolkite to Sebeta line, and the corresponding simulation results are shown in Figure 4.9. Load flow analysis was conducted using the run mode of Power World Simulator to evaluate bus voltages, real and reactive power flows, and line losses under this contingency. Table 4.5 presents the recorded bus voltage values for Case 4, as obtained from Power World Simulator.

Table 4. 5: Voltage Profile following Contingency (Wolkite to Sebeta Line Outage)

Number	Name	Area Name	Monitor	Limit Group	PU Volt	Volt (kV)	Limit Low PU Volt	Limit High PU Volt	Contingency Limit Low PU Volt	Contingency Limit High PU Volt
1	Gondar II	1	YES	Default	0.75156	172.860	0.90	1.10	0.90	1.10
2	Bahir Dar II	1	YES	Default	0.75163	172.874	0.90	1.10	0.90	1.10
3	D/Markos	1	YES	Default	0.95273	219.127	0.90	1.10	0.90	1.10
4	Bus 4	1	YES	Default	0.98851	227.357	0.90	1.10	0.90	1.10
5	Bus 5	1	YES	Default	0.78507	180.567	0.90	1.10	0.90	1.10
6	Bus 6	1	YES	Default	0.98136	225.713	0.90	1.10	0.90	1.10
7	Bus 7	1	YES	Default	0.97568	224.407	0.90	1.10	0.90	1.10
8	Bus 8	1	YES	Default	0.94883	218.231	0.90	1.10	0.90	1.10
9	Bus 9	1	YES	Default	0.97799	224.937	0.90	1.10	0.90	1.10
10	Bus 10	1	YES	Default	0.99964	229.916	0.90	1.10	0.90	1.10
11	Bus 11	1	YES	Default	1.00000	230.000	0.90	1.10	0.90	1.10
12	Bus 12	1	YES	Default	1.00000	230.000	0.90	1.10	0.90	1.10
13	Bus 13	1	YES	Default	1.00002	230.005	0.90	1.10	0.90	1.10

Case 5: Voltage Profile Improvement by Insertion of Using D-FACTS

D-FACTS (Distributed Flexible AC Transmission Systems) are power electronic devices installed directly on transmission lines to dynamically control and optimize power flow, improve voltage stability, and reduce losses offering a cost-effective, modular alternative to traditional FACTS devices. The integration of D-FACTS devices into the transmission line is implemented to improve the overall voltage profile of the network. These devices help regulate power flow, reduce line losses, and maintain voltage levels within acceptable limits, thereby enhancing the stability and reliability of the power system. These devices are observed in blue color as indicated in Figure 4.10 and the voltage profile results are recorded in Table 4.6 as shown below. Most of the bus voltages are improved due the insertion of D-FACTS.

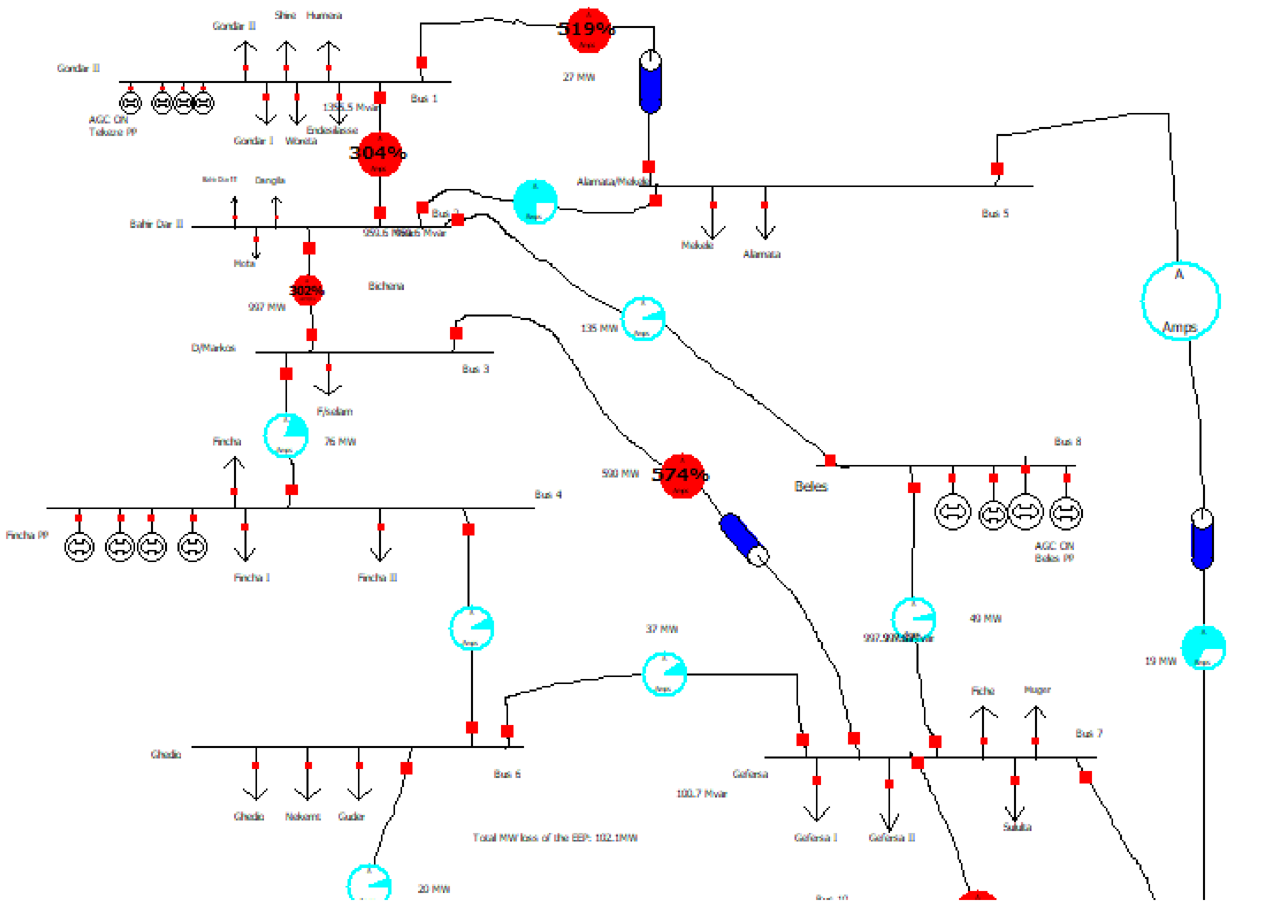


Figure 4. 10: D-FACTS insertion in the transmission lines

Table 4. 6: Voltage Profile result after D-FACTS insertion

Number	Name	Area Name	Monitor	Limit Group	PU Volt	Volt (kV)	Limit Low PU Volt	Limit High PU Volt	Contingency Limit Low PU Volt	Contingency Limit High PU Volt
1	Gondar II	1	YES	Default	1.16477	267.897	0.90	1.10	0.90	1.10
2	Bahir Dar II	1	YES	Default	1.16428	267.784	0.90	1.10	0.90	1.10
3	D/Markos	1	YES	Default	0.97958	225.304	0.90	1.10	0.90	1.10
4	Bus 4	1	YES	Default	1.00001	230.001	0.90	1.10	0.90	1.10
5	Bus 5	1	YES	Default	1.22000	280.600	0.90	1.10	0.90	1.10
6	Bus 6	1	YES	Default	0.99785	229.507	0.90	1.10	0.90	1.10
7	Bus 7	1	YES	Default	0.99897	229.763	0.90	1.10	0.90	1.10
8	Bus 8	1	YES	Default	0.99900	229.770	0.90	1.10	0.90	1.10
9	Bus 9	1	YES	Default	1.00105	230.242	0.90	1.10	0.90	1.10
10	Bus 10	1	YES	Default	1.00327	230.753	0.90	1.10	0.90	1.10
11	Bus 11	1	YES	Default	1.00000	230.000	0.90	1.10	0.90	1.10
12	Bus 12	1	YES	Default	1.00000	230.000	0.90	1.10	0.90	1.10
13	Bus 13	1	YES	Default	1.00012	230.027	0.90	1.10	0.90	1.10

The overall voltage profile is shown in Table 4.7 shown below. This table presents a comparative summary of bus voltage magnitudes (in p.u.) under various scenarios, including the base case, multiple line outages, and after the insertion of D-FACTS devices. It highlights the impact of each case on system voltage stability across all buses, and the comparison is presented in Figure 10.

Table 4. 7: Overall voltage profile for all cases

Bus Number	**Base Case(1)**	**Contingency cases**			**After Rehabilitation (D-FACTS)**
		Case 2	**Case 3**	**Case 4**	
1	0.6850	0.72516	0.75189	0.75156	1.16477
2	0.6851	0.76772	0.75200	0.75163	1.16428
3	0.9597	0.76772	0.78571	0.95273	0.97958
4	1.0000	0.85910	0.95107	0.98851	1.00000
5	0.7304	0.98425	0.96551	0.78507	1.22000
6	0.9890	0.98851	0.97168	0.98136	0.99785
7	0.9833	0.99043	0.98344	0.97568	0.99897
8	1.0000	0.99294	1.00000	0.94883	0.99900
9	0.9858	1.00000	1.00000	0.97799	1.00105
10	0.9892	1.00000	1.00046	0.99964	1.00327
11	1.0000	1.00000	1.00408	1.00000	1.00000
12	1.0000	1.00000	1.00408	1.00000	1.00000
13	1.0000	1.00000	1.00408	1.00000	1.00000

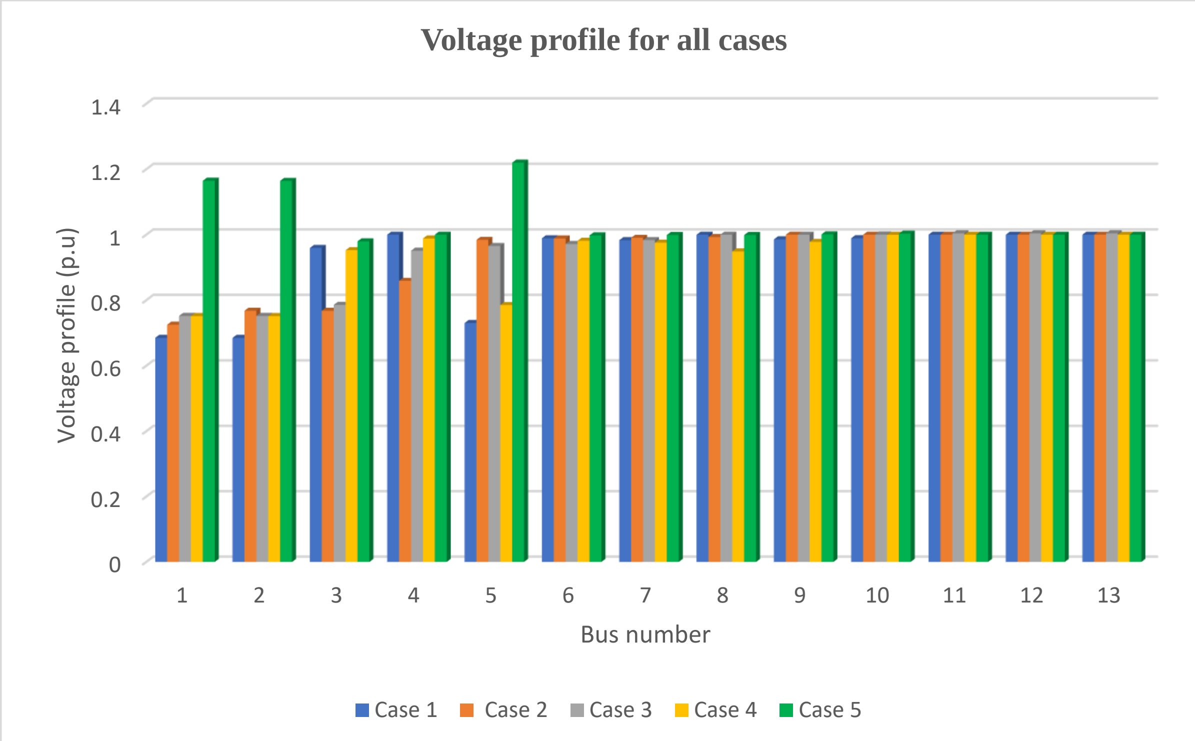


Figure 4. 11: Voltage profile for all cases

4.4. Result Summary: Discussions on the Comparison of All Cases

The voltage profile comparison across the 13 buses under different operating conditions: Base Case, three contingency cases (Case 2, Case 3, Case 4), and the after-rehabilitation scenario (D-FACTS) demonstrates clear distinctions in system performance and voltage stability.

