Addis Ababa University

Addis Ababa Institute of Technology

School of Electrical and Computer Engineering

Prevention of Blackout Using an Automated SCADA System in Case of EEP

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Declaration

I declare that, this thesis represents my own work, except where due acknowledgement is made, and that it has not been previously submitted to this university or to any other institution for a degree or other qualification**.**

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Abstract

Nowadays the stability, reliability, sustainability and security of power system are the main concerning issues in Ethiopia because of frequently happening disturbances which will lead to total or partial power system blackout. When disturbances occur in power grid, monitoring and controlling of a power system are required to stop the grid degradation, restore it to a normal state, and hence minimize the effects of disturbances. However, in wide area power grid resulting from large and complex interconnection of power system network, classical systems based on manual operation and decisions are not able to rapidly respond for disturbances, which may cause a local or complete system collapse. Therefore the introduction of automated SCADA system with advanced measurement and very fast communication technologies provide better ways to detect rapidly the disturbances and protect the overall grid from the propagation of the fast cascading outages. Automation system improve the performance by taking advantage of faster computer control instead of human reaction times and also used to increase the efficiency of control by trading off high personnel costs for low computer system costs.

This thesis presents the design of an automated SCADA system that can prevent the grid system from blackout in real time through active and reactive power balancing. Active power and reactive power of the system are the most essential parameters in the monitoring, control, and protection of power systems and electric equipments because when a fault or a significant disturbance occurs in a power system, the frequency and voltage varies in time and space.

A modeling of electrical system elements was developed to have a complete one line diagram of the existing network using DIgSILENT power factory software version 15.1. The study has employed conventional power flow and dynamic analysis for assessing the stability and reliability of the system. Different type of faults has been used for the analysis, which leads the system to cascade outage. Finally, to mitigate these problems, necessary control measures have been presented. The result shows that whatever any disturbance experienced to grid has been controlled automatically without operator intervention and lead to normal operation condition. From the test results, the proposed technique presents better controlling method in comparison with that of the existing manual based control system in black out mitigation along with improvement in stability of the system.

The method is implemented on the whole EEP grid and tested on specifically for northern and north western region.

Key words: SCADA, RTU, Blackout, EEP and DIgSILENT.

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List of Abbreviations and Symbols

Abbreviations

EEP	Ethiopian Electric Power.
SCADA	Supervisory Control and Data Acquisition.
RTU	Remote Terminal Unit.
PLC	Programmable Logic Controller.
MTU	Master Terminal Unit.
HMI	Human Machine Interface.
AGC	Automatic Generation Control
LDC	Load Dispatch Center.
EMS	Energy Management System.
EEU	Ethiopian Electric Utility.
HPP	Hydro Power Plant.
CT	Current Transformer.
VT	Potential Transformer.
ACE	Area Control Error.
AVR	Automatic Voltage Regulator.
IED	Intelligent Electronic Devices
LAN	Local Area Network.
SLD	Single Line Diagram.
HPP	Hydro Power Plant
GERD	Grand Ethiopian Renaissance Dam
BB	BusBar

Symbols

MW	Mega Watt
KV	Kilo Volt
Q	Reactive Power
HZ	Hertz
ϖr	Rotor Speed
B	Frequency Bias
KA	kilo Ampere
K	Gain
P.U	per Unit
X	Inductance
α	Alpha (constant)
P_{Gi}	Real power generation at bus i
P_D	System demand
P_{Loss}	Total real power loss
Q_G	Reactive power generation at bus i
Q_D	Reactive power demand
Q_{Loss}	Total reactive power loss
$\|V\|_k$	Voltage magnitude at bus k
N_g	Number of generators
N_b	Number of buses
P	Active power
$\|V\|_k^{min}$	Minimum voltage magnitude
P_{Gi}^{min}	Minimum generator output power
P_{Gi}^{max}	Maximum generator output power
$\|V\|_k^{max}$	Maximum voltage magnitude
Q_{Gi}^{min}	Maximum generator reactive power limit
Q_{Gi}^{max}	Minimum generator reactive power limit
MVar	Mega var

CHAPTER ONE

INTRODUCTION

1.1 Back Ground

The history of electricity goes back as far as 1820, when the British scantiest Michael Faraday discovered that a changing magnetic flux creates an electric field. Currently, electricity is a critical infrastructure and have been characterized as the largest man-made systems. It finds innumerable uses in home, industry, agriculture, transport, defense, aviation, public center, etc. Electrical energy is not only for doing desired activities but also to improve quality of life of the peoples. In general life without electricity is now unimaginable [1].

Even though, it is a critical infrastructure, the power systems operated by the utilities in countries especially in developing countries suffer from a large gap between demand and generation, inadequate transmission capacity, and non-uniform location of the load centers and generating stations. Occurrences of faults in such systems, in most of the cases, end up in complete interruption of electricity supply to all consumers in a large area. A long-term complete interruption is extremely expensive and is considered as national disaster. Direct impacts include lost production by industrial and commercial firms, safety, etc. Indirect costs include secondary effects on firms unable to conduct business with blacked-out firms, public health and looting [2] [3] [4].

Much effort has been made to improve the reliability of power systems against complete interruption (blackout), many researches have been conducted, different methods are used to be utilized and promises to end blackouts have been made for decades, but they ignore the reality that complex systems built and operated by humans will fail. The power system owned by Ethiopian electric power (EEP), the sole public utility for generation and transmission in Ethiopia, has evolved to a vulnerable position. The main reasons are engineering faults, ineffective communication, and inability of system operators. And also the fact that electricity supply has special and unique as compared to other types of industry. The end product has to be delivered instantaneously and automatically upon the consumer's demand [5] [6].

When disturbances occur in power grid, monitoring, control and protection systems are required to stop the grid degradation, restore it to a normal state, and hence minimize their effects. However, for a more vulnerable system like the Ethiopian grid, classical systems based on manual operation and decision are not able to rapidly respond for the power grid disturbances and are not able to avoid the blackout. The introduction of the automated SCADA system, advanced measurement and smart communication technologies provide a better ways to detect rapidly the disturbances and protect the overall grid from the propagation of the fast-cascading outages to avert a blackout in real time. Automation systems are used to increase the efficiency of control by trading off high personnel costs for low computer system costs. And also contribute to improve performance by taking advantage of faster computer control instead of human reaction times [7] [8].

SCADA systems are highly distributed systems used to control geographically dispersed assets, often scattered over thousands of square kilometers, where centralized data acquisition and control are critical to system operation. It is extensively used electrical power grids systems due to the ability to control of geographically dispersed generation and substation sites through field devices (RTU, PLC). A SCADA control center performs centralized monitoring and control field devices over long-distance communications networks. Based on information received from remote stations, automated or operator-driven supervisory commands can be pushed to remote station to control field devices. Field device (RTU-Remote Terminal Unit) control local operations such as opening and closing breakers, collecting data from sensor systems, and monitoring the local environment.

SCADA encompasses the collecting of the information via a RTU, transferring it back to the central site, carrying out any necessary analysis and control and then displaying that information on a number of operator screens or displays. A SCADA system gathers data from sensors and instruments located to remote sides. Then, it transmits data at a central site for controller monitoring process. SCADA system consists of one or more field data interface devices (RTUs or PLCs).A communication system such as radio, telephone, cable, satellite, etc., a central host computer sever or severs (also called a SCADA center, or Master Terminal Unit (MTU)) and a collection of standard and/or custom software (Human Machine Interface (HMI)). Remote Terminal Unit (RTU), also called a remote telemetry unit, is special purpose data acquisition and control unit designed to support SCADA remote stations. RTUs are field devices often equipped with wireless radio interfaces to support remote situations where wire-based communications are unavailable. Sometimes PLCs are implemented as field devices to serve as RTUs; in this case, the PLC is often referred to as an RTU [9] [10] [11].

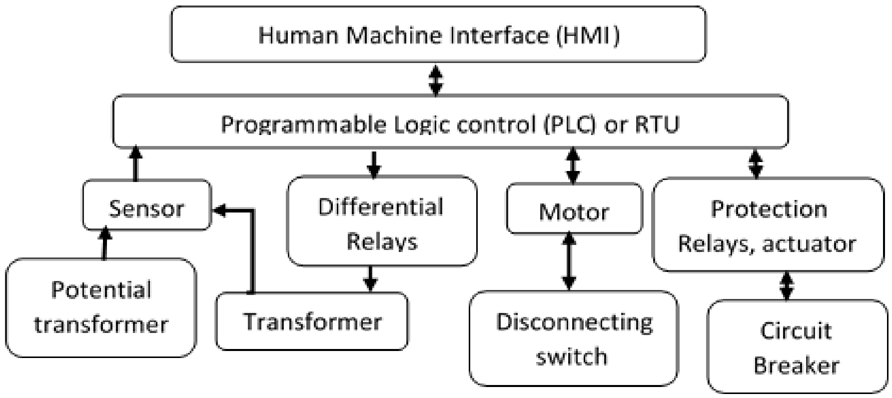

Figure 1.1 Block diagram of simple substation RTU [7]

The remote terminal unit (RTU) is able to send a switching signal to the circuit breaker through a Suitably designed actuator. The circuit breaker is also able to send its position (ON or OFF) through the RTU and the same microwave link to the operator's panel. The older type of hardwired panel is largely being replaced by electronic displays and the controller is able to receive and view system status through touch panel capabilities or through networked computers in the control room.

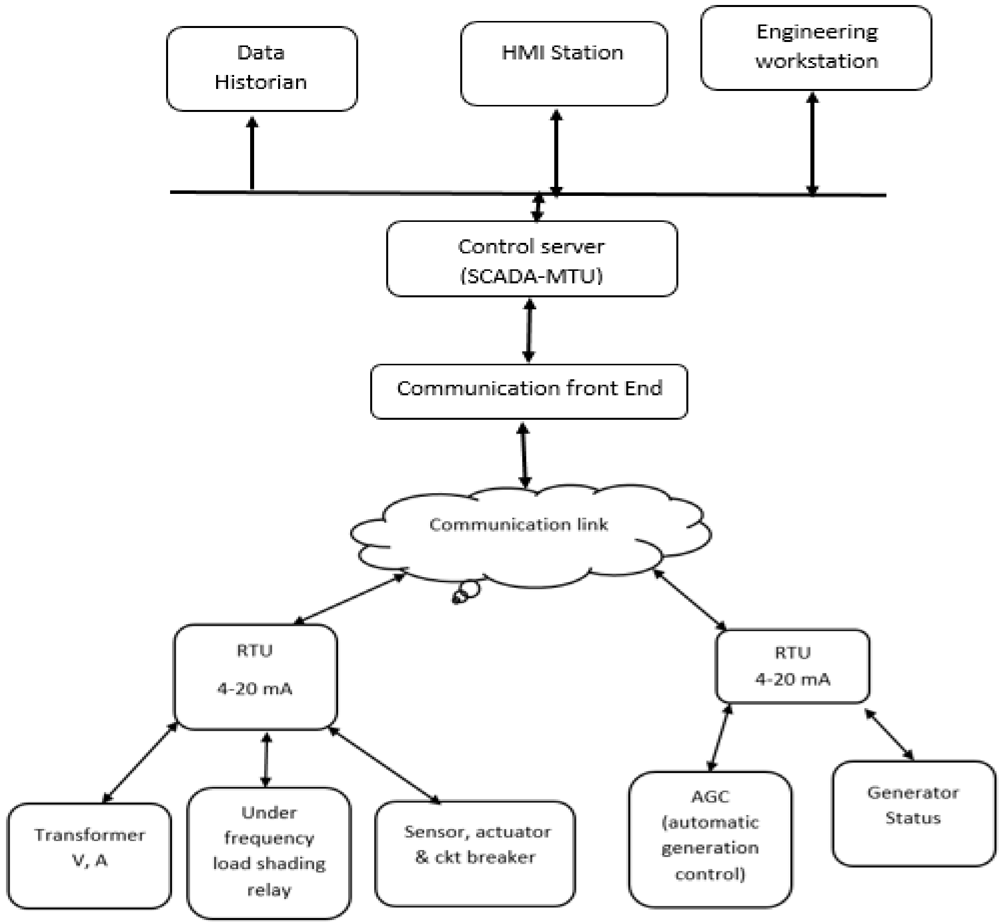

Figure 1.2 Generalized simple SCADA system

Upon occurrence of a fault on a line or at a bus or in any part of a grid system, the balance between the mechanical power input to and the electrical power output from the synchronous generators is affected. As a result, the rotor angles vary indefinitely from each other. Then the output frequencies of the machines, the power flows in the lines, and the voltages at the buses are subjected to non-diminishing swings resulting in cascaded outages in the system, which is the manifestation of the blackout phenomenon.

If this happens to the system, The automatic local devices used for fault clearing, load shedding and generation ejection AGC (automatic generation control) or governor are triggered instantaneously just prior to the blackout to disconnect the faulty area and load or generation in several steps from the feeders until the system frequency meets the desired or predefined or normal value [12] [13].

1.2 Problem Statement and Motivation

The reliability of delivering electricity to customers without interruptions and within acceptable levels of frequency and voltage regulation is an essential aspect of operating a bulk electric power system. It is also required to provide for power delivery while withstanding possible disturbances and equipment failures.

It is very clear that, we are suffered by very frustrate and frequent power cut that deteriorate our living standard and growth of our country. Ethiopian Electric power (EEP) has been running a Load Dispatch Center (LDC), which is tasked with the responsibility of an optimal power dispatch and eliminate the frequent power cut because of disturbance through automated operation. However, to date most operational decisions are done manually. Under such circumstance, integrated energy management (EMS) and power system dispatch become more challenging as more and more plants, substations and load centers with different technologies are to be added in coming years. According to the data sourced from EEP, the Ethiopian grid suffered by a blackout to darken millions of homes. And still now protecting of the grid system from blackout is a challenging task for real time operators. To provide an efficient, reliable and stable power supply to the customer throughout the country, the power operator should have to supervise the overall system performance and system disturbance to be occurred.

As one of the nation's most complex, large-scale networked systems, electric power has become increasingly automated in the past decades due to technological advances. But the advanced automated technology is still new in Ethiopia even if we have a SCADA system installed by French firm called AREVA.

In Ethiopian grid system remote stations (generation, distribution & substation) has to be supervised manually by phone from load dispatch center (LDC) real time operators and it is real that complex systems operated by this way will fail. So the intent of this application note is to present a defense mechanism against successive disturbances (mostly end up with blackout) frequently happened in EEP using automated SCADA and smart communication systems. The application of automated SCADA in power system improves the overall efficiency of the system by providing the supervision and control over the generation, transmission and distribution systems. SCADA in the power system network increases the system's reliability and especially stability for integrated grid operation because stability of such system is of a great concern, since it is subjected to different disturbances that may cause a local or complete system collapse if no adequate actions are taken to prevent it. Automating electrical distributions systems by implementing a supervisory control and data acquisition (SCADA) system is the one of the most cost-effective solutions for improving system performance.

1.3 Significance of the Study

It will result to me a good understanding of the operation and control of SCADA based complex power system. And mainly, the study will help the power operators to provide a sustainable, reliable, stable and uninterrupted power supply to respected customers through efficient energy management system in an optimal way. It is also possible to identify potential vulnerabilities and potential solutions. In addition the findings of this study could also provide useful lessons for power system operators regarding the power sector.

1.4 Objective of the Thesis

1.4.1 General Objective

The prime objective of this M.Sc. thesis work is to study, design, evaluate and simulate the automated SCADA system for EEP that helps to prevent the grid system from blackout and presents methodology for the system to survive the grid from large disturbances.

1.4.2 Specific Objective

The study in this thesis will address the following specific objectives:

- To critically analyze and understand the basic operation principles of SCADA control system in power network.
- To critically review the existing methods for determining and evaluating energy management and disturbance controlling systems.
- To assess and propose some technological measures to avert blackout in EEP's generation and substations.

1.5 Scope of the Study

The scope of this thesis is to study, design, simulate and evaluate the automated SCADA control system for EEP. The performance analysis in this thesis work has been carried out based on the simulation of proposed work using appropriate software.

1.6 Methodology

In order to achieve the main aim of the study there are various procedural tasks followed by the author. And the following formal methodologies will be followed subjected to changes if need be in the due course of the work.

- Literature Review: The work of this thesis is necessarily based on what has already been done by other scholars related to this selected topic. So as to look into the works of these scholars and get necessary and important information related to the topic; different literatures will be referred from different available sources such as books, papers, journals, internet, etc. Therefore the literature review includes reading books, articles, papers, journals, simulation tools and searching internet related to SCADA based power system control.
- Data Collection: Due to the fact that the successfulness of this research is determined by the required data, various data will be collected from EEU and EEP and verification of data at the site is performed. This is followed by studying the major causes of disturbance and blackout. And also methods of mitigating or avoiding this problem based on the system we have will be revised.
- Then study and analysis of the collected data will be undertaken.
- Based on the result of the analysis evaluation and design will be done and simulated using DIgSILENT software.
- Then after analyzing the designed system, the whole work of the thesis will be concluded by suggesting implied recommendation on the area.

1.7 Organization of Thesis

This thesis is organized under six chapters which are briefly summarized as shown below. In the first chapter introduction of blackout and SCADA system has been discussed and also describes objective, statement of the problem, scope and methodology of the research.

Chapter 2 Presents definition and description on theoretical background and literature survey required to understand the concepts of System blackout, cause of system blackout, impacts of system blackout and prevent mechanisms that was taken by power system operators.

Chapter 3 Provides the details of power system control, mathematical calculation, specific techniques and variables to be controlled.

Chapter 4 In This chapters modeling and design of SCADA system has to be done to prevent and mitigate system blackout in Ethiopia.

Chapter 5 and 6 explains the simulation and conclusion of the thesis and also recommendation will be presented.

CHAPTER TWO

THEORETICAL BACKGROUND AND LITRATURE REVIEW

2.1 Theoretical Background

The purpose of this chapter is to provide the necessary background and literature survey required to understand the concepts of power System blackout, cause of power system blackout, impacts of power system blackout and review of black outs in Ethiopia.

Blackout is a total power failure over a large area, usually caused by the failure of major generating equipment or transmission facilities. Major blackouts of electric power systems in which many customers are left without power are rare events. However, the effects of blackouts, for instance, can be catastrophic for security of energy supply. It is the most severe form of power outage that occurs.

Depending on the root cause of the blackout, restoring power is often a complex task that utilities and power stations must undertake and repair time depend on the configuration of the affected electrical network.

2.2 Literature Review

This study has been focused on finding similar and comparable studies of the research problems for the thesis. Literature has been searched and different articles, books and previous master thesis have been revised, especially the literatures mentioned below have been in great favor.

When designing any system, it is important to learn from past research experience, which has resulted in many contrasting technologies with different strengths and weaknesses.

Different methods have been designed, devised and employed by different scholars over the world to prevent subsequent black out due to large disturbances among them,
S. Shahnawaz Ahmed [14] mentioned that the sole public utility for generation and transmission in Bangladesh, has evolved to a vulnerable position because of lack of funds for timely rehabilitation of the existing generation plants and transmission lines, and installation of new ones to meet

a demand that increases every year. So that the system facing drastic load shedding, lack of spinning reserve, low-voltage profile, and frequent disruptions varying from wide-area outages to total blackouts. Hence, there is a need to employ the way to prevent blackout in real time through controlled segregation of a system into a number of viable islands together with generation and/or load shedding. The nature and location of any fault that warrants such islanding can be ascertained in real time through monitoring the active-power (megawatt) flows at both ends of a number of pre specified lines.

Witchaya Pimjaipon, Tormit Junrussameevilai [15] discussed that the stability, reliability and security of power system are the concerned issues in Thailand due to the lessons from the blackout around the world in 2003. There is a need to employ blackout prevention plan by studying power system analysis (load flow and transient stability). And the analysis results will lead to understand the system problems as overviews and classified the problem according to the characteristics of the events. These results will be the direction to select the appropriate preventive mechanism for each problem.

Barkans J., Zalostiba D. [13] the authors of this paper presented that the existing protections employ diversified local intelligent devices. However, incessant blackouts evidence that these protections are sometimes insufficient. When analyzing the system blackouts it has been established that their development can include up to 12 various processes. So the management of a power system is based on the hierarchical principle that means more investment should be allocated for pre emergency to stop cascading events and pre- emergency guiding instructions should be implemented.

Sitinurainbinti Abdulkadir [16] has mentioned the problems of power system protection devices for contributing to system disturbance. Because the current major blackouts found that false tripping of these devices play an important role in initiating and propagating cascading events. He develop a technique based on fuzzy to reduce blackouts during emergency conditions. The first he analyze the power flow which is used to find the input data to apply to fuzzy technic. In the second stage, fuzzy logic method is used to detect the capability of power that should be shedding from the system in case of line outage happen in the power system. By using the proposed technique various power system blackouts may be prevented.

Xiaoming Wang, Wei Shao, and Vijay Vittal [17] this paper presented an appropriate control strategies to prevent blackout various preventive and corrective control strategies have been studied to cope with power systems in the different operational states. The authors are primarily focuses on the corrective control strategies for power systems under emergency and in extremis states. In this paper, two corrective control approaches (transmission system reconfiguration and controlled system islanding) have been investigated and new algorithms have been developed. When the system is in the emergency state, two reconfiguration strategies, line switching and bus-bar switching, have been presented to solve the problems of overloads or voltage violations.

Yusheng Xue [18] this paper describes the experiences, new requirements and prospects of security defense schemes for power systems in China. Adaptive optimal control schemes have served well for 2-3 years to periodically refresh the decision table for preventive control and emergency control to track operating conditions. After thoroughly investigating recent blackouts around the world, a wide-area measurement based defense scheme, named as Wide ARea Monitoring Analysis Protection-control (WARMAP) is proposed to against cascading blackouts. Its essentials are acquisition and integration of wide area measurements from RTUs, PMUs, fault recorders and protection systems, trajectory-based data mining and security analysis, adaptive optimization of preventive control, emergency control and restoration control, coordination among various stability controls. Based on relevant research achievements, such a scheme is well on the way to building in East China Power Grid.

Massoud Amin, Phillip F. Schewe [19] need to construct a smarter grid to prevent blackout and they deduce that the power grid must be made smarter. A self-healing smart grid can best be built if its architects try to fulfill three primary objectives. The most fundamental is real-time monitoring and reaction. The second goal is anticipation. The system must constantly look for potential problems that could trigger larger disturbances, such as a transformer that is overheating. The third objective is isolation if failures were to occur, the whole network would break into isolated “islands,” each of which must fend for itself. Each island would reorganize its power plants and transmission flows as best it could. But the grid would be costly, though not prohibitively so given historic investments.

Hamid Bentarzi [8] give an alternative view to stop the cascade outages due to large disturbance. When disturbances occur in power grid, monitoring, control and protection systems are required to stop the grid degradation, restore it to a normal state, and hence minimize their effects. However, in wide area power grid resulting from large extension and interconnection with neighbor grids, classical systems based on local independent measurements and decisions are not able to consider the overall power grid disturbances and then they are not able to avoid the blackout. The introduction of the advanced measurement and communication technologies in these systems may provide better ways to detect rapidly these disturbances and protect the overall grid from the propagation of the fast-cascading outages.

2.2 Electrical Blackouts: A Systemic Problem

During the first half of the last century, the electricity supply in most countries was provided by separate power systems whose failures were of a local nature. With the construction of large high voltage transmission lines, constant rise in demand for electricity and rise of power productions increases the connection of regions and the systems becomes complex. Highly interconnected power grid provides economic benefits and a greater level of service reliability. Unfortunately, interconnectivity gives rise to increased probability and vulnerability of cascading failures due to disturbances [13].

Disturbances to the electric power system are presented all the time, but they are not of equal likelihood, or of equal impact. Large disturbances are cascaded and lead the system to black out.

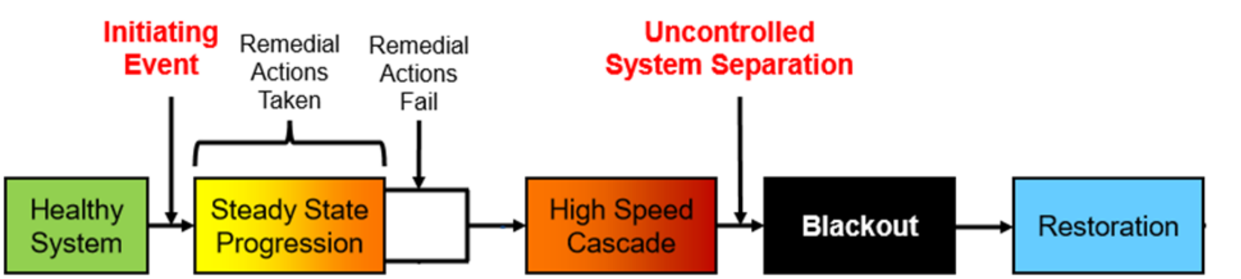

Figure 2.1 A generic path to blackout up to restoration

In the old good days, when the power system was very small, the vertically integrated monopoly power system management structure was more secure. The power industries were dedicated as service oriented and driven completely by the government. However, when the systems became large with increasing demand, managerial efficiency was reduced. Deregulation of power industries was introduced to improve their managerial efficiency. In this case, the power industries were forced to be driven by a commercially made market structure. This competitive market structure increased the system utilization. However, it also increased the risk on system operations by stressing the power systems and reducing the predictability of operations [20]**.** Further, interconnection with neighboring countries or sub systems made the network stronger. However, when the network covers large areas it increases the risk on external interferences. The possibility of having many disturbances at the same time or within a short time interval is also increased. Therefore designing the power system network to sustain N-l contingency, where normally the faulted system is expected to be restored within a maximum of 30 minutes, becomes unguaranteed to provide full security to the power system [21].

Nowadays the phenomena of Blackouts in power systems happen quite frequently. The causes which provoke these blackouts are varies such as equipment failure, weather conditions, vandalism, and human error [22]. The dominant causes triggering blackouts cannot be written in the equations of a software code. It is very difficult to written equations of a software code due to blackouts causes triggering state. Therefore, if we want to understand the global dynamics of power system blackouts, we need to emphasize the random character of the events that trigger them and the overall response of the system to such events [23] [24].

Blackout is considered as unexpected phenomena in electrical power grids because it happens without warning which makes effect analysis and modelling to be relatively complicated. Electric power utilities throughout the world therefore accept this fact and endeavor to meet customer demands as economically as possible at a reasonable service of reliability. To meet customer demands and reliable power system, the power utility has evolve to control the overall system performance and system disturbance to be occurred.

The first massive power failure in the history of power system operation was occurred in USA Northeast power on 9th November 1965 [25]. The main cause was the weak transmission line. At heavy loading conditions, the backup protection tripped one line out of five. This is mainly due to relay was set to low load level. Thus successively tripped other four lines and divert 1700 MW of power, which overloaded several other lines and finally the system was collapsed [26].

2.3 Causes of System Blackout

Electric power grid networks are complex systems that are commonly run near their operational limits. Such systems can undergo non-periodic major cascading disruptions that have serious consequences. Individually, these disruptions or blackouts can be triggered and escalated by specific causes. The possible causes of these disruption identified from literature survey and from review of past incidents are as listed below.

- Delay in fault clearance
- Tripping of large generating units
- Cascade tripping of transmission line(s) resulting from tripping of a heavily loaded transmission line
- Equipment failure
- Protection mal-operation
- Slow response of generating units
- Slow response of manual load shedding during low frequency
- Inclement weather (heavy rainfall, fog, dust storm etc.)
- Inadequate reactive reserves leading to voltage collapse
- Inadequate safety net in the form of under frequency, Under Voltage and Rate of Change relay load shedding
- Human error
- Combination of above events

2.4. Effect (Impact) of Power Blackout

The electric power grid is crucial for economic prosperity, and national security. Disruptions to electrical power grids paralyze the daily life in modern societies causing huge economic and social costs for these societies.

In a power system, a large-scale blackout rarely occurs and if it does, it causes enormous economic and social damages, including the security of the country. Catastrophic failures in power grid systems bring great inconvenience to people's living and very harmful for power industries.

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Blackouts have impacts that are both direct (the interruption of an activity, function, or service that requires electricity) and indirect (due to the interrupted activities or services). Examples of direct impacts include food spoilage, damage to electronic data, and the inoperability of life-support systems in hospitals and homes. Indirect impacts include property losses resulting from arson and looting, overtime payments to police and fire personnel, and potential increases in insurance rates. Direct and indirect impacts can be characterized by whether they are quantifiable in monetary terms (economic impacts); relate to the interruption of leisure or occupational activities (social impacts); or result in organizational, procedural, and other changes in response to blackout conditions (organizational impacts). Direct impacts can be avoided if the end-user has backup systems, but these have often proved unreliable. Indirect impacts may be partially mitigated through contingency planning, improved communications, customer education, social programs, and other planning approaches [4].

Estimating the costs of electric power outages is difficult and imprecise because the economic value of electric reliability to different customers is not well-understood. Only recently has much progress been made in developing economic values for reliability, including the development of analytical techniques for measuring or estimating the direct and indirect costs of actual and hypothetical outages.

2.5. Overview of power blackouts in Ethiopia

Ethiopia is Africa's 2nd most populist, fastest economic growth and hub of renewably energy source in the region. EEP operates and maintains more than 12 hydropower and three wind power plants distributed in different parts of the country with installed capacity of more than 4290MW, transmitted through a high-voltage transmission lines across the country, which covers more than 9,000km with varying voltage levels ranging from 400kV to 132kV; and more than 100 substations with the above mentioned voltage levels.

The interconnected system of EEP consists of large interconnected power systems with dispersed and geographically isolated generators and loads connected by long transmission lines. This poses high chances of disturbances and contingencies more and more frequently which affected the customers. Following the occurrence of these disturbances, the power system transmissions are loaded to their limits and the substations voltage deviate from the normal limit range thus making it susceptible to partial or total blackout under minor/major disturbances**.** Efforts are underway to reinforce the grid by deploying automatic control equipment, rehabilitating distribution transmission lines and increase production further but still there is a big problem to supply uninterrupted power to the customers. According to the data sourced from national grid control center (NGCC) the Ethiopian grid system experiences a partial and full black out 18 times in 2013, 14 times in 2014 and 12 times in 2015 i.e. every month or two months the Ethiopian grid experiences a blackout large enough to darken millions of homes. And the blackout I have assessed for this research work were summarized in the following tables.