► **Base Case**:

The initial voltage profile shows relatively low voltage magnitudes at Buses 1, 2, and 5, indicating possible voltage drop concerns at those points. Most other buses maintain voltages close to or at 1.0 p.u., suggesting a generally stable system in the normal operating condition, except for the weak buses.

► **Contingency Cases**:

Case 2 (Gefersa–D/Markos Outage): This results in noticeable voltage improvements at Buses 1 through 5, indicating a redistribution of power flow, although possibly at the cost of overloading elsewhere in the system. However, some mid-system buses experience slight voltage dips.

Case 3 (Sebeta–Gefersa Outage) and Case 4 (Wolkite–Sebeta Outage): These contingencies affect a broader set of buses. For instance, Bus 5 in Case 4 drops significantly to 0.78507, and Bus 8 also experiences voltage depression to 0.94883, reflecting the adverse impact of this line outage on system support and load sharing.

- **After Rehabilitation (D-FACTS)**:

The insertion of D-FACTS devices leads to a significant and uniform voltage improvement across almost all buses:

- ✓ Buses 1 and 2, which were critically low in the base and contingency cases, see major improvements to over 1.16 p.u.
- ✓ Bus 5 enhaned to 1.22 p.u., indicating effective voltage support in previously weak areas.
- ✓ Mid and downstream buses also stabilize near or above 1.0 p.u., showing that D-FACTS provides dynamic voltage regulation and enhances system reliability.

Generally, the D-FACTS integration effectively mitigates the voltage depressions seen during contingencies and improves overall voltage stability across the network. Compared to the base case and all three contingency scenarios, the rehabilitation case ensures a well-balanced and strengthened voltage profile.

4.5. Contingency performance analysis using ANN

Let as consider the contingency performance analysis using ANN to compare the result with the numerical analysis (NR method) at a particular loading condition. One of the performance metrices was presented in chapter 3 with equation 3.28 as follow. The PIv is already calculated with the numerical method and comparing this result with predicted by ANN.

Voltage power performance index (PIv): This index shows the relative severity of the outage in terms of bus voltage limit violation and given as (Satyanarayana Burada, Deepak Joshi , & Khyati D. Mistry, 2016).

As the PIv is high, the severity of the outage is very high for violation of voltage limit.

$$PI_V = \sum_{i=1}^{n}\left[\left(\frac{W}{2z}\right)\left(\frac{\left(|V_i| - |V_i^{sp}|\right)}{\Delta V_i^{\lim}}\right)^{2z}\right]$$

Let's us take the following Assumptions as many articles suggested for the variables in this equation to calculate the PIv.

- V_i^{sp}=1.0pu (specified/reference voltage)
- ΔV_i^{lim}=0.05 p.u
- z=2 (penalty exponent)
- W_i=1, for all buses

Table 4. 8: The result of voltage profile at a particular loading condition

Number	Name	Area Name	Monitor	Limit Group	PU Volt	Volt (kV)	Limit Low PU Volt	Limit High PU Volt	Contingency Limit Low PU Volt	Contingency Limit High PU Volt
1	Gondar II	1	YES	Default	0.75189	172.934	0.90	1.10	0.90	1.10
2	Bahir Dar II	1	YES	Default	0.75200	172.959	0.90	1.10	0.90	1.10
3	D/Markos	1	YES	Default	0.95107	218.746	0.90	1.10	0.90	1.10
4	Bus 4	1	YES	Default	0.98344	226.190	0.90	1.10	0.90	1.10
5	Bus 5	1	YES	Default	0.78571	180.714	0.90	1.10	0.90	1.10
6	Bus 6	1	YES	Default	0.96551	222.067	0.90	1.10	0.90	1.10
7	Bus 7	1	YES	Default	0.97168	223.486	0.90	1.10	0.90	1.10
8	Bus 8	1	YES	Default	1.03252	237.480	0.90	1.10	0.90	1.10
9	Bus 9	1	YES	Default	1.00408	230.939	0.90	1.10	0.90	1.10
10	Bus 10	1	YES	Default	1.00500	231.151	0.90	1.10	0.90	1.10
11	Bus 11	1	YES	Default	0.96000	220.800	0.90	1.10	0.90	1.10
12	Bus 12	1	YES	Default	1.00000	230.000	0.90	1.10	0.90	1.10
13	Bus 13	1	YES	Default	1.00046	230.106	0.90	1.10	0.90	1.10

Table 4. 9: Data sets for ANN and PIv results both numerical and ANN

Bus number	V(p.u)	P (MW)	Q (MVAr)	PIv (Numerical)	PIv (ANN)
1	0.75189	156	72	28.34	24.54
2	0.75200	135	66	22.31	25.25
3	0.95107	56	22	0.96	0.3093
4	0.98344	15	9	0.28	0.2175
5	0.78571	52	24	19.76	18.33
6	0.96551	42	21	0.5368	0.4883
7	0.97168	740	320	0.5684	0.4529
8	1.03252	0	0	0.42	0.4026
9	1.00408	543	207	0.01	0.13
10	1.00500	40	20	0.01	0.02428
11	0.9600	58	32	1.60	1.597
12	1.000	0	0	0.00	0.03981
13	1.00046	143	66	0.00	0.004181

As shown in the above Table 4.9 the heist ranking for the severity are as follows:

The different results are gained due to the ANN requires huge amounts of data sets. But here are limited data sets. So that the ANN results somewhat differ from the numerical method. The accuracy of ANN is mostly depends on the number of datasets used. The differences in PIv (Voltage Performance Index) values between the Numerical method and the ANN (Artificial Neural Network) method in this table arise due to the fundamental differences in how these two approaches work. Here's a clear breakdown:

Model Nature: Analytical vs. Approximate

Numerical Method: This approach directly computes PIv using power system equations and physical laws. It's typically very precise but computationally expensive.

ANN Method: An ANN is a data-driven, approximatively model that learns from past input-output pairs. Its predictions rely on how well it has learned the patterns in the training data, so it's prone to small errors or deviations.

Limited Data for Training

The table shows that only a small number of data points (13 buses) were likely used for training the ANN or validating it. ANN performance heavily depends on large, diverse, and representative datasets. Limited data can lead to:

- Under-fitting: Model doesn’t learn the complex nonlinearities of the system.
- Poor generalization: ANN may not predict well on unseen or edge-case scenarios.

Nonlinearity and System Sensitivity

- Voltage profile and loading conditions can exhibit highly nonlinear relationships.
- Even small variations in input (e.g., in P, Q, V) can cause noticeable shifts in PIv.
- ANN may smooth over such variations, especially with limited training.

Error Tolerance of ANN

ANNs are generally optimized to minimize a mean error metric (e.g., MSE), not necessarily to perfectly match each individual output.

For instance, At Bus 3:

- PIv Numerical = 0.96
- PIv ANN=0.3093

This indicates a localized error in prediction, possibly due to underrepresented patterns during training.

Training Algorithm and Hyperparameters

The choice of activation functions, hidden layers, learning rate, etc., also impacts accuracy. If the ANN is not well-tuned, its performance can degrade, especially in smaller datasets.

Summary:

The difference in PIv, values is due to the approximate, data-driven nature of the ANN method, which can only learn as well as the data allows. Limited data means the ANN lacks full knowledge of the system's behavior, leading to deviations from the more accurate numerical method.

Most Severe Buses:

- Bus 1: PIv ≈ 24.54
- Bus 2: PIv ≈ 24.52
- Bus 5: PIv ≈ 18.33

These buses are most critical under this voltage condition and should be prioritized for mitigation (e.g., DG, STATCOM, and reconfiguration).

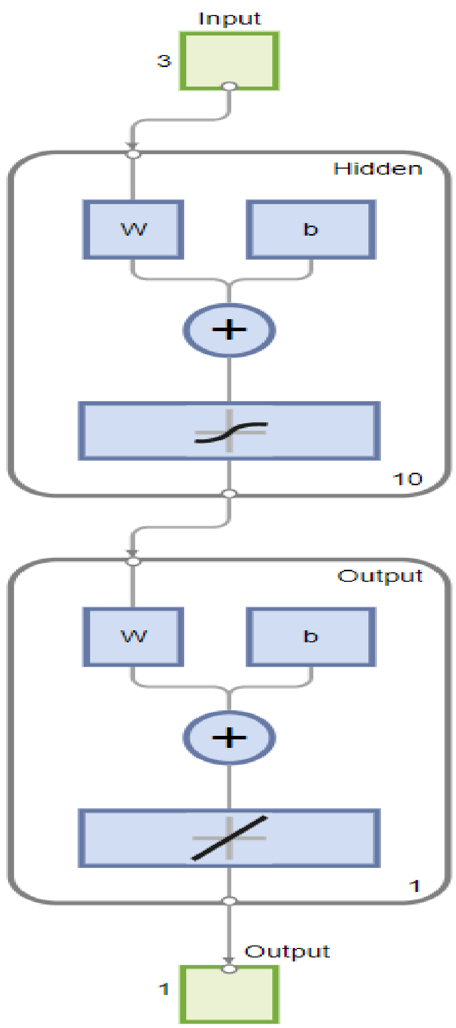


Figure 4. 12: ANN layout for training the network

It is observed that in Figure 4.12 the number of hidden neurons is 10 in order to minimize the computational burden and to minimize the complicity of the system. In Figure 4.12, the architecture of the Artificial Neural Network (ANN) used for training is illustrated. The network consists of an input layer(X_1, X_2, X_3), a single hidden layer (**Weight Matrix W**, **Bias vector B** and **Summation block** ∑), and an output layer. Notably, the hidden layer contains 10 neurons. This number is chosen strategically it strikes a balance between learning capability and system simplicity. Using 10 neurons helps ensure the network can capture the underlying patterns in the data without becoming overly complex or computationally expensive. In essence, this setup allows the model to train efficiently while avoiding overfitting or excessive resource use.

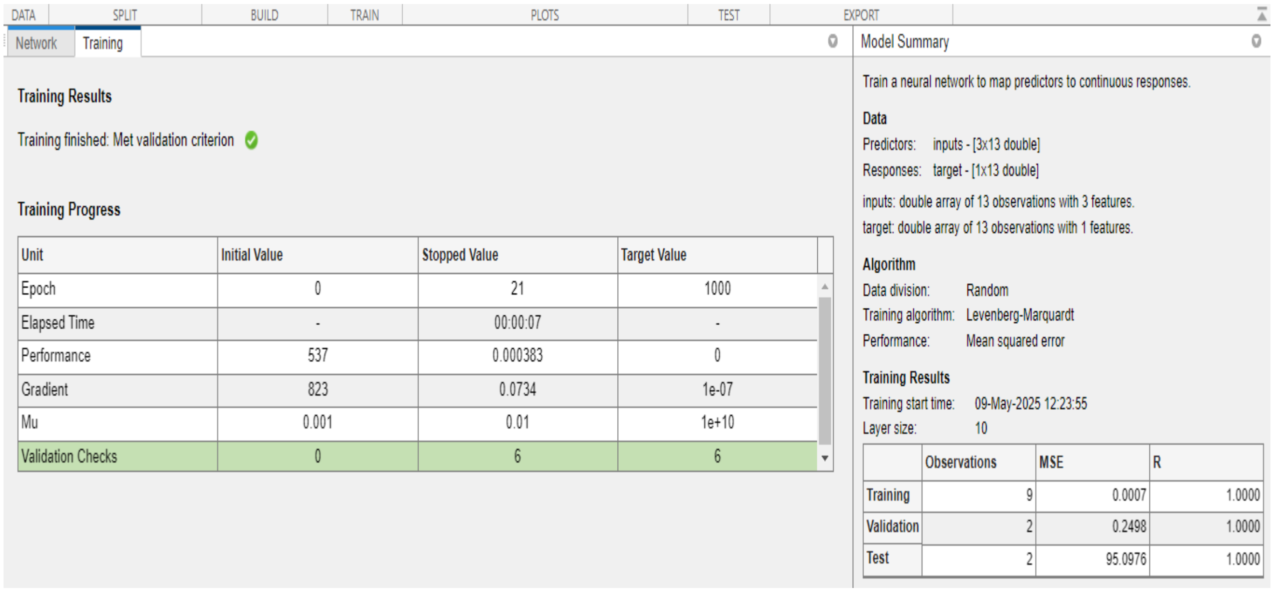


Figure 4. 13: The training results of ANN

Figure 4.13 depicts the summary results during the training of variables and the performance values with their training, validation and testing. Figure 4.13 presents the outcome of training an ANN designed to predict a continuous output variable in this case, likely the voltage performance index (PIv). The figure includes several important indicators of how well the network has learned the relationship between inputs (voltage, real power, and reactive power) and the target output (PIv).

Training Progress Overview

- ❖ Epochs: The training process stopped after 21 iterations (epochs), which indicates that the model converged quickly.
- ❖ Performance (MSE): The performance metric used is Mean Squared Error (MSE). The final training performance value was 0.000383, showing excellent learning accuracy on the training set.
- ❖ Gradient: The gradient dropped from 823 to 0.0734, which suggests that the network weights were adjusting effectively and converged toward optimal values.
- ❖ Mu (Learning Parameter): The adaptive learning rate (Mu) also decreased from 0.001 to 1e-10, which is a strong indicator that the algorithm has reached a minimal error zone.
- ❖ Validation Checks: The training stopped based on 6 consecutive validation failures, which is a built-in mechanism to prevent overfitting.

Model Summary

- The ANN was trained with 3 input features (probably V, P, Q) and 1 output feature (PIv), using 10 hidden neurons as specified.
- Algorithm: The Levenberg-Marquardt backpropagation algorithm was used, which is suitable for fast and accurate function approximation in regression tasks.
- Data Division:
  - Training set: 9 observations
  - Validation set: 2 observations
  - Test set: 2 observations

Performance Metrics

- ✓ MSE Values:
  - Training: 0.0007
  - Validation: 0.2498
  - Test: 95.0976
- ✓ Correlation Coefficient (R):
  - All three phases (Training, Validation, and Test) report R = 1.0000, which implies perfect correlation between predicted and actual outputs.

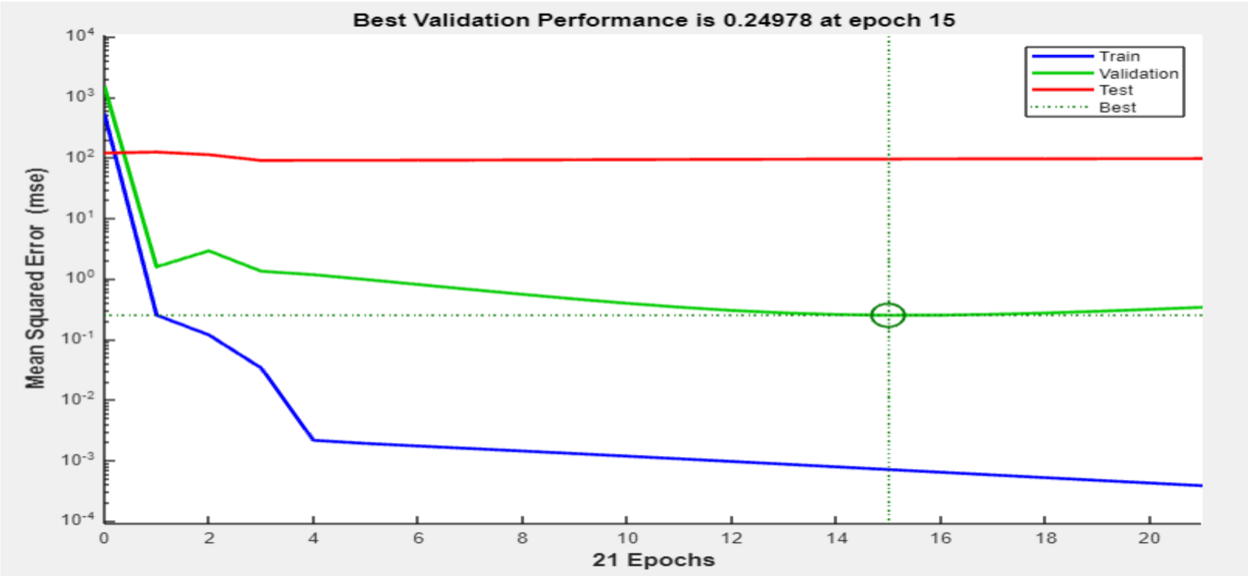


Figure 4. 14: Performance validation

Here, the graph shown in Figure 4.14 indicates how the performance validation, training and testing in terms of MSE. Best validation is found at epoch 15 with the MSE value of 0.24978. It also shows the mean squared error (MSE) performance of the neural network during training, validation, and testing over 21 epochs. The best validation performance occurred at epoch 15 with an MSE of 0.24978, indicating the optimal point before overfitting. The training error decreased consistently, showing effective learning, while the validation error initially dropped then stabilized, triggering early stopping. However, the test error remained significantly higher and nearly constant, suggesting limited generalization likely due to the small dataset or differences in the test set. Overall, the network performed well within training and validation phases.

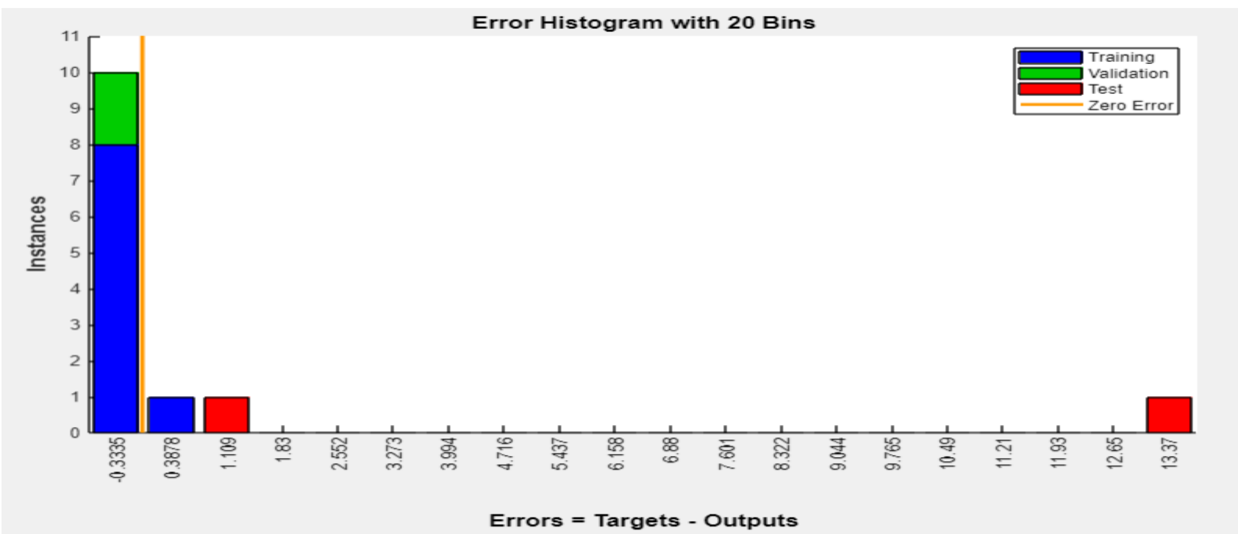


Figure 4. 15: Error histogram between the target and model output for the training datasets

Figure 4.15 presents the error histogram for training, validation, and test datasets, showing the distribution of prediction errors (target minus output). Most of the errors are concentrated around zero, especially for the training and validation sets, indicating accurate predictions with minimal deviation. However, there are a few significant outliers in the test set (red bars), including one with a large error exceeding 13, suggesting that the model did not generalize well for some test data points. This indicates the need for a larger or more balanced dataset to improve overall generalization.

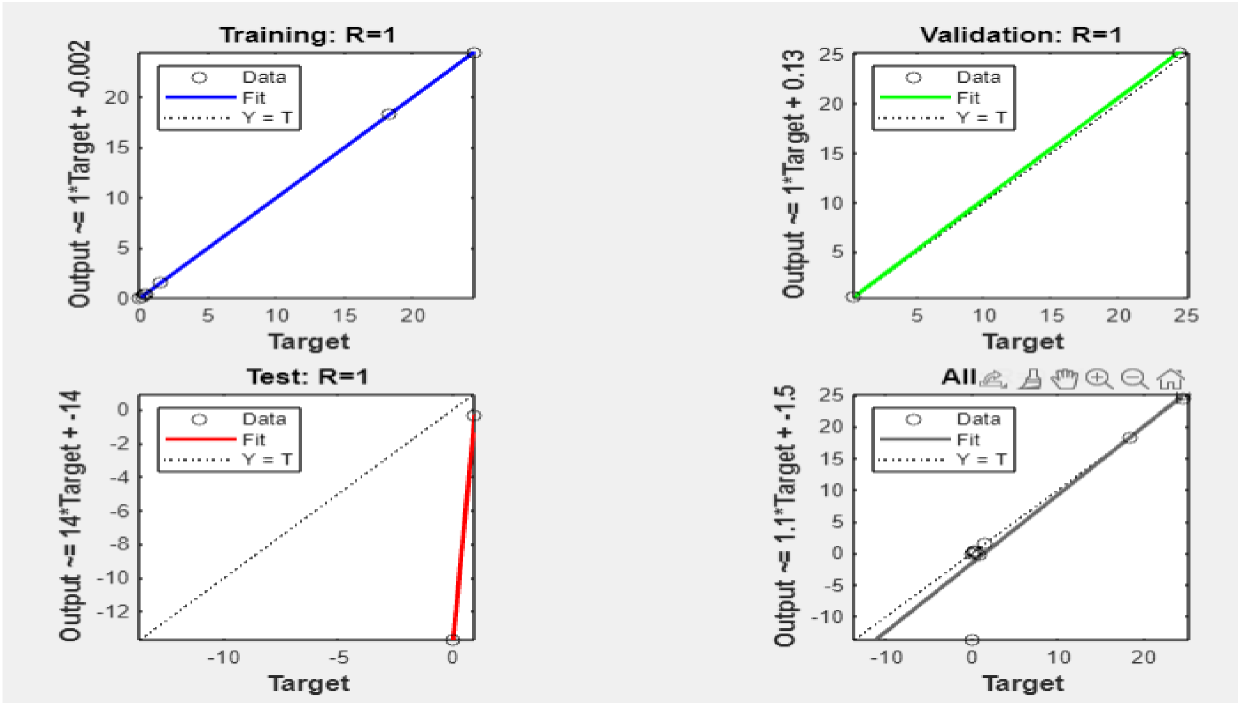


Figure 4. 16: Training and validation result using ANN

The Figure 4.16 depicts that the training and validation results obtained by ANN. Regression R Values measure the correlation between outputs and targets. An R value of 1 means a close relationship, 0 a random relationship.