2013

Date	Affected areas	Main cause (initial cause)	Power before blackout (MW)	Load lost (MW)
Jan 28 & Feb 3	Southern part of Ethiopia	Earth fault on Sebeta II_Gilgel gibe II 400kv transmission line due to natural or self-initiated desert fire under the transmission line	1,108	746
Mar 3	Southern & some part of central region	Earth fault on Gehdo_Geffersa 230kv transmission line at a location of 50.82 km from Gehdo substation due to old breaker.	970	542
Mar 6	Southern & some part of central region	Earth fault on Gehdo_Geffersa 230kv transmission line at a location of 50.82km from Gehdo substation due to old breaker.	1,334	735
April 22	all	Earth fault on Bahirdar_Markos 400kV transmission line at a location of 107 km from Bahirdar substation due to some one who wants to kill himself on the tower (commite a susiced).	1,247	1,090
April 26	All except Bahirdar, Gondar,Motta, D/Markos , Sekoru centeral region	Outage of all generating units at Tekeze hydro Power plant and the resulting immediate change in magnitude and diraction of power flow from Beless thrugh Bahirdar to Alamata 230kV transmisssion line caused a temprory earth fualt at a location of 121.6 km from Alamata substation.	1,036	895
May 22	Northern part of central region	Outage of Kality I_Sebeta I 230kV high voltage transmission line becuase of a short circuit fault.	868.1	476
May 25	All	Outage of Beless_Bahirdar II 400kV high voltage transmission line becuase of an Earth fault and the outage of all generating units at Beless Hydro Power Plant (HPP).	1,176.5	981.5

July 27	All	Outage of Bahirdar II_Alamata and at the same time the outage of Ashegoda_Alamata 230kV high voltage transmission line becuase of an Earth fault.	1,140	1,104
Sept 13	Most of central region	Total outage of all Auto transformers at Gefersa Substation and its cascaded outages.	1,247.82	1,220
Sept 20	Northern region	Total outage of all Generating units at Tekeze Power plant.	1,247.82	1,220
Oct 5	Most of central region	Total outage of all Auto transformers at Gefersa Substation and its cascaded outages.	1,247.82	1,220
Oct 7	Northern region	Outage of all Generating units at Tekeze Power plant.	1,247.82	1,220
Oct 24	All	The outage of Finchaa-Debre markos and Legetafo-Combolcha II 230KV transmission line due to earth fault and over current signals respectively.	702	680
Nov 12	Mostly central region	Outage of Sebeta I-Kality I and Sebeta I_Sebeta II 230kV transmission line due to earth fualt.	1,118.91	512.2
Nov 17	Southern and eastern region	Outage of Kality I 132kv busbar due to break down of phase -C Kality I_Kality II 132kv transmission line and falling on the busbar.	1,115.89	933.8
Dec 06	Northern re-gion	Outage of Combolcha II-Alamata and Debre Markos_Finchaa 230kV transmission line due to earth fualt.	1105.74	959.9

Table 2.1 EEP blackouts in 2013

2014

Date	Affected areas	Main cause (initial cause)	Power before blackout (MW)	Load lost (MW)
Feb 28	Central region	The 132KV Gefersa-Addis North Line tripped at 11:55 Hrs .This caused tripping of 132 KV Addis North- Addis east II line as this was the only line available to feed the load at Addis east II.	1,108	746
Feb 02	All	Outage of Kality I 132kv busbar due to break down of phase -C Kality I_Kality II 132kv transmission line and falling on the busbar.	1,279.51	1,259.5
Mar 08	all	Due to time synchronization problem and also due to lack of enough data in the SCADA/EMS it was challenging to know the root cause for the occurrence of the blackout.	1,399.54	1,325.5
April 03	All	Earth Fault Occurred on Gefersa- Addis north 132KV line 7.5Km from Gefersa substation. The conductor is found broken at this location.	1,169.21	1,124.2
April 05	Central region	Earth fault on Kaliti I - Sebeta I 230kv line.	1,091.61	591
May 07	Central region	Fault on Sebeta I – Klaiti I 230KV line as the fault current on this line is much higher than the others (which is 1.44KA on Phase C) and the other transmission lines might detect this fault and trip.	1,085.15	989.25
May 11	Northern and central region	Sebeta l- Kaliti l 230 KV tripped due to over voltage at 07:30 (local time).	970.06	542.12

June 08	All	Bahir Dar – Alamata 230KV line tripped at 12:24 and the breaker was opened at Alamata end whereas Bahir Dar Side did not tripped. Following the above event unit 4 of Beles generating unit tripped at 12:24.	1,113.22	996.04
June 17	Western region	Fault was detected on phase C of Finchaa – Ghedo 230KV line at 77.77 Km from Finchaa at 12:57 with a fault current of IC=1.812KA.	1,342.73	1,127.4
August 08	All	Beles – Bahir Dar 400KV line tripped at 23:17hrs with distance protection device fail and tele protection fail signal.	882.07	872.07
Sept 03	Northern and southern region	Outage of 230kV Fincha- Debre Markos line because of collapse of tower.	1,239.02	1,207.0
Oct 24	All	Failure of 110V DC Battery at Beles switch yard (spark is seen) and the resulting tripping of 400KV side of the generator transformers of all units and the complete isolation of Beles Power plant with a loading of 280MW.	1,079.71	1,079.7
Nov 05	Northern region	Fincha – Ghedo 230KV line tripped due to over current and earth fault at 12:30 hrs.	1,309.11	1,309.1
Nov 6	Central and northern region	Occurred at 23:58 is the observed fire on the bus bar coupler CT at Beles power plant and the resulting manual opening of the bus bar coupler by the operator’s action and then isolation of 3 units from the system.	826.5	816.5

Table 2.2 EEP blackouts in 2014

2015

Date	Affected areas	Main cause (initial cause)	Power before blackout (MW)	Load lost (MW)
Jan 15	1st and 2nd stage of under frequency at Addis Ababa region	The fault current on D/markos- Fincha line.	1,176	220
Mar 15	Except Bahir Dar and Gonder. All areas are affected	Outage of Bahir dar – D/markos 400 kv line with over current, outage of Bahir dar – Alamata 230KV line with over voltage and Mota – Bahir dar 230kv line due to over current.	983	560.31
April 22	All/Total black out	Earth fault occurred on Phase B of Finchaa – D/Markos 230KV line at 20:20 and the fault is cleared from D/Markos end whereas the fault was not cleared from Fincha End, which results in tripping of Fincha generating units by under frequency.	1,306.25	1,306.25
May 08	All	Transient Earth fault on phase B of Bahir dar-D/markos 230kv line & Bahir dar – Alamata 230 kv line which isolates Beles and Tekeze power plants from the system with load of 402.7Mw and 70MW consecutively.	746.38	746.38
May 26	Addis Ababa, Central, East, North east region	Tripping of Sebeta ll – Gibe ll 400kv line due to Earth fault causes to trip all units of Gibe II.	1,077.1	980
July 27	Except B/Dar, D/Markos, Mota, Gonder and Ghedo all are affected	Permanente earth fault on Sebeta II – G/Gibe II 400KV and transient earth fault on Sebeta I – Kaliti I 230KV lines.tree fallen on conductor suspected by LDC.	1261.21	370

August 14.	Except North West region and Ghedo all are affected	Fault on the incoming Geferssa – Addis Alem 45kv line flam is seen and t phase dropped to ground and burnt.	1,419.9	1,359.9
August 16	Partial of Addis Ababa and Central region, all parts of East, North and North East region were affected	Sebeta l transformer l (The transformer is disconnected at 22:50 when the flam is seen on 132KV side, after finishing the maintenance when the transformer is connected which causes the tripping of all 230KV lines and which results in partial blackout).	938.72	586.62
Nov 28	All network area were affected	Tripping of GERD – Beles 400KV line by earth fault at 12:15 Hrs.	1,318.04	395.4
Nov 29	All areas were affected	Because of false teleprotection command on Beles – Bahir dar 400kv line l.	1,081.32	1,081.32
Dec 11	All area is affected	Earth Fault on Mekanisa -Kaliti 132KV Earth Fault on Finchaa II –Finchaa I 230KV	880.62	880.62
Dec 25	All network areas were affected	Tripping of Bahir Dar II- Gonder II 230kv line by over voltage	838.96	838.96

Table 2.3 EEP blackouts in 2015

As we can see from the above Tables most of the disruption was mainly caused by earth fault due to natural and extreme weather conditions such as natural or self-initiated desert fire under the transmission line, heavy windy rain, fallen tree on the conductor and a failure of the transmission line. The disturbance due to the fault was then not limited to the transmission line only but propagated and cascaded to power plant due to bad defense mechanism (as LDC always recommended at the end of each report) such as old breaker, frequency relay malfunction, operators error at substation and poor communication between real time operator and remote operators. And the rest of disruption was triggered by outage of generating units, short circuit fault on high voltage transmission line, Tele control signal error and over current signal. Following the disruption the event cascade to the whole grid and the grid system collapsed by over voltage, over current, under frequency and over frequency.

The rapid cascaded line failures the system was jeopardize operator intervention to stabilize and restore critical generation station.

Restoration

After the system disturbance is occurred, fast restoration is an important task of power system operators. However, in case of EEP to restore an important loads took up to 30 minutes if it is minor disturbance but if it large disturbance it will took up to 12 hours. As we can see the restoration is too long because of:

- Communication (telephone) problem
- Switching problems on different substations and power plants.
- The operation problems in power plants, most of the power plants were having voltage at switch yard, but too late to synchronize.
- The power plants are after ideal run, they were not possible to give supply by line charging.
- The circuit breaker problem (The breaker is very important for synchronization)
- Synchronization cannot be carried out at all substations due to problem on the synchronoscop and also lack of knowledge how to synchronize and use synchronoscop.
- The system voltage was very high during restoration and it was one of the factor the lengthened the restoration.

In general EEP has a very bad defence mechanise against blackout. And the current protection system coordination will not save the grid from catastrophic failure because of:-

- There is no automatic defense system implemented to help the system operator during emergency conditions. Everything has to be done manually to limit a disturbance, which is most of the time is too late to save the system from partial or total blackout.
- Updated and confirmed protection setting data is not available also on some substations fault record information could not be collected from substation due to the luck of reading ability from protection relays.
- Operational warning limits on the SCADA are not valid. Which tricks the system operator to make wrong decision and also confusing.

- The available under frequency load shedding is not working very well.
- Voice & Data Communication system is so poor.
- Circuit Breaker operation performance is low due to aging and infrequent maintenance.
- Overload conditions most of the substations and transmission lines are now under overload situations.

CHAPTER THREE

POWER SYSTEM ANALYSIS AND CONTROL

3.1 Structure of the Power System

The term "power system" describes the collection of devices that make up the physical systems that generate, transmit, and distribute power. The function power system is to connect the power stations to the consumers' loads by means of interconnected system of transmission & distribution networks. The traditional architecture of Electrical Power Systems (EPS) is based on power generation, transmission, distribution and usage interconnected subsystems [27] [28].

Therefore an electrical power system consists of three principal components:

1. Power Station (Generation)
2. Transmission Lines and
3. Substations

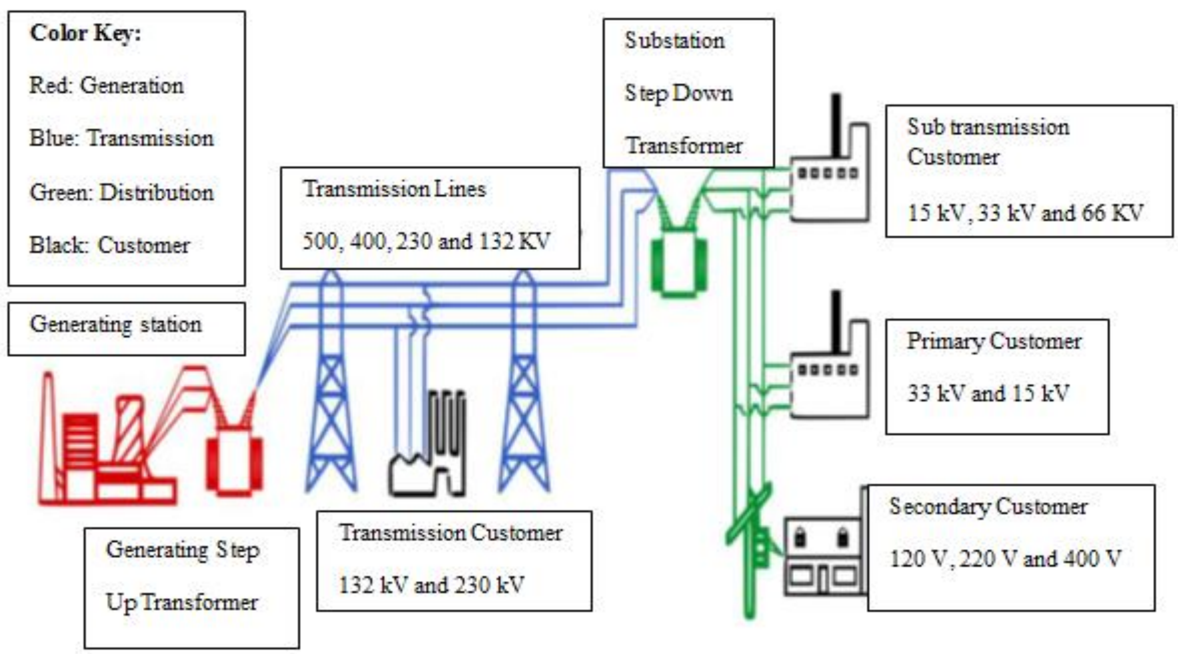


Figure 3.1 The basic structure of power system

As we can see from the above Figure, an electrical grid is an interconnected network for delivering electricity from suppliers to consumers. It consists of generating stations that produce electrical power, high-voltage transmission lines that carry power from distant sources to demand centers, and distribution lines that connect individual customers. Power stations may be located near a fuel source, at a dam site, or to take advantage of renewable energy sources, and are often located away from heavily populated areas. They are usually quite large to take advantage of the economies of scale. The electric power which is generated is stepped up to a higher voltage at which it connects to the transmission network.

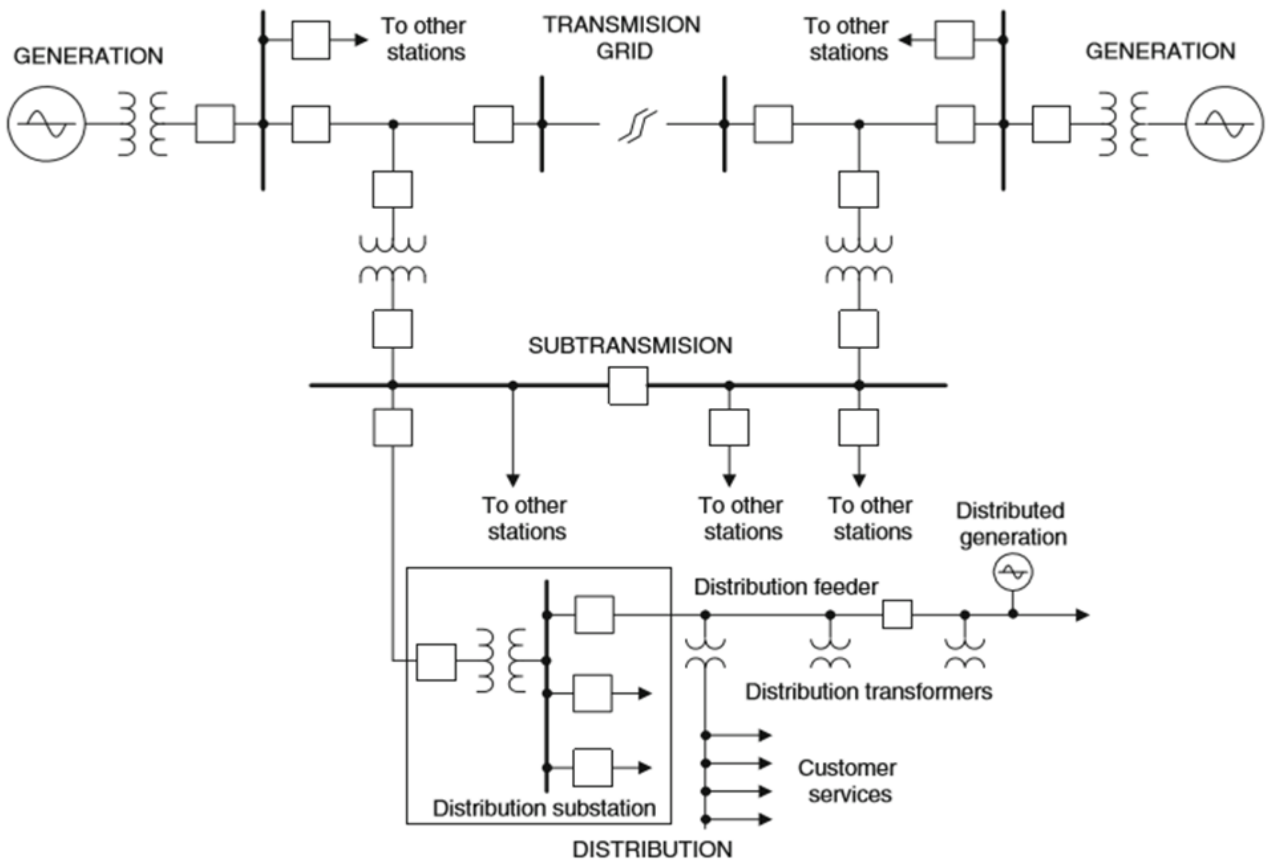


Figure 3.2 One-line diagram of power system from generation to consumption [29]

Even though electrical power system encompasses the above mentioned basic elements, I will give emphasis on substations because most control actions are takes place at substations to stabilize the system when the disturbance experienced to the system.

3.2 Substations

3.2.1 Role and Types of Substations

Substations are key parts of electrical generation, transmission, and distribution systems. Substations transform voltage from high to low or from low to high as necessary. Substations also dispatch electric power from generating stations to consumption centers. Electric power may flow through several substations between the generating plant and the consumer, and the voltage may be changed in several steps. A substation receives its power from the transmission network; the power is stepped down with a transformer and sent to a bus from which feeders fan out in all directions across the countryside. These feeders carry three-phase power, and tend to follow the major streets near the substation. As the distance from the substation grows, the fan-out continues as smaller laterals spread out to cover areas missed by the feeders. This tree-like structure grows outward from the substation, but for reliability reasons, usually contains at least one unused back up connection to a nearby substation. This connection can be enabled in case of an emergency, so that a portion of substation's service territory can be alternatively fed by another substation [30]. Substations can be generally divided into three major types:

1. *Transmission substations* integrate the transmission lines into a network with multiple parallel interconnections so that power can flow freely over long distances from any generator to any consumer. This transmission grid is often called the bulk power system. Typically, transmission lines operate at voltages above 132 kV. Transmission substations often include transformation from one transmission voltage level to another.
2. *Sub-transmission substations* typically operate at 33 kV through 132 kV voltage levels, and transform the high voltages used for efficient long distance transmission through the grid to the sub-transmission voltage levels for more cost-effective transmission of power through supply lines to the distribution substations in the surrounding regions. These supply lines are radial express feeders, each connecting the substation to a small number of distribution substations.
3. *Distribution substations* typically operate at 2.4–33 kV voltage levels, and deliver electric energy directly to industrial and residential consumers. Distribution feeders transport power from the distribution substations to the end consumers' premises. These feeders serve a large

number of premises and usually contain many branches. At the consumers' premises, distribution transformers transform the distribution voltage to the service level voltage directly used in households and industrial plants, usually from 220 to 600 V [30].

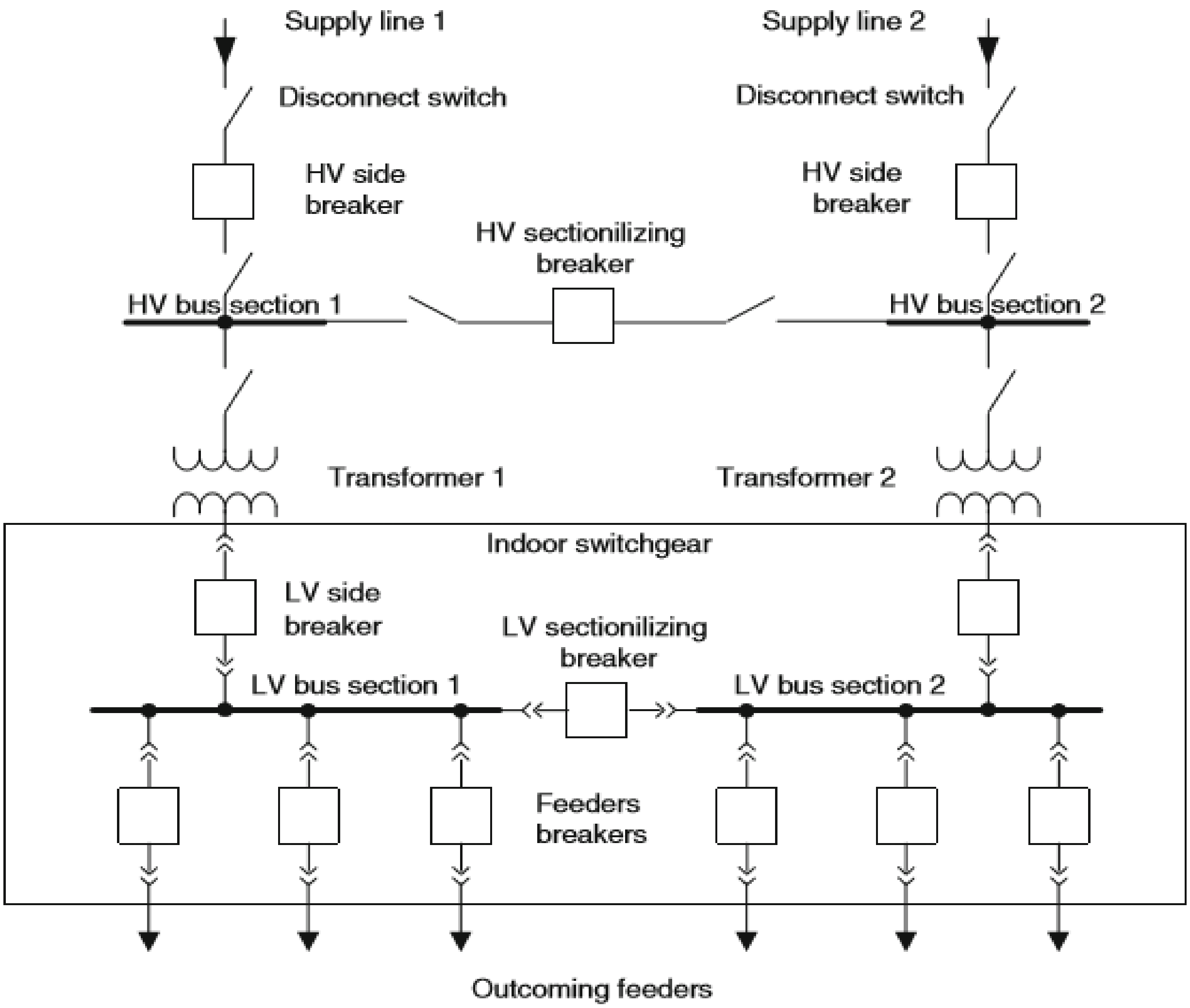


Figure 3.3 One-line diagram of a distribution substation [29]

3.3 Distribution Substation Components

A distribution substation is an assembly of various electrical equipments connected to step down electric power at higher voltages i.e. 132kV/33kV to 15kV and to clear faults in the system. Distribution substations are comprised of the following major components.

Supply Line

Distribution substations are connected to a sub-transmission system via at least one supply line, which is often called a primary feeder. However, it is typical for a distribution substation to be supplied by two or more supply lines to increase reliability of the power supply in case one supply line is disconnected. A supply line can be an overhead line or an underground feeder, depending on the location of the substation, with underground cable lines mostly in urban areas and overhead lines in rural areas and suburbs. Supply lines are connected to the substation via high voltage disconnecting switches in order to isolate lines from substation to perform maintenance or repair work.

Transformers

A transformer is static peace of apparatus with two or more windings which, by electromagnetic induction, transform a system of alternating voltage and current in to another system of alternating voltage and current usually of different values and at the same frequency for the purpose of transmitting electrical power. It can change high voltage to low voltage and the other way around. And also Transformer is a device that transforms step up or down voltage & current reversely by keeping the power constant. A varying Current in the primary winding creates a self-inductance in the primary winding which causes a voltage to be created on the secondary windings, varying magnetic field through the secondary winding i.e. mutual inductance.

Distribution substations usually employ three-phase step down transformers; however, banks of single-phase transformers can also be used. For reliability and maintenance purposes, two transformers are typically employed at the substation, but the number can vary depending on the importance of the consumers fed from the substation and the distribution system design in general. The transformer is a key component of the electrical network as it links the generators, the transmission lines and the distribution networks [31] [32] [33].

Figure 3.4 Power Transformer

Instrumental Transformers

One of the crucial components of protection, measuring and controlling system are instrument transformers [34]. The most common usage of instrument transformers is to operate instruments or metering from high voltage or high current or vice versa circuits control circuitry from the high voltages or currents.

They are basically the current transformers and voltage transformers.

a) Current transformers: When current in a circuit is too high to directly apply to measuring instruments, a current transformer produces a reduced current accurately proportional to the current in the circuit, which can be conveniently connected to measuring and recording instruments. The CT is typically described by its current ratio from primary to secondary.

b) Voltage transformers: Voltage transformers are usually connected on the feeder side of the circuit breaker. However they are also connected on the bus bar side for synchronization. They step down extra high voltage signals and provide a low voltage signal, for measurement or to operate a protective relay.

Bus bars

A bus bar is a thick strip of copper or aluminum that conducts electricity within a switchboard, distribution board, substation or other electrical apparatus. Bus bars are used to carry very large currents, or to distribute current to multiple devices within switchgear or equipment. Bus bars are typically either flat strips or hollow tubes as these shapes allow heat to dissipate more efficiently due to their high surface area to cross sectional area ratio. The size of the bus bar is important in determining the maximum amount of current that can be safely carried. Bus bar may either be supported on insulators, or else insulation may completely surround it. Bus bars are protected from accidental contact either by a metal enclosure or by elevation out of normal reach. Bus bars may be connected to each other and to electrical apparatus by bolted or clamp connections [35].

In distribution substations, bus bars are used at both high side and low side voltages to connect different circuits and to transfer power from the power supply to multiple out coming feeders. Feeder bus bars are available for indoor and outdoor construction. Outdoor bus bars are designed to operate reliably despite exposure to the weather.

Common Bus bar Schemes:

- ✓ Single Bus
- ✓ Double Bus.

Figure 3.5 Busbar (upper conductors) with voltage transformers

Isolator

In electrical systems, an isolator switch is used to make sure that an electrical circuit is completely de-energized for service or maintenance. Such switches are often found in electrical distribution and industrial applications where machinery must have its source of driving power removed for adjustment or repair. High-voltage isolation switches are used in electrical substations to allow isolation of apparatus such as circuit breakers and transformers, and transmission lines, for maintenance.

An isolator can open or close the circuit when either a negligible current has to be broken or made or when no significant voltage change across the terminals of each pole of isolator occurs. It can carry current under normal conditions and can carry short circuit current for a specified time. They can transfer load from one bus to another and also isolate equipments for maintenance.

Figure 3.6 Isolators in a substation

Relays

A relay is an electrically operated switch. Relays are used where it is necessary to control a circuit by a low-power signal (with complete electrical isolation between control and controlled circuits), or where several circuits must be controlled by one signal. Relays with calibrated operating characteristics and sometimes multiple operating coils are used to protect electrical circuits from overload or faults; in modern electric power systems these functions are performed by digital instruments still called "protective relays".

Protective relay

A protective relay [36] is a device that detects the faults & initiates the operation of the circuit breakers to isolate the defective element from the rest of the system. The relay [37] detects the different under normal & fault conditions. Having detected the faults, the relay operates to close the trip circuit of the breaker. This results in the opening of the breaker & disconnection of the faulty circuit. When the short circuit [38] occurs at a point on the transmission line, the current flowing in the line increases to an enormous value resulting a heavy current flow through the relay coil, causing the relay to operate by closing its contacts. This in turn closes the trip circuit [39] of the breaker, making the circuit breaker open & isolating the faulty section from the rest of the system. Thus the relay ensures the safety of the circuit equipment from damage.

Circuit Breaker

A circuit breaker is an automatically operated electrical switch designed and used for the controlling and protection of the power system to protect an electrical circuit from damage caused by overload or short circuit. A circuit breaker is a mechanical switching device that is capable of breaking or connecting currents under normal or abnormal conditions, such as a short circuit. The circuit breaker is an important component of the switchgear. Whenever there is a fault, the circuit breaker helps in disconnecting the circuit on load and breaking the fault current. Circuit breakers have a medium for arc extinction and this is what distinguishes them from isolators. In the simplest model, the circuit breaker is assumed to be an ideal switch whose impedance changes instantaneously from an infinite value for the open switch condition to a zero value at the closing switch condition. This performance can be represented at any point of a power cycle. A closing operation can produce transient over voltages whose maximum peaks depend on several factors, such as the closing instant, the network representation on the source side of the breaker, or the trapped charge on transmission lines in a reclosing operation. The closing instant, which can be different for every pole of a three-phase breaker, has more influence on the maximum peak of the over voltages subjected to the power system. Unlike a fuse, which operates once and then has to be replaced, a circuit breaker can be reset (either manually or automatically) to resume normal operation. Circuit breaker is the most critical part of power system protection and control [40].

Lightening Arrestors

A lightning arrester is a device used on electrical power systems and telecommunications systems to protect the insulation and conductors of the system from the damaging effects of lightning. The typical lightning arrester has a high-voltage terminal and a ground terminal. When a lightning surge (or switching surge, which is very similar) travels along the power line to the arrester, the current from the surge is diverted through the arrestor, in most cases to earth. In telegraphy and telephony, a lightning arrestor is placed where wires enter a structure, preventing damage to electronic instruments within and ensuring the safety of individuals near them.

Earthing

The function of an earthing system is to provide an earthing system connection to which transformer neutrals or earthing impedances may be connected in order to pass the maximum fault current. The earthing system also ensures that no thermal or mechanical damage occurs on the equipment within the substation, thereby resulting in safety to operation and maintenance personnel. The earthing system also guarantees equipotential bonding such that there are no dangerous potential gradients developed in the substation.

Control and relay panel

Control and relay panel of a grid substation has all controls, indications, meters and protective relays mounted on the front. These panels are free-standing, floor mounting type suitable chambers for indoor installation. Panels are rigid structural frames enclosed completely with smooth finished rolled sheet steel.

Figure 3.7 Control and relay panel

Multifunction meters

The MFM is an IED that can calculate values once the inputs from the secondary of the CTs and PTs have been given. Each MFM is dedicated to a particular panel, be it, outgoing or incoming. The MFM calculates and displays values on a hand held programming and display unit. These values depend on the programmed primary value corresponding to the CT and PT ratio, pertaining to that feeder. There is a communication port available for each MFM. It uses the RS 485 connection scheme.

Capacitor Banks

A capacitor (originally known as condenser) is a passive two-terminal electrical component used to store energy in an electric field. The forms of practical capacitors vary widely, but all contain at least two electrical conductors separated by a dielectric (insulator); for example, one common construction consists of metal foils separated by a thin layer of insulating film. Capacitors are widely used as parts of electrical circuits in many common electrical devices.

When there is a potential difference (voltage) across the conductors, a static electric field develops across the dielectric, causing positive charge to collect on one plate and negative charge on the other plate. Energy is stored in the electrostatic field. An ideal capacitor is characterized by a single constant value, capacitance, measured in farads.

Capacitors are widely used in electronic circuits for blocking direct current while allowing alternating current to pass, in filter networks, for smoothing the output of power supplies, in the resonant circuits that tune radios to particular frequencies, in electric power transmission systems for stabilizing voltage and power flow, and for many other purposes.

Tap Changer

A device used to increase or decrease a transformer's voltage to alter the level of current it can draw (tap) from the circuit supplying electricity. Changing the tap of a transformer or regulator serves the same function in an electrical circuit as turning the tap handle of a water faucet serves to adjust water flow.

Outcoming Feeders

A number of outcoming feeders are connected to the substation bus to carry power from the substation to points of service. Feeders can be run overhead along streets, or beneath streets, and carry power to distribution transformers at or near consumer premises. The feeders' breaker and isolator are part of the substation low-voltage switchgear and are typically the metal-clad type. When a fault occurs on the feeder, the protection will detect it and open the breaker. After detection, either automatically or manually, there may be one or more attempts to reenergize the feeder. If the fault is transient, the feeder will be reenergized and the breaker will remain closed. If the fault is permanent, the breaker will remain open and operating personnel will locate and isolate the faulted section of the feeder [30].

3.4 Power System Control

The term power systems control is used to define the application of control theory and technology, optimization methodologies, expert and intelligent systems to improve the performance and functions of power systems during normal and abnormal operations. Power system controls keep the power system in a secure state and protect it from dangerous phenomena. The role of power system controls (using automatic processing and human operating) is to preserve system integrity and restore the normal operation subjected to a physical (small or large) disturbance. In other words, power system control means maintaining the desired performance and stabilizing of the system following a disturbance, such as a short circuit and loss of generation or load [41].

From the view point of control engineering, a power system is a highly nonlinear and large-scale multi-input multi-output dynamical system with numerous variables, protection devices, and control loops, with different dynamic responses and characteristics. Because of this characteristics the power system network, the operation, control and management of the system becomes one of the most challenging tasks. One of the main reason is that power system comprising many dynamic components (thus, the number of variables and states is very high), which interact with each other in various ways and in different time scales, i.e., dynamics speed ranging from milliseconds to years. Dynamics present in power systems may be very nonlinear and have a hybrid nature, i.e., both continuous and discrete state variables are involved [42].

To avoid uncontrolled operation of power system, it is necessary to analyze the main parameters (dynamic variables) that frequently vary with load and generation to experiences system disturbance and then by controlling those variables in real-time at operating value the grid will be safe every time.

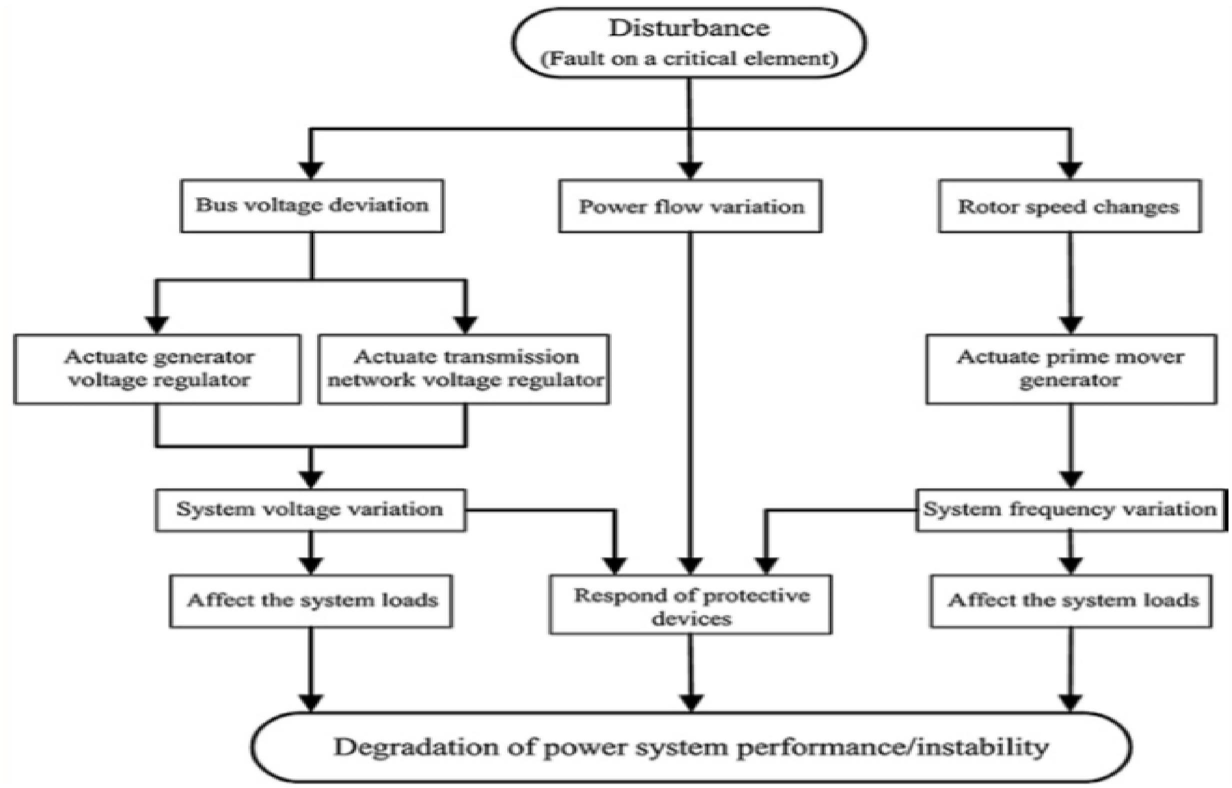


Figure 3.8 Progressive power system response to a serious disturbance [41]

3.5 Proposed Control Theory

The main variables that ensure the power system stability of any electrical network are system frequency (Active power) and voltage profile (Reactive power). To provide sufficient power, it is necessary to extend the electrical power network by adding either new generating units or transmission lines. Due to economic and environmental constraints for new installation, and consequent growth of loads that create overload situation due to extremely loaded network or increased transmission lines flow on existing transmission lines, power system stability has become more susceptible to various disturbances and outages [43].