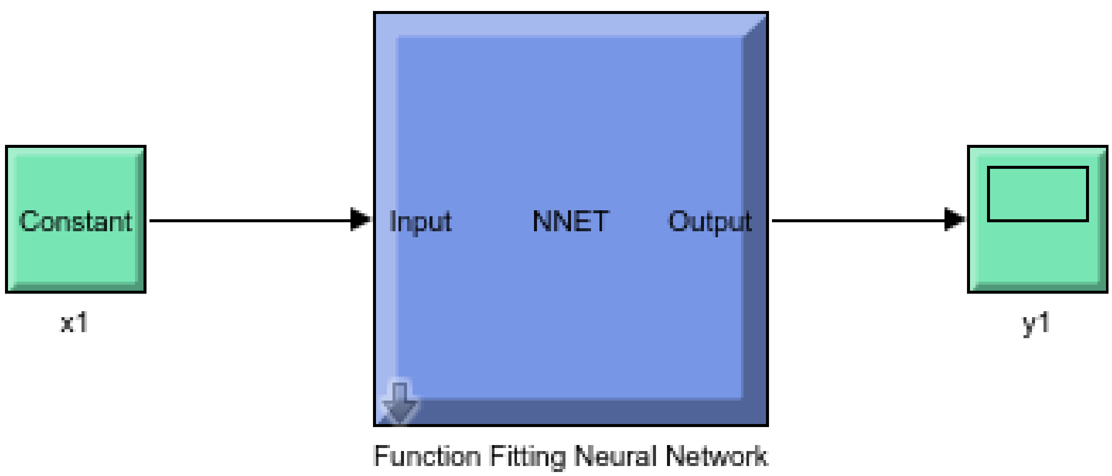


Figure 4. 17: ANN input output relationship Simulink diagram after training

The diagram in Figure 4.17 shows a Simulink diagram representing the input-output relationship of a trained Artificial Neural Network (ANN) for function fitting. A constant input x1 feeds into the "Function Fitting Neural Network" block labeled "NNET," and the output of the ANN is y1. This diagram illustrates a simple model where the ANN learns to map a constant input to a specific output value after training.

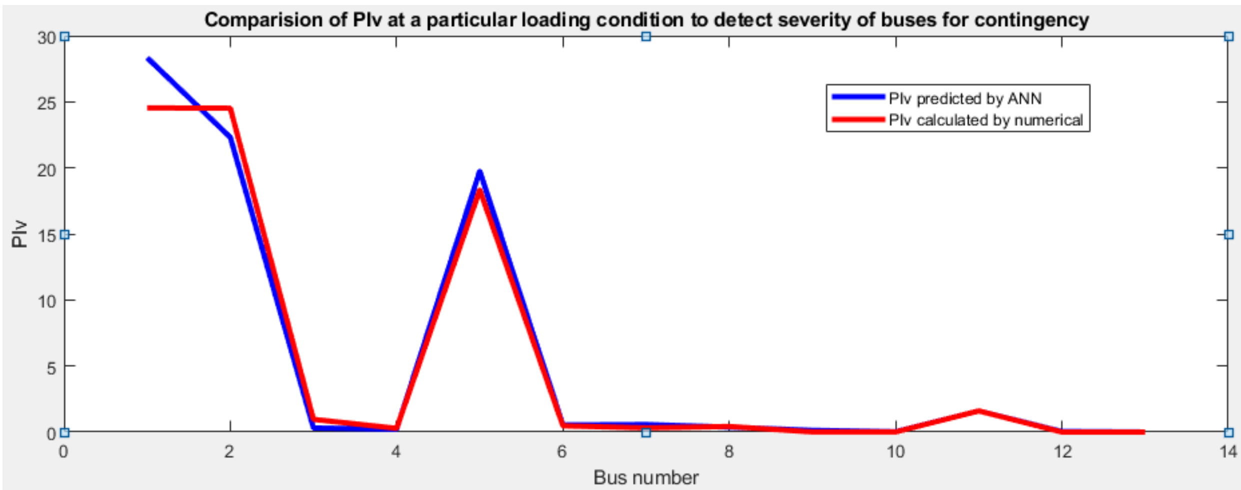


Figure 4. 18: Comparison evaluation of PIv with numerical and ANN

The result in Figure 4.18 shows that the predicted performance index (PIv) using ANN is significantly very near to the performance index that has been computed using the numerical load flow method. Therefor ANN model is effective at predicting the line outage performance index with good accuracy. The graph compares PIv values calculated numerically and predicted by an Artificial Neural Network (ANN) across different buses to assess the severity of buses during a contingency. The ANN's predictions generally align with the numerical calculations, suggesting its effectiveness. Buses 4 and 5 exhibit the most significant changes in PIv, indicating they are the most critically affected by the contingency. This comparison helps identify vulnerable buses in the power system.

Generally, the values of D-FACTS are to enhance voltage, the findings from the simulation are all the under-voltage bus improved significantly after the insertion of D-FACTS as shown in Table 4.6, which is show that Bus 1, 2 and 5 enhanced from 172.86V to 267.89V, 172.87V to 267.78V and 180.56 to 280.60V respectively. Therefore, the percent of enhancement is that about 55%.

CHAPTER FIVE

5. CONCLUSION, RECOMMENDATION AND FUTURE WORK

5.1 Conclusion

The simulation results of line outage contingency analysis performed for the 230kV transmission line show that most of the line outage has an impact on the others. The findings from the contingency analysis conducted in this chapter reveal critical vulnerabilities within the Ethiopian high-voltage transmission network. The simulation results demonstrate that specific line outages can lead to overloading and voltage instability, posing significant risks to system security. For instance, during the Gefersa to D/Markos outage, cascading failures were triggered, ultimately leading to a total system blackout. The Sebeta to Gefersa outage resulted in severe loading conditions, with affected lines operating well beyond their rated capacities, emphasizing the interconnectedness and fragility of the network. Conversely, the integration of D-FACTS devices proved to be a highly effective measure for mitigating these risks. The installation of D-FACTS led to notable improvements in voltage stability across nearly all buses, demonstrating that dynamic voltage regulation can enhance system reliability significantly. These results highlight the necessity for ongoing infrastructure enhancements and strategic contingency planning to maintain a robust and reliable power supply. Finally, ANN predicts the severity of the buses to rank the contingency, which helps with fast convergence to find the solution.

5.2. Recommendation

To enhance the reliability and security of the Ethiopian power system, several key recommendations emerge from the findings of this chapter.

First, Ethiopian Electric Power (EEP) should invest in advanced monitoring and control technologies that deliver real-time data on voltage levels, line loading, and overall system performance. Implementing a Supervisory Control and Data Acquisition (SCADA) system is crucial for facilitating immediate responses to contingencies, thereby minimizing the risk of cascading failures. Additionally, regular updates to both software and hardware are essential to keep pace with technological advancements.

Second, using D-FACTS, a double line transmission system, and capacitors at critical points within the transmission network will improve the security of the power system. Areas that are susceptible to voltage instability or frequent outages should be equipped with these devices to enhance dynamic voltage regulation and overall system resilience.

Finally, EEP should establish a routine schedule for conducting contingency analysis and simulations that involve various outage scenarios. Such exercises will strengthen the awareness of system operators and improve their decision-making abilities during actual outages.

5.3. Suggestion for Future Work

- ► This thesis focuses exclusively on the 230 kV high-voltage transmission line network of EEP. Future research should encompass the entire high-voltage grid system, including 400 kV, 132 kV, 66 kV, and 45 kV transmission lines, to evaluate both transmission line losses and transformer losses.
- ► This study provides a thorough analysis of N-1 contingency scenarios to evaluate technical transmission line losses as well as the voltage profile of the buses. Future work should incorporate an assessment contingency analysis, including non-technical transmission losses, voltage profiles considering the simulations of N-2 contingencies, to further analyze the system.
- ► It is imperative that the high-voltage transmission network and substations be expanded in tandem with EEP's current progress toward the completion of the Grand Renaissance Dam and other power plants. In the absence of this, a large number of transformers and transmission lines will be overloaded, which could result in overloading, voltage dips, and even partial or complete blackouts during emergency situations. Thus, the security evaluation of EEP's networked grid system should be the main focus of future research.

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APPENDICES

Appendix A: Single Line Diagram of Ethiopian Power Network

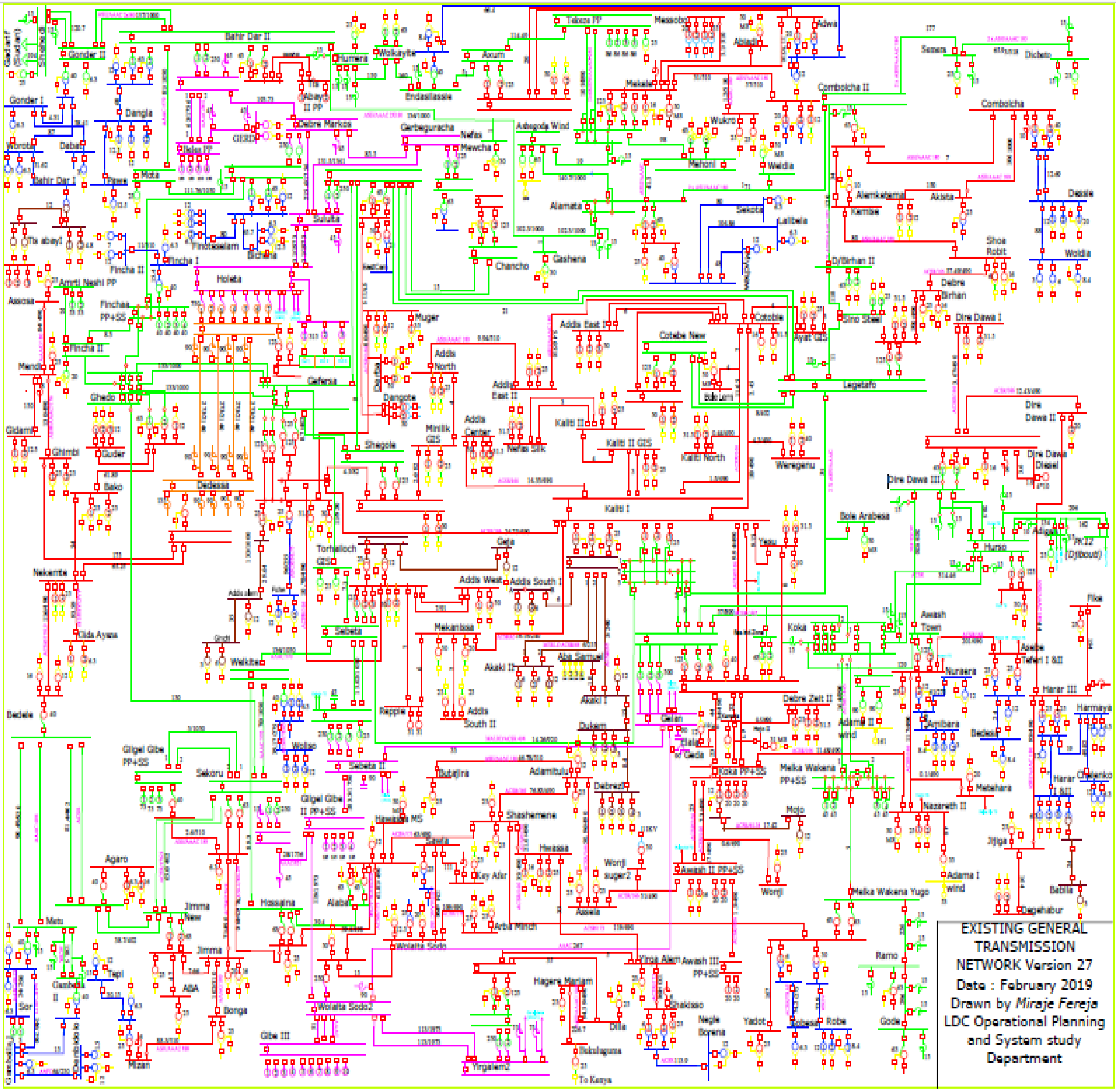

Figure A.1: Single line diagram of Ethiopian power network

Appendix B: Load Data

Table B.1: North Region Load

No	Name of Substation /Bus	P[MW]	Q[MVAR]
1	Abiadi-Mob	8.2731	4.0042
2	Adigrat	13.5123	6.5402
3	Adwa	21.4294	10.3709
4	Alamata	39.3945	17.2993
5	Axum	9.8837	3.9535
6	Humera	10.4526	5.0589
7	Mehoni	4.076	1.6039
8	Mekelle	45.8829	22.2074
9	Mesobo	38.3763	16.7636
10	Shire	26.293	12.363
11	Tekeze	2.3015	1.1615
12	Welkayt	11.1532	5.5916
13	Wukro	7.2479	3.5232