Accordingly, I decided that by maintaining the system parameters viz. frequency and bus bar voltage remain close to nominal values at any time throughout the day the system will be under control and can withstand any disturbance. Frequency control is closely related to active power control, voltage control is closely related to reactive power control. As constancy of frequency and voltage are important factors in determining the quality of power supply, the control of active power and reactive power is vital to satisfactory performance of power system.

Hence, the proposed control algorithm for the thesis is that black out can be prevented by controlling the Voltage and frequency to its nominal value.

1. To maintain frequency stability there should be a balance between power generation and load demand; consequently, the load flow equations can be satisfied.

$$\sum_{i=1}^{N_g} P_{Gi} = P_D + P_{Loss} \qquad P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max} \qquad i = 1,2 \ldots \ldots \ldots \ldots N_g \tag{1}$$

$$\sum_{I=1}^{N_g} Q_{Gi} = Q_D + Q_{Loss} \qquad Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max} \qquad i = 1,2, \ldots \ldots \ldots \ldots \ldots N_g \tag{2}$$

2. The bus voltage magnitude $|V_k|$ should be within the prescribed limit, i.e. it is between 0.95 to 1.05 p.u.

$$|V|_k^{min} \leq V_k \leq |V|_k^{max} \qquad k = 1,2 \ldots \ldots \ldots \ldots \ldots \ldots N_b \tag{3}$$

Where:

P_{Gi} represents real power generation at bus i, P_D is the system demand; P_{Loss} is the total real power loss in the transmission network; Q_{Gi}, Q_D, Q_{Loss} represent reactive power generation at bus i, system demand, total loss in the transmission network respectively; $|V|_k$ is the voltage magnitude at bus k, N_g and N_b being the number of generators and buses respectively.

If any of the constraints are violated, the system may experience disruption that could result in a black-out.

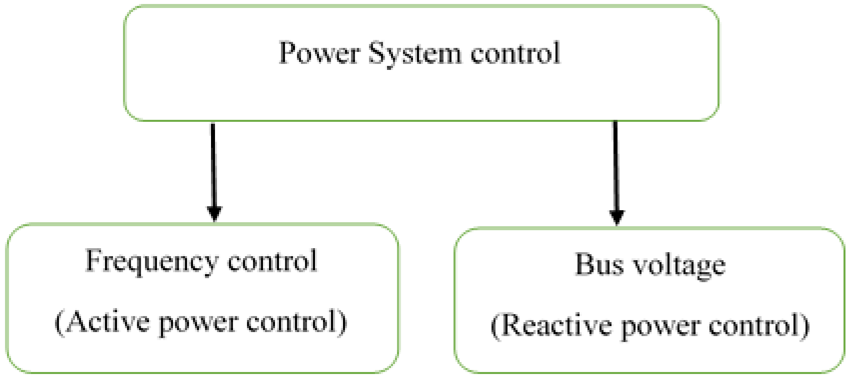


Figure 3.9 Power system control chart

The main theme behind the proposed method is to develop a computerized procedure for controlling the frequency and voltage in a systematic way so that in the controlling process will be automatic, manual work will be minimized. This computerized controlling scheme will be easy to operate and having fewer complexities with a proper user friendly interface provided with the system. Simulation results', using the above proposed control theory, verifies the suitability of choosing such an automated control system.

3.5.1 Frequency control

Frequency and active power control (in short named *f/P control)* is the ability of maintaining the frequency band to its permissible limit. The Frequency Limits in the EEP Transmission System has been stated in the Table below.

Operating condition	**Frequency limits**
Under normal operation	49.50 Hz to 50.50 Hz
Under system disturbance	49.00 Hz to 51.00 Hz
Maximum band under fault system	48.75 Hz to 51.25 Hz
Under extreme system operation or fault condition	f<47.50 Hz or f>51.50 Hz for 20 sec.

Table 3.1 Frequency limits in the EEP transmission system

Frequency deviation or rise is a direct result of an imbalance between the electrical load and the power supplied by the connected generators, so it provides a useful index to indicate the generation and load imbalance. A permanent out of range frequency may affect power system operation, security, reliability, and efficiency by damaging equipments, degrading load performance, overloading transmission lines, and triggering the protection devices. Frequency control is becoming more significant today due to the increasing size, changing structure, and the complexity of interconnected power systems. Increasing economic pressures for power system efficiency and reliability have led to a requirement for maintaining system frequency closer to scheduled values as much as possible.

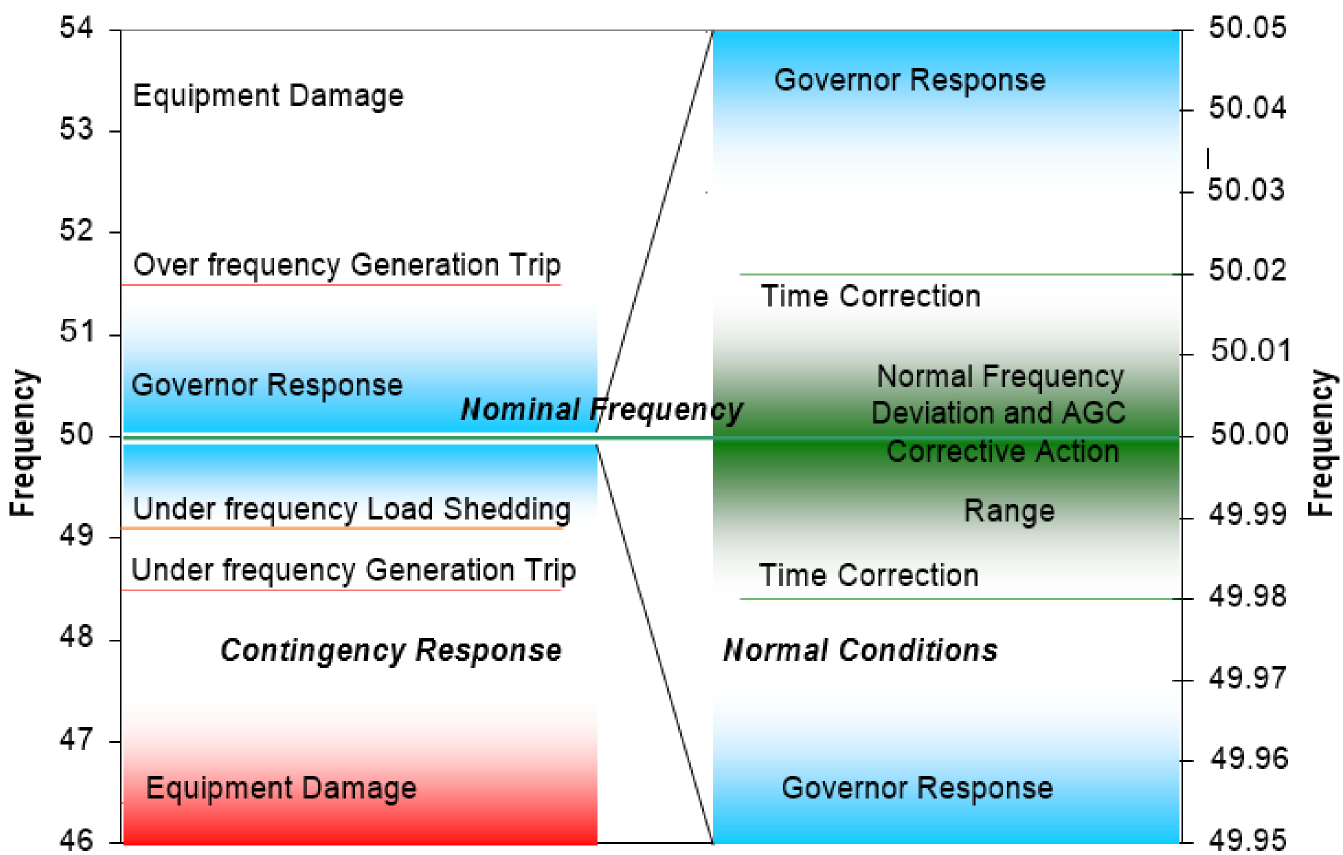


Figure 3.10 Frequency regulation

Over frequency

If the generation exceeds the demand, the frequency rises above the nominal value. For relatively small rise of frequency' the governor starts to respond and minimizing the generation by controlling the speed of the turbine. Monitoring the generation unit status in order to evaluate the risk of reaching system instability would be accomplished by selecting the best speed controlling method and sending change of frequency and change of active power signals to servomotor for further action. In order to maintain system stability, frequency variation must be inside a secure operating range when an emergency condition is presented [44] [45].

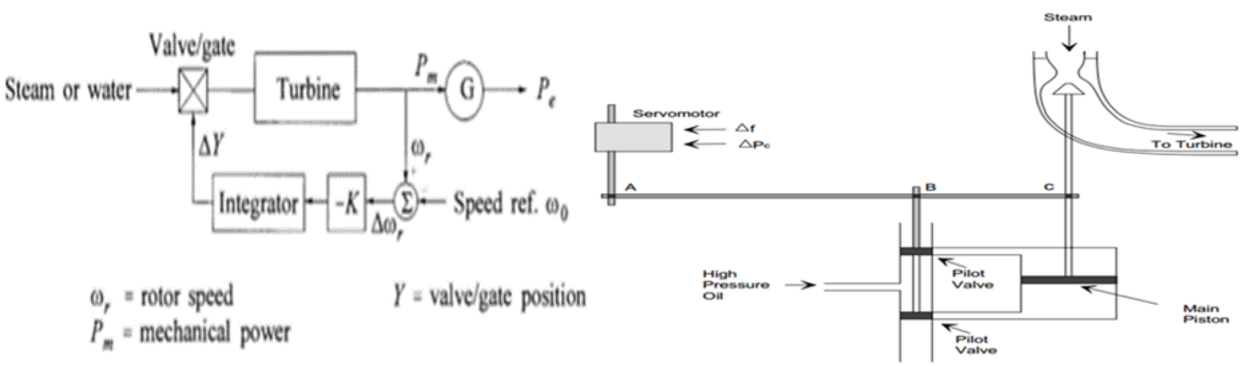


Figure 3.11 Governor Control loop and Speed control respectively

Where:

ΔPc (position of the power changer) and Δf (change of frequency) respectively, going into the governor used as input for servomotor. These inputs determine the position of the steam/hydro valve.

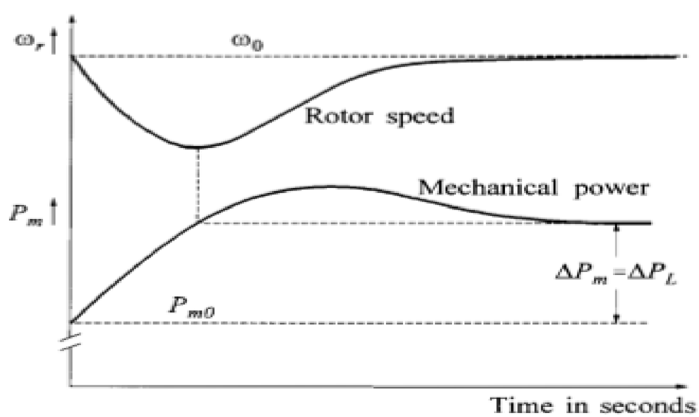


Figure 3.12 Response of generating unit with a governor [41]

Where: P_m is Mechanical power and ω_r is speed of rotor

When the frequency of the system exceeds highly from the nominal value the AGC (automatic generation control) start to respond by measuring a control error signal, called the area control error (ACE), which represents the real power imbalance between generation and load, and is a linear combination of net interchange and frequency deviations. After filtering, the ACE is used to perform an input control signal for a usually proportional integral (PI) controller. Since the frequency generated in an electric network is proportional to the rotation speed of the generator, the problem of frequency control may be directly translated into a speed control problem of the turbine-generator unit [41].

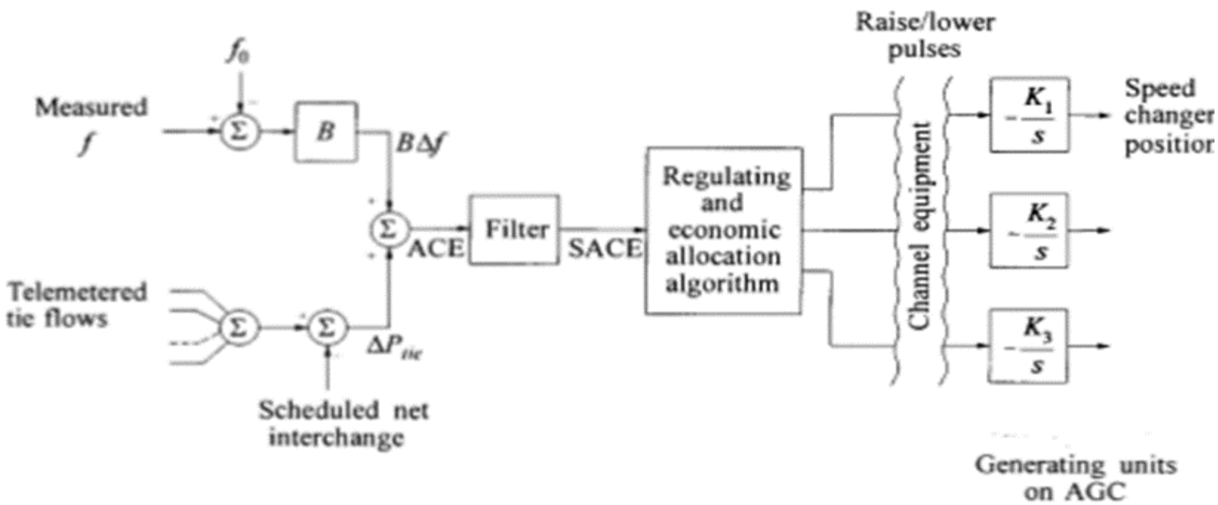


Figure 3.13 Automatic Generation Control (control loop) [41]

Where: ACE =area control error, SACE =Smoothed Area Control Error, B =frequency bias,
f =frequency and p=power $f_{0=}$ Actual frequency.

The Automatic Generation Control (AGC) system is a set of equipment and computer programs that applies closed loop feedback control to achieve the following objectives:

- To regulate frequency to a scheduled value.
- To maintain all scheduled power transactions to the contract value as well as the net power interchange at the value required by the interchange contracts.
- To maintain each unit's operation at the most economic value (Economic Dispatch).
- The errors are used to determine the control signals to the individual generators in such a way that the frequency returns to the scheduled value and the power transactions are regulated to the scheduled value.

Under frequency

Power system frequency falls down rapidly if mismatch occurs between generation and the load demand in case a power disturbance occurs [46]. In order to solve this frequency issue and return the system back to the normal state, UFLS (under frequency load shedding) schemes would be put into the action. In case of high frequency deviation, Load-shedding is the ultimate solution to re-store system frequency and ensure availability of electrical power to critical loads in the plant. Load-shedding is a process by which the electrical authority handles the dearth of the electrical power being consumed by the society. When the frequency of the power generator falls down, the authority lacks the scheduled amount of power & this leads the authority to perform a shedding. Under frequency load shedding schemes implement relays to disconnect appropriate amount of load and maintain system stability [47] [48].

If generation is smaller than load, system frequency and generation response will be:

- ✓ The generator closer to the disturbance location show a faster rate of initial frequency decay.
- ✓ Generators with higher inertia constant have lower rate of frequency decline and less frequency decline.
- ✓ Load damping factor is an important parameter in the settling system frequency following a disturbance. However, it has no significant effect on the initial frequency behavior of generator after a disturbance [49].

Design of UFLS (Under Frequency Load Shedding)

For faults or disturbances relatively small compared to total generation, the proposed scheme uses the EMD (Estimating magnitude of disturbance) method which is based on the generator swing equation. Equation (1) shows the linearized form of this equation for the ith Generator.

$$\frac{2H_i}{f_n}\frac{df_i}{dt} = p_{m_i} - p_{e_i} = p_{dist_i} \qquad i = 1, 2, 3, \ldots, N \qquad (1)$$

Where:

P_{mi} represents the mechanical power input by the turbine in pu, P_{ei} is the electric power usage output in pu, P_{disti} the total imbalance in pu, H_i is the inertia constant of the ith generator in seconds,

f_i is the frequency and f_n is the rated value in Hz. By summing (1) for the overall N generators the following expression for the total imbalance between generation and load forms:

$$P_{dist} = \sum_{i=1}^{N} P_{dist_i} = \frac{2\sum_{i=1}^{N} H_i}{f_n} \frac{df_c}{dt} = \alpha \frac{df_c}{dt} \tag{2}$$

Since the frequency of equivalent inertia center, f_c and constant α can be calculated in advanced they can be treated as known parameters of the equation. They are defined as below:

$$f_c = \sum_{i=1}^{N} H_i f_i \Big/ \sum_{i=1}^{N} H_i \tag{3}$$

and

$$\alpha = 2\sum_{i=1}^{N} H_i \Big/ f_n \tag{4}$$

A negative value of df_i/dt will imply that the electric power usage seen from the machines point of view is greater than the mechanical power input of the turbine. In other words an overload will occur, resulting in the reduction of system frequency [50].

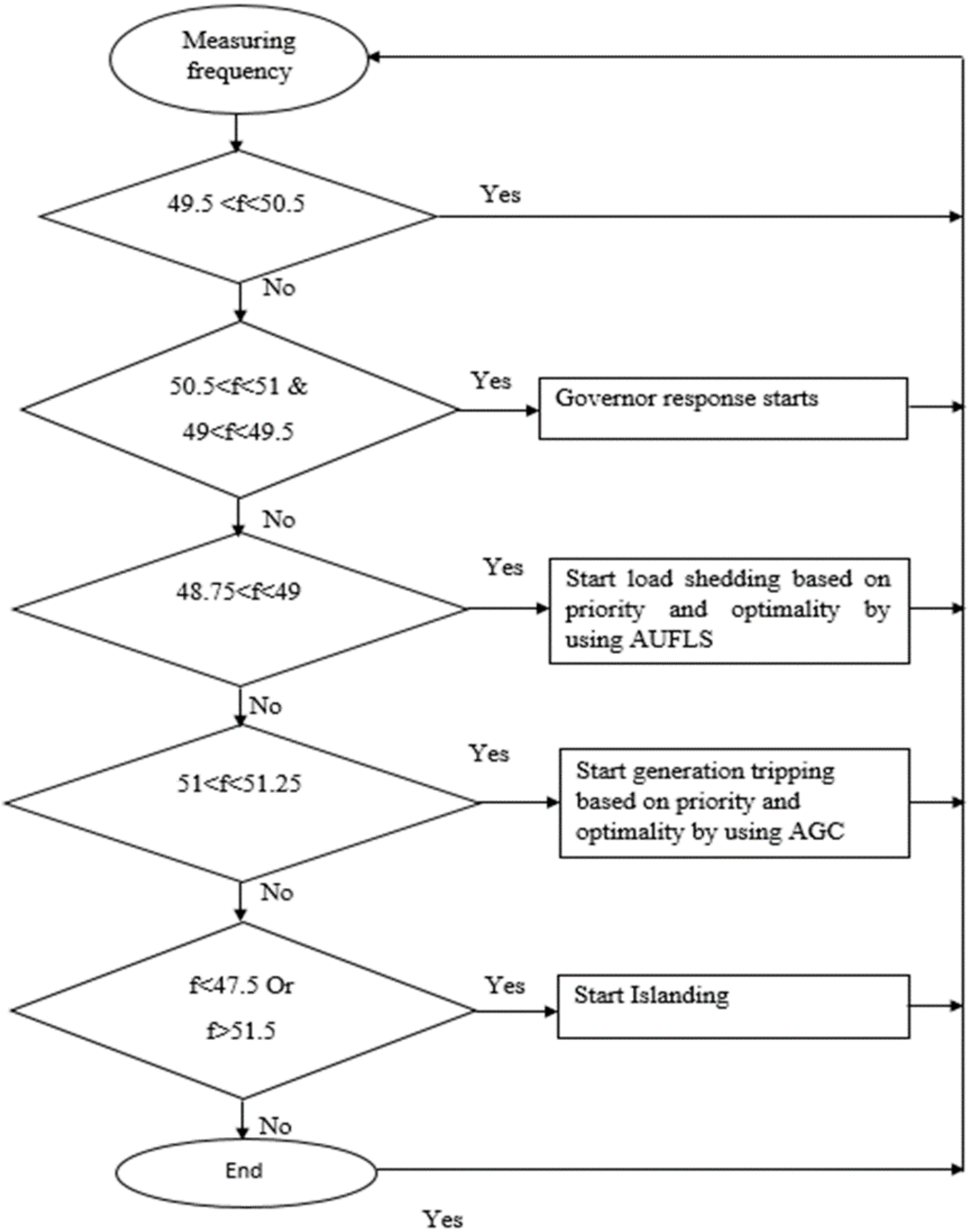


Figure 3.14 Frequency or Active power control flow chart

3.6 Voltage Control

Voltage control means maintaining the desired value and stabilizing of the system following a transient effect or a short circuit and loss of generation and load [51]. The problem of maintaining voltages with in required limits is complicated by the fact that the power system supplies power to a vast number of loads and is fed from many generating units. As load vary, reactive power requirements of the transmission line vary. Since the reactive power cannot be transmitted over long distance, voltage control has to be affected by using special devices dispersed throughout the system. This is in contrast to the control of frequency which depends on the overall active power balance. The various loads along distribution feeders result in resistive (I^2R) and reactive (I^2X) losses in the distribution system. If these losses are left uncompensated, an additional problem of declining voltage profile along the feeder will result [52].

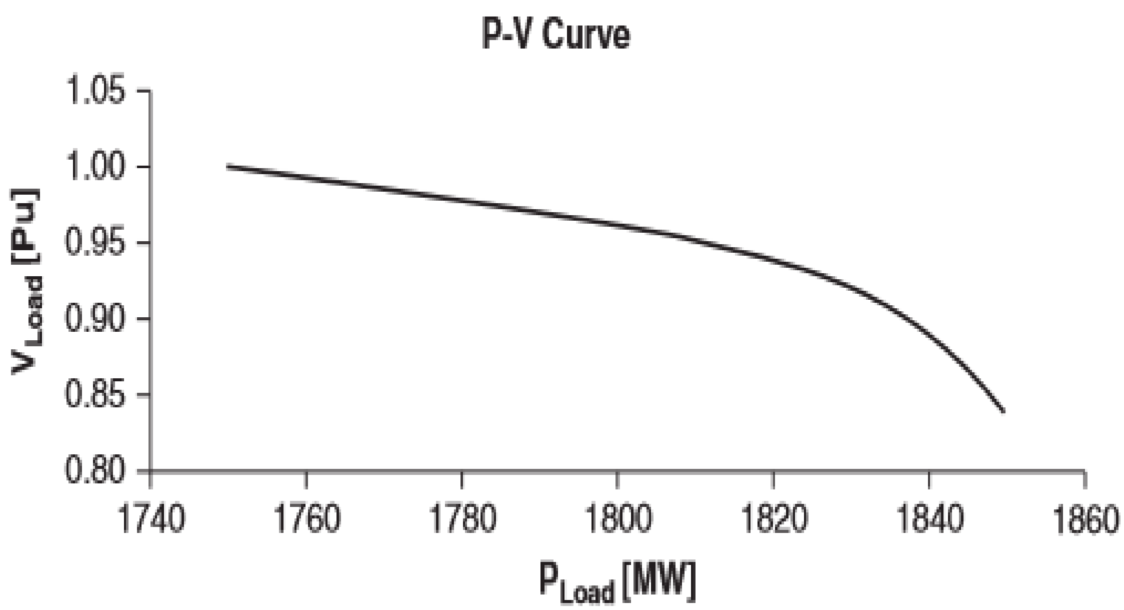


Figure 3.15 Power-Voltage curve

Operating Range

As defined on the Operating Policy Guidelines of EEP (up to 132KV level) the operating range of the voltage at various voltage levels of grid is as follows:

	Normal operating condition		Single contingency	
Nominal	Maximum	Minimum	Maximum	Minimum
400	420	380	440	360
230	242	218	253	207
132	138	125	145	119

Table 3.2 Voltage range of EEP

The generally accepted steady-state range for bus voltages on any power system is 0.95-1.05 per unit (p.u.), meaning that the voltage at the bus is between 95 and 105% of the nominal voltage of the bus. While, for during contingency bus voltage ranges are between 0.9 and 1.5 per unit (p.u.).

For efficient and reliable operation of power systems, the control of voltage and reactive power should satisfy the following objective.

- ✓ The reactive power flow is minimized so as to reduce losses. This ensure that the transmission system operates efficiently.
- ✓ System stability is enhanced to maximize utilization of the transmission system
- ✓ Voltage stability is whereby the system is capable of sustaining stable voltages at all buses in a network following a disturbance [53]. Voltage instability is when voltages in a network considerably drop continuously to the point where the system becomes unstable and supply of power to the load is disturbed. This may lead to voltage collapse.

Voltage control in an electrical power system is important for proper operation of electrical power equipment,

- to prevent damage such as overheating of generators and motors,
- to reduce transmission losses, and
- To maintain the ability of the system to withstand and prevent voltage collapse.

In general terms, decreasing reactive power causes voltage to fall while increasing it causes voltage to rise. A voltage collapse occurs when the system try's to serve much more load than the voltage can support

3.6.1 Concept of voltage control (Voltage rise and drop)

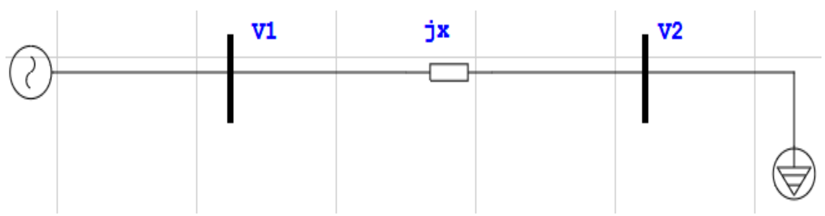


Figure 3.16 Two bus transmission line

Load connected to the source through a line

$$V_2 = \left(V_1 - {}^{QX}/_{V_1}\right) - j\,{}^{PX}/_{V_1} \qquad (1)$$

V2= (V1-QX/V1) (2)

The line has an impedance of (R + j X) Ω and Taking voltage V_2 as reference, its phasor diagram will be

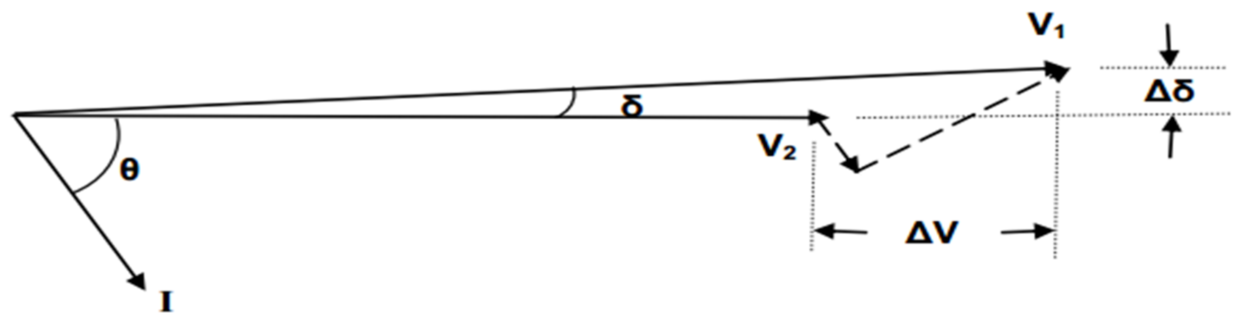


Figure 3.17 Phasor diagram

From the phasor diagram, we can write

$$|V_1|^2 = (|V_2| + \Delta V)^2 + \Delta\delta^2 \qquad (3)$$

Where,

$$\Delta V = |I|R\cos\theta + |I|X\sin\theta \qquad (4)$$

$$\Delta\delta = |I|X\cos\theta - |I|R\sin\theta \qquad (5)$$

Knowing that $|V_2||I|\cos\theta = P \; and \; |V_2||I|\sin\theta = Q$

$$|I|\cos\theta = \frac{P}{|V_2|} \; and \; |I|\sin\theta = \frac{Q}{|V_2|} \qquad (6)$$

Substituting eq. (6) in eqns. (4) and (5), we get

$$\Delta V = \frac{R.P}{|V_2|} + \frac{X.Q}{|V_2|} \qquad (7)$$

$$\Delta\delta = \frac{X.P}{|V_2|} - \frac{R.Q}{|V_2|} \qquad (8)$$

Generally, $\Delta\delta$ will be much smaller as compared to $|V_2| + \Delta V$. Thus from eq. (3), we can write

$$|V_1|^2 = (|V_2| + \Delta V)^2 \leftrightarrow |V_1| = |V_2| + \Delta V \qquad (9)$$

Therefore, voltage drop in the transmission line is

$$|V_1| - |V_2| = \Delta V$$

$$= \frac{RP}{|V_2|} + \frac{XQ}{|V_2|} \qquad (10)$$

For most of power circuit, resistance R will be much less as compared to reactance X.

Neglecting the resistance of the transmission line, we get

$$\Delta V = \frac{XQ}{|V_2|} \qquad (11)$$

In a day, during the peak hours, Q-flow will be heavy, resulting more voltage drop. However, during off-peak hours, the load will be very small and the distributed shunt capacitances throughout the transmission line become predominant making the receiving-end voltage greater than the sending-end voltage.

Thus during off-peak hours there may be voltage rise in the transmission line from sending-end to receiving-end reactive power flow (Q-flow) in the transmission line**.** During off-peak period, “voltage rise” can be reduced by absorbing the reactive power. While during peak period, “voltage drop” can be raised by supplying reactive power.

Methods of Voltage control

Voltages and reactive power control (*v/Q control)*, is accomplished by controlling the production, absorption, and flow of reactive power at all level in the system. The generating units provide the basic means of voltage control; for relatively small voltage variation, the automatic voltage regulators (AVR) control field excitation to maintain a scheduled voltage level at the terminal of the generators.

While, for a larger voltage variation additional means are usually required to control voltage throughout the system. The devices used for this purpose are:

1. Source or sink of reactive power, such as shunt capacitor, shunt reactors and synchronous condensers

2. Line reactance compensator, such as series capacitors.
3. Regulating transformers, such as tap-changing transformers and boosters.

Shunt capacitors and reactors provide passive compensations. They are connected to transmission line either manually or automatically. They contribute to voltage control by modifying the network characteristics.

Shunt reactors are used to compensate for effects of the line capacitance, particularly limit voltage rise on open circuit or light load. While, shunt capacitor supply reactive power and boost local voltage. Switched shunt capacitors are used extensively for feeder voltage control.

Reactors are reactive power consumers which are mostly installed in substations and at the end of long transmission lines in parallel. Basically, a circuit breaker is installed with reactors to connect them to the network, when it is needed. Usually, the reactor is switched on when the network load is minimum, and it is switched off when the network load is high.

Capacitors are passive devices that generate reactive power, with some advantages:

- ✓ Significant real-power losses around 2–3% from the rated power;
- ✓ Low operating expense;
- ✓ Possibility to space out payment of investment by gradually developing the capacitor bank with new elements.

Capacitor banks are composed of individual capacitor connected in series and/or parallel in order to obtain the desired capacitor-bank voltage and capacity rating

While, Inductors are passive devices that absorb reactive power. The inductors are shunt connected to high voltage transmission lines or to the tertiary autotransformer’s winding with purpose to absorb capacitive power generate by these lines in low load operation. In this case there were reduced possibilities to have in the system overvoltage produced by capacitive currents flow. Inductors are built in three phases or formed with three single phases. Frequently the principle of reactive power control consists in modifying the number of inductors in shunt connection

(i) In the event of high voltage, on observing persistent high voltage for more than half an hour at sub-stations (e.g., 400kV bus voltages above 420kV), the following specific steps would be taken at grid substations / generating station at their own,

- ➢ The bus reactors be switched in / Taken in service
- ➢ The manually switch able capacitor banks be taken out
- ➢ The switch able line/ tertiary reactors are taken in
- ➢ All the generating units connected on bus bar shall absorb reactive power within capability limits of the respective generating units

(ii) **In the event of low voltage**, on observing persistent low voltage for more than half an hour (e.g., 400kV bus voltages going down below 380kV), the following specific steps would be taken by the respective grid substations / generating station at their own, The bus reactors be switched out

- The capacitor banks be switched in
- The switch able line / tertiary reactors are taken out
- All the generating units shall generate reactive power within capability limits of the respective generating units

In general, power system control issue can be summarized in the following Table.