Table B.2: North East Region Load

No	Name of Substation /Bus	P[MW]	Q[MVAR]
1	Akista	10.1134	4.6027
2	Alem-Ketema	1.5368	0.7439
3	Combolcha I	10.0648	4.6596
4	Combolcha II	16.5623	8.019
5	Dessie	19.5664	7.0153
6	Dichato	4.1228	6.1842
7	Kemissie	5.3021	1.3679
8	Semera	5.7104	2.7638
9	Showa-Robit	7.2314	1.9098
10	Woldiya	5.9046	2.8578

Table B.3: East Region Load

No	Name of Substation /Bus	P[MW]	Q[MVAR]
1	Adigala	0.4291	-0.8785
2	Asebe-Teferi	8.4587	3.6776
3	Deghabur	3.9118	0.917
4	D/Dawa I	43.3899	12.8368
5	D/Dawa II	4.352	2.108
6	D/Dawa III	10.5089	7.7678
7	Djib-Pk12	60	15
8	Fik	0.9551	0.4775
9	Gode	1.022	0.494
10	HararIII	29.754	11.694
11	Hurso	0.4291	0.2077
12	Jigjiga	12.573	6.078138

Table B.4: South Region Load

No	Name of Substation /Bus	P[MW]	Q[MVAR]
1	Alaba	17.8741	8.6491
2	Arba-Minch	24.0781	11.658
3	Boculuguma	2.8366	1.3753
4	Dilla	8.3768	3.8624
5	Hager-Maryam	5.7304	2.7697
6	Hawassa	35.3376	12.269
7	Hosaina	17.3617	9.3454
8	Key-Afer	1.5732	1.5732
9	Ramo	7.3635	3.5616
10	Shawla	2.3496	3.5754
11	Shashemene	20.6051	8.6503
12	WolaytaI	9.7294	3.9704
13	WolaytaII	13.7278	5.8345
14	YirgalemI	20.7707	8.4226
15	YirgalemII	11.2951	5.4686

Table B.5: South Region Load

No	Name of Substation /Bus	P[MW]	Q[MVAR]
1	Adamitulu	19.5934	11.2552
2	Assela	26.7983	14.307
3	AwashII	9.4242	4.6084
4	AwashIII	3.4959	1.692
5	Awash-7-Kilo	11.3533	5.5434
6	D/BirhanI	8.7905	3.9525
7	D/BirhanII	1.5699	0.7594
8	Gerbe-Gurcha	8.8419	4.2795
9	Knoria-Text	61.0065	25.3573
10	Koka	20.5249	8.8032
11	M/Wak.Yugo	13.3586	4.7223
12	Nazereth	44.8905	17.5671
13	Wolkite	20.9066	10.1855

Table B.6: Addis Ababa Region Load

No	Name of Substation /Bus	P[MW]	Q[MVAR]
2	Addis-North	28.5815	13.8115
3	Ayat	0.3409	-0.3059
4	Cotebie	144.8231	60.4114
5	Gefersa	148.8636	64.493
6	Gelan230	68.2417	9.535
7	Gelan132	57.6971	29.0096
8	Kaliti I	211.4	93.3476
9	Legetafo	42.8642	20.7428
10	Mekanisa	66.427	32.3476
11	Minilik	7.0191	3.1385
12	SebetaI	181.0447	69.3994
13	SebetaII	53.6222	14.436
14	Shegole	64.2676	31.0944
15	Sino-Steel	20.855	9.931
16	Sululuta	76.4474	17.4122
17	Torhayiloch	7.3592	3.5456

Table B.7: North West Region Load

No	Name of Substation /Bus	P[MW]	Q[MVAR]
2	Debre-Markos	28.1355	11.8202
3	GonderII	36.5479	17.1236
4	Metema	1.9444	0.9411
5	Mota	2.4699	1.1955
6	Shehdi	109.944	56.25

Table B.8: South West Region Load

No	Name of Substation /Bus	P[MW]	Q[MVAR]
1	Agaro	4.821	2.335
2	Bedelle	5.8128	2.8138
3	Gambella	8.1316	3.8722
4	Jimma	29.0609	16.622
5	Metu	7.0282	3.4016
6	GibeSS/Sekoru	6.7961	2.3868

Table B.9: West Region Load

No	Name of Substation /Bus	P[MW]	Q[MVAR]
1	Assosa	5.516	2.672
2	Bako	3.7613	1.6924
3	Dedessa	1.9282	0.9641
4	Fincha-II	4.74	2.2928
5	Finchag	7.4014	3.5824
6	Gerd	15.7935	7.602
7	Ghedo	23.6887	10.8253
8	Ghimbi	7.5594	0.8172
9	Gidami	1.9282	0.9352
10	Mendi	3.206	1.553
11	Nekemte	13.7156	6.6118

Appendix C: Transmission Lines Parameters

Table C.1: 132kv Transmission Lines Parameters

Line Name	R[Ω]	X[Ω]	B(μS)	Length [Km]	Line Rating [MVA]
AbiadiMBTP to Adwa	8.19	15.397	98.244	36.4	89
Adamitulu to Asela	13.311	21.624	136.68	51	82
AddissEastII to AddisNorth	2.1087	4.2273	26.75	9.9	91
Adwa to Akum L1	4.5	8.46	53.98	20	89
Adwa to Akum L2	4.5	8.46	53.98	20	89
Akista to Alemketema	31.993	64.135	405.84	150.2	91
Alaba to Hawassa	19.08	35.87	228.88	84.8	89
Alaba to Shashemene	14.22	26.734	170.58	63.2	89
Awash7k to Asebeteferi	25.839	41.976	265.32	99	82
Awashg to Kokag L1	6.6294	10.77	68.072	25.4	82
Awashg to Kokag L2	6.6294	10.77	68.072	25.4	82
AwashIIg to Asela	13.363	21.709	137.22	51.2	82
AwashIII to AwashII	0.3915	0.633	4.0965	1.5	82
Ayat to Legetafo	0.783	1.272	8.04	3	82
Bako to Ghedo	13.925	26.179	167.04	61.89	89
CombolchaI to Akista	22.578	45.262	286.41	106	91
CombolchaII to I	1.491	2.989	18.914	7	91
Cotobie to Ayat	1.044	1.696	10.72	4	82
Cottobie to Addis EastII	1.1715	2.3485	14.861	5.5	91
D/DawaII to HararIII	9.329	18.703	118.35	43.8	91
D/DawaIII to D/DawaI	0.9657	1.5688	9.916	3.7	82
D/DawaIII to D/DawaII	3.2364	5.2576	33.232	12.4	82
D/Birhan to ShoaRobit	15.008	24.38	154.1	57.5	82
Dedessa to Ghimbi	13.964	27.666	178.59	65.25	91
Dilla to H/mariam	19.26	38.16	246.33	90	91
Gefersa to Sebeta I	3.0798	5.0032	31.624	11.8	82
Gelan to Yesu	1.712	3.392	21.896	8	91
Ghimbi to Mendi	25.68	50.88	328.44	120	91
GibeSS to Jimma	16.043	30.16	192.44	71.3	89
H/mariam to Bukulugum	36.38	72.08	465.29	170	91
HararIII to Fik	32.956	65.296	421.5	154	91
HararIII to Jigjiga	20.235	40.565	256.69	95	91

Hawasa to Yirgalem	9.1611	14.882	94.068	35.1	82
Hossana to Alaba	8.91	16.751	106.88	39.6	89
Jigjiga to Degehabur	19.26	38.16	246.33	90	91
Kaliti I to Gefersa	6.4728	10.515	66.464	24.8	82
Kaliti I to Gelan L1	2.4012	3.9008	24.656	9.2	82
Kaliti I to Gelan L2	2.4012	3.9008	24.656	9.2	82
Kaliti I to Mekanisa	4.2282	6.8688	43.416	16.2	82
Kaliti I to Cotobie viaKNT	5.22	8.48	53.6	20	82
Kaliti I to CotobieviaWGT	5.22	8.48	53.6	20	82
Kemise to Combplcha II	8.874	14.416	91.12	34	82
Knoria tex to Gelan	4.708	9.328	60.214	22	91
Kokag to gelan L1	15.321	24.889	157.32	58.7	82
Kokag to gelan L2	15.321	24.889	157.32	58.7	82
Kokag to Knoria	8.2604	16.366	105.65	38.6	91
Lagatafa to Debre Birhan	26.1	42.4	268	100	82
M/Wak.Yugo to Shashemen	26.82	50.422	321.72	119.2	89
Mekelle to AbiadiMBTP	18.068	33.967	216.73	80.3	89
Mekelle to AbiadiMBTP2	1.1475	2.1573	13.765	5.1	89
Mekelle to WukroTP	6.975	13.113	83.669	31	89
Mendi to Assosa	17.04	34.16	216.16	80	91
Mendi to Gidami	25.56	51.24	324.24	120	91
Minilik to Addis North	1.044	1.696	10.72	4	82
NazarethII to Awash7k	30.537	49.608	313.56	117	82
NazarethII to Kokag	3.0015	4.876	30.82	11.5	82
Nekemte to Bako	12.15	22.842	145.75	54	89
Nekemte to Bedelle	24.708	49.532	313.43	116	91
Nekemte to Dedessa	13.898	27.862	176.31	65.25	91
OldGibe to Hossana	15.885	29.864	190.55	70.6	89
Reppieg to Mekanissa	1.827	2.968	18.76	7	82
Reppieg to Sebeta I	1.566	2.544	16.08	6	82
Sawla to Keyafer	23.643	47.397	299.92	111	91
Sebeta I to Mekanisa	2.0384	3.3114	20.931	7.81	82
Shashemene to Adamitulu	20.045	32.563	205.82	76.8	82
Shashemene to Hawasa	5.6376	9.1584	57.888	21.6	82
Shegole to Gefersa	1.1745	1.908	12.06	4.5	82
Shegole to Minilik	0.6786	1.1024	6.968	2.6	82
Shoarobit to Kemise	17.04	34.16	216.16	80	91