Controlled parameter	Short term (~ 1sec)	Medium term (~ 5 sec – 1 min)	Long term (~ 15 min – 1 hr.)
Voltage (Reactive power)	AVR (Automatic voltage regulator)	Taps	Switching
Frequency (Active power)	Inertia	Governor & UFLS Dispatch	

Table 3.3 The power system control issue

CHAPTER FOUR

Design and implementation of automated SCADA control system

4.1 Automated control system (Automation)

Power system automation is the act of automatically controlling the power system via automated processes within computers and intelligent instrumentation & control devices. The processes rely on data acquisition, power system supervision, and power system control all working together in a coordinated automatic fashion. The commands are generated automatically and then transmitted in the same fashion as operator initiated commands.

Power system automation includes processes associated with generation and delivery of power. A subset of these processes deal with delivery of power at transmission and distribution levels, which is power delivery automation. Together, monitoring and control of power delivery systems in the substation and on the pole top reduce the occurrence of outages and shorten the duration of outages that do occur.

Substation automation refers to using IED data, control and automation capabilities within substation, and control commands from remote users to control power system devices. Since true substation automation relies on substation integration, the terms are often used interchangeably.

Power system automation, consists of the following main components:

- ✓ Electrical protection
- ✓ Control
- ✓ Measurement
- ✓ Monitoring
- ✓ Data communications

Control and automation of electricity networks play the key role in electricity business environment for different enterprises of production, supply, bulk transmission, delivery or distribution and metering [54].

4.2 Automated system control versus conventional system control

The automated control has much distinguishing benefits over the conventional control advancing into new level of power generation, transmission and distribution. The aspects of handling uncertainties, failure prediction and automatic system control makes power restoration easier.

Renewable sources are also to be utilized judiciously. Hence there is a need to optimize the energy use and reduce waste. Automation of power systems is a solution toward this goal, and every sector of the power system, from generation, to transmission to distribution to the customer is being automated today to achieve optimal use of energy and resources. The automated control system answers the question of power system disruption, which is the concern of this thesis, with high priority automatic monitoring, coordinating and operating the distribution, generation and transmission network components in a real-time mode from remote locations. It can automatically perform the fault detection, isolation and service restoration activities without an intervention of operators. It can also identify the fault location and assist the control center operators and the repair crews during the fault management activities.

In general SCADA based automated system has many advantages over traditional way of control, among them:

- Reduced human influence and errors, as the values are accessed automatically, and the meter reading and related errors are avoided.
- Gives fast response to disturbance.
- Increased reliability.
- Lower operating costs, as there is less personnel involvement due to automation.
- Faster restoration of power in case of a breakdown, as the faults can be detected faster and action taken.
- Better active and reactive power management, as the values are accurately captured in the automation system and appropriate action can be taken.
- Faster decision making, as a wealth of information is made available to the operator about the system conditions to assist the operator in making accurate and appropriate decisions.
- Optimized system operation, as optimization algorithms can be run and appropriate performance parameters chosen.

- Is there any modification and future extension, we can easily update in PLC & SCADA.
- In substation and generation, many switches are used, if there any one of the switch is trip means we can easily identify the particular area.

4.3 Basics of SCADA System

SCADA systems are highly distributed systems used to control geographically dispersed assets, often scattered over thousands of square kilometers, where centralized data acquisition and control are critical to system operation. They are used in distribution systems such as water distribution and waste water collection systems, oil and gas pipelines, electrical power grids, and railway transportation systems. A SCADA control center performs centralized monitoring and control for field sites over long distance communications networks, including monitoring alarms and processing status data. Based on information received from remote stations, automated or operator-driven supervisory commands can be pushed to remote station control devices, which are often referred to as field devices. Field devices control local operations such as opening and closing valves and breakers, collecting data from sensor systems, and monitoring the local environment for alarm conditions [10] [11].

SCADA systems integrate data acquisition systems with data transmission systems and HMI software to provide a centralized monitoring and control system for numerous process inputs and outputs. SCADA systems are designed to collect field information, transfer it to a central computer facility, and display the information to the operator graphically or textually, thereby allowing the operator to monitor or control an entire system from a central location in real time. Based on the sophistication and setup of the individual system, control of any individual system, operation, or task can be automatic, or it can be performed by operator commands.

4.4 SCADA System Architecture

SCADA systems consist of both hardware and software. Typical hardware includes an MTU (Master Terminal Unit) placed at a control center, communications equipment (e.g., radio, telephone line, cable, or satellite), and one or more geographically distributed field sites consisting of either an RTU or a PLC, which controls actuators and/or monitors sensors. The MTU stores and processes the information from RTU inputs and outputs, while the RTU or PLC controls the local process.

The communications hardware allows the transfer of information and data back and forth between the MTU and the RTUs or PLCs. The software is programmed to tell the system what and when to monitor, what parameter ranges are acceptable, and what response to initiate when parameters go outside acceptable values. An IED, such as a protective relay, may communicate directly to the SCADA master station, or a local RTU may poll the IEDs to collect the data and pass it to the SCADA master station. IEDs provide a direct interface to control and monitor equipments and sensors. IEDs may be directly polled and controlled by the SCADA master station and in most cases have local programming that allows for the IED to act without direct instructions from the SCADA control center. SCADA systems are usually designed to be fault-tolerant systems with significant redundancy built into the system architecture.

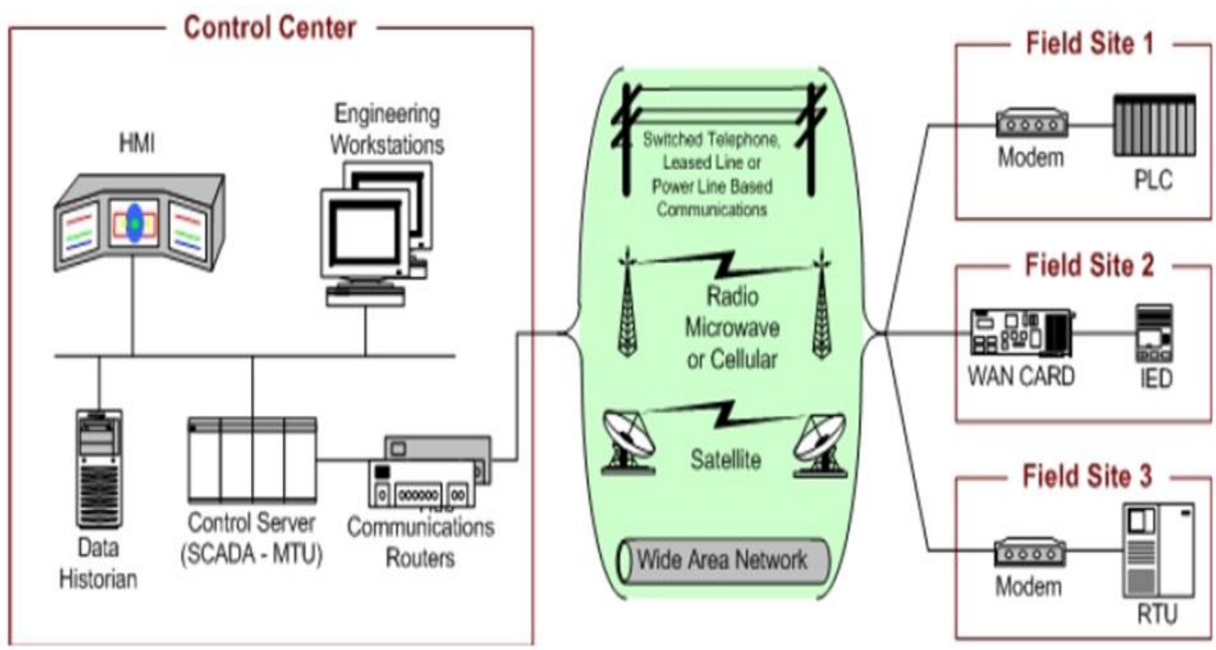


Figure 4.1 SCADA System General Layout [9]

Figure 4.1 shows the components and general configuration of a SCADA system. The control center houses consists of a control server (MTU) and the communications routers. Other control center components include the HMI, engineering workstations, and the data historian, which are all connected by a LAN. The control center collects and logs information gathered by the field sites, displays information to the HMI, and may generate actions based upon detected events.

The field site performs local control of actuators and monitors sensors. Field sites are often equipped with a remote access capability to allow field operators to perform remote diagnostics and repairs usually over a separate dial up or WAN connection. Standard and proprietary communication protocols running over serial communications are used to transport information between the control center and field sites using telemetry techniques such as telephone line, cable, fiber, and radio frequency such as broadcast, microwave and satellite [55].

MTU-RTU communication architectures vary among implementations. The various architectures used, including point-to-point, series, series-star, and multi-drop. Point-to-point is functionally the simplest type; however, it is expensive because of the individual channels needed for each connection. In a series configuration, the number of channels used is reduced; however, channel sharing has an impact on the efficiency and complexity of SCADA operations. Similarly, the series-star and multi-drop configurations' use of one channel per device results in decreased efficiency and increased system complexity [56].

4.5 SCADA in Power System Controlling

SCADA systems are globally accepted as a means of real-time monitoring and control of electric power systems, particularly for generation, transmission and distribution systems. RTUs (Remote Terminal Units) are used to collect analog and status telemetry data from field devices, as well as communicate control commands to the field devices. Installed at a centralized location, such as the utility control center, are front-end data acquisition equipment, SCADA software, operator GUI (graphical user interface), engineering applications that act on the data, historian software, and other components. Recent trends in SCADA include providing increased situational awareness through improved GUIs and presentation of data and information; intelligent alarm processing; the utilization of thin clients and web-based clients; improved integration with other engineering and business systems; and enhanced security features.

The SCADA encompasses the collecting of information via RTU (Remote Terminal Unit) relocating it back to central site carrying out decisive rehash and control and then displaying that information on a number of operating screens or displays. Based on information received from remote stations, automated or operator-driven supervisory commands can be pushed to remote station control devices, which are often referred to as field devices. Field devices control local operations such as opening and closing breakers, collecting data from sensor systems, and monitoring the local environment for alarm conditions.

4.6 SCADA Monitoring and control process

As we can see from the Figure 4.2 below the monitoring part translates in to an operator in a control room, being able to "see" the remote process on the operator console, complete with all the information required displayed and updated at the appropriate time intervals. This will involve the following steps:

- ✓ Collect the data from the field.
- ✓ Convert the data into transmittable form.
- ✓ Bundle the data into packets.
- ✓ Transmit the packets of data over the communication media.
- ✓ Receive the data at the control center.
- ✓ Decode the data.
- ✓ Display the data at the appropriate points on the display screens of the operator.

While the control process will ensure that the control command issued by the system operator gets translated into the appropriate action in the field and will involve the following steps:

- ✓ The operator or automatically initiates the control command.
- ✓ Bundle the control command as a data packet.
- ✓ Transmit the packet over the communication media.
- ✓ The field device receives and decodes the control command.
- ✓ Control action is initiated in the field using the appropriate device actuation.

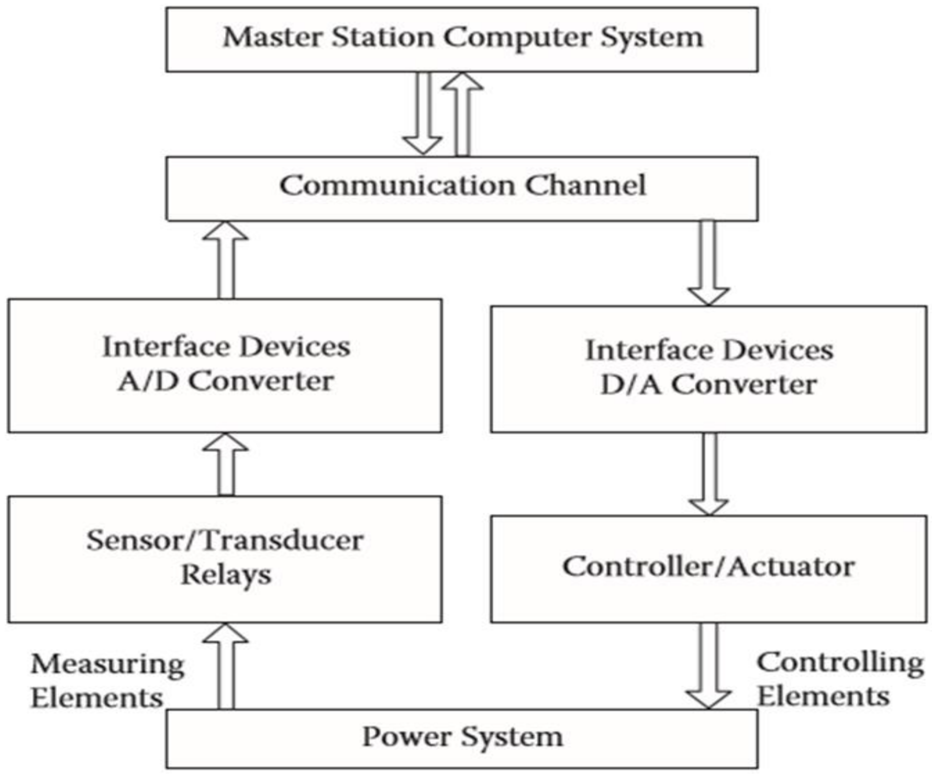


Figure 4.2 monitoring and control process [57]

4.7 Basic components of SCADA System

In general, SCADA system consists of host in control station, communication network, and remote terminal unit in hardware as well as data base, control software, and application programs for software.

A SCADA system usually consists of the following subsystems:

Master Terminal Unit (MTU) – allows operators to view the state of any part of the plant equipment and drives most operator interaction by alarms. It provides displays of process status information, including alarms and other means. The dual roles of the master computers are to provide the information such as meter readings and equipment status to human operators in a digestible form and to allow the operators to control the field equipment the master computers, and interface with the system using operator consoles which communicate with the master computers over a network.

Remote terminal units (RTUs) RTU, is an IED that can be installed in a remote location, and acts as a termination point for field contacts. A dedicated pair of copper conductors are used to sense every contact and transducer value. These conductors originate at the power system device, are installed in trenches or overhead cable trays, and are then terminated on panels within the RTU.

RTU converts sensor signals to digital data. They have telemetry hardware capable of sending digital data to the supervisory system, as well as receiving digital commands from the supervisory system. RTUs often have embedded control capabilities such as ladder logic in order to accomplish Boolean logic operations. RTUs are equipped with input channels for sensing or metering, output channels for control. The RTU can transfer collected data to master terminal unit and receive data and control commands from other devices through a serial port.

RTU serves as the eyes, ears, and hands of a SCADA system. The RTU acquires all the field data from different field devices, as the human eyes and ears monitor the surroundings, process the data and transmit the relevant data to the master station. At the same time, it distributes the control signals received from the master station to the field devices, as the human hand executes instructions from the brain. Today Intelligent Electronic Devices (IEDs) are replacing RTUs.

A programmable logic controller, PLC, is used in place of RTU as field devices because they are more economical, versatile, flexible, and configurable but PLC needs an extra telemetry hard ware. Here, for this research I will use RTU for system design because RTU is already installed on the existing network (the concern of this thesis).

Communication system is typically used to connect RTUs with MTU or control centers, data warehouses, and the enterprise. Examples of wired telemetry media used in SCADA systems include leased telephone lines and WAN circuits and fiber. Examples of wireless telemetry media used in SCADA systems include satellite, licensed and unlicensed radio, cellular and microwave.

Direct copper - A copper communication cable dedicated to power system communications between two devices.

Land line telephone - Conventional dial-up or leased lines dedicated to power system communications.

Power line carrier - A method of passing data on the power line conductor at high frequency.

Fiber - Fiber applications communicate data in the form of light conducted over a single direct connection or multiple direct connections bundled together.

Human–machine interface or HMI is the apparatus or device which presents processed data to a human operator, and through this, the human operator monitors and interacts with the process. HMI consists a supervisory (computer) system, gathering (acquiring) data on the process and sending commands (control) to the RTU. The HMI is a client that requests data from a data acquisition server.

Intelligent Electronic Devices (IEDs) includes electronic meters, relays and controls on specific substation equipment. It has the capabilities to support serial communications to a SCADA sever and reports to modern RTU via communication channels. It performs all functions of protection, control, monitoring, metering and communication. Here we use the SCADA systems for monitoring and controlling the power.

Flow of information from remote to control center and vice versa

The flow of information in a SCADA system can be tracked by analyzing the flow of an analog signal from the field. As an example, a bus bar voltage, say 220 kV, is illustrated. Starting from the substation bus bar in the field, the potential transformer connected to the bus converts the 220 kV into 110 V. This 110 V is converted into a 4 to 20 mA analog signal by a voltage transducer. The 4 to 20 mA analog signal is converted to a digital signal by the analog input (AI) module of the RTU. Further, this digital signal obtained is packaged into a data packet in the RTU, according to the communication protocol existing between the RTU and the master station. The data packets are then transmitted to the master station along the communication medium available. In the master station, the packets are received by the front- end processor/ communication front end (FEP/ CFE), decoded, and the data retrieved. The data are then scaled up to the 220 kV range and displayed at the appropriate bus bar in the mimic diagram of the operator console, completing the monitoring cycle [58].

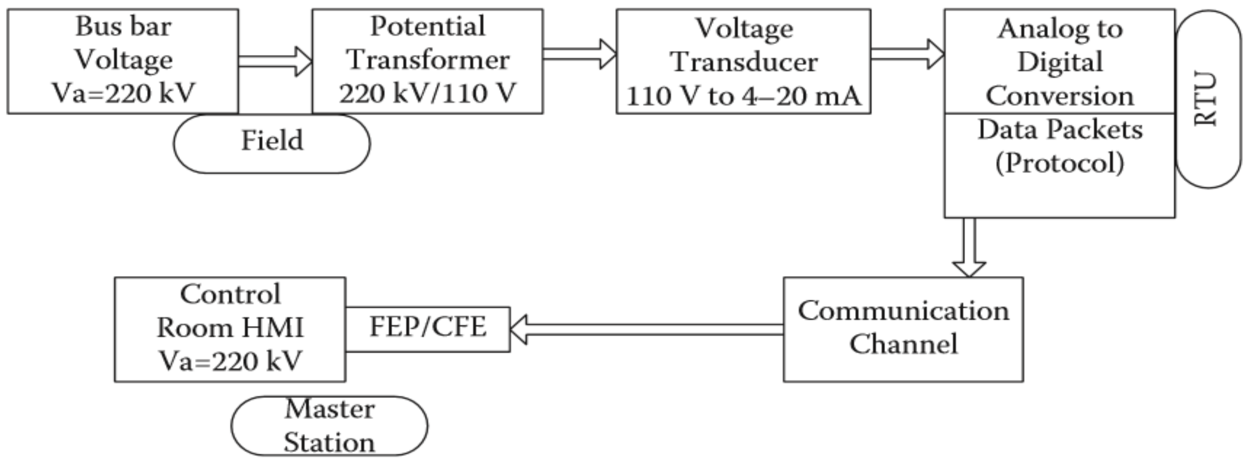


Figure 4.3 Data transfer from the bus bar to the control center HMI [57]

The same sequence could be retraced from the master station to the field, in the case of a control command issued by the operator, to be executed in the field. And it is also the same for another electrical variables such as frequency, power etc...

SCADA Protocols

Protocol defined as a set of conventions governing the treatment and especially the formatting of data in an electronic communication system. Communications protocol is a system of rules that allow two or more entities of a communications system to transmit information via any kind of variation of a quantity. The information/control signals exchanged between SCADA devices and other control systems through a network, or other media including handshaking, error detection, and error recovery is governed by rules and conventions that can be set out in technical specifications called Communication protocols standards.

The important part of any complex SCADA system design is involved in matching the protocol and communication parameters between connecting devices. Protocol designs in SCADA are compact and are so designed as to send information to master terminal unit (MTU) only in case the RTU is polled for information by the MTU. Standard protocols are IEC 60870-5-101 or 104, IEC 61850 and DNP3. These communication protocols are standardized and recognized by all major SCADA vendors [59].

Distributed network protocol (DNP3) DNP3 is a protocol that defines communications between master stations, remote terminal units (RTUs), and IEDs in SCADA. IEEE has opted DNP3 as a standard for Electric power system communications. It is also widely used in water infrastructure, oil, gas, security and other industries. Initially, DNP3 was designed without any security features. DNP3 is extended to DNP3 Secure Authentication (SA), which was designed to meet requirements of IEC 62351-59, which is a standard developed by IEC (international electro technical commission). Implementation presumes that both master station and outstation share a common secret key, called an update key, which is used to generate a session key. The recently released DNP3SA5 reinforces overall security for data information gathering, exchange, and use in SCADA systems [59]. Both DNP3 and IEC60870-5-101 serve similar functions they both [60].

- ✓ Reliably and efficiently transfer field data to the master station or the control center.
- ✓ Allow commands to be issued to the field with a very high degree of control security.
- ✓ Suit medium bandwidth communication channels.
- ✓ Include good data link frame integrity checking.
- ✓ Support application layer data object identification.
- ✓ Include data validity checking flags.
- ✓ Supports the transmission of digital (on/off) and analog data (in integer or floating point formats), counters and digital and analog control commands or set points.
- ✓ Support transfer of files, setting of clock etc.

IEC 60870-5-101 also supports some electric power specific objects related to transformers and substation protection devices. IEC 60870-5-101 is a standard for power system monitoring, control & associated communications for telecontrol, teleprotection, and associated telecommunications for electric power systems. The standard is suitable for multiple configurations like point-to-point, star, multi dropped etc.

4.8 SCADA system design

The goal of this thesis is to design and simulate an automated SCADA power system. This thesis presents a substation and generation automation. Faults caused by earth leakage current and other disturbances create interruptions of electricity supply to the customers. The engineers and technicians have to manually locate the fault point and spend plenty of time and this tedious work may last for extend periods of time. These operations are mostly based on manual and automatic operations. The advent of RTU and the introduction of numerical relays have improved the function of fault management system. Now it is possible to record the fault currents at the feeding distribution substations and the restoration process is also done automatically and is accelerated faster.

The following steps has been considered while designing the SCADA control system:

1. Definition of various components of the SCADA as expressed above.
2. Identifying controlled variable and equipment (f, v and relay &circuit breaker respectively).
3. Introduce the set point, SLD (single line diagram) and priorities useful for control action.
4. Controlling equipments based on the set point and measured value.

4.8.1 Design Requirements

When designing the SCADA control system the following hard wares and soft wares are needed:

1. Communication system

The most used topology in SCADA system is Point-to-multipoint since, Point-to-multipoint is a communication link among three or more stations with one station being a communication arbitrator (master) that controls when the other stations (remote stations) can communicate.

2. RTU: As explained above the key purpose of the RTU is to interface objects, do the acquisition of data parameters from objects local/substation, transmit them to the MTU and control objects using commands from MTU (e.g. using SCADA) and the wireless capability has also been important to transfer data. Thus the need for RTU used as the remote monitoring and control of field equipment is enabled via two-way wireless communication.

3. Main control center (MTU)

At this center computer system for the SCADA will be installed. This system consists of hardware and software. This includes all the hardware devices needed to implement the SCADA system that consists of:

- ✓ SCADA server computer: this server needs to have very good specification. And will be used to install all the SCADA software packages that include software programs and tools.
- ✓ Backup SCADA server, used as a backup of the main server and for redundancy. Work-station: from 2 to 3 workstations for the supervisor and operators.
- ✓ Local Area Network: Ethernet LAN needed to connect the servers, printers and the client workstations with each other's.

4. Other components needed

Power Source: system components require a reliable auxiliary voltage supply and with the addition of modules/components, (which have some power consumption) the rating of the auxiliary power system increases.

CTs: needed for feeding measured currents (transformed down to the relay levels)

VTs: needed for feeding measured voltage (transformed down to the relay levels) but only in case the need is supported by the financial capability.

Sensors: for current and/or voltage measurements (as an alternative to CTs and VTs) but in a different manner. The issue with using sensors for MV measurements is that the number of available IEDs compatible with them is few and the manufacturers have designed them based on the standards for instrument transformers in the absence of the ones specifically defined for MV sensors.

Wiring: for connecting the components to the IED and LAN cables for connecting computers, servers (EMS server, data base server etc.).

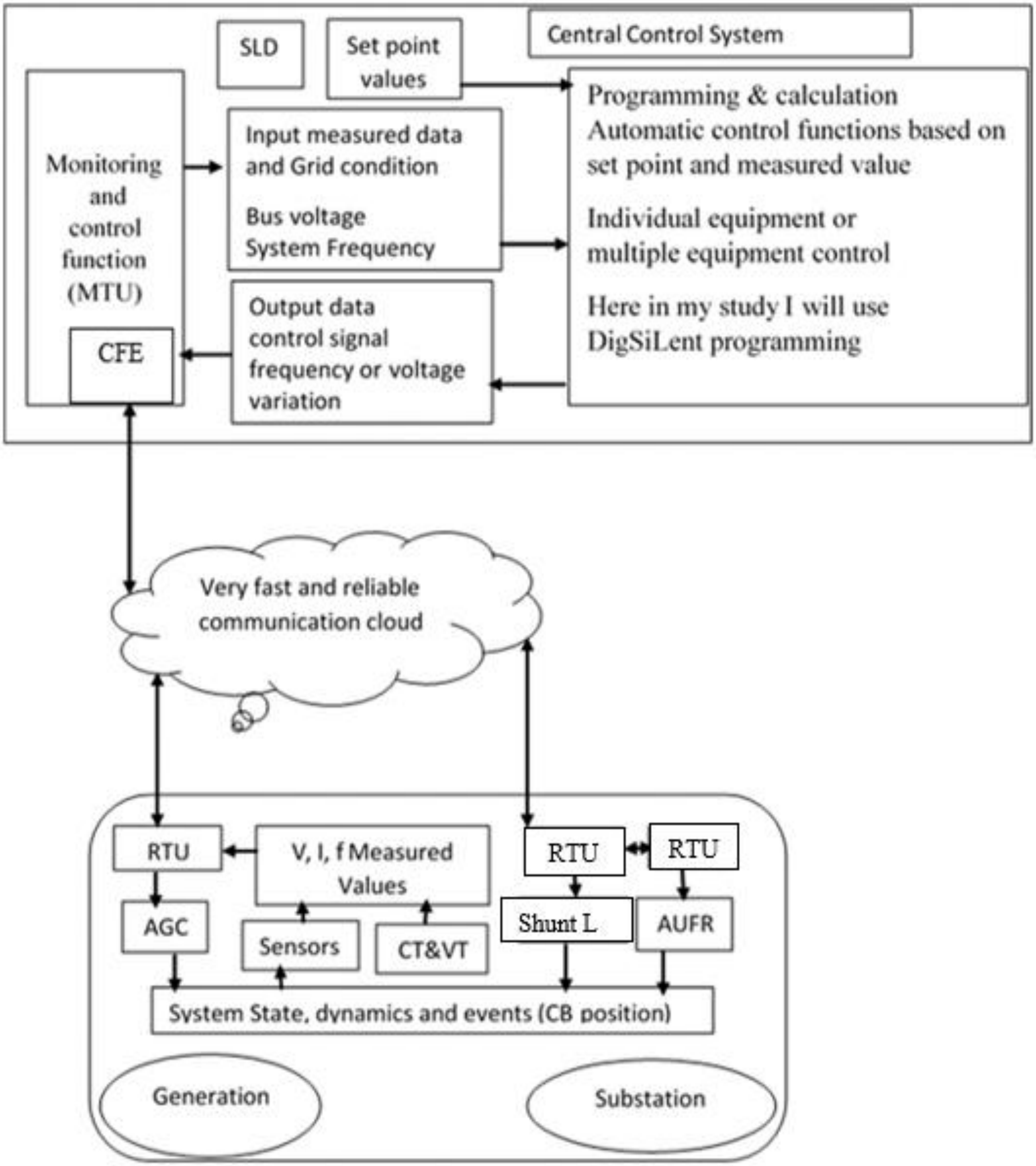


Figure 4.4 Overall hardware system design.

Software requirement

Software tools used for simulating my project is a Germany based DIgSILENT GmbH PowerFactory15.1 software. DIgSILENT GmbH PowerFactory15.1 is used to draw the single line diagram (SLD) and analyze the design and modeling of an automated DIgSILENT power system for controlling system variables. DIgSILENT will include all software packages needed to implement the SCADA system.

I will model the Ethiopian grid system using a calculation program called PowerFactory, written by DIgSILENT version 15.1. The name DIgSILENT stands for "DIgital SImuLation and Electrical NeTwork calculation program" [61]. It is a computer aided engineering tool for the analysis of industrial, utility, and commercial electrical power systems. It has been designed as an advanced integrated and interactive software package dedicated to electrical power system and control analysis in order to achieve the main objectives.

Power Factory works with three different classes of graphics: single line diagrams, block diagrams, and virtual instruments. They constitute the main tools used to design new power systems, controller block diagrams and displays of results. The network model contains the electrical and graphical information for the grid in which all graphical and electrical data which defines the networks and the single line diagrams of the power system under study. This set of data is referred as the network data model. The proposed Ethiopian electric power (EEP) grid, shown in Figure 4.6 and 4.7, is modelled using this software.

DIgSILENT PowerFactory is the most economical solution, as data handling, modelling capabilities and overall functionality replace a set of other software systems, thereby minimizing project execution costs and training requirements. In addition, the PowerFactory have rich interfacing and system integration options (e.g. GIS, SCADA, and EMS). The elements data used to carry out PowerFactory analyses will be explained next.

EEP single line Diagram by using DigSILENT

DigSILENT is a graphical environment based software for building single line diagrams of power system models. The elements for the single line diagram can be chosen from the Drawing Toolbox (figure 4.5) by dragging them in the main graphical environment.

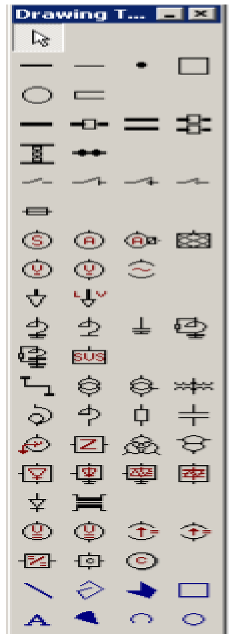


Figure 4.5 Drawing Toolbox window

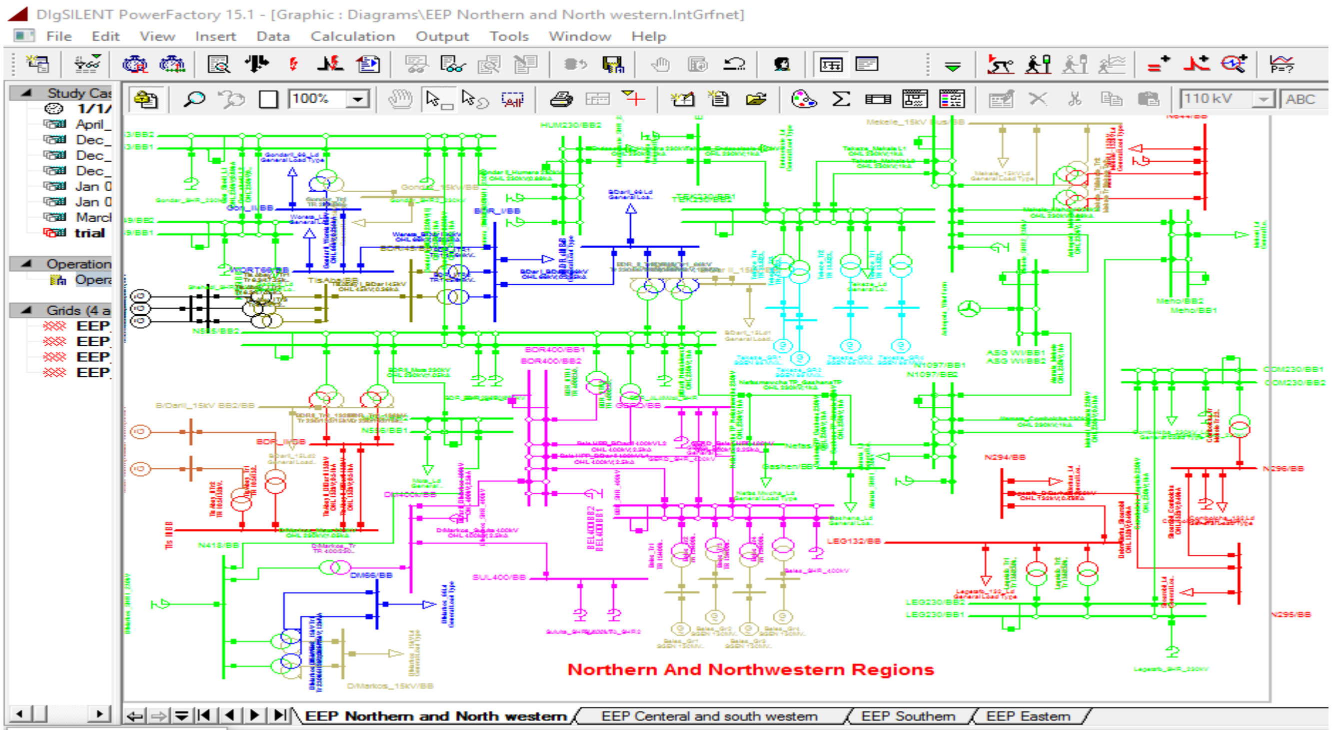
The user can define the data of the model very simple by either double-clicking on an object or by accessing the Data Manager through icon in the main toolbar.

The EEP grid system consists of the fallowing regions with different production and consumption characteristics.

- 'North and north western' with medium levels of hydro generation and low level of consumption
- 'Central and south western' with low level of generation and high level of consumption.
- 'Southern' with high level of generation and some load.
- 'Eastern' with more wind and diesel production and moderate consumption.

The transmission system consists of the main transmission network such as 400kV, 230kV, 130kV and feeder transmission systems which operate at 66kV, 45kV and below up to 4KV.

A general graphical outline of the network is presented in figures below while the detailed system data representation can be found in Appendix Table A.



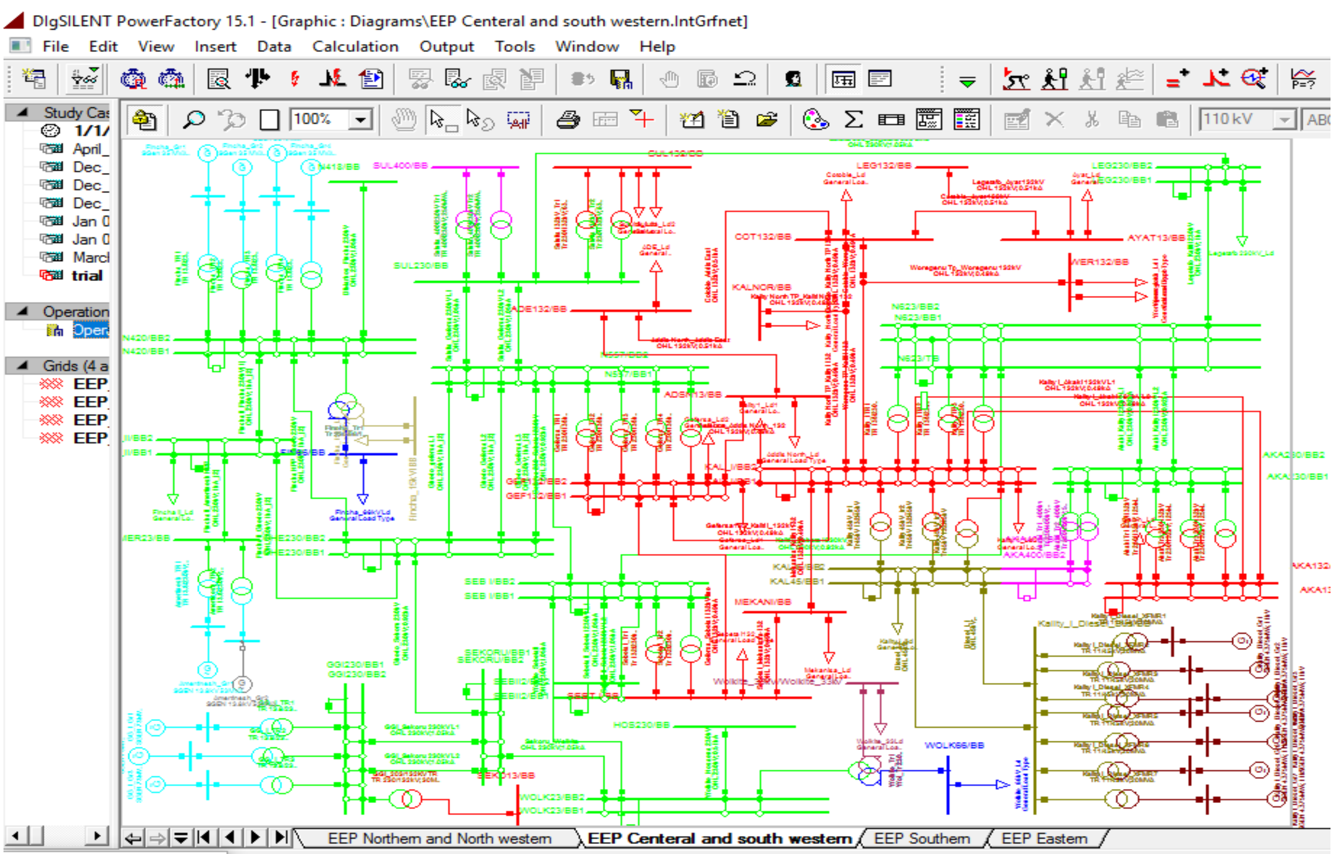
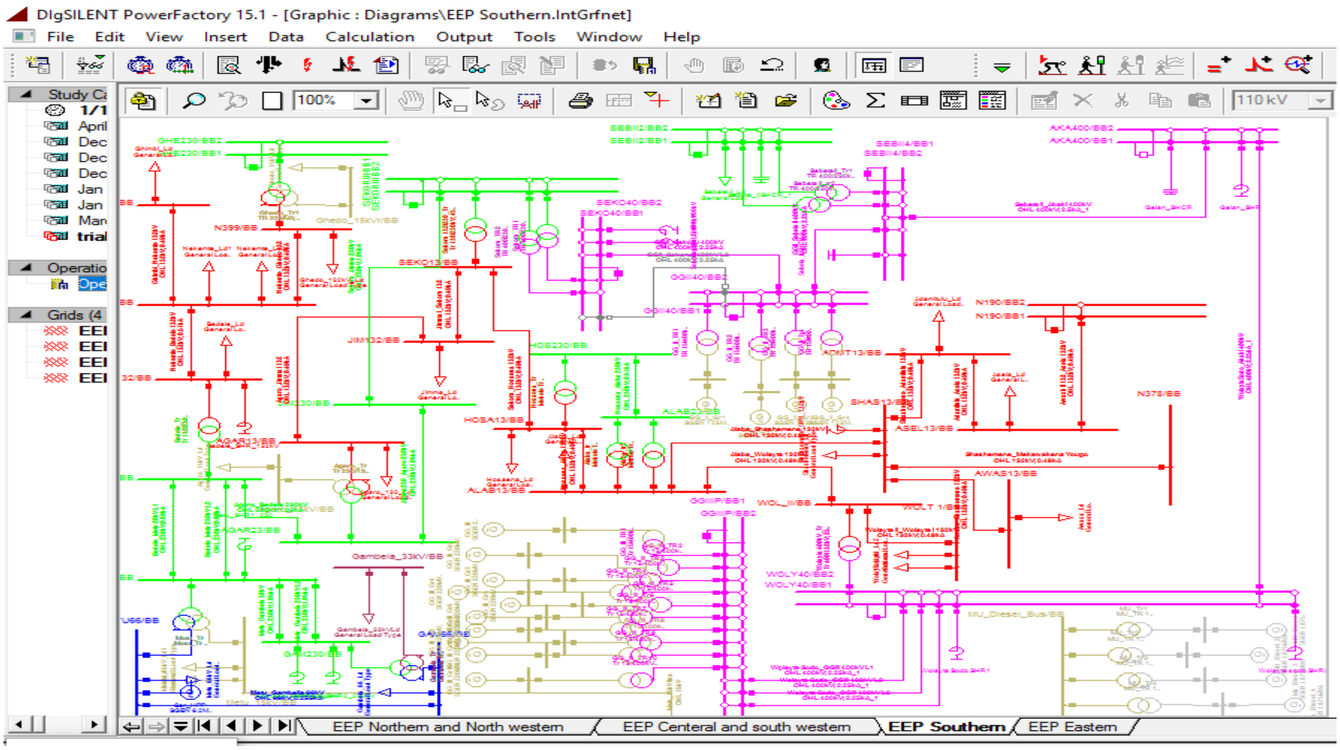


Figure 4.6 Single line diagram of Northern and North western, central and south western region



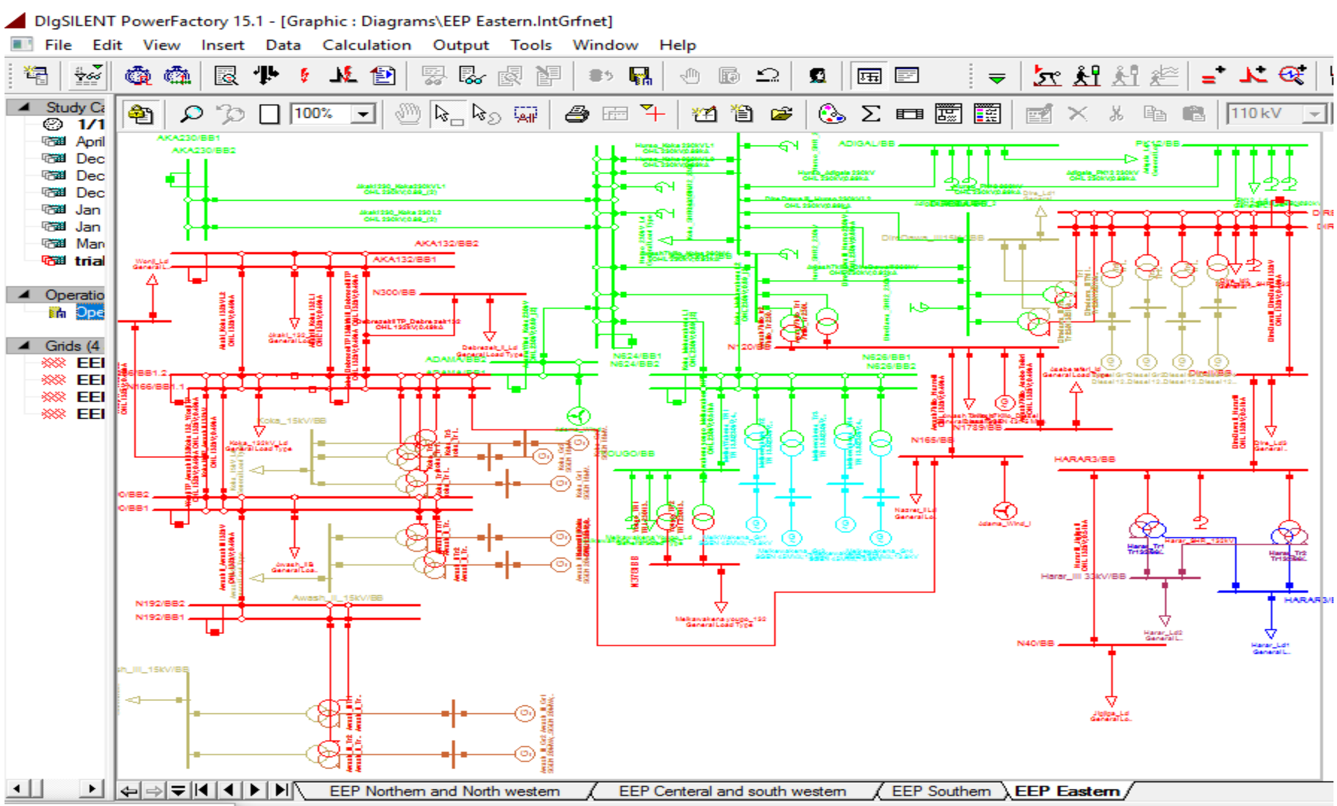


Figure 4.7 Single line diagram of Southern and Eastern region respectively

The Ethiopian high voltage grid data of transmission lines, transformers, generators, loads and bus bares have been collected from EEP concerned offices and analysis of this data has been made to make for simulation. The collected data and the data prepared for simulation have been presented in the next sections.

The input parameters of the DigSILENT are:

- ✓ Generator data
- ✓ Load data
- ✓ Transformer data
- ✓ Transmission line Data
- ✓ Bus data
- ✓ Shunt reactors

Generator Data (Synchronous Data)

Synchronous generators are selected using the button from the Drawing Toolbox. After placing them to the bus bar that are connected the ElmSym object is created in the database. The model then has to be edited in the following way.

The basic data have to be assigned in ElmSym object. These data concern the name of the machine, if it acts as a motor or as a generator, the mode of the local voltage controller (power factor/ voltage) the reactive power limits, etc.

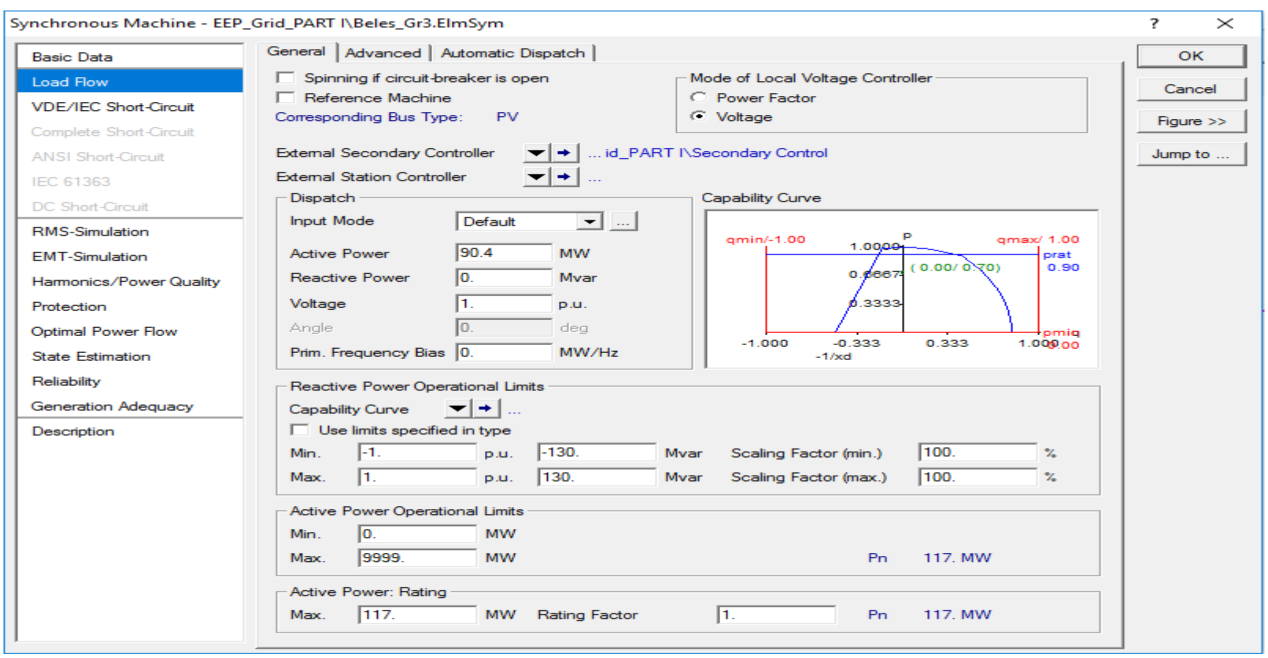


Figure 4.8 Beles Generator 3 Synchronous machine definition

The Ethiopian ICS high voltage grid generators (units) data has been collected and compiled in Appendix Table A.1.

Load Data

The loads in PowerFactory are selected with the  button from the Drawing Toolbox and dragging them to the Bus bar or the Terminal that are connected. Doing so, an ElmLod object is created in the database which describes the load. Loads are edited by double clicking on them and information about the active and reactive consumption can be assigned. Additional parameters like the voltage and frequency exponents for a static load model representation can be defined by selecting the New Project Type… option.

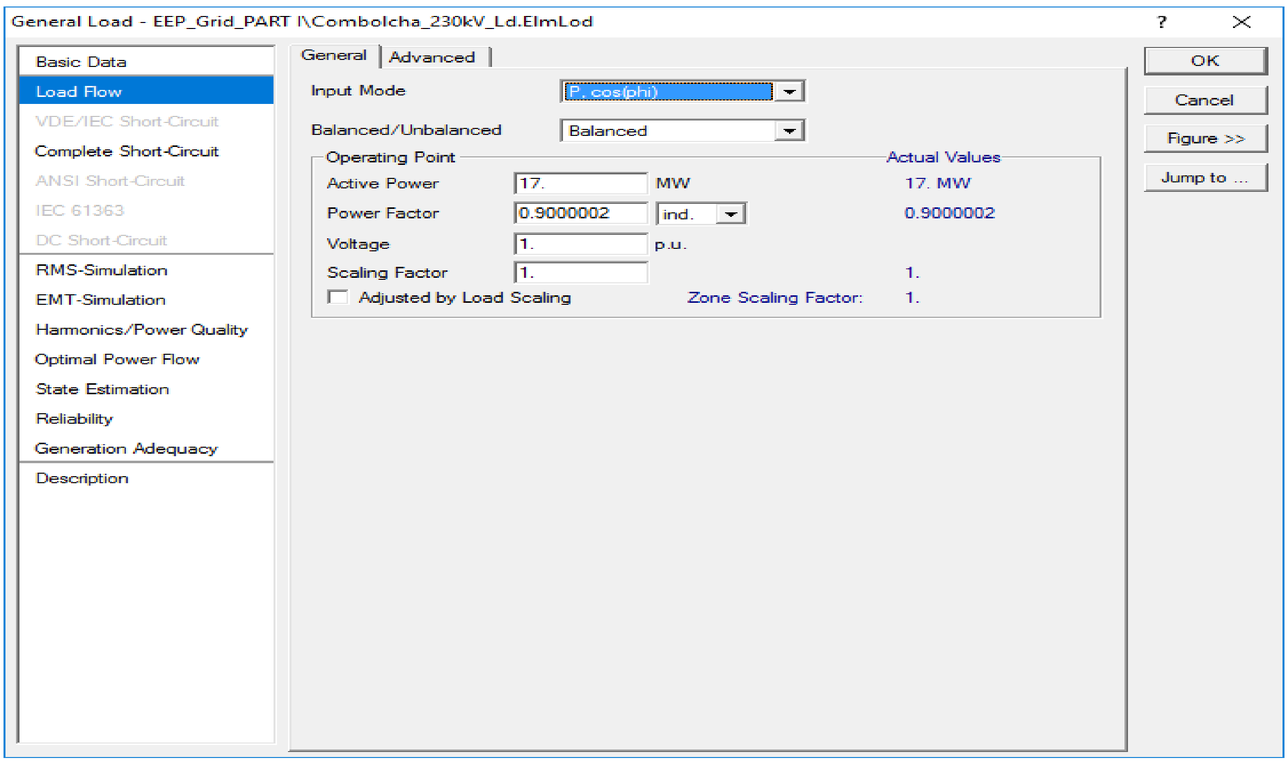


Figure 4.9 Combolcha 230kv general load definition

Active and reactive power load data for each bus of the entire grid have been collected and rearranged for the entire EEP ICS grid system. It is compiled in Appendix Table A.2

Transformers Data

PowerFactory incorporates the modeling of transformers, such as 2 Winding Transformer ( ) and 3-Winding Transformer ( ). The transformer is simply connected to the appropriate bus bars by dragging it in the single line diagram and left clicking on the chosen nodes. An ElmTr2 object is then created in the database. In case of wrongly connection between the high and low voltage side an error message will be displayed. In this case the usage of Flip Connection button will reverse the connections.

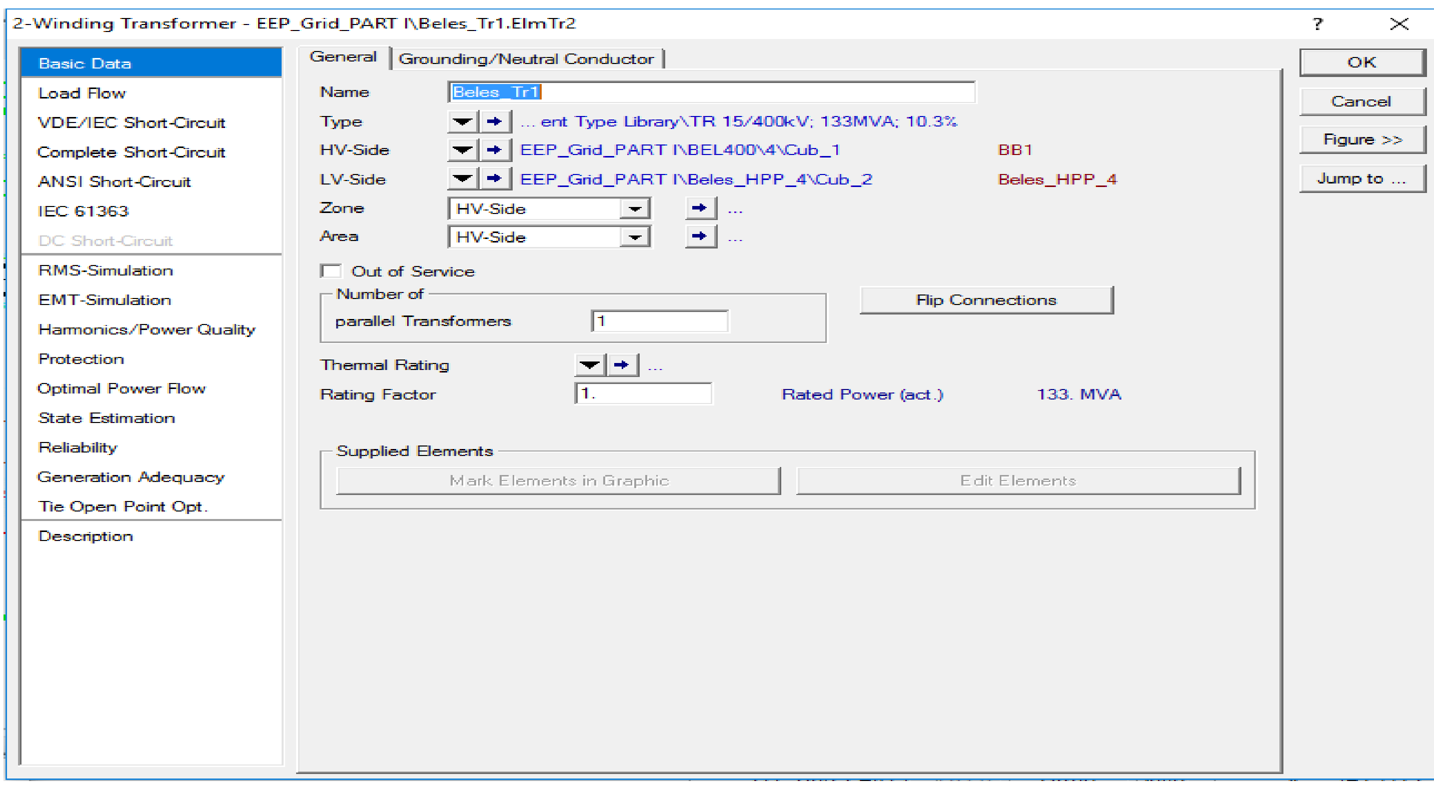


Figure 4.10 Two winding Beles Tr_1 definition

Ethiopian interconnected power system grid three winding and two winding transformers data have been collected from EEP concerned offices and have been arranged in proper way as given in the following subsections.

A. Three winding transformer: The EEPCO power system grid three winding transformers short circuit data has been collected and arranged in Appendix Table A.4.

B. Two-winding Transformer: the two-winding transformers short circuit data of the high voltage grid has also been collected and arranged in Appendix Table A.3.

Transmission Line Data

Lines in PowerFactory are simply represented as one-to-one connection between two nodes. Using the  icon and left clicking on the appropriate nodes a connection between them is established. A line is represented by an ElmLne object in the database which can be edited after double-clicking on the line. A type for the line needs to be defined. For this model new project types were created for each line according to their electrical characteristics. The electrical characteristics (nominal voltage, resistance, inductance and susceptance per km) were assigned to the lines according to the figure below.

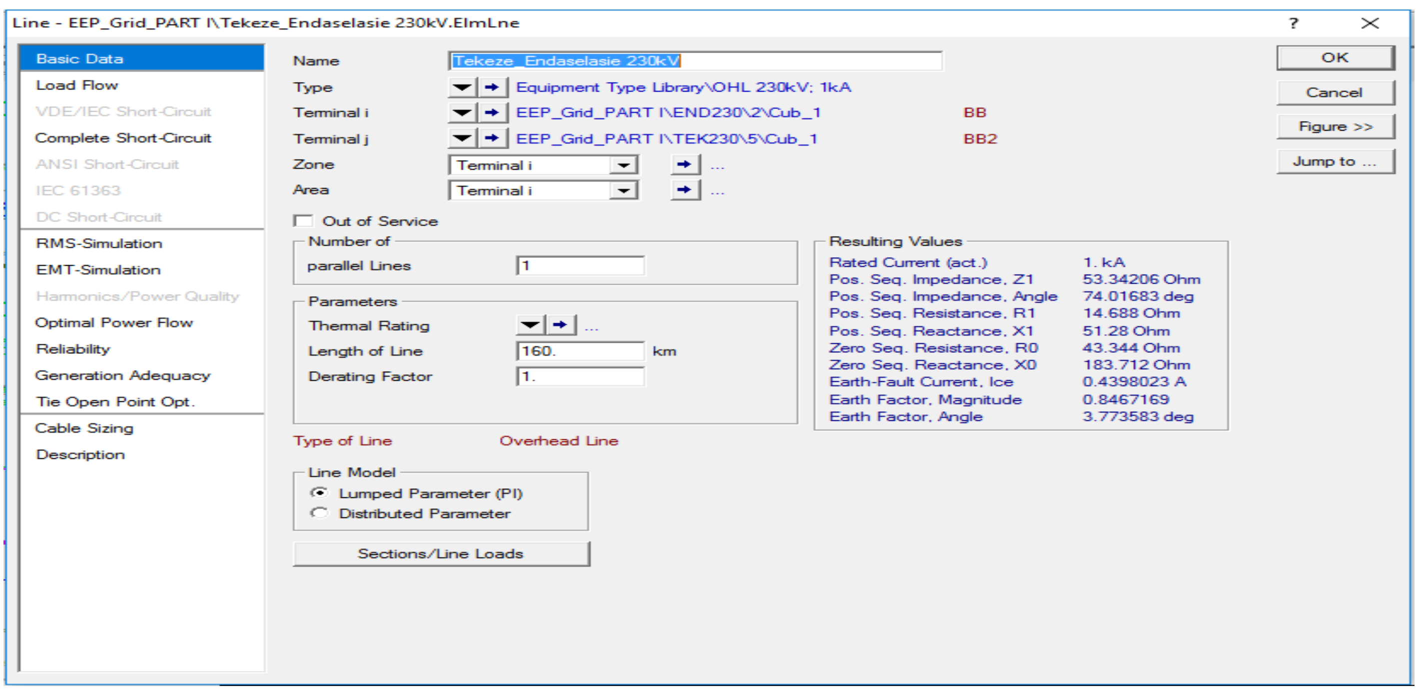


Figure 4.11 Tekeze-Shire transmission line definition

The Ethiopian Electric power high voltage interconnected system transmission lines data has been collected. Then the collected data have been complied in a proper way as it is presented in Appendix Table A.5.

Bus bar data

Two different types of node elements were used, Terminals ( ) and Bus bars ( ). A terminal is the simplest node representation and was used in those cases were neither generators nor transformers were connected. For these cases a bus bar was preferred instead of a terminal. PowerFactory gives many alternatives for the representation of a bus bar such as Bus bar, Single Bus bar System With Tie Breaker, Double Bus bar System etc. For the needs of this work a single and double Bus bar was selected. After placing the Bus bar to the single line diagram and double clicking on it a pop up dialogue for the required data will be appeared.

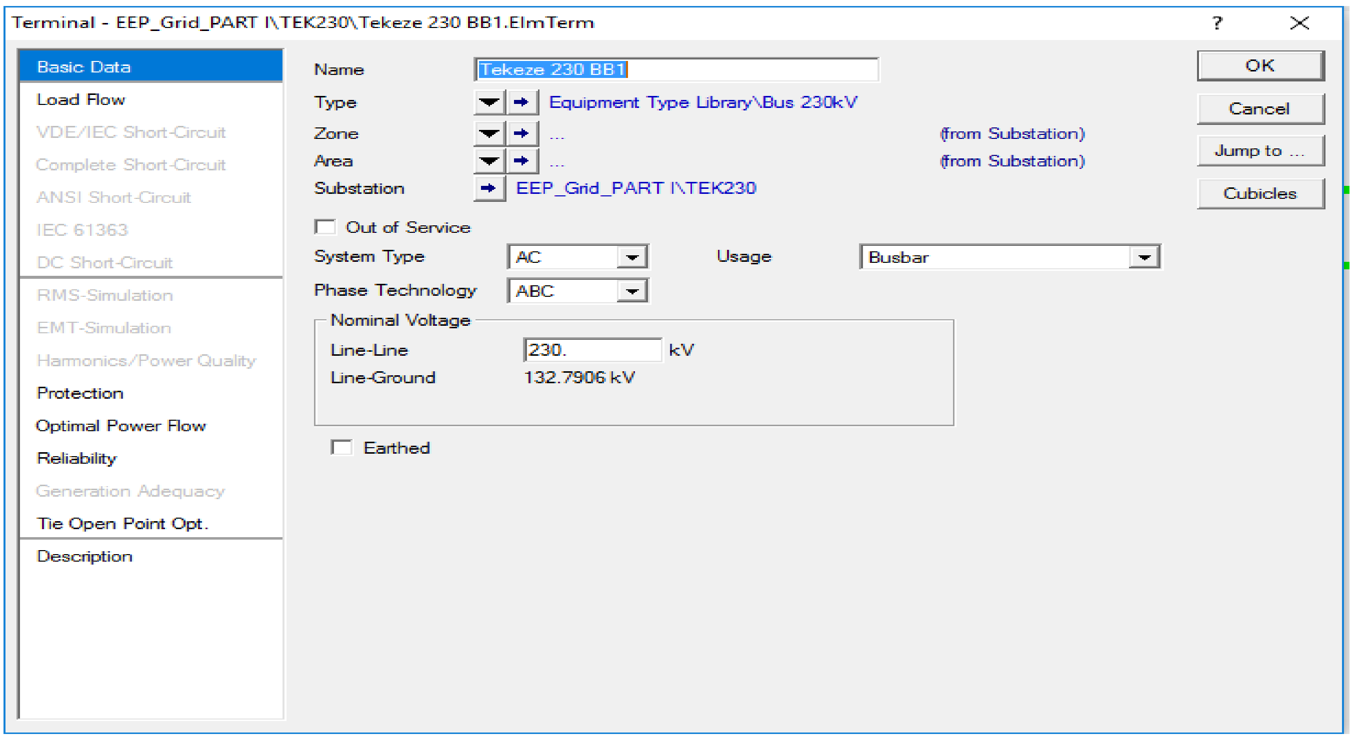


Figure 4.12 Tekeze 230 BB1 Definition

The Ethiopian Electric power high voltage nodes (terminals and bus bar) data has been collected. But the bus bar data has been complied in a proper way as it is preference for this project and presented in Appendix Table A.6.

Shunt Impedances

PowerFactory supports five combinations of shunt impedances such as Shunt RLC ( ), Shunt RL ( ), Shunt C ( ), and more. For the modeling of this project shunt reactors were used. The connection of a shunt element creates an ElmShnt object in the database. The nominal voltage, the shunt type and the design parameters for each specific shunt type are some of the data that are required.

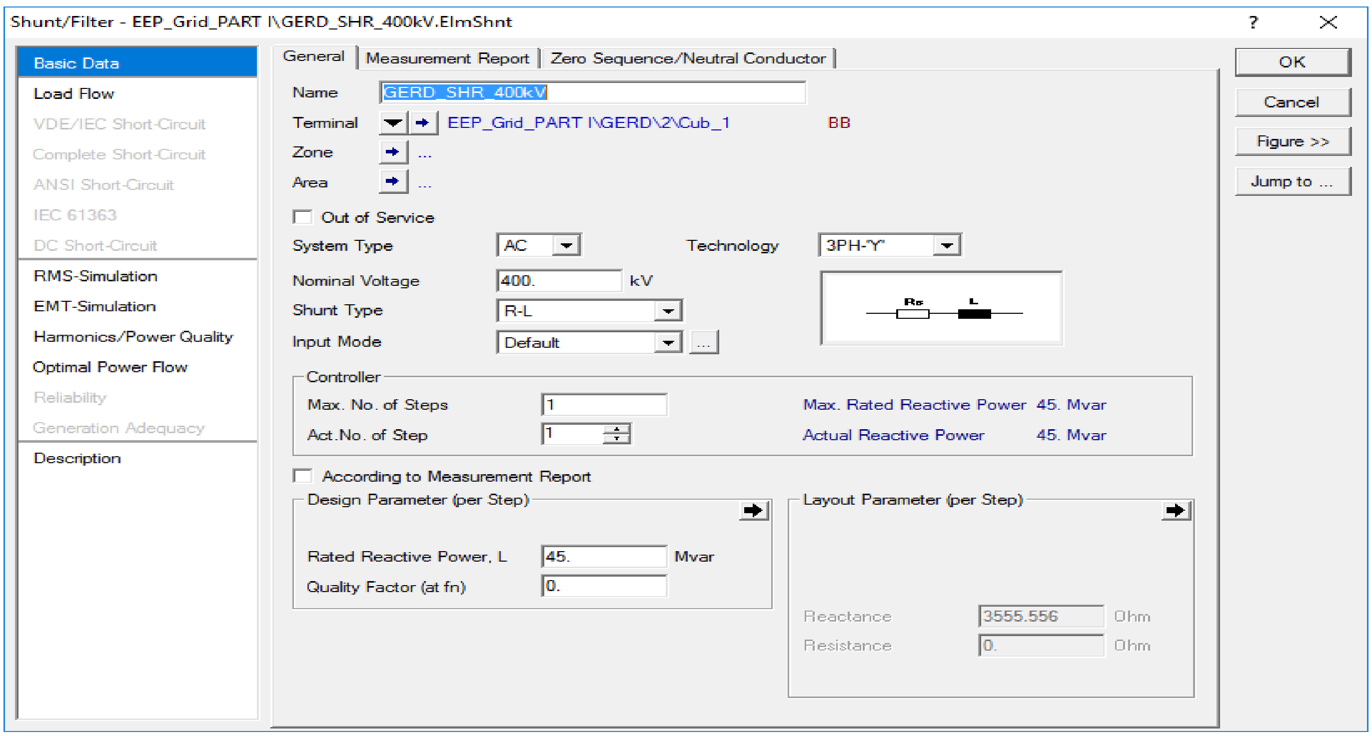


Figure 4.13 Grand Ethiopian Renascence Dam 400KV shunt reactor

Ethiopian high voltage grid has also shunt reactors to absorb shunt capacitance generated by the long distance transmission lines during light loads but a few of them are operational. Those are collected and compiled in Appendix table A.6.