T/AbayIIg to B/DarII	6.206	12.296	79.373	29	91
T/AbayIIg to B/DarII	6.206	12.296	79.373	29	91
W/Sodo to Arbaminch	24.548	46.149	294.46	109.1	89
W/Sodo to Sawla	26.412	52.948	335.05	124	91
W/SodoII to Alaba	13.905	26.141	166.8	61.8	89
W/SodoII to W/Sodo	3.375	6.345	40.485	15	89
WukroTP to Adigrat	12.735	23.942	152.76	56.6	89
WukroTP to Wukro	0.27	0.5076	3.2388	1.2	89
Yesu to Kaliti I	1.949	3.9071	24.723	9.15	91
YirgalemII to Dilla	7.455	14.945	94.57	35	91
YirgalemII to Yirgalem	1.278	2.562	16.212	6	91

Table C.2: 230kv Transmission Lines Parameters

Line Name	R[Ω]	X[Ω]	B(µS)	Length [Km]	Line Rating [MVA]
Adigala to Hurso	11.18	54.34	356.46	130	274
Adigala to PK12-DJIB	8.56	26.08	281.76	80	318
Agaro to Bedelle L1	8.7205	25.836	296.9	81.5	318
Agaro to Bedelle L2	8.7205	25.836	296.9	81.5	318
Amertneshg to FinchaII	3.1244	9.5192	102.84	29.2	318
Ashegoda WF to Mekelle	1.5836	4.6916	53.916	14.8	318
AshegodaWF to Alamata	12.84	38.04	437.16	120	318
Axum to Endesilasie	5.457	16.167	185.79	51	318
B/DarII to Mota	6.806	35.109	226.92	83	280
B/DarII to Alamata	36.487	111.17	1201	341	318
B/DarII to GonderII L1	14.659	44.662	482.51	137	318
B/DarII to GonderII L2	14.659	44.662	482.51	137	318
Bedelle to Metu L1	9.6835	29.503	318.74	90.5	318
Bedelle to Metu L2	9.6835	29.503	318.74	90.5	318
Combolcha II to Alamata	18.062	53.51	614.94	168.8	318
CombolchaII to Semera	18.19	53.89	619.31	170	318
CombolchaII to D/BirhanII	12.84	38.04	437.16	120	318
D/BirhanII to Sinosteel	12.626	37.406	429.87	118	318
D/DawaIII to Awash7K	17.63	83.845	576.46	205	274
Endesilasie to Humera	13.878	41.115	472.5	129.7	318
Finchag to D/Marcos	7.8064	40.27	260.28	95.2	280
Finchag to FinchaII	0.8881	2.7058	29.233	8.3	318

Finchag to Ghedo	5.3088	28.493	183.46	67.2	284
FinchaII to Ghedo	7.4579	22.722	245.48	69.7	318
G/GibeIg to GibeSS L1	0.43	2.045	14.03	5	274
G/GibeIg to GibeSS L2	0.43	2.045	14.03	5	274
Gefersa to T/Hailoch	1.177	3.586	38.742	11	318
Gelan to Kaliti I L1	0.8832	3.8732	25.015	9.2	257
Gelan to Kaliti I L2	0.8832	3.8732	25.015	9.2	257
Ghedo to Gefersa L1	14.231	43.358	468.43	133	318
Ghedo to Gefersa L2	14.231	42.161	484.52	133	318
GibeSS to Ghedo	11.248	54.674	358.65	130.8	274
GibeSS to Jimma L1	7.0192	20.795	238.98	65.5	318
GibeSS to Jimma L2	7.0192	20.795	238.98	65.5	318
GibeSS to Wolkite	7.597	23.146	250.06	71	318
GonderII to Shehedi L1	17.655	52.305	601.1	165	318
GonderII to Shehedi L2	17.655	52.305	601.1	165	318
Hossana to Alaba	17.655	12.877	139.12	39.5	318
Hurso to D/DawaIII L1	1.6954	7.2936	49.236	17.66	257
Hurso to D/DawaIII L2	1.6954	7.2936	49.236	17.66	257
Hurso to PK12-DJIB	21.4	63.4	673.4	200	318
Indesilasie to Wolkayite	17.12	50.72	538.72	160	318
Jimma to Agaro L1	4.1409	12.268	140.98	38.7	318
Jimma to Agaro L2	4.1409	12.268	140.98	38.7	318
Kaliti I to Legetafo	3.7343	11.063	127.14	34.9	318
Kaliti I to Sebeta I	1.2298	5.9774	39.211	14.3	274
Koka to AdamaIIWF	1.3375	4.075	44.025	12.5	318
Koka to Awash7K	11.12	54.047	354.54	129.3	274
Koka to Gelan L1	4.8848	23.231	159.72	56.8	274
Koka to Gelan L2	4.8848	23.231	159.72	56.8	274
Koka to Hurso L1	33.705	99.855	1147.5	315	318
Koka to Hurso L2	27.09	128.84	885.78	315	274
Legetafo to Cotobie L1	0.856	2.536	29.144	8	318
Legetafo to Cotobie L2	0.856	2.536	29.144	8	318
M/Wakenag to Koka L1	15.744	69.044	445.92	164	257
M/Wakenag to Koka L2	15.744	69.044	445.92	164	257
M/Wak.g to M/Wak.Yug	0.535	1.585	18.215	5	318
M/Wak.Yugo to Ramo	21.4	63.4	728.6	200	318
Mekelle to Mekhoni	10.486	31.066	357.01	98	318

Mekhoni to Alamata	4.5582	13.504	155.19	42.6	318
Metu to Gambela L1	10.754	32.763	353.96	100.5	318
Metu to Gambela L2	10.754	32.763	353.96	100.5	318
Mota to D/Marcos	9.1676	47.291	305.66	111.8	280
Ramo to Gode	21.4	63.4	728.6	200	318
Sebeta I to Sebeta II L1	1.23	6.225	42.06	15	280
Sebeta I to Sebeta II L2	1.23	6.225	42.06	15	280
Sebeta I to Wolkite	11.168	57.613	372.37	136.2	280
Semera to Dichito	5.885	17.93	193.71	55	318
Shegole to Gefersa	0.9309	2.7579	31.694	8.7	318
Sinosteel to Legetafo	1.177	3.487	40.073	11	318
Sululta to Gefersa	1.7869	5.2939	60.838	16.7	318
Sululta to Legetafo L1	2.247	6.657	76.503	21	318
Sululta to Legetafo L2	2.247	6.657	76.503	21	318
Sululta to Shegole	0.856	2.536	29.144	8	318
T/Hailoch to Sebeta I	0.7811	2.3141	26.594	7.3	318
Tekeze to Mekelle L1	11.235	33.285	382.52	105	318
Tekeze to Mekelle L2	11.235	33.285	382.52	105	318
Tekezeg to Axum	12.25	36.293	417.09	114.49	318
Wolkayite to Humera	17.013	50.403	579.24	159	318
Wolkite to Hossana	9.5551	29.112	314.51	89.3	318

Table C.3: 400kv Transmission Lines Parameters

Line Name	R[Ω]	X[Ω]	B[μS]	Length [Km]	Line Rating [MVA]
B/DarII4 to D/Marcos4	4.8425	63.727	726.76	193.7	1341
Beles to B/DarII L1	1.5072	19.468	235.56	62.8	1341
Beles to B/DarII L2	1.5072	19.468	235.56	62.8	1341
D/Marcos to G/Guracha	2.1875	28.788	328.3	87.5	1314
D/Marcos to Sululta	5.39	70.932	808.93	215.6	1314
G/GibeIIg to W/SodoII	2.975	39.151	446.49	119	1314
G/GibegII to GibeSS	0.6975	9.1791	104.68	27.9	1314
G/GibeIIg to SebetaII	4.5875	60.372	688.49	183.5	1314
G/GibeIIIg to W/SodoII L1	1.275	16.779	191.35	51	1314
G/GibeIIIg to W/SodoII L2	1.275	16.779	191.35	51	1314
G/Guracha to Sululta	3.2875	43.264	493.39	131.5	1314
Sebeta II to Gelan	0.825	10.857	123.82	33	1314

W/SodoII to Gelan L1	6.408	82.77	1001.5	267	1314
W/SodoII to Gelan L2	6.408	82.77	1001.5	267	1314
W/SodoII to YirgalemII L1	2.825	37.177	423.98	113	1314
W/SodoII to YirgalemII L2	2.825	37.177	423.98	113	1314

Appendix D: Shunt Reactors and Capacitors

Table D.1: Bus Connected Shunt Reactors

Bus name	Bus voltage [kv]	Rating[MVAR]
Gode	230	15
Ramo	230	15
Dire Dawa III	132	8
Metu	230	15
Indesilasie	230	15
Humera	230	15
D/Marcose	400	45

Table D.2: Line Connected Shunt Reactors

Line name	Line voltage [kv]	Rating[MVAR]	Connection
Gode to Ramo	230	15	Both End
M/Wakena Yugo to Ramo	230	15	Both End
Hurso to Adigala	230	10	At Hurso
Hurso to PK12-DJIB	230	15	At Hurso
Adigala to PK12-DJIB	230	15	At Adigala
Koka to Hurso L1 &L2	230	15	Both End
Metu to Gambella L1&L2	230	15	At Gambella
B/DarII to Alamata	230	15	Both End
Wolkayit to Humera	230	15	At Humera

Table D.3: Shunt Capacitors

Bus name	Bus voltage [kv]	Rating[MVAR]
Gelan	400	90
SebetaII	400	90
SebetaII	230	45

Appendix E: Ethiopian Transmission Lines and Substation under Operations as of 2025 G.C

Table E.4: Ethiopian Transmission lines under operations (2025 G.C)

No	Name of Transmission line	Voltage(KV)	In service year	Length(KM)	EEP Region
1	Debre Markos-Sululta	400	2011	432	Central1&NW
2	Gebragurach-Lilo	400	2017	4	Central 1
3	Sululta Holeta	400	2017	33	Central 1
4	Gelan-W/Sodo	400	2003	250	Central2 & south2
5	Gelan -Koye Abo	400	2022	14.02	Central2
6	Gelan-D/Zeit III	400	2020	66	Central 2
7	Sebeta II- Gibe II	400	2009	225	Central3
8	Sebeta 2-Gelan	400	2014	33	Central3
9	Sebeta 2- holeta	400	2017	40	Central3
10	Gelan-Holeta	400	2017	100	Central3
11	Debre Markos- Sululta	400	2011	120	NW & Central1
12	Beles-B/Dar	400	2011	134	NW
13	B/Dar-D/Markos	400	2011	193.77	NW
14	Beles-Hidassie	400	2010	241	NW
15	W/Sodo II-Gibe II	400	2016	32	SW&SE
16	G/Gibe2 HPP-G/Gibe2 (sokoru)	400	2009	28	SE
17	Genale Dawa _Yirgalem 2	400	2020	548	South 1
18	W/sodo2(T.No 103)-Yirgalem2	400	2019	105.3	South 1
19	Gelan-W/Sodo(Upto T.No.300)	400	2016	308	South2
20	Gibe3- Welayta line E1 &E2	400	2016	120	South2
21	Gibe3-Welayta line F-2	400	2016	61	South 2
22	W/sodo2-Gibe2	400	2016	88	South1
23	W/Sodo-Yirgalem2(UptoT.No102)	400	2019	92.7	South1
24	Sululta-Gefersa	230	2010	33.46	Central1
25	Sululta -legetafo	230	2012	41.2	Central 1
26	Sululta -Chancho	230	2017	40	Central 1
27	Legetafo-Cottobe	230	2012	16	Central1
28	Legatafo-Kaliti1	230	2014	37	Ctrl1
29	D/Birhan-Legatafo	230	2012 &2018	102.17	Cntrl 1
30	Legatafo-D/Birhan(Ind.zone Tap)	230	2018	5.4	Cntrl 1
31	Koye Abo-Kilinto	230	2020	12.6	Cntrl1
32	Kilinto-Bole Lemi II	230	2020	11.2	Cntrl 1
33	Ghedo-Gefersa I	230	1997	133.14	Cntrl 3
34	Ghedo – Gefersa 2	230	1997	266.28	Cntrl3
35	Gefersa Ghedo-Ginchi Lilo	230	2020	2.24	Cntrl1
36	Gefersa-sululta –Shegole lilo	230	2019	5	Cntrl 1