CHAPTER FIVE

SIMULATION RESULT AND DISCUSSION

5.1 Introduction

The proposed concept of an automated SCADA control system for blackout prevention is being tested on a simulation environment implement in DIgSILENT power factory. As stated on the scope, the simulation studies consider the whole network of EEP. But to simulate the whole system will be very complex and the results will not be clearly understandable and tedious. So I will select and simulate the northern grid to get better result and better understanding about controlling and implementation of the control algorithm I have developed. The basic principle for the rest of the network is similar to the one I will work on.

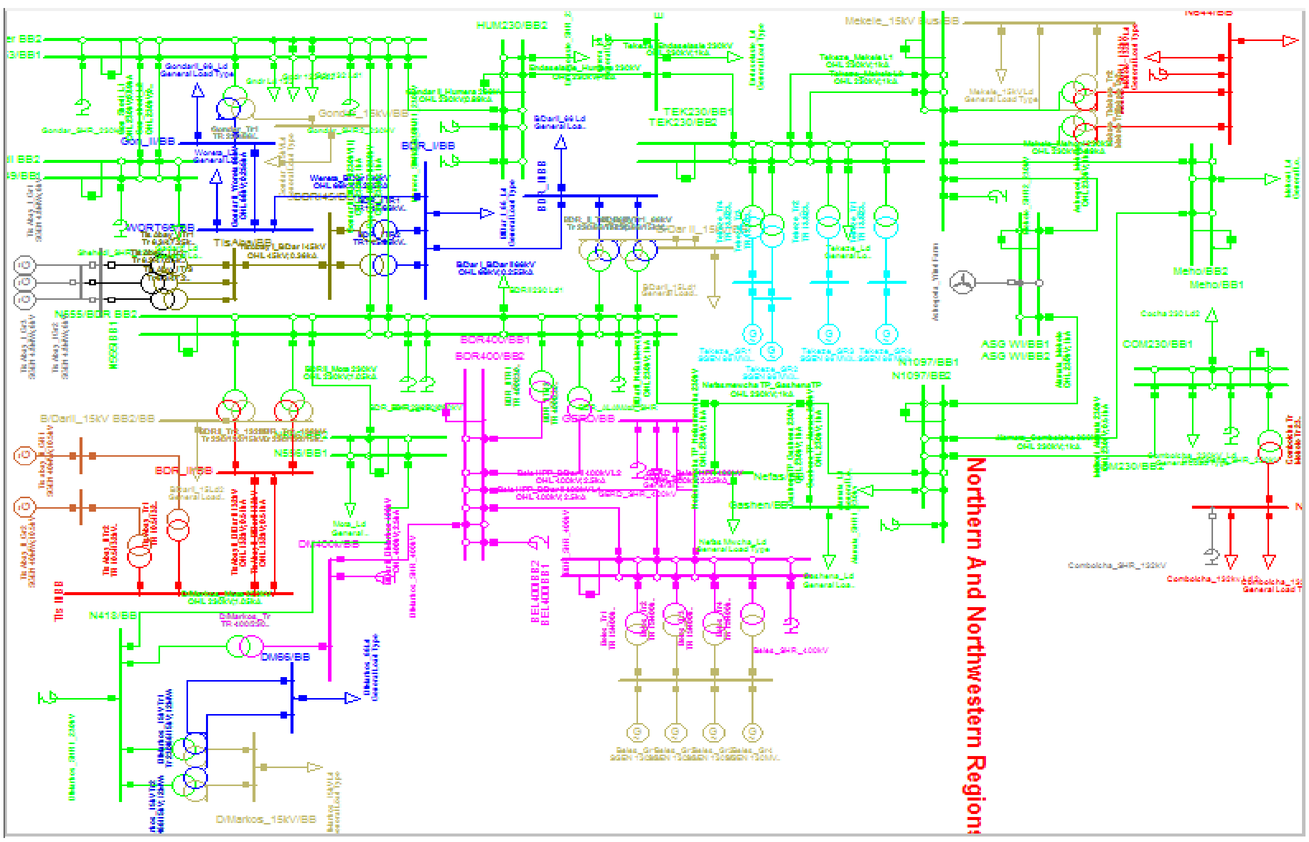


Figure 5.1 North and north western EEP grid

```
|                 |                                                       |   DIgSILENT   | Project:                      |
|                 |                                                       | PowerFactory  |-------------------------------
|                 |                                                       |    15.1.7     | Date:  9/20/2017              |
-----------------------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------------------
| Load Flow Calculation                                                                                        Grid Summary |
-----------------------------------------------------------------------------------------------------------------------------
|    AC Load Flow, balanced, positive sequence            |   Automatic Model Adaptation for Convergence          No        |
|    Automatic Tap Adjust of Transformers         No      |   Max. Acceptable Load Flow Error for                           |
|    Consider Reactive Power Limits               Yes     |      Nodes                                            1.00 kVA  |
|                                                         |      Model Equations                                  0.10 %    |
-----------------------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------------------
| Grid: EEP_Grid_PART I      System Stage: EEP_Grid_PART I | Study Case: trial LF              | Annex:                / 1  |
-----------------------------------------------------------------------------------------------------------------------------
| Grid: EEP_Grid_PART I      Summary                                                                                        |
|                                                                                                                           |
| No. of Substations     35        No. of Busbars       61        No. of Terminals     571       No. of Lines          31     |
| No. of 2-w Trfs.       19        No. of 3-w Trfs.      9        No. of syn. Machines  13       No. of asyn.Machines  0      |
| No. of Loads           30        No. of Shunts        19        No. of SVS            0                                    |
|                                                                                                                           |
| Generation            =     568.23  MW          -36.11   Mvar      569.38  MVA                                            |
| External Infeed       =       0.00  MW            0.00   Mvar        0.00  MVA                                            |
| Inter Grid Flow       =       0.00  MW            0.00   Mvar                                                             |
| Load P(U)             =     554.52  MW          204.54   Mvar      591.04  MVA                                            |
| Load P(Un)            =     554.52  MW          204.54   Mvar      591.04  MVA                                            |
| Load P(Un-U)          =       0.00  MW           -0.00   Mvar                                                             |
| Motor Load            =       0.00  MW            0.00   Mvar        0.00  MVA                                            |
| Grid Losses           =      13.71  MW         -612.09   Mvar                                                             |
| Line Charging         =                        -736.95   Mvar                                                             |
| Compensation ind.     =                         371.44   Mvar                                                             |
| Compensation cap.     =                           0.00   Mvar                                                             |
|                                                                                                                           |
| Installed Capacity    =     849.60  MW                                                                                    |
| Spinning Reserve      =      81.77  MW                                                                                    |
|                                                                                                                           |
| Total Power Factor:                                                                                                       |
|   Generation          =        1.00  [-]                                                                                  |
|   Load/Motor          =  0.94 / 0.00  [-]                                                                                 |
```

Figure 5.2 Grid summery of northern and north western region

The main aim of this program is to prevent blackout by controlling voltage and frequency (the main causes for disturbance) to its permissible value automatically based on DIgSILENT programming in combination with SCADA system. DIgSILENT offers a suite of fully integrated electrical engineering software solutions including arc flash, load flow analysis, short circuit analysis, transient stability, relay coordination, cable capacity, optimal power flow, and more. Its modular functionality can be customized to fit the needs of any company, from small to large power systems by using adaptive Newton Raphson iteration up to iteration of 99 with precise 0.0001.

5.2 Base case simulation (Load Flow Analysis)

Power (load) flow analysis refers to the determination of the steady-state operation condition of a power system for a given set of network configuration. Mathematically, the power flow analysis problem is formulated as a set of nonlinear algebraic equations, and well-developed solution methods are available, including the fast decoupled method and the Newton–Raphson method.

Power flow (load) analysis are used to calculate various bus voltages, current, and active and reactive power flow along the transmission system and also power flow analysis is used to determine the condition of a power system operating at steady state. Load flow calculations are used to analyze power systems under steady-state non-faulted (short-circuit free) conditions. Where steady-state is defined as a condition in which all the variables and parameters are assumed to be constant during the period of observation. A load flow calculation is stated to be a steady state analysis because it reflects the system conditions for a certain point in time, such as for instance at 18:00 hrs. Or 15 hrs. As an example, if we require determining the behavior of the system for every hour of the day, then 24 load flows need to be performed; if the behavior for every second is required then the number of load flow calculations needed would amount to 86 400. The purpose of power flow studies is to plan ahead and account for various hypothetical situations. For example, if a transmission line is be taken off line for maintenance, can the remaining lines in the system handle the required loads without exceeding their rated values. Power flow or load-flow studies are important for planning future expansion of power systems as well as in determining the best operation of existing systems. In this thesis design analysis, DIgSILENT software is carried out with an approach to overcome the problem of electrical parameter deviation.

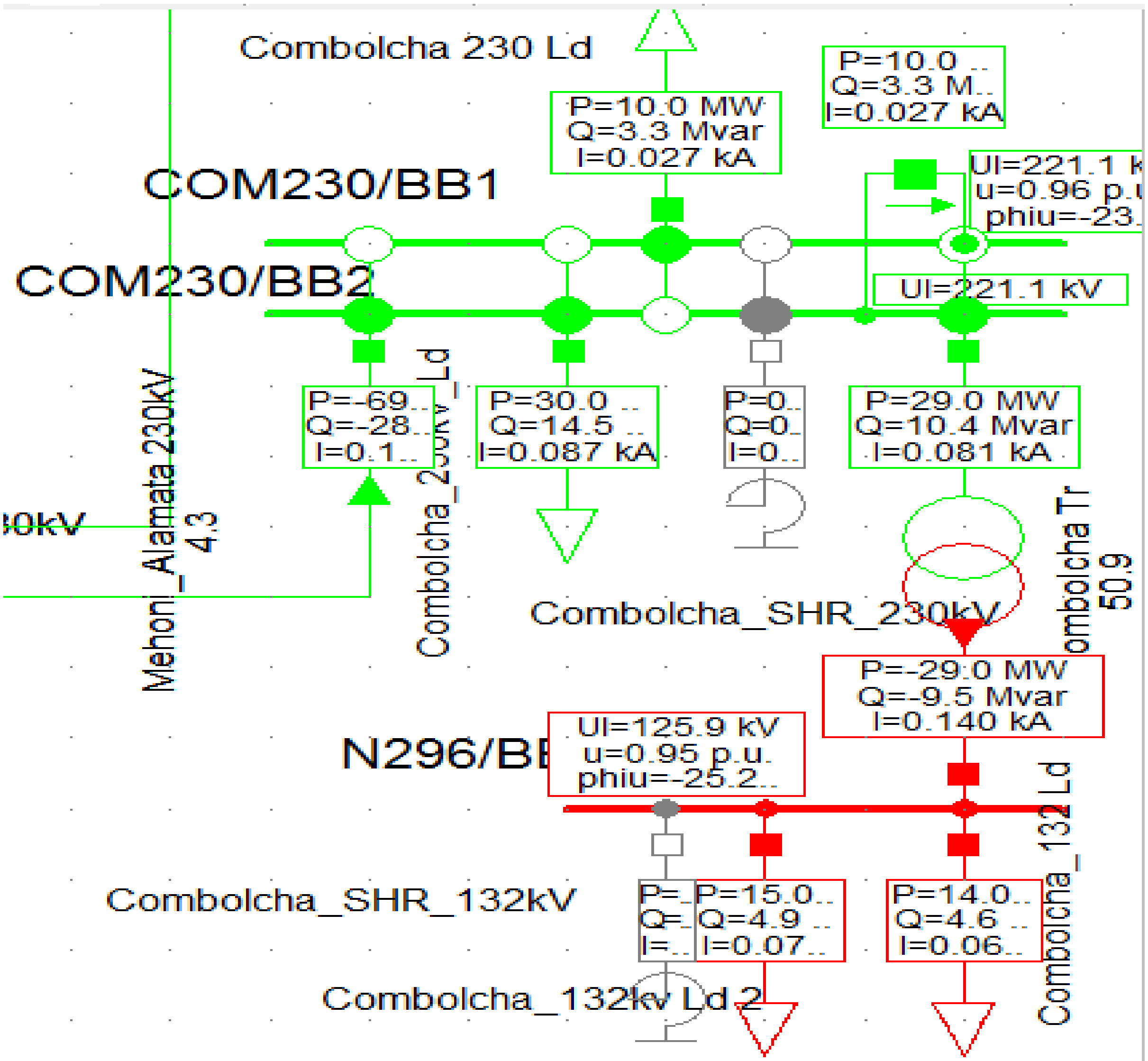


Figure 5.3 A partial view of Combolcha city load flow result

As we can see from the Figure above a load flow calculation determines the active and reactive power flows for all branches, and the voltage magnitude and phase for all buses and nodes. And graphically the value of some parameters is shown below within respective units.

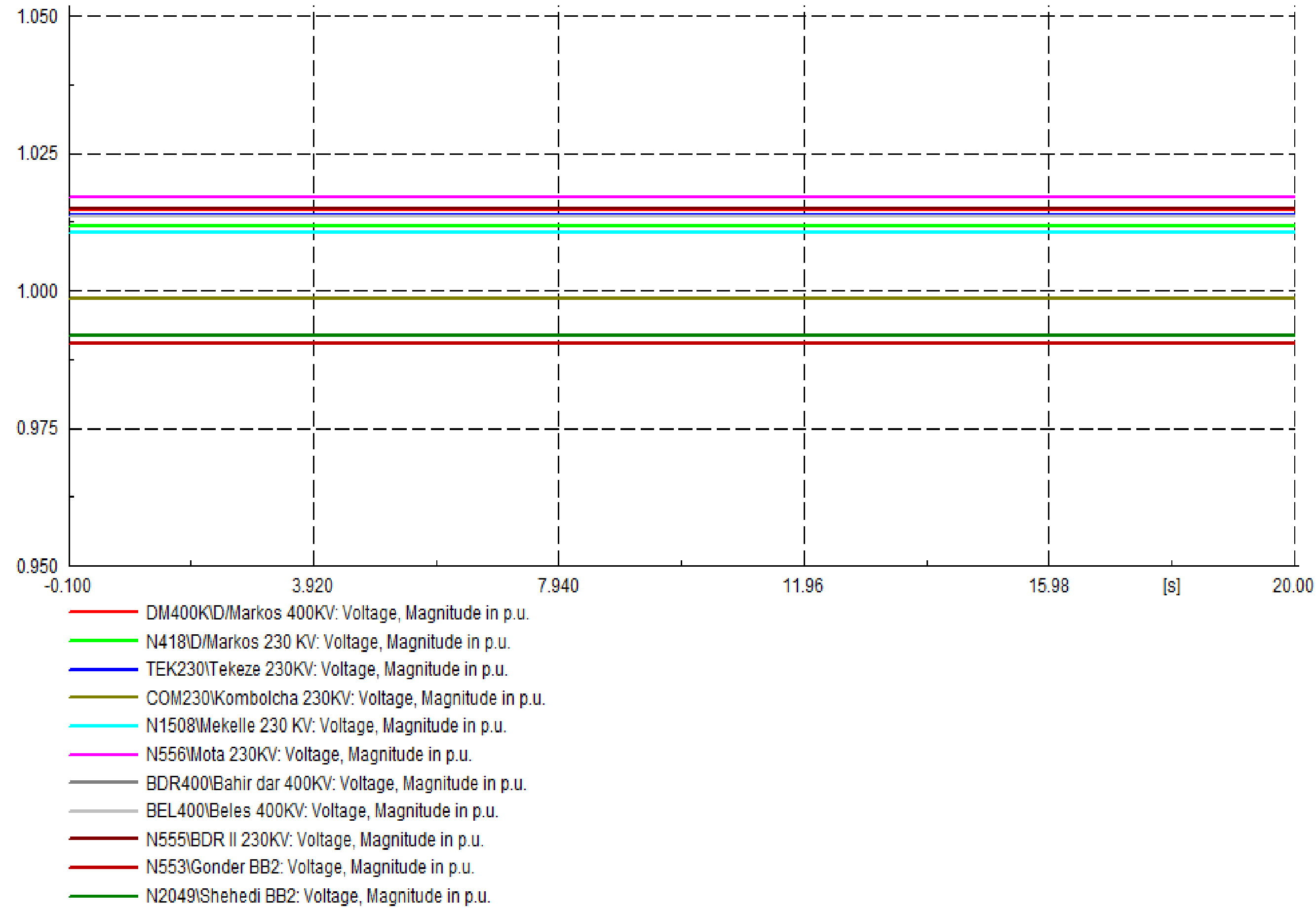


Figure 5.4 Steady state Bus Voltage (selected buses)

As we can see from the Figure above the bus voltage value is constant over a period of time since the network is at steady state (short-circuit free) condition. For steady-state voltage, the magnitudes of voltages in a system must be within specified ranges. Values of these ranges may depend on the contingency condition, region of the system, and voltage levels. EEP used ranges between 0.95 and 1.05 pu for normal condition as seen on the above graph and between 0.9 and 1.1 pu for contingent condition.

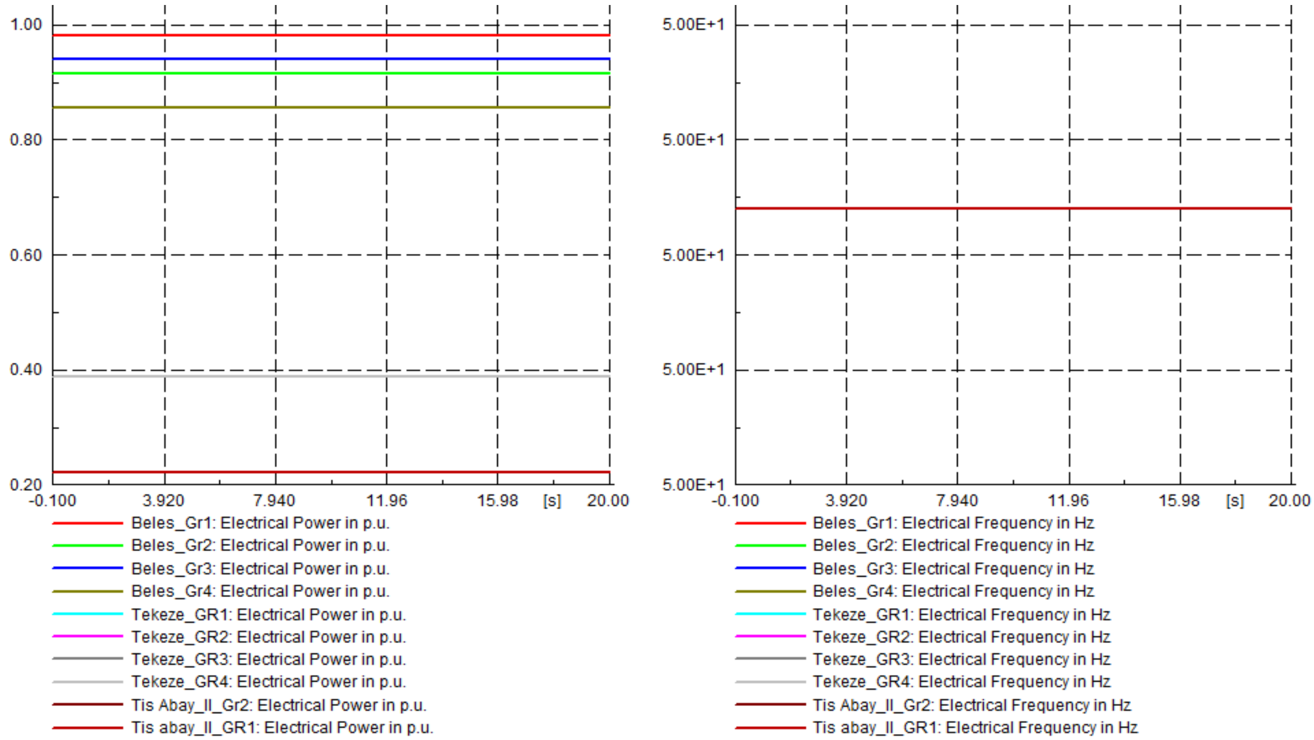


Figure 5.5 Steady state generator active power in p.u and frequency in Hz

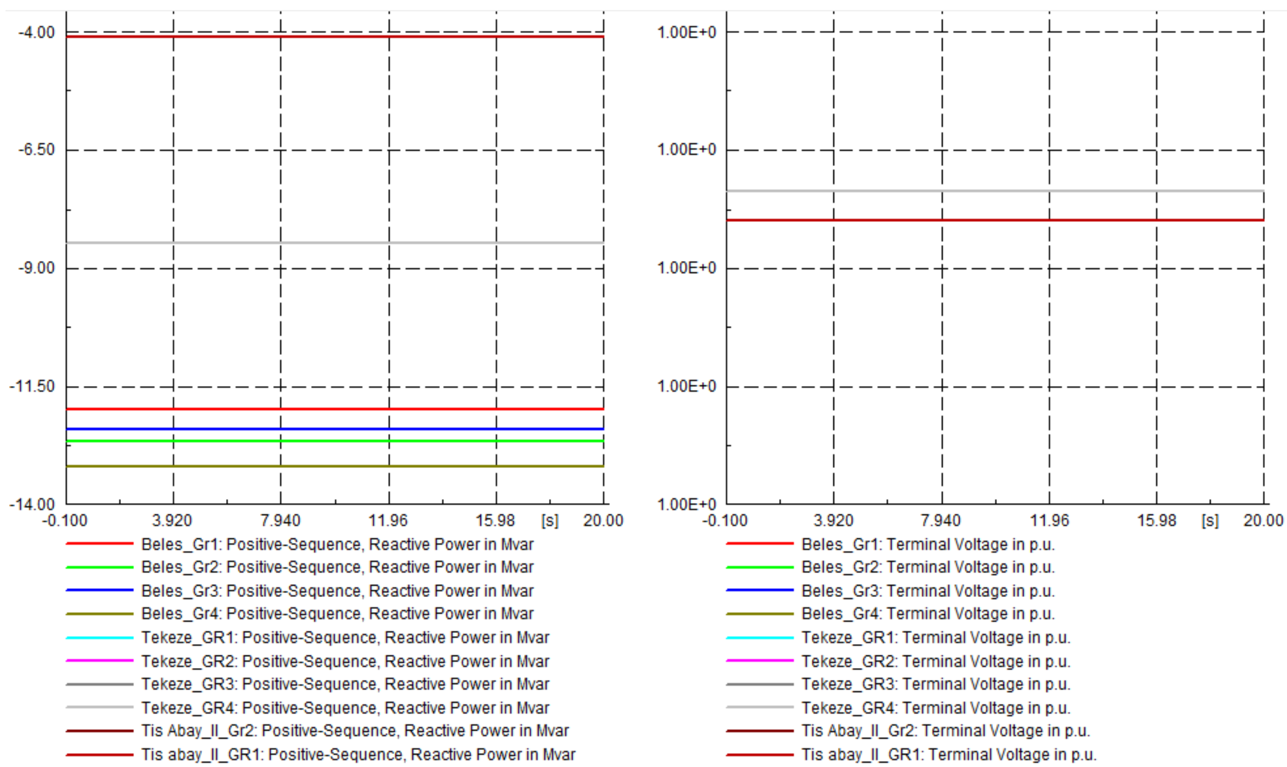


Figure 5.6 Steady state generator Reactive power in Mvar and Terminal voltage in p.u respectively

The graph shows the system is in its steady state, which is the values of the power flows, generator frequency and active power production generator reactive power and terminal voltage calculated by the simulation program would not change from one time step to the next and also it is in its permissible value except Tis Abay II generation station[1]. This implies that the generation and load-injection power flows remain constant from one time step to another, and hence the frequency value in the network remain constant.

Under steady-state conditions, there is equilibrium between the input mechanical torque and the output electrical torque of each machine, and the speed remains constant. If the system is perturbed, this equilibrium is upset, resulting in acceleration or deceleration of the rotors of the machines according to the laws of motion of a rotating body. This tends the system in to dynamic condition.

5.3 Dynamic Analysis

The load flow calculation, detailed in previous topic considers the network under a single set of operating conditions. But when we come to the real world power system operation the system can no longer be within operating limits. So that the parameter values are deviate from the normal operating point and undergo in to dynamical operating conditions. Dynamic analysis deals the analysis of the system under disturbances due to fault, load fluctuations or changes of the set values of system parameters. These change exhibits cascading failures which often lead to blackouts. Blackouts are often initiated by weather, operator error, or device malfunction or failure such as false line trips or substation fires.

Dynamic analysis is achieved by running power flow by creating different faults on the power system network such as transmission line fault, load variation and generator faults. Such type of incident will leads a cascade-wise tripping of generating units if a measurement action will not be taken faster and finally the whole system will collapsed. Therefore the automatic protection complex against blackouts should apply for preventive (and fast) removal of the root cause of blackouts. For this research, I have to take different causes (faults) that leads to system black outs in Ethiopia since 2013 and test the system what I proposed.

[1] Tis Abay II power station is off during simulation.

5.4 Power system Blackouts and Protective Automatics

1. April 26 /2013

System Condition Prior to Collapse

On April 26 /2013 at 13:10 hrs the total system generation in northern and north western grid were 568.2 MW generated from hydro generations. Whereas the total grid system generation is 1,036 MW. The system load at the time was 554.23 MW for northern grid. The transnational exchange was 19.56 MW exported to Djibouti and the system frequency observed on the EMS was around 50 Hz. Due to lack of rainfall around some hydro plants' reservoir, Tis Abay I & II, and Awash II and III HPPs were not capable of supplying power to their full capacity. Tis Abay I HPP was completely down at the time and Beles HPP was generating 272 MW only (60 % of its capacity).

The above steady state system condition prior to disturbance has been simulated and the results have been depicted in Figure 5.7. The voltages of important substations like, Motta 230kV, D/markos 230kV, Mekelle 230kV, Tekeze 230kV and Gonder 230kV substations were deteriorated and hence a further disturbance on the system could affect the steady state stability of the system.

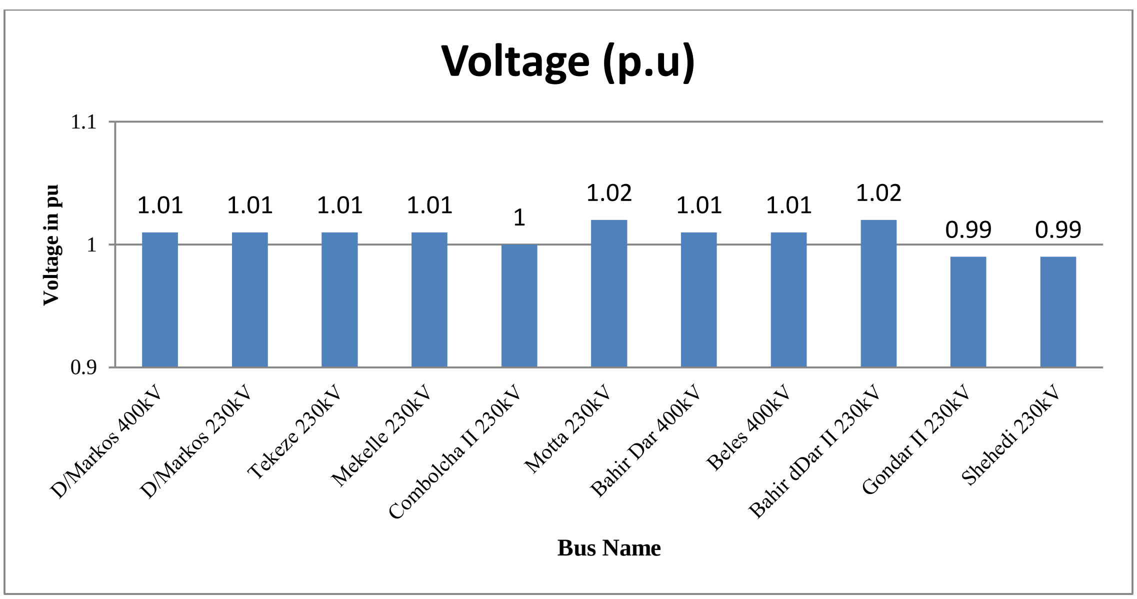


Figure 5.7 Voltages of some buses prior to system collapse

Bus name	Voltage (p.u)
D/Markos 400kV	1.01
D/Markos 230kV	1.01
Tekeze 230kV	1.01
Mekelle 230kV	1.01
Combolcha II 230kV	1
Motta 230kV	1.02
Bahir Dar 400kV	1.01
Beles 400kV	1.01
Bahir Dar II 230kV	1.02
Gondar II 230kV	0.99
Shehedi 230kV	0.99

Table 5.1 Voltages of some buses prior to system collapse

There was no overloaded equipment under this steady state conditions. The power flows on important lines that interconnect the regional power systems are indicated in Table 5.2. The total grid loss was 13.27 MW.

Line Name	MVA flow
Bahir Dar II_Nefas mewucha TP 230kV line	$90 + j48$
Nefas mewucha TP_Gashena TP 230kV line	$4 + j1.7$
Gashena TP_Alamata 230kV Line	$10 + j4.5$
Tekeze _Mekelle 230kV line I	$40 + j15$
Bahir Dar_D/Markos 400kV line	$148 + j66$
Bahir Dar_Motta 230kV line	$18 + j7$
Sebeta II_GG II 400kV line	$278 + j76$

Table 5.2 Flows on important lines affected by the event

From the steady state conditions, the synchronous speed, the terminal voltages, the active and reactive power supplied by each generator was obtained and it was observed that all these parameters were within the limits. The synchronous speed (ω_s) and the terminal voltages of each generator were synchronized to 1.0 pu. The steady state value of the reactive power supplied by each HPP generator was given in Table 5.3.

HPP Generators	Reactive power (MVAr)
Tis Abay II	-4.1
Beles	-12.4
Tekeze	-8.5

Table 5.3 Reactive power supplied by each HPP generator at steady state

The reactive power supplied by each generator was also within the normal operating ranges prior to the disturbance and is indicated in Table 5.3. The turbine power input and the electrical power output prior to the disturbance were equal and there was no accelerating power and the generators run at their synchronous speed as is indicated in Table 5.4.

HPP Generators	Turbine power (pu)	Electrical power (pu)
Beles	0.95	0.95
Tekeze	0.859	0.859
Tis Abay II	0.229	0.229

Table 5.4 Turbine power input and electrical power output of HPP generators at steady state

Initiating Event

The initiating event that caused the total system collapse was the the outage of all generating units at Tekeze Hydro Power plant. Resulting in the complete isolation of Tekeze Power plant with a loading of 120MW.

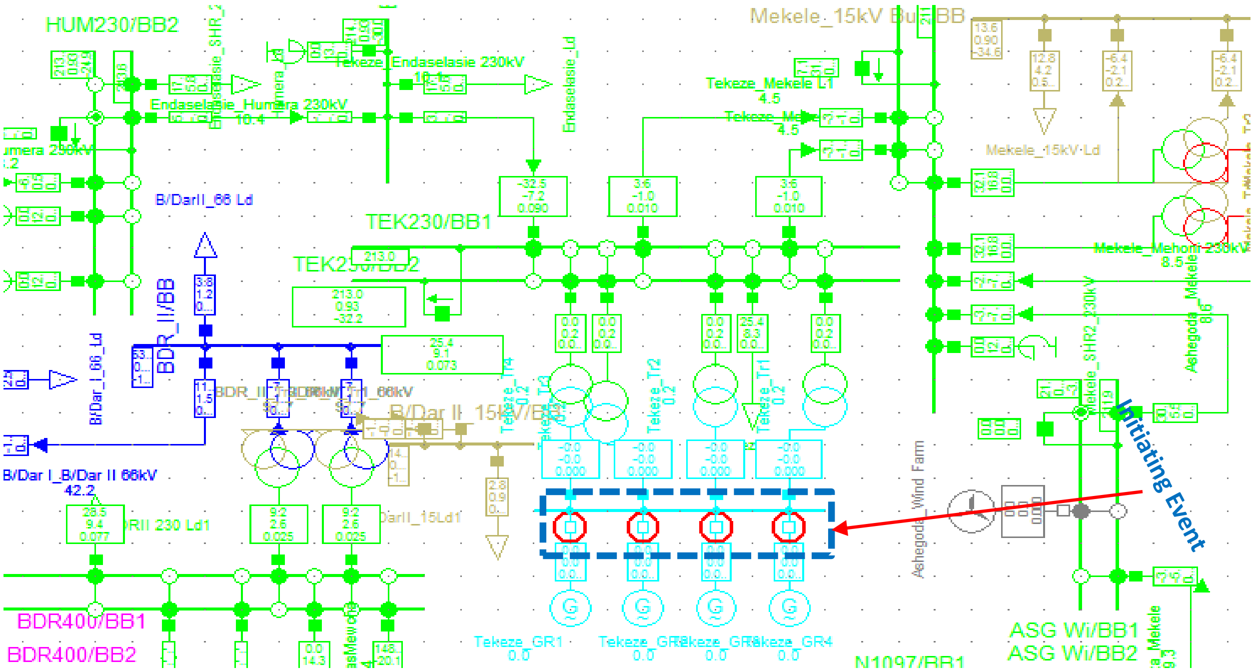


Figure 5.8 Outages of all units of Tekeze HPP

Having this information, the effects of the initiating disturbance on the behavior of EEP system have been studied in a systematic manner by performing the following dynamic simulations and analyses:

- ✓ The generators speed, terminal voltages and their corresponding reactive power drawn are traced and analyzed.
- ✓ The voltages of important buses that contributed a lot for the safe operation of the system are observed with their corresponding frequency deviations.

During the disturbance, the speed of HPP generators was decreased. Specifically, the speed of Beles and Tis Abay II generators were decelerating faster whereas Tekeze HPP was accelerating faster due to inertia. The loading of power production of Beles HPP generators were increased to 1.15 pu and Tis Abay Abay II was increased from 0.3 to 0.54 pu, and that of Tekeze was decreased to 0 pu.

The behavior of the power system during the disturbance is shown in Figure below.

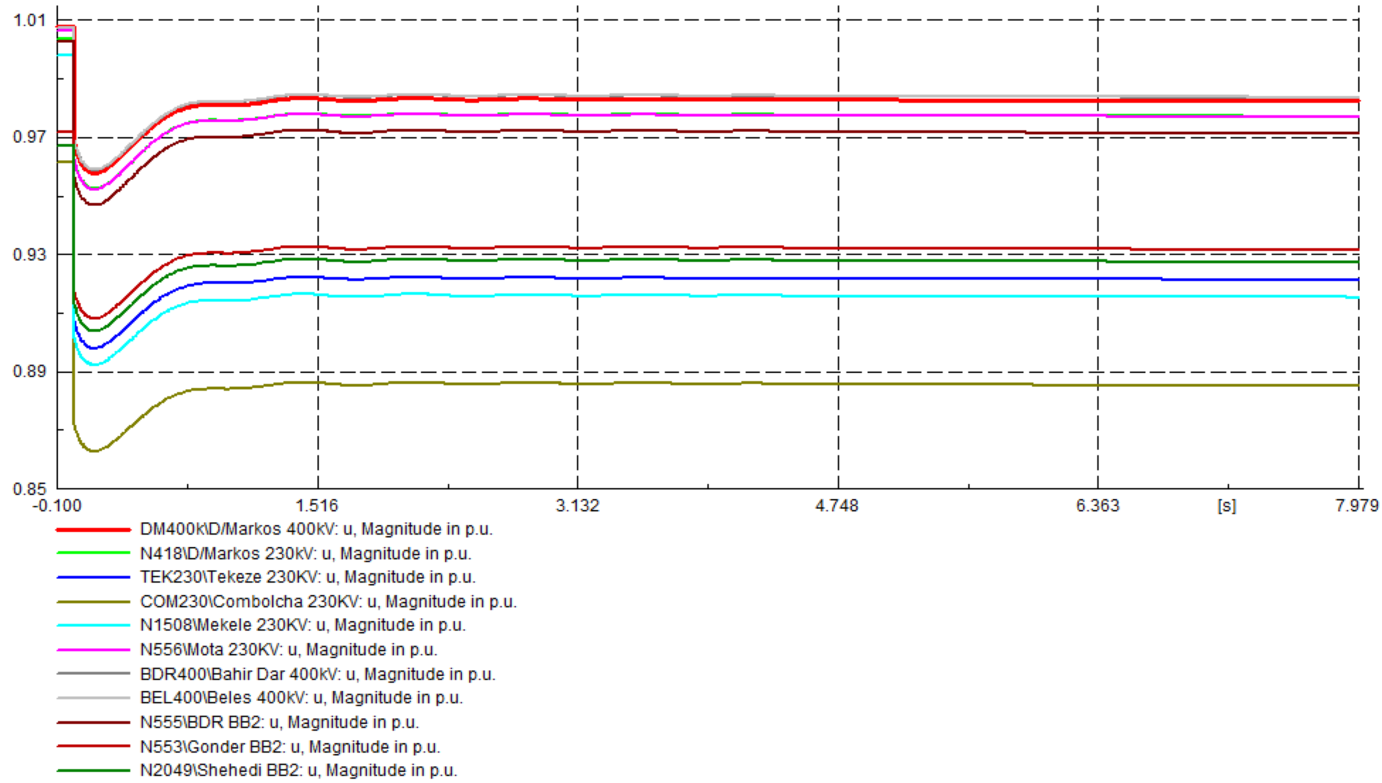


Figure 5.9 Bus voltage of selected buses during fault

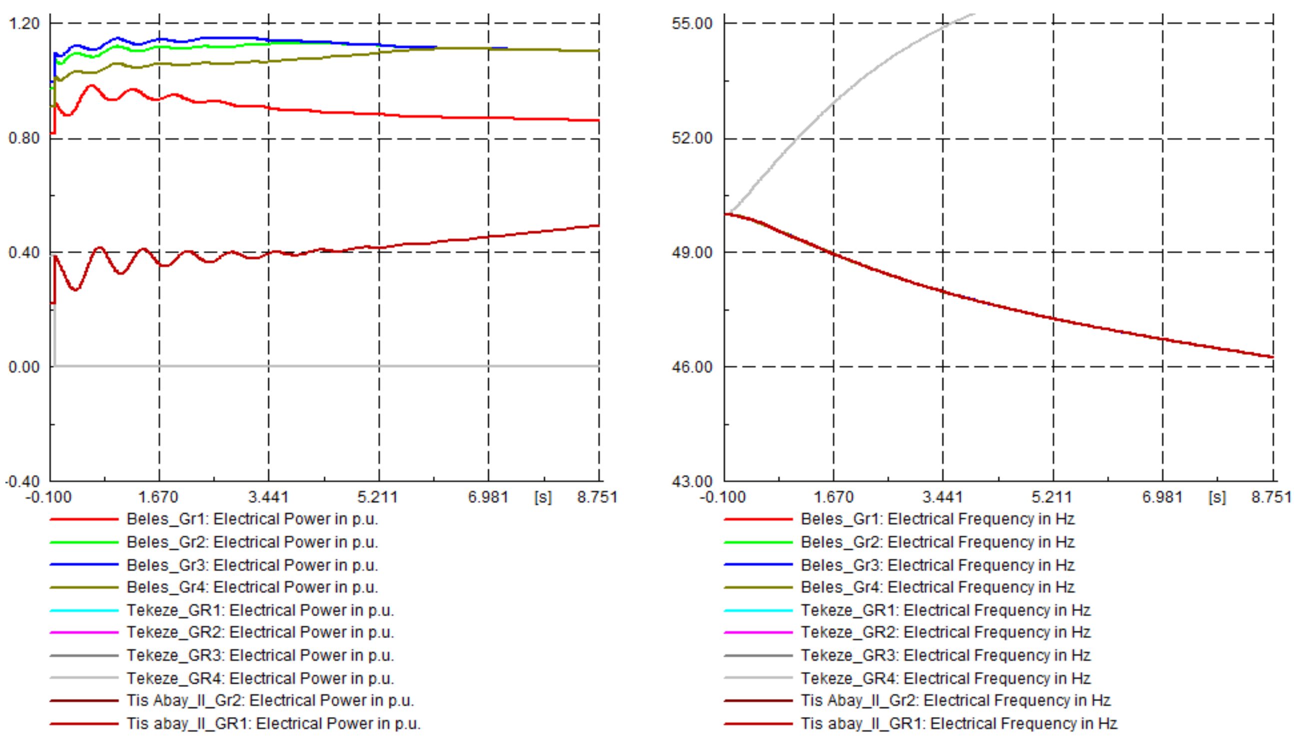


Figure 5.10 Generator active power and frequency after the incidence

(t=0.05m) the critical bus voltage recovery duration limit was violated.

(t=0.781m) Generator out of step (pole slip).

(t=1.612m) Minimum frequency limit was violated

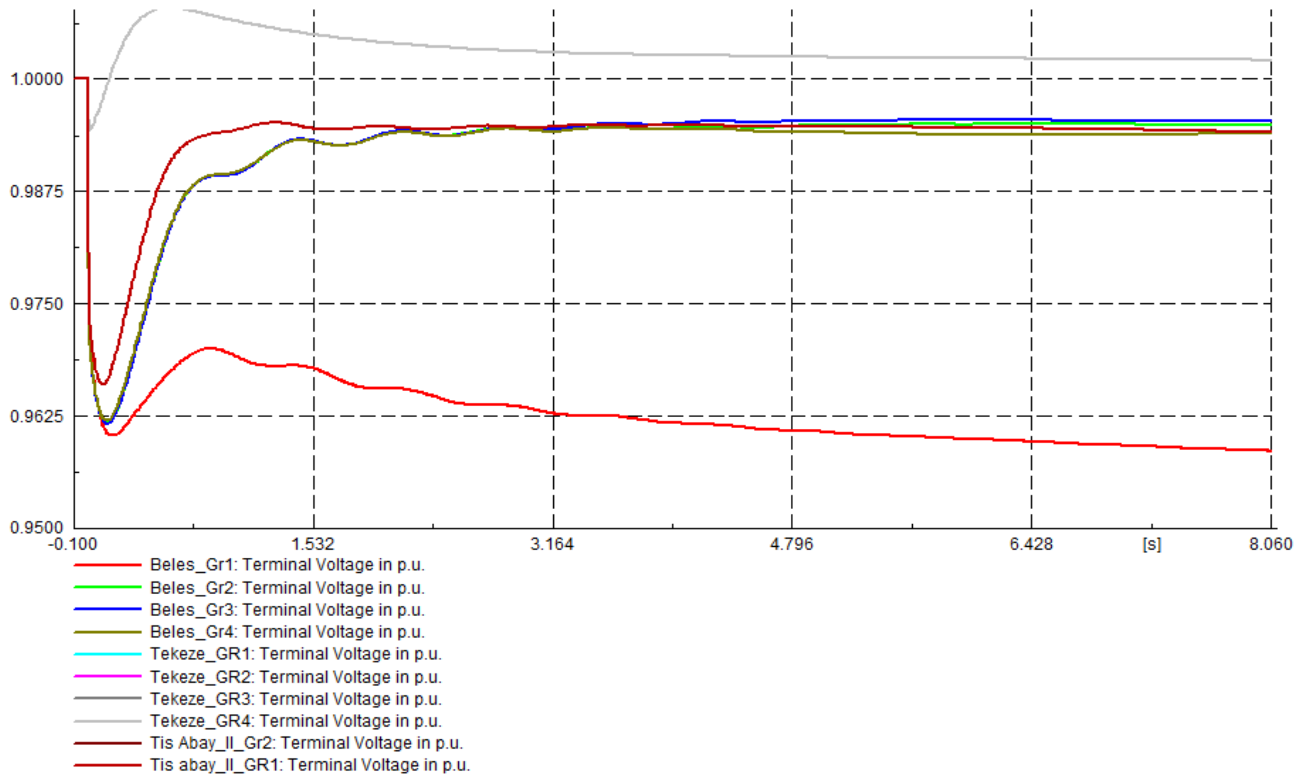


Figure 5.11 Generator terminal voltage after the fault

Cascading Events

As observed from the simulation results above, up to around 3 second the power system operates in disturbance condition after that first and second stage loads ware disconnected from the grid the system cannot be survived because the action is too late and further cascaded to Alamata _Bahir Dar transmission line. Meanwhile Beles and Tis Abay II generators were became overloaded and later they acted as a motor. Therefore, the protection relays installed at Tis Abay II power plants tripped the corresponding generators and the cascaded tripping started.

Therefore, the cascading event continued when Bahir Dar _ Alamata 230kV Line I was tripped after 3 seconds. Some of the sequence of events observed on the SCADA/EMS was indicated in Table 5.5.

Line/Gen/Transformer	**Outage time**	**Reason**
Tekeze HPP	13:10	Over frequency
Bahirdar_Alamata 230kV line	13:11	Earth fault, Fault location = 279.9 km
Alamata_Bahirdar 230kV line	13:11	Earth fault,Fault location=121.6 km
Koka_Dire Dewa 230kV line	13:11	Over voltage
Kality I_Mekanissa 132kV line	13:11	Short circuit
GGII HPP	13:13	Over frequency
Awash II HPP	13:14	Over frequency
Awash III HPP	13:14	Over frequency
Koka HPP	13:16	Over frequency
Finchaa HPP	-	Load rejection
GGI HPP	13:22	Load rejection
Melka Wakena HPP	13:36	Overload

Table 5.5 Sequence of tripping with time observed on the SCADA

The main cause for the partial blackout was due to the outage of all generating units at Tekeze Hydro Power plant and the resulting immediate change in magnitude and diraction of power flow from Beless thrugh Bahirdar to Alamata 230kV transmisssion line caused a temprory earth fualt at a location of 121.6km from Alamata substation which was a weak point of the line due to broken insulators. This disturbance has caused major disturbance on the system as the outage of 260MW resulted in the outage of first stage & Second stage underfreqency lines which has also an impact on system voltage to increase to higher limit. The sequence of events has been shown below.

1st. Outage of all units at Tekeze HPP

2rd . Outage of all first stage and Second stage loads

3$^{nd.}$. Outage of Alamata_Bahirdar 230kV line

4th . Outage of Koka Dire Dawa 230kV line

5th . Outage of Koka, AwashII, AwashIII HPP

6th. Outage of Kality I_Mekanisa 132kv line

7th. Outage of Koka, AwashII, AwashIII HPP

8^{h}. Outage of all units at GGII HPP

9th. Outage of all units at Melka Wakena HPP

After Automatic SCADA System Application

When there is an outage of all units of Tekeze HPP (fault happen), The SCADA Master Terminal Unit receives the information via RTU and then send the information to DigSiLent programing unit. The programing unit generates a command automatically based on the set points and priorities and send back to Maser Terminal Unit. Then the MTU send a command to remote site via RTU. The RTU then open feeder breaker to balance the production and demand of power. This operation has been takes place within milliseconds so that the substation bus voltage and generator frequency return back to an acceptable range while the frequency of Tekeze HPP generators are shoot above the permissible level due to inertia and this will not affect our system because it was isolated from the grid due to tripping. This is achieved by automatic fast reduction of loads. This shows that the conventional method is too late to respond so that the system can no longer survive from disturbances while the automatic system is too fast to respond.

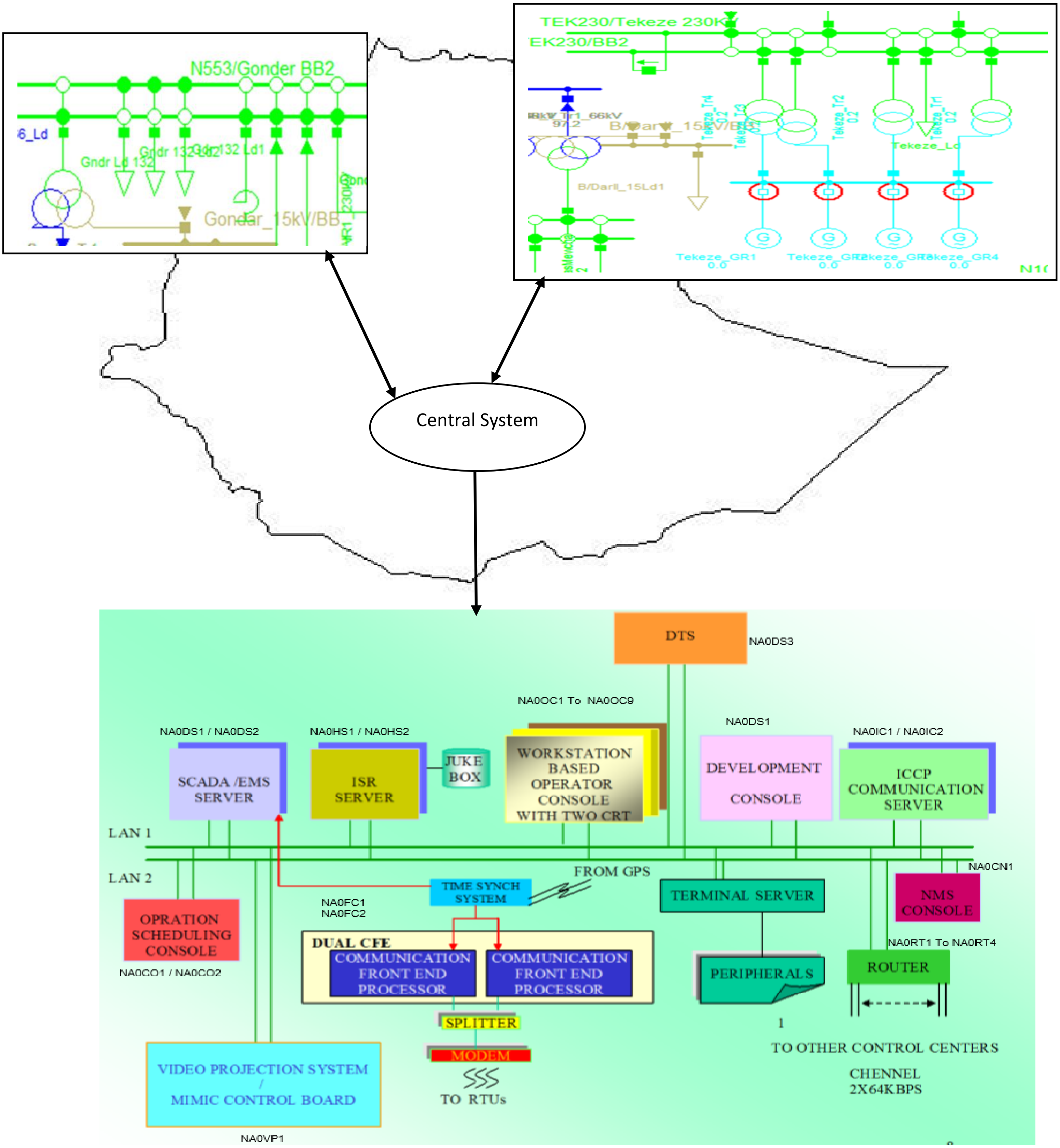


Figure 5.12 Control System Physical Structure

Immadetly following the fault on Tekeze power plant, the combolcha 230 kv substation bus barwas dropped from 230 to 203 Kv, where as Mekelle 230 Kv substation bus voltage ware dropped fro 230 to 210 Kv and Tekeze substation bus voltage ware dropped from 230 Kv to 211 Kv, then the potential transformer connected to the bus converts thos voltage labels into a 4 to 20 mA analog signal by a voltage transducer. The 4 to 20 mA analog signal is converted to a digital signal by the analog input (AI) module of the RTU. Further, this digital signal obtained is packaged into a data packet in the RTU, according to the communication protocol existing between the RTU and the master station. The data packets are then transmitted to the master station along the communication medium available. In the master station, the packets are received by the front- end processor/ com-munication front end (FEP/ CFE), decoded, and the data is give to the programming unit and athe a control signal is generated automatticaly and send to Gondar substation RTU in the same fashion to open some feeders that can balance power production and demand.And it is also the same for another electrical variables such as frequency, power etc...

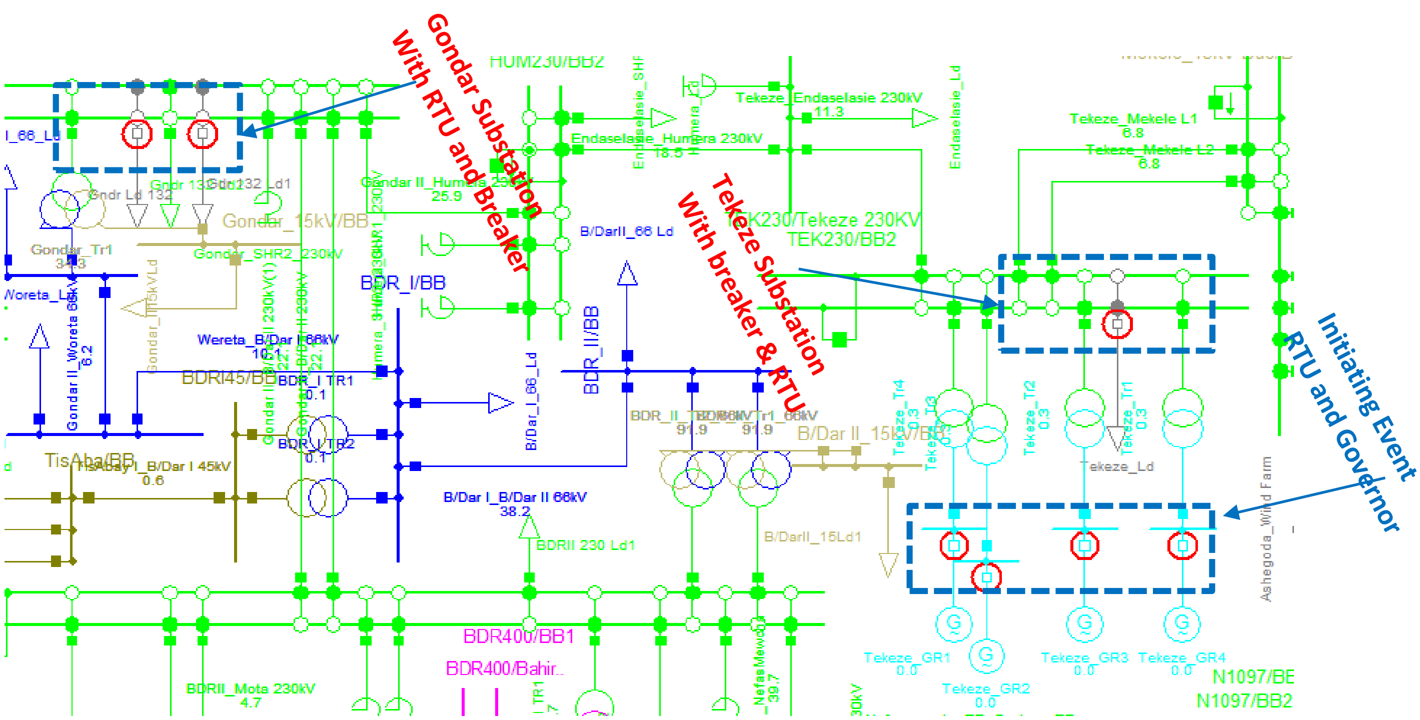


Figure 5.13 Grid network after 120MW have been shaded and Tekeze isolated

After the RTU has been acted, the active power production loading of Beles HPP generators were swing between 0.855 pu to 1.06 pu whereas the Active power production loading of Tis Abay II power Plant is swing between 0.242 to 0.402 and after 22ms the active power production loading of these HPP generators were stabilized as indicated in Figure below. The frequency of HPP generators were stabilized after 23 seconds. The bus voltage near to the faulty area swings more than the other buses far from the faulty area as indicated in the Figure below as an example Mekelle substation bus voltage rises more than the others as indicated by the blue line. The bus voltage swings between 0.91 and 1.05 and finally stabilized after 30ms.

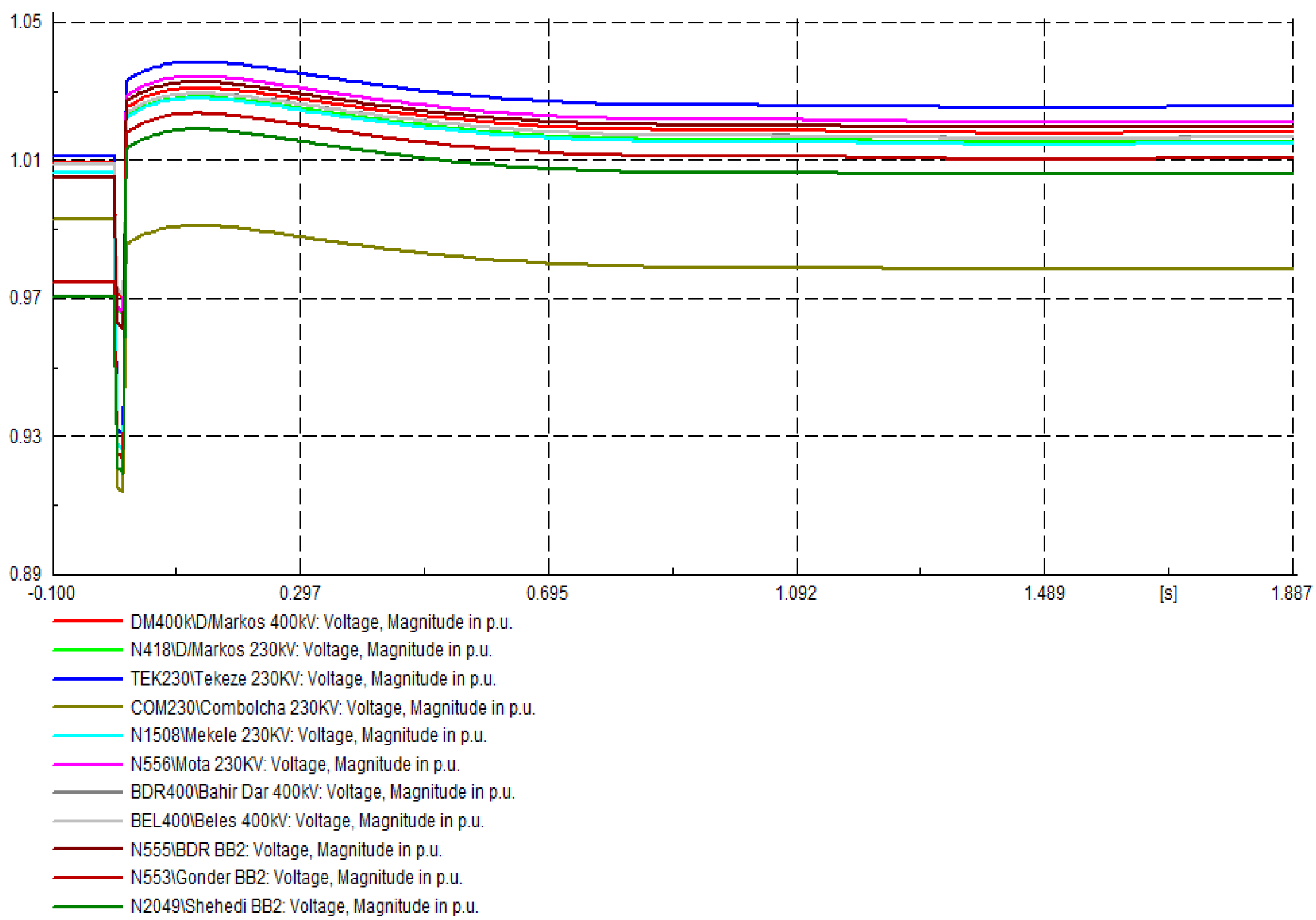


Figure 5.14 Bus voltage of selected buses after control action

The above controlled system condition after the disturbance has been simulated and the results have been depicted in Figure 5.13. The bus voltages of substations especially near to the faulty area such as Combolcha II 230kV, Mekelle 230kV and Tekeze 230kV substations were deteriorated for a period of 30ms. Over voltages were also observed on the above substations after the system is survived from complete collapse.

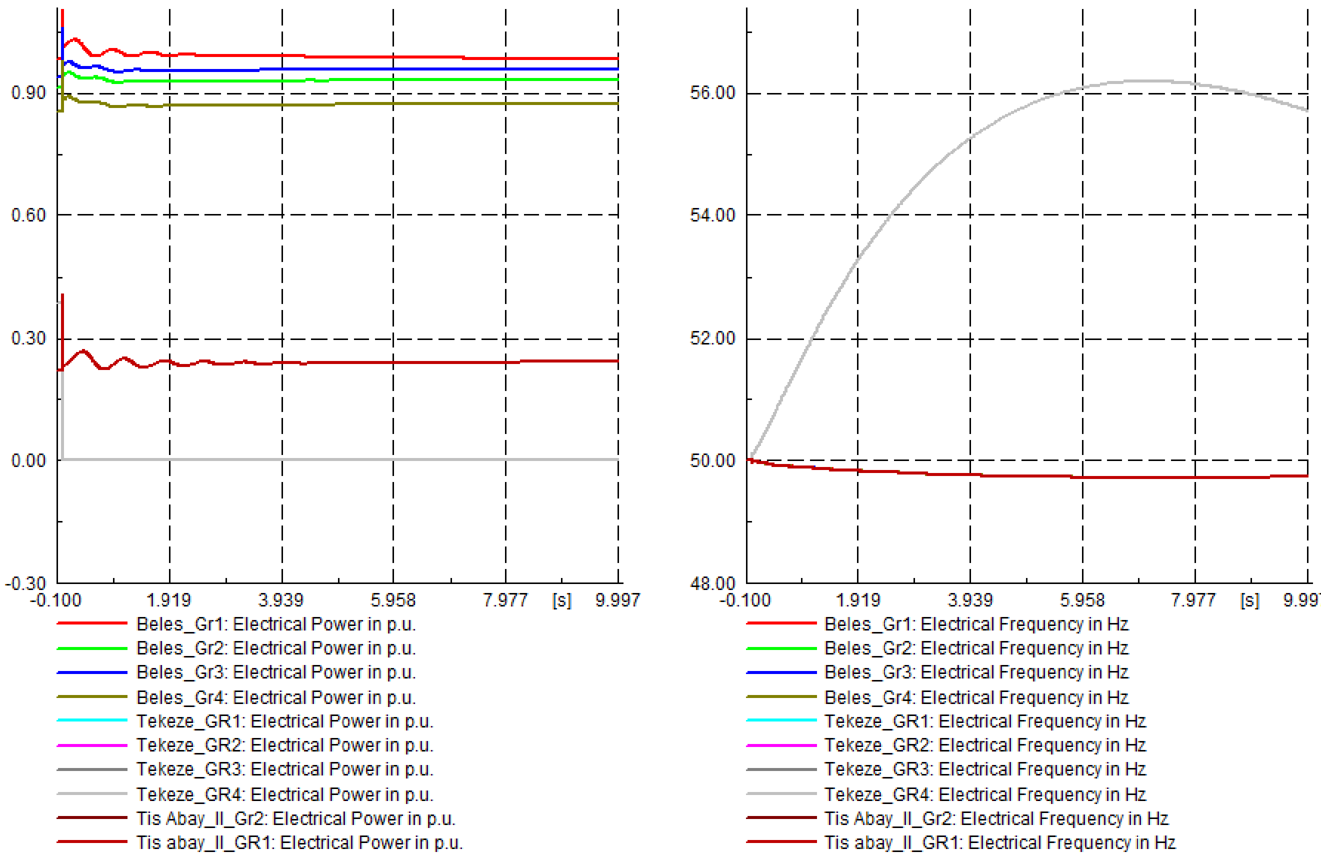


Figure 5.15 Generator active power and frequency after control action

The frequency deviations observed on generation units were around 0.6 Hz at 0.1 seconds with under damped oscillations. The frequency on, Beles and Tis Abay II power plants wear decreased below 50 Hz for small period of time while Tekeze generation station frequency was increased above 55 Hz because of inertia and will not affect our system because it is completely disconnected from our system.

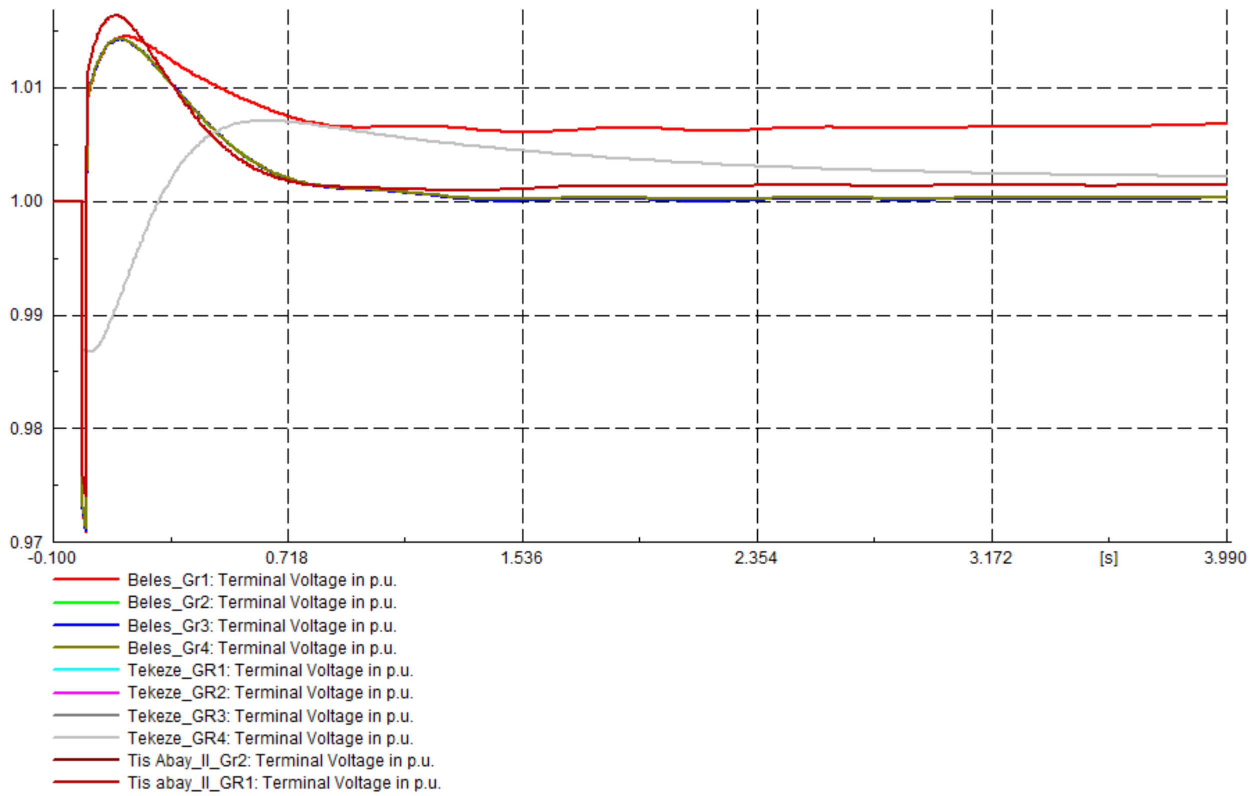


Figure 5.16 The terminal voltages of generators after control action taken

The terminal voltages of Beles and Tis Abay II generators were swing between 0.978 pu and 1.02 where as that of Tekeze was with in small swing between higher and lower limit. Of course, for the fault duration of small seconds, the terminal voltage of the HPP generators was decreased and increased beyond their limits. After the RTU takes a proper decision, their terminal voltage were returned to the steady state value as depicted in Figure above. The reactive powers supplied by each generator were recovered to the original values with small oscillations. The turbine power of each HPP generator was almost constant and their corresponding electrical power output was oscillating with centered at their original values. The same analysis would be true for the rest of simulations.