37	Gelan- Kaliti I	230	2014	14	Cntrl 2
38	Gelan-Koka	230	2014	114	Central 2
39	Koka-Awash 7kilo	230	2017	125	Central 2
40	Adama windII-Koka	230	2011	12.5	Central 2
41	Koka-kaliti east Industry Tap	230	2013	3.5	Central 2
42	Koka- hurso	230	2016	250	Central 2
43	Melka wakena-Koka	230	2014	327.72	Central 2
44	D/Zeit III-Dukem	230	2022	11	Central 2
45	D/Zeit III- Modjo	230	2022	20	Central 2
46	Sebeta i-Torhailoch GIS	230	2014	5.14	Central 3
47	Torhailoch GIS-Gefersa	230	2014	11	Central 3
48	Welkite-Sebeta 1	230	2003	165	Central 3
49	Sabata II-Sabata I	230	2009	32	Central 3
50	Sebeta 2-sebeta Train station	230	2016	2	Central 3
51	Welkite -Hosaina	230	2003	56	Cntl3 &SE
52	Kaliti I-sabata	230	1996/1977	14.26	Central 3
53	Fincha-D/Markos	230	1994	45.39	NW &West
54	D/Markos -Mota	230	2006	111	NW
55	Mota-Bahirdar II	230	2006	82	NW
56	B/Dar II-Alamata	230	1998	177.5	NW&NS
57	Gashena Tap-Gashena	230	2010	1	NW
58	N/Mewucha Tap-N/Mewucha	230	2001	1	NW
59	B/dar II –Gonder II (azezo) line1	230	2002	136.98	NW
60	B/dar II –Gonder II(Azezo) Line2	230	2002	137.156	NW
61	Metema-Sudan Boarder	230	2003	76.96	NW
62	Shire -Humera	230	2012	66	North
63	Welkayit-Tap 230KV	230	2012	66	North
64	Gonder II(Azezo)- Metema	230	2000	244	NW
65	Alamata-Ashegoda	230	2012	126	North
66	Mekelle -Tekeze	230	2012	210	North
67	Mekelle -Ashegoda	230	2012	14.8	North
68	Tekeze-sire	230	2012	160	North
69	Aksum-Tap 230KV	230	2012	5.1	North
70	Mekelle -Mehoni	230	2016	200	North
71	Mehoni-Alamata	230	2016	41	North
72	G/Gibe I HPP-G/gibe II (sokoru)	230	1996	5.64	SW
73	G/Gibe II(sokoru)-Wolkite	230	2012	73.12	SW
74	G/Gibe II(sokoru)- Ghedo	230	2004	43	SW & West
75	Bedele-Metu	230	1990	180.68	SW
76	Metu-Gambella2	230	2010	276	SW
77	Agaro-Bedelle	230	2016	166	SW
78	Jimma II-Agaro	230	2016	77.4	SW
79	G/Gibe II I??(sokoru)- Jimma	230	2016	132	SW

80	Fincha-D/Markos	230	1994	49.61	West & NW
81	G/Gibe II(sekoru)_Ghedo	230	2004	88	West & SW
82	Fincha-Ghedo	230	1973	67.19	West
83	Fincha II - Ghedo	230	2006	58.59	West
84	Fincha I-Fincha II	230	2003	8.3	West
85	Fincha II Branch-Fincha II	230	2003	22.6	West
86	Fincha II -Neshe	230	2003	29.247	West
87	Alamata-Kombolcha II	230	2011	340.98	NE1
88	B/Dar-II-Alamata	230	1998	211.02	NW & NE1
89	Kombolcha-2-D/Birhan2	230	2012	369.66	NE1
90	Kombolcha 2-Semera	230	2011	174.8	NE2
91	Semera-Dichoto	230	2017	65.93	NE2
92	Semera-Afdera	230	2022	195.5	NE 2
93	M/Wakena -Ramo	230	2012	207	South 1
94	Hawassa II-Yirgalem	230	2012	94	South 1
95	Raitu-Gode	230	2012	207	South 1
96	Wolkite(upto T.No 79)-Hossaina	230	2003	33	South2
97	Alaba-Hossaina	230	1972	40	South2
98	Koka-Hurso line 1&2	230	2010	406	East1
99	Hurso-Adigala	230	2011	236	East 1
100	Addigala- Ayisha-PK12	230	2011	248	East1
101	Awash 7kilo-Dire Dawa III	230	1995	205.1	East1
102	Hurso-Dire Dawa III	230	2017	35.32	East1
103	Hurso SS-Hurso Rail station	230	2017	1.23	East1
104	Hurso Rail st.-Lonnis Rail station	230	2017	38.8	East 1
105	Lonnis Rail st.-Milo Rail Station	230	2017	44	East1
106	Milo Rail-Addigala SS	230	2017	45.2	East1
107	Addigala SS-Addigala Rail station	230	2017	10.7	East1
108	Addigala Rail –Ayisha Rail Station	230	2017	47.6	East1
109	Ayisha Rail- Dewanle Rail station	230	2017	46.5	East1
110	Dewanle Rail-Djibouti Boarder	230	2017	3.9	East1
111	Raitu –Gode	230	2012	90	East2
112	Kaliti I-Gefersa	132	1997	25	Central 1
113	Gefersa-Minilik	132	2016	9.5	Central 1
114	Minilik-Addis North	132	2016	1.5	Central 1
115	Addis East II-Addis North	132	2005	9.9	Central 1
116	DerbaMidroc Tap-Debra Cement	132	1976	49.5	Central 1
117	Sululta -Dangote	132	2014	57	Central 1
118	Sebeta 1-Gefersa	132	2017	25	Central 1
119	Kaliti I-Kotobie(kaliti North tap)	132	1976	1	Central 1
120	Kaliti North Tap-kotobie 1	132	1998	18	Central 1
121	Kaliti I-Kotobie I(Weregenu Tap)	132	1976	18	Central 1
122	Woregenu tap-Cotobie 1	132	1984	4.5	Central 1
123	Woregenu tap- weregenu(bole)	132	1984	4.5	Central 1

124	Kotobie- Hayat	132	2016	10	Central 1
125	Ayat- legetafo	132	2016	3	Central 1
126	Legetafo- D/berhane	132	2012	94	Central 1
127	Kotobie-Addis East II	132	2005	5.5	Central 1
128	Kotobie-Addis East I	132	2017	8	Central 1
129	Gefersa- Mugher	132	1976	80	Central 3
130	Hormat-Guder Mobile tap	132	2020	0.4	Central 3
131	Ghedo-Hormat(Guder)	132	1990	33.99	Central 3
132	Gelan-Kality I	132	2014	14	Central 2
133	Gelan- Yesu	132	2014	9	Central 2
134	Kality- Yesu Turning Point	132	2004	18	Central 2
135	Kaliti I-Kaliti II Line Two(New)	132	2016	8	Central 2
136	Kaliti –Endode Rail 132KV	132	2016	5	Central 2
137	Koka-Adama II	132	2006	11.485	Central 2
138	AdamaII-Awash7kilo(metehartap)	132	2005	117.841	Central 2
139	Methra Tap-Methara	132	2005	0.05	Central 2
140	Adama II-Nazreth Methara-awash7kilo lilo	132	2020	7.72	Central 2
141	Koka-Awash II	132	1964	50	Central 2
142	Awash II-Awash III	132	1964	1.45	Central 2
143	Wonji tap-Wonji	132	1979	0.6	Central 2
144	Awash II-Asella	132	1979	51.2	Central 2
145	Awash II-Asela Wonji Tap	132	1979	6	Central 2
146	Gelan-Koka(D/Zeit II Tap)	132	2014	116	Central 2
147	D/Zeit II Tap-D/Zeit II	132	2014	0.05	Central 2
148	Koka-Gelan Modjo Mobile Tap	132	2014	65	Central 2
149	Elala Geda Tap	132	1990	4.9	Central 2
150	Koka-Gelan line Kanoria lilo	132	2014	13	Central 2
151	Adama Wind I-nazret II	132	2010	4.8	Central 2
152	Methara SS-Melka Jilo TS	132	2017	48	Central 2
153	MelkaJilo TS_Methara TS	132	2017	1.53	Central 2
154	Methara TS-Awash TS	132	2017	29	Central 2
155	Awash TS-Awash 7kilo SS	132	2017	2.4	Central 2
156	Nazret II SS-Mojo TS	132	2017	14.9	Central 2
157	Modjo TS-Wolenchiti TS	132	2017	33.94	Central 2
158	Wolenchiti TS-Awash II PP	132	2017	28	Central 2
159	Kaliti I-Addis Center	132	2001	14	Central 2
160	Kaliti I-Kaliti GIS	132	2016	5.8	Central 2
161	Kaliti GIS-Kaliti II	132	2016	7	Central 2
162	Kality II-Nifasilk	132	2016	7	Central 2
163	Kaliti I-Mekenisa	132	2016	16	Central 3
164	Mekenissa-Sebeta I	132	2007	7.81	Central 3
165	Mekenisa-Gofa I(Addis South)	132	2007	1.29	Central 3
166	Sebeta I-Addis West	132	2007	12	Central 3

167	Addis West-Tikur Anbesa	132	2017	11	Central 3
168	Repi/Koshe-Kaliti Mekenisa Lilo	132	2018	6	Central 3
169	Asella –Adami Tulu	132	1980	50.96	Central 3
170	Adami Tulu-Butajera	132	2003	46.78	Central 3
171	Butajira- Bu'ee	132	30		Central 3
172	T/Abay-Bahidar-II(Double Ckt)	132	1999	57.92	North West
173	Mekelle-Adigrat	132	1998	90.332	North
174	Wukro Tap-Wukro	132	1999	1.168	North
175	Mekele-Adama	132	2006	117	North
176	Mekelle-Mesobo	132	1999	5.08	North
177	Axum-Adwa	132	2018	32.52	North
178	G/Gibe I Sub(omo)-Hossaina	132	1986	15	SW&SE
179	G/Gibe HPP I-Jima	132	1987	71.32	SW
180	Jimma II-Jimma I	132	2017	7	SW
181	Jimma 2-Aba	132	2017	66.67	SW
182	Jimma-Bonga	132	2005	102.48	SW
183	Bonga-Mizan	132	2005	88.3	SW
184	G/Gibe old-G/Gibe I	132	1994	2.6	SW
185	Ghedo -Nekemte	132	2000	115.89	West
186	Nekemte -Gimbi	132	2000	84.29	West
187	Nekemte-Bedele	132	2005	116	West
188	Gimbi-Mendi	132	2005	84	West
189	Mendi-Asossa	132	2005	84	West
190	Nekemte-Gidayana	132	2012	94	West
191	Mendi-Gidami	132	2018	148	West
192	Kombolcha-II-Kemise	132	2016	34	NE 1
193	Kemise –Shoarobit	132	2016	86.12	NE 1
194	D/Berhane-Shoarobit	132	1985	57.49	NE 1
195	Kombolcha I-Kombolcha II	132	2002	11	NE 1
196	Aqesta-Alem Ketema	132	2012	150	NE 1
197	Kombolcha I-Akista	132	2006	82	NE 1
198	Alaba-Shashemene	132	2017	63	South 1
199	Alaba-Hawassa II	132	2017	60	South 1
200	Shashamene –Adami Tullu	132	2000	76.82	South 1
201	Shashamene-Hawassa II-Awassa I	132	1979	21.6	South 1
202	Hawassa-Yirgalem	132	1985	35	South 1
203	Yirgalem -Shakisso	132	1986	133.21	South 1
204	Shashemene-M/Wakena	132	2002	119.19	South 1
205	Yirgalem- Dilla	132	2006	39.71	South 1
206	Dilla-H/Mariam	132	2006	94.59	South 1
207	H/Mariam-Bukulu Boma	132	2011	226	South 1
208	M/Wakena-yadot	132	2013	167	South 1
209	Alaba-W/Sodo I-Sodo II	132	1983	61.81	South 2
210	W/Sodo-Arbaminch	132	1986	109.13	South 2

211	W/Sodo-Sawla	132	2007	124	South 2
212	Sawla -Keyafer	132	2013	93	South 2
213	Awash 7Kilo-Miesso Tap	132	1997	201.49	East 1
214	Measo Tap-Asebe Teferi II	132	2008	52	East 1
215	AsebeTeferi- Afdem Rail Station	132	1997	56.13	East 1
216	Afdem rail –Gota-Station	132	1997	33.14	East1
217	Gotra Rail-Hurso SS	132	1997	39.24	East1
218	Hurso-DD#4 Tap	132	2019	17.66	East 1
219	DD#4 tap-DD#4 SS	132	1997	1.9	East 1
220	DD#4 Tap-DD III	132	1997	3.6	East 1
221	DD III-DD I	132	1960	4	East 1
222	DD III-DD II	132	1994	12.35	East 1
223	DD II-Harar III	132	2005	43.81	East 1
224	Awash-Sirba Rail Station	132	2017	30.02	East 1
225	Sirba rail-Mieso rail Station	132	2017	42.1	East 1
226	Mieso rail- Asebeteferi	132	2017	19.2	East 1
227	Diredawa 1 –DD National cement	132	1997	3	East 1
228	Harar III-Jigjiga II	132	2005	95.09	East 2
229	Harar III- Fik	132	2012	154	East 2
230	Jigjiga-Degahabur	132	2019	205	East 2
231	Gode-Kebri Dehar	132	2019	175	East 2
232	H/Mariam-Bukulu Boma-Yabelo T	132	2020	4.696	South 1
233	Awash-Miesso Tap	132	2008	90	East
234	Yirgalem 2-Dilla(Tap Point)	132	2020	8.2	South 1
235	Dedessa-Holata Line 1	500	2018	240	Central 1 and West
236	Dedessa –Holata line 3	500	2018	240	Central 1and West
237	GRED-Dedessa line GA1	500	2017	687.9	West
238	GRED-Dedessa line GB 1	500	2017	686.14	West
239	Dedessa-Holata Line 1	500	2018	312	West
240	Dedessa-Holata line 3	500	2018	310	West
241	Wolayita (T.no 593-kenya –kenya boarder)	500	2022	159	South 2
242	Wolayita (T.no 1-592)-Kenya boarder	500	2022	265.6	South 2

Table E.2: Ethiopian Power Substation under operations (2025 G.C)

No	Name of power substation	Voltage(KV)	In service(EC)	Location
1	Addis Center	132	1999	Addis Abeba
2	Addis East	132	2017	Addis Abeba
3	Addis East II	132	2005	Addis Abeba
4	Addis North	132	1984	Addis Abeba
5	Addis South II [Gofa]	132	2007	Addis Abeba
6	Addis West	132	2017	Addis Abeba
7	Anfomeda	230	2016	Addis Abeba
8	Ayat	132	2016	Addis Abeba
9	Bole Lemi I	132	2021	Addis Abeba
10	Bole Lemi II	230	2020	Addis Abeba
11	Kotobie	230	1976	Addis Abeba
12	Eiz	230	2015	Addis Abeba
13	Gefersa	230	1997	Oromia
14	Gelan	400	2014	Oromia
15	Kaliti I	230	1966	Addis Abeba
16	Kaliti II	132	1996	Addis Abeba
17	Kaliti New	132	2016	Addis Abeba
18	Kaliti North	132	2015	Addis Abeba
19	Kanoria	132	2017	Oromia
20	Kilinto	230	2021	Addis Abeba
21	Koye Abo	400	2021	Addis Abeba
22	legetafo	230	2012	Oromia
23	Mekanisa	132	2016	Addis Abeba
24	Minilik New	132	2016	Addis Abeba
25	Nifassilk	132	2016	Addis Abeba
26	Nifassilk GIS	132	2016	Addis Abeba
27	Reppie EFW	132	2018	Addis Abeba
28	Sebeta I	230	1966	Oromia
29	Sebeta II	400	2009	Oromia
30	Shegole	230	2019	Addis Abeba
31	Sino Steel	230	2018	Amhara
32	Sululta	400	2010	Oromia
33	Tikur Anbesa	132	2018	Addis Abeba
34	Weregenu	132	1984	Addis Abeba
35	Yesu	132	2004	Addis Abeba
36	Endode Ts	132	2017	Addis Abeba
37	Sebeta Ts	230	2016	Oromia
38	Adama I wind farm	132	2012	Oromia
39	Adama II	230	2022	Oromia
40	Adama II Wind farm	230	2015	Oromia
41	Adami tulu	132	2007	Oromia

42	Asella	132	1977	oromia
43	Awash 7Kilo	230	1984	Afar
44	Awash 7kilo	230	2004	Afar
45	Awash II	132	1966	Oromia
46	Awash III	132	1968	Oromia
47	Awash Ts	132	2017	Afar
48	Buei	132	2021	Oromia
49	Butajira	132	2003	South
50	Chancho	230	2017	Oromia
51	Dangote	132	2016	Oromia
52	D/Berhan	132	2014	Amhara
53	D/berhan II	230	2018	Amhara
54	Debrezeit II	132	2016	Oromia
55	Debrezeit II	400	2021	Oromia
56	Derba	132	2011	Oromia
57	Dukem II	230	2015	Oromia
58	Gebreguracha	400	2017	Oromia
59	Ginchi	230	2021	Oromia
60	Guder	132	-	Oromia
61	Habesha Cement	132	2018	Oromia
62	Holeta	500	2017	Oromia
63	Hormat(Guder)	132	1991	Oromia
64	Ilala Geda	132	1984	Oromia
65	Koka	132	1960	Oromia
66	Melka Wakena	230	1986	Oromia
67	Melka Wakena Yugo	230	1986	Oromia
68	Metahara	132	2017	Oromia
69	Methara Ts	132	2017	Oromia
70	Modjo	132	2017	Oromia
71	Modjo II	230	-	Oromia
72	Modjo Ts	132	2017	Oromia
73	Mugher	132	1976	Oromia
74	Nazret II	132	2006	Oromia
75	Tulefa	132	-	Amhara
76	Wolenchiti	132	2017	Oromia
77	Wolkite	230	2003	South
78	Wonji	132	1999	Oromia
79	Wonji Sugar II	132	2018	Oromia
80	Adigala	230	2011	Somali
81	Adigala TS	230	2017	Somali
82	Afdem	132	2017	Somali
83	Asebe Teferi II	132	2000	Oromia
84	Ayisha II	230	2022	Somali
85	Ayisha Ts	132	2017	Somali

86	Dawanle	230	2017	Somali
87	Degahabour	132	2020	Somali
88	Dire Dawa I	132	1960	Dire Dawa
89	Dire Dawa II	132	1994	Dire Dawa
90	Dire Dawa III	230	1997	Dire Dawa
91	Dire Dawa IV	132	2022	Dire Dawa
92	Dire Dawa national cement	132	1997	Dire Dawa
93	Fik	132	2012	Somali
94	Gode	230	2012	Somali
95	Gota	132	2017	Somali
96	Harar III	132	2005	Harere
97	Hurso	230	2016	Somali
98	Hurso Ts	230	2017	Somali
99	Jigjiga I	132	2005	Somali
100	Kebridehar	132	2020	Somali
101	Lonni Ts	230	2017	Somali
102	Melka Jilo	132	2017	Oromia
103	Mieso Ts	132	2017	Oromia
104	Milo Ts	230	2017	Somali
105	Sirba Onkur	132	2017	Somali
106	Abi Adi	132	-	Tigray
107	Adigrat	132	1998	Tigray
108	Adwa	132	2010	Tigray
109	Alamata	230	1999	Tigray
110	Ashigoda Wind farm	230	2006	Tigray
111	Axum	230	2012	Tigray
112	Humera	230	2012	Tigray
113	Mehoni	230	2016	Tigray
114	Mekele	230	2007	Tigray
115	Mesobo	132	1999	Tigray
116	Shire	230	2006	Tigray
117	Tekeze	230	2009	Tigray
118	Wolkayit	230	2019	Tigray
119	Wukro	132	1999	Tigray
120	Afdera	230	2022	Afar
121	Akesta	132	2006	Amhara
122	Alem Ketema	132	2012	Amhara
123	Kombolcha I	132	2013	Amhara
124	Kombolcha II	230	2011	Amhara
125	Dicheto	132	2017	Afar
126	Gashena	230	2010	Amhara
127	Kemise	132	2016	Amhara
128	Semera	230	2010	Afar
129	Shoa Robit	132	1985	Amhara

130	Woldiya	132	-	Amhara
131	Azezo	230	2002	Amhara
132	B/dar II	400	2011	Amhara
133	Beles	400	2011	Amhara
134	D/Markos	400	2011	Amhara
135	D/tabor	230	-	Amhara
136	Jawi	132	-	Amhara
137	Metema	230	2008	Amhara
138	Mota	230	2006	Amhara
139	Nefas Mewucha	230	2010	Amhara
140	Tis Abay II	132	2001	Amhara
141	Arbaminch	132	2006	South
142	Bukula Goma	132	2011	Oromia
143	Dilla	132	2006	South
144	Genale Dawa III	400	2019	Oromia
145	G/Gibe III	400	2009	South
146	Hageremariam	132	2006	South
147	Halaba	230	2015	South
148	Hawas I	132	2016	South
149	Hawassa II	230	2019	South
150	Hosana	230	2009	South
151	Keyafer	132	2013	South
152	Raytu(Ramo)	230	2012	Oromia
153	Sawla	132	2007	South
154	Shakiso	132	1988	South/Oromia
155	Shashamene	132	2002	Oromia
156	Wolayita III(Convertor Station)	500	2021	South
157	Wolayita I	132	2013	South
158	Wolayta II	400	2016	South
159	Yabelo	132	2018	Oromia
160	Yadot	132	2013	Oromia
161	Yirgalem I	132	2006	South
162	Yirgalem II	400	2019	South
163	Aba	132	2007	Oromia
164	Agaro	230	1989	Oromia
165	Bedele	230	2006	Oromia
166	Bonga	132	2006	South
167	Gambella II	230	2010	Gambela
168	G/Gibe I	230	2004	Oromia
169	G/Gibe I(Old Gibe)	132	1987	Oromia
170	Gibe new(Sokoru)	400	2009	Oromia
171	G/Gibe II	400	2009	South
172	Jimma II	230	2017	Oromia
173	Jimma I	132	1987	Oromia

174	Metu	230	1990	Oromia
175	Mizan	132	2005	South
176	Asosa	132	2006	Benishangul
177	Bako	132	-	Oromia
178	Dedesa	500	2017	Oromia
179	Fincha	230	2003	Oromia
180	Fincha II	230	2012	Oromia
181	Ghedo	230	2006	Oromia
182	Gidami	132	2018	Oromia
183	Gidayana	132	2011	Oromia
184	Gimbi	132	2001	Oromia
185	Grand Renaissance	500/400	2017	BeniShangul
186	Mendi	132	2006	Oromia
187	Nedjo	132	2021	Oromia
188	Nekemte	132	2001	Oromia
189	Neshe	230	2011	Oromia
190	Shambu	230	2022	Oromia
191	Gorga Shoe	132	-	Oromia
192	Wuda	132	2022	Oromia