CHAPTER SIX

CONCLUSION AND RECOMMENDATION

6.1 Conclusion

This chapter discusses the main conclusions and recommendations via recalls the key parts of the work undertaken. Recommendations are also proposed. The research presented in this thesis mainly focused on prevention blackout in case of EEP. In this thesis, design and simulation of automated SCADA system for prevention blackout (Disruption) has been studied.

A detailed background and literature survey of the cascade processes triggering the blackout development in a power system have been presented. and power system and its major components such as, circuit breakers, transformers, disconnectors, surge arrestors, busbars and relays which are the core of one substation has been explained. And also methods ware proposed to mitigate blackout by balancing electricity supply and demand. Moreover, different controlled parameters such as, voltage or reactive power and frequency or active power that can stabilize the system during disturbances were explained briefly.

This Thesis has also described SCADA system technologies that help maintain power quality on the grid with a focus on voltage and frequency control techniques for managing grid voltage and frequency of a system, which will become an important issue in the future. SCADA provides management with real time data on production operations.

The presented simulation demonstrate an operation of the proposed automated control system helps to mitigate a black out for different disturbances. The developed advanced software model is realized in DIgSILENT PowerFactory software. The model is used to investigate all aspects of the frequency and voltage stability for various scenarios of the power imbalances.

This research leads to significant contributions to the development of a more reliable and secure power grid.

6.2 Recommendation

The quality and reliable power supply has a dominant factor in the development of the country socially and economically since, every technology used by customers is dependable on electrical power. To achieve this, it is recommended that the Ethiopian Electric Power has to consider Automated SCADA System for proper operation, control and monitoring of the overall power system

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APPENDIX A

A.1 Grid Data

A.1.1 Generator Data

Table A.1: Existing Generator data of the Ethiopian High Voltage Grid

No	Name	Sn [MVA]	Type	Un [kV]	P [MW]	Pmin [MW]	Pmax [MW]	Qmin [MVAr]	Qmax [MVAr]
1	Gilgel Gibe III G1	441	Hydro	15	75	0	220	-100	100
2	Gilgel Gibe III G2	441	Hydro	15	10	0	220	-100	100
3	Gilgel Gibe III G3	441	Hydro	15	10	0	220	-100	100
4	Gilgel Gibe III G4	441	Hydro	15	10	0	220	-100	100
5	Gilgel Gibe III G5	441	Hydro	15	10	0	220	-100	100
6	Gilgel Gibe III G6	441	Hydro	15	10	0	220	-100	100
7	Gilgel Gibe III G7	441	Hydro	15	10	0	220	-100	100
8	Gilgel Gibe III G8	441	Hydro	15	10	0	220	-100	100
9	Gilgel Gibe III G9	441	Hydro	15	10	0	220	-100	100
10	Gilgel Gibe III G10	441	Hydro	15	10	0	220	-100	100
11	Beles G1	133	Hydro	15	88	0	115	-130	130
12	Beles G2	133	Hydro	15	100	0	115	-130	130
13	Beles G3	133	Hydro.	15	90	0	115	-130	130
14	Beles G4	133	Hydro	15	100	0	115	-130	130
15	Gilgel Gibe II G1	125	Hydro	15	95	0	105	-50	50
16	Gilgel Gibe II G2	125	Hydro	15	95	0	105	-50	50
17	Gilgel Gibe II G3	125	Hydro	15	95	0	105	-50	50
18	Gilgel Gibe II G4	125	Hydro	15	95	0	105	-50	50
19	Tekeze G1	90	Hydro	13.8	66	0	78	-38	38
20	Tekeze G2	90	Hydro	13.8	40	0	78	-38	38
21	Tekeze G3	90	Hydro	13.8	40	0	78	-38	38
22	Tekeze G4	90	Hydro	13.8	40	0	78	-38	38
23	Ashegoda	150	Wind	230	31.4	0	120	-150	150
24	Tis Abay I G1	4.8	Hydro	6	4	0	4	-2.9	2.9
25	Tis Abay I G2	4.8	Hydro	6	4	0	4	-3.84	3.84
26	Tis Abay I G3	4.8	Hydro	6	4	0	4	-2.9	2.9
27	Tis Abay II G1	40	Hydro	10.5	27	0	36	-40	40
28	Tis Abay II G2	40	Hydro	10.5	27	0	36	-40	40
29	Fincha G1	35	Hydro	13.8	29	0	33.33	-16	14
30	Fincha G2	35	Hydro	13.8	29	0	33.33	-16	14
31	Fincha G3	35	Hydro	13.8	29	0	33.33	-16	14
32	Fincha G4	35	Hydro	13.8	29	0	33.33	-16	14
33	Gilgel Gibe I G1	73	Hydro	13.8	60	0	70	-21	21
34	Gilgel Gibe I G2	73	Hydro	13.8	60	0	70	-21	21

No	Name	Sn [MVA]	Type	Un [kV]	P [MW]	Pmin [MW]	Pmax [MW]	Qmin [MVAr]	Qmax [MVAr]
35	Gilgel Gibe I G3	73	Hydro	13.8	60	0	70	-21	21
36	Neshe G1	53	Hydro	13.8	15	0	50	-25	19
37	Neshe G2	53	Hydro	13.8	15	0	50	-25	19
38	Kality G1	4.375	Diesel	11	3.5	0	3.5	-3.5	3.5
39	Kality G2	4.375	Diesel	11	3.5	0	3.5	-3.5	3.5
40	Kality G3	4.375	Diesel	11	3.5	0	3.5	-3.5	3.5
41	Kality G4	4.375	Diesel	11	3.5	0	3.5	-3.5	3.5
42	Kality G5	4.375	Diesel	11	3.5	0	3.5	-3.5	3.5
43	Kality G6	4.375	Diesel	11	3.5	0	3.5	-3.5	3.5
44	Kality G7	4.375	Diesel	11	3.5	0	3.5	-3.5	3.5
45	Dire Dawa G1	12.5	Diesel	15	10	0	10	-10	10
46	Dire Dawa G2	12.5	Diesel	15	10	0	10	-10	10
47	Dire Dawa G3	12.5	Diesel	15	10	0	10	-10	10
48	Dire Dawa G4	12.5	Diesel	15	10	0	10	-10	10
49	Adama II	190	Wind	230	73.67	0	150	-190	190
50	Adama I	60	Wind	132	26.82	0	48	-60	60
51	Melka wakena G1	45	Hydro	13.8	35	0	38.25	-42	35
52	Melka wakena G2	45	Hydro	13.8	35	0	38.25	-31.5	30.15
53	Melka wakena G3	45	Hydro	13.8	30	0	38.25	-31.5	30.15
54	Melka wakena G4	45	Hydro	13.8	30	0	38.25	-31.5	30.15
55	Koka G 1	18	Hydro	10.5	10	0	13	-12	11.6
56	Koka G 2	18	Hydro	10.5	10	0	13	-12	11.6
57	Koka G 3	18	Hydro	10.5	10	0	13	-12	11.6
58	Awash II G1	20	Hydro	10.5	6	3	15	-15	13
59	Awash II G2	20	Hydro	10.5	6	3	15	-15	13
60	Awash III G1	20	Hydro	10.5	9	3	15	-15	13
61	Awash III G2	20	Hydro	10.5	9	3	15	-15	13
62	MU G1	1.875	Diesel	4.16	1.68	0	1.7	-1.5	1.5
63	MU G2	1.875	Diesel	4.16	1.68	0	1.7	-1.5	1.5
64	MU G1	1.875	Diesel	4.16	1.68	0	1.7	-1.5	1.5
65	MU G1	1.875	Diesel	4.16	1.68	0	1.7	-1.5	1.5
66	AWASH 7 KILO 11A	4.375	Diesel	11	3	0	4.375	-3.5	3.5
67	AWASH 7 KILO 11B	4.375	Diesel	11	3	0	4.375	-3.5	3.5

A.1 Grid Data

A.1.2 Load Data

Table A.2: Existing Load data of the Ethiopian High Voltage Grid.

No	Load name	Network Level	Load Type	Load Input	P [MW]	u [%]	cosphi [p.u.]
2	HARAR II 33	33	Load	P, cosphi and u	4.89	100	0.95
3	BABILE 15	15	Load	P, cosphi and u	1.1	100	0.95
4	JIJIGA I 15	15	Load	P, cosphi and u	1.1	100	0.95
5	JIJIGA II 33	33	Load	P, cosphi and u	5.1	100	0.95
6	CHELENKO 15	15	Load	P, cosphi and u	2.2	100	0.95
7	HARAR II 15	15	Load	P, cosphi and u	2.75	100	0.95
8	ALEMAYA 15	15	Load	P, cosphi and u	2.3	100	0.95
9	DIRE DAWA II 15	15	Load	P, cosphi and u	2.2	100	0.95
10	DIRE DAWA I 15	15	Load	P, cosphi and u	9.4	100	0.95
11	JIJIGA II 15	15	Load	P, cosphi and u	5.41	100	0.95
12	DIRE DAWA III 15	15	Load	P, cosphi and u	2.53	100	0.95
13	AWASH 7 KILO 15	15	Load	P, cosphi and u	2.2	100	0.95
14	AMIBARA 15	15	Load	P, cosphi and u	2.2	100	0.95
15	ASEBE TEFERI 15	15	Load	P, cosphi and u	2.2	100	0.95
16	BEDESA 15	15	Load	P, cosphi and u	2.31	100	0.95
17	METEHARA 15	15	Load	P, cosphi and u	4.66	100	0.95
18	KALITI I 15	15	Load	P, cosphi and u	6	100	0.95
19	AKAKI S.P FACTORY 15	15	Load	P, cosphi and u	4.62	100	0.95
20	DEBRE ZEIT I 15	15	Load	P, cosphi and u	1.87	100	0.95
21	DUKEM 15	15	Load	P, cosphi and u	0.88	100	0.95
22	ABA SAMUEL 15	15	Load	P, cosphi and u	0.88	100	0.95
23	AKAKI I 15	15	Load	P, cosphi and u	3.74	100	0.95
24	ADDIS SOUTH I 15	15	Load	P, cosphi and u	9.24	100	0.95
25	SEBETA 15II	15	Load	P, cosphi and u	40.3	100	0.95
26	ADDIS WEST 15A	15	Load	P, cosphi and u	13.35	100	0.95
27	MEKANISSA 15	15	Load	P, cosphi and u	40	100	0.95
28	KALITI II 15B	15	Load	P, cosphi and u	20	100	0.95
29	NEFAS SILK 15	15	Load	P, cosphi and u	12.65	100	0.95
30	ADDIS CENTER 15	15	Load	P, cosphi and u	52.8	100	0.85
31	WEREGENU 15	15	Load	P, cosphi and u	13	100	0.95
32	KALITI NORTH 15	15	Load	P, cosphi and u	7.48	100	0.95
33	ADDIS EAST I 15	15	Load	P, cosphi and u	10	100	0.88
34	ADDIS EAST II 15	15	Load	P, cosphi and u	41	100	0.88

35	DEBRE BIRHAN 15	15	Load	P, cosphi and u	3.12	100	0.95
36	SHOA ROBIT 15	15	Load	P, cosphi and u	1.43	100	0.95
37	DEBRE ZEIT II 15	15	Load	P, cosphi and u	16	100	0.95
38	ELALA GEDA 15	15	Load	P, cosphi and u	4.4	100	0.95
39	YESU FACTORY 15	15	Load	P, cosphi and u	3.3	100	0.95
40	KOKA 15	15	Load	P, cosphi and u	2.2	100	0.95
41	MODJO 15	15	Load	P, cosphi and u	2.2	100	0.95
42	NAZRETH I 15	15	Load	P, cosphi and u	3.74	100	0.95
43	KOKA HYDRO 15	15	Load	P, cosphi and u	0	100	0.95
44	METU 15	15	Load	P, cosphi and u	2.42	100	0.95
45	BEDELE 15	15	Load	P, cosphi and u	4.18	100	0.95
46	NEKEMTE 15	15	Load	P, cosphi and u	3.63	100	0.95
47	AGARO 15	15	Load	P, cosphi and u	3.12	100	0.95
48	BONGA 15	15	Load	P, cosphi and u	3	100	0.95
49	BONGA 33	33	Load	P, cosphi and u	1.1	100	0.95
50	GUDER 15	15	Load	P, cosphi and u	4.46	100	0.95
51	GILGEL GIBE 15	15	Load	P, cosphi and u	1.65	100	0.95
52	ARBAMINCH 15	15	Load	P, cosphi and u	6.05	100	0.95
53	WOLAYITA SODDO 15	15	Load	P, cosphi and u	5.14	100	0.95
54	Alaba15KV	15	Load	P, cosphi and u	2.2	100	0.95
55	AWASA 15	15	Load	P, cosphi and u	7.8	100	0.95
56	SHASHEMENE 15	15	Load	P, cosphi and u	12.1	100	0.95
57	DILLA I 15	15	Load	P, cosphi and u	4.29	100	0.95
58	YIRGA ALEM 15	15	Load	P, cosphi and u	3.86	100	0.95
59	SHAKISSO 15	15	Load	P, cosphi and u	7.04	100	0.95
60	NEGELE BORENA 15	15	Load	P, cosphi and u	1.65	100	0.95
61	BUTAJIRA 33	33	Load	P, cosphi and u	1.29	100	0.95
62	ASELA 15	15	Load	P, cosphi and u	6.4	100	0.95
63	BUTAJIRA 15	15	Load	P, cosphi and u	2.2	100	0.95
64	TEPI 33	33	Load	P, cosphi and u	1.1	100	0.95
65	TEPI 15	15	Load	P, cosphi and u	1.65	100	0.95
66	MIZAN 15	15	Load	P, cosphi and u	1.65	100	0.95
67	MIZAN 33	33	Load	P, cosphi and u	0.88	100	0.95
68	GHIMBI 15	15	Load	P, cosphi and u	1.65	100	0.95
69	FINCHAA 15A	15	Load	P, cosphi and u	1.1	100	0.95
70	DABAT 15	15	Load	P, cosphi and u	1.43	100	0.95
71	PAWE 15	15	Load	P, cosphi and u	1.65	100	0.95
72	GONDER I 15B	15	Load	P, cosphi and u	0.55	100	0.95
73	GONDER I 15A	15	Load	P, cosphi and u	0.55	100	0.95
74	DANGLA 15	15	Load	P, cosphi and u	3.74	100	0.95
75	WERETA 15	15	Load	P, cosphi and u	2.53	100	0.95
76	BAHIR DAR II 15A	15	Load	P, cosphi and u	5.4	100	0.95
77	BAHIR DAR I 15	15	Load	P, cosphi and u	4.4	100	0.95
78	BITCHENA 15	15	Load	P, cosphi and u	1.65	100	0.95
79	DEMBI DOLO 15	15	Load	P, cosphi and u	2	100	0.95

80	FINCHA SUGAR II 15	15	Load	P, cosphi and u	2.2	100	0.95
81	FINCHA SUGAR I 15	15	Load	P, cosphi and u	2.75	100	0.95
82	GAMBELA 15	15	Load	P, cosphi and u	2	100	0.95
83	FINOTE SELAM 15	15	Load	P, cosphi and u	3	100	0.95
84	GONDER II 15	15	Load	P, cosphi and u	8.25	100	0.95
85	BAHIR DAR II 15B	15	Load	P, cosphi and u	2.2	100	0.95
86	DEBRE MARKOS 15	15	Load	P, cosphi and u	1.65	100	0.95
87	AWASH III 15	15	Load	P, cosphi and u	0	100	0.95
88	AWASH II 15A	15	Load	P, cosphi and u	1.925	100	0.95
89	AWASH II 15B	15	Load	P, cosphi and u	1.925	100	0.95
90	WONJI 15	15	Load	P, cosphi and u	8	100	0.95
91	COMBOLCHA 15	15	Load	P, cosphi and u	7.48	100	0.95
92	WOLDIA 15	15	Load	P, cosphi and u	2.64	100	0.95
93	DESSIE 15	15	Load	P, cosphi and u	5.17	100	0.95
94	ROBE 15	15	Load	P, cosphi and u	3.67	100	0.95
95	GOBESA 33	33	Load	P, cosphi and u	1.1	100	0.95
96	MELKA WAKENA 15	15	Load	P, cosphi and u	2.97	100	0.95
97	ADWA 15	15	Load	P, cosphi and u	6.82	100	0.95
98	MAYCHEW 15	15	Load	P, cosphi and u	1.21	100	0.95
99	SEKOTA 15	15	Load	P, cosphi and u	0.55	100	0.95
100	LALIBELA 15	15	Load	P, cosphi and u	0.66	100	0.95
101	WUKRO 15	15	Load	P, cosphi and u	2.2	100	0.95
102	ADIGRAT 15	15	Load	P, cosphi and u	3.3	100	0.95
103	ENDASELASIE 15	15	Load	P, cosphi and u	1.5	100	0.95
104	MEKELE 15	15	Load	P, cosphi and u	12	100	0.95
104	ADIGRAT 66	66	Load	P, cosphi and u	0	100	0.95
105	MESSOBO 6	6	Load	P, cosphi and u	13.2	100	0.95
106	ALAMATA 15A	15	Load	P, cosphi and u	1.1	100	0.95
107	FITCHE 33	33	Load	P, cosphi and u	4	100	0.95
108	GEFARSA 15B	15	Load	P, cosphi and u	6	100	0.95
109	ADDIS ALEM 15	15	Load	P, cosphi and u	3.1	100	0.95
110	MUGER 15	15	Load	P, cosphi and u	25	100	0.95
111	FITCHE 15	15	Load	P, cosphi and u	4	100	0.95
112	ADDIS NORTH 15	15	Load	P, cosphi and u	31.5	100	0.95
113	GEDJA 15	15	Load	P, cosphi and u	1.1	100	0.95
114	WOLISSO 15	15	Load	P, cosphi and u	3.3	100	0.95
115	WOLKITE 15	15	Load	P, cosphi and u	1.65	100	0.95
116	WOLKITE 33	33	Load	P, cosphi and u	1.1	100	0.95
117	GHEDO 15	15	Load	P, cosphi and u	1.87	100	0.95
118	FINCHAA 15 B	15	Load	P, cosphi and u	1.1	100	0.95
119	Hos 15KV	15	Load	P, cosphi and u	3.3	100	0.95
120	NEGELE BORENA 33	33	Load	P, cosphi and u	0.88	100	0.95
121	MOTA 33	33	Load	P, cosphi and u	1.1	100	0.95
122	HARAR I 15	15	Load	P, cosphi and u	3.3	100	0.95
123	ADAMITULU 15	15	Load	P, cosphi and u	4.4	100	0.95

No	Load name	Network Level	Load Type	Load Input	P [MW]	u [%]	cosphi [p.u.]
124	COTOBIE 15B	15	Load	P, cosphi and u	13	100	0.95
125	GEFARSA 15A	15	Load	P, cosphi and u	5	100	0.95
126	ADDIS WEST 15B	15	Load	P, cosphi and u	9.35	100	0.95
127	TEKEZE6.6KV	6.6KV	Load	P, Q and (u)	5	100	0.8
128	HAGEREMARIAM33KV	33	Load	P, Q and (u)	2.35	100	0.9
129	YIRGALEM15B	15	Load	P, Q and (u)	1.7	100	0.9
130	SEBETA 15I	15	Load	P, Q and (u)	2	100	0.9
131	SEBETA 15III	15	Load	P, Q and (u)	8	100	0.9
132	MEKANISSA 132	132	Load	P, cosphi and u	43	100	0.95
133	NAZARETH 15NEW	15	Load	P, cosphi and u	18	100	0.95
134	DEBREZIT II 15A	15	Load	P, Q and (u)	13	100	0.8
135	ASEEBE TEFERI15	15	Load	P, cosphi and u	2.5	100	0.95
136	ASEBE TEFERI33	33	Load	P, cosphi and u	0.02	100	0.95
137	DEBREZIET II33KV	33	Load	P, cosphi and u	0.7	100	0.95
138	debreziet II15Kv	15	Load	P, cosphi and u	6	100	0.95
139	MUGER NEW33KV	33	Load	P, cosphi and u	3	100	0.95
140	MUGER NEW15	15	Load	P, cosphi and u	1	100	0.95
141	HUMERA33KV	33	Load	P, cosphi and u	1	100	0.95
142	HUMERA15KV	15	Load	P, cosphi and u	1	100	0.95
143	METU15KV	15	Load	P, cosphi and u	10	100	0.95
144	MESOBO6.3B	6.3	Load	P, cosphi and u	5	100	0.95
145	Mesobo New6.3A	6.3	Load	P, cosphi and u	5	100	0.95
146	GEF15UEAP	15	Load	P, cosphi and u	10	100	0.95
148	Gadarif	230	Load	P, cosphi and u	100	100	0.83
149	Gidayana 33	33	Load	P, cosphi and u	5	100	0.83
150	Denbidolo 33	33	Load	P, cosphi and u	2	100	0.95
151	Gambela 33	33	Load	P, cosphi and u	2	100	0.95
152	Dangote 11.5kv	11.5Kv	Load	P, cosphi and u	5	100	0.83
153	GAMBLA33KV	33	Load	P, cosphi and u	10	100	0.83
154	Jimma 15	15	Load	P, cosphi and u	6.08	100	0.95
155	Jimma I 15KV	15	Load	P, cosphi and u	6.08	100	0.95
156	JimmaI 15kv	15	Load	P, cosphi and u	6.08	100	0.95
157	Hosana 15KV	15	Load	P, cosphi and u	6.08	100	0.95
158	Sawla33KV	33	Load	P, cosphi and u	10	100	0.83
159	Key Afer33KV	33	Load	P, cosphi and u	10	100	0.83
160	lEGETAFO230KV	230	Load	P, cosphi and u	48	100	0.83
161	gef33KVNEW	33	Load	P, cosphi and u	5	100	0.83
162	gef 15kv	15	Load	P, cosphi and u	5	100	0.83
163	weregenu 15KVbb1	15	Load	P, cosphi and u	13	100	0.83
164	Weregenu Mobile 132KV	15	Load	P, cosphi and u	10	100	0.83
165	SULULTA 15	15	Load	P, cosphi and u	19	100	0.83
166	Sululta 33	33	Load	P, cosphi and u	5	100	0.83
167	metu33KV	33	Load	P, cosphi and u	5	100	0.83

A.1 Grid Data

A.1.3 Transformer Data

Table A.3: Existing two winding transformer data of the Ethiopian High Voltage Grid

No	Element Name	Network Level	Un1 [kV]	Un2 [kV]	Sn [MVA]
1	JIJIGA I TR	45	45	16	1.5
2	BABILE TR	45	45	16	1.5
3	HARAR I TR	45	45	15	6
4	HARAR II TR	66	66	15	9.6
5	DIRE DAWA II TR1	132	128	16	16
6	CHELENKO TR	66	66	15	6.3
7	MU DIESEL TR1	15	15	4.16	10
8	MU DIESEL TR2	15	15	4.16	10
9	MU DIESEL TR3	15	15	4.16	10
10	DIRE DAWA I TR1	132	128	16.5	12
11	DIRE DAWA I TR2	132	128	16.5	12
12	DIRE DAWA DIESEL TR	132	141.3	15	33
13	AWASH 7 KILO TR	132	132	16	25
14	AWASH 7 KILO DIESEL TR1	15	15	11	25
15	AMIBARA TR1	66	66	16	3
16	ASEBE TERFERI TR	66	66	16	3
17	BEDESA TR	66	66	15	3
18	KALITI I DIESEL TR	15	15	11	20
19	ADDIS SOUTH I TR1	45	45	15	6
20	AKAKI SP FACTORY TR1	45	45	15	6
21	ABA SAMUEL TR	45	45	15	1.5
22	DEBREZEIT I TR	45	45	15.8	3
23	AKAKI TR	45	45	15	9
24	SHOA ROBIT TR	132	132	16	6
25	DEBRE BIRHAN TR	132	132	16	6
26	COTOBIE TR1	132	132	16	12
27	WEREGENU TR1	132	132	15	16
28	KALITI NORTH TR1	132	132	15	16
29	ADDIS EAST I TR1	45	45	15	6
30	ADDIS EAST II TR1	132	132	15	20
31	ADDIS CENTER TR1	132	132	15	25
3	MEKANISSA TR1	132	132	15	20
33	NEFASILK TR	45	45	15	20
34	KALITI II TR2	132	132	15	20
35	DEBRE ZEIT II TR1	132	132	15	16
36	ELALA GEDA TR	132	132	16	12
37	YESU FACTORY TR	132	132	15	10

No	Element Name	Network Level	Un1 [kV]	Un2 [kV]	Sn [MVA]
38	MODJO TR1	45	45	15.8	3
39	NAZRETH I TR1	45	45	15.8	3
40	ADAMITULU TR	132	132	16	12
41	SOR POWER PLANT TR1	66	66	3	3.15
42	METU TR	66	66	15	3
43	BEDELE TR	132	132	15.75	6.3
44	NEKEMTE TR1	132	132	15	20
45	AGARO TR	132	132	15.75	6.3
46	GUDER TR1	132	132	16	12
47	GILGEL GIBE TR1	132	132	15.75	6.3
48	ARBAMINCH TR	132	132	15.75	12.5
49	ALABA TR	132	132	16	6
50	AWASA TR1	132	132	16	12
51	SHASHEMENE TR	132	132	15	20
52	DILLA TR	45	45	15	9
53	ASELA TR	132	132	16	12
54	MIZAN TR	66	66	15	6.3
55	FINCHAA TR1	230	230	13.2	24.2
56	GILBEL GIBE PP TR1	230	235	13.8	51
57	TIS ABBAY II PP TR1	132	132	10.5	24
58	TIS ABAY I PP TR1	45	47.25	6.3	4.8
59	BAHIR DAR I TR1	45	45	15	4.8
60	WERETA TR	66	66	15	6.3
61	DANGLA TR	66	66	15	6.3
62	GONDER I TR1	66	66	15	3
63	DABAT TR	66	66	15	3
64	BITCHENA TR	66	66	15	6.3
65	FINCHAA SUGAR I TR	66	66	15	7
66	FINCHAA TR	66	66	15	6.3
67	MOTA TR	230	230	33	20
68	AWASH II TR3	132	132	15	20
69	WONJI TR	132	135	16	16
70	DESSIE TR2	66	66	16	9
71	WOLDIA TR1	66	66	16	3
72	MELKA WAKENA PP TR1	230	230	13.8	45
73	ROBE TR1	66	66	15	3
74	GOBESA TR	66	66	33	6.3
75	WUKRO TR	132	132	15	20
76	MESSOBO TR1	132	132	6	16
77	MUGER TR1	132	132	16	12
78	ADDIS ALEM TR1	45	45	16	3
79	GEFARSA TR	66	66	45	6
80	ADDIS NORTH TR1	132	132	15	20

No	Element Name	Network Level	Un1 [kV]	Un2 [kV]	Sn [MVA]
81	ADDIS NORTH TR2	132	132	15	20
82	GEDJA TR	45	45	15.8	3
83	WOLISSO TR1	66	66	16	3
84	WOLKITE TR	66	66	15	6.3
85	ADDIS SOUTH I TR2	45	45	15	6
86	AWASA TR2	132	132	16	12
87	ADDIS EAST I TR2	45	45	15	6
88	ADDIS WEST TR1	45	45	15	9
89	ADDIS WEST TR2	45	45	15	9
90	GILBEL GIBE PP TR2	230	235	13.8	51
91	GILBEL GIBE PP TR3	230	235	13.8	51
92	MEKANISSA TR2	132	132	15	20
93	ALEMAYA TR	66	66	15	6.3
94	MESSOBO TR2	132	132	6	16
95	PAWE TR	66	66	15	6.3
96	FITCHE TR	66	66	15	6.3
97	FITCHE TR	66	66	33	6.3
98	HARAR I TR1	66	66	15	6.3
99	HARAR I TR2	66	66	15	6.3
100	HARAR I TR3	66	66	15	6.3
101	FINOTE SELAM TR1	66	66	15	6.3
102	FINOTE SELAM TR2	66	66	15	6.3
103	WEREGENU TR2	132	132	15	25
104	ADDIS EAST II TR2	132	132	15	20
105	WOLDIA TR2	66	66	16	3
106	WOLISSO TR2	66	66	16	3
107	DIRE DAWA II TR2	132	128	16	16
108	AWASH 7 KILO DIESEL TR2	15	15	11	25
109	FINCHAA TR2	230	230	13.2	24.2
110	FINCHAA TR3	230	230	13.2	24.2
111	FINCHAA TR4	230	230	13.2	24.15
112	FINCHA SUGAR II TR	66	66	15	3
113	TIS ABBAY II PP TR2	132	132	10.5	24
114	HOSAINA TR	132	132	15.75	6.3
115	MUGER TR2	132	132	16	12
116	SOR POWER PLANT TR2	66	66	3	3.15
117	ADDIS CENTER TR2	132	132	15	25
118	GONDER I TR2	66	66	15	6.3
119	NEKEMTE TR2	132	132	15	20
120	GHIMBI TR1	132	132	15	20
121	GHIMBI TR2	132	132	15	20
122	KALITI NORTH TR2	132	132	15	16
123	TIS ABAY I PP TR2	45	47.25	6.3	4.8

No	Element Name	Network Level	Un1 [kV]	Un2 [kV]	Sn [MVA]
124	TIS ABAY I PP TR3	45	47.25	6.3	4.8
125	MELKA WAKENA PP TR4	230	230	13.8	45
126	MELKA WAKENA PP TR3	230	230	13.8	45
127	MELKA WAKENA PP TR2	230	230	13.8	45
128	MAYCHEW TR	66	66	15	6.3
129	ENDASELASIE TR	66	66	15	6.3
130	LALIBELA TR	66	66	15	6.3
131	SEKOTA TR	66	66	15	6.3
132	DESSIE TR1	66	66	16	9
133	AMIBARA TR2	66	66	16	3
134	AKAKI SP FACTORY TR2	45	45	15	6
135	AKAKI SP FACTORY TR3	45	45	15	6
136	ROBE TR2	66	66	15	3
137	DEBRE ZEIT II TR2	132	128	15	16
138	ADDIS ALEM TR2	45	45	16	3
139	GUDER TR2	132	132	16	12
140	NAZRETH I TR2	45	45	15.8	3
141	DUKEM TR1	45	45	15.8	3
142	BAHIR DAR I TR2	45	45	15	4.8
143	METEHARA ATR	132	132	15	18
144	KALITI I ATR1	230	230	138	45
145	KALITI I ATR2	230	230	138	45
146	KALITI I ATR3	230	230	138	45
147	GEFARSA ATR1	230	230	138	24.2
148	GEFARSA ATR2	230	230	138	24.2
149	GEFARSA ATR3	230	230	138	24.2
150	GEFARSA ATR4	230	230	138	24.2
151	SEBETA ATR1	230	230	135	63
152	SEBETA ATR2	230	230	135	63
153	SEBETA ATR3	230	230	135	63
154	BAHIR DAR ATR	66	66	45	9
155	GILGEL GIBE ATR	230	230	132	30
156	SEBETA ATR4	66	66	45	6.3
157	SEBETA TR3	132	132	15	18
158	MELKA WAKENA ATR	230	230	138	63
159	2T1161	132	132	33	20
160	Addis Alem new Trafo	45	45	15	12
161	Addis Alem new Trafo	45	45	15	12
162	2T1193	132	132	15	40
163	TekezeT1	230	230	13.8	90
164	TekezeT2	230	230	13.8	90
165	Tekeze T3	230	230	13.8	90
166	Tekeze T4	230	230	13.8	90

No	Element Name	Network Level	Un1 [kV]	Un2 [kV]	Sn [MVA]
167	Beles Tr1	15	400	15	125
168	Beles Tr2	15	400	15	125
169	Beles Tr3	15	400	15	125
170	Beles Tr4	15	400	15	125
171	Akaki Tr1	400	400	230	250
172	Akaki Tr2	66	400	230	250
173	Akaki Tr3	400	400	230	250
174	Sululita Tr1	400	400	230	250
175	Sululita Tr2	400	400	230	250
176	Sululita Tr3	400	400	230	250
177	Gilgel Gibe III Tr1	15	15	400	133
178	Gigel Gibe III Tr2	15	15	400	133
179	Gigel Gibe III Tr3	15	15	400	133
180	Gigel Gibe III Tr4	15	15	400	133
181	BDR II Tr1	400	230	132	125
182	BDR II Tr2	400	230	132	125
183	D/markos Tr1	400	230	132	125

A.1 Grid Data

A.1.3 Transformer Data

Table A.4: Existing three winding transformer data of the Ethiopian High Voltage Grid

No	Element Name	Network Level	Un1 [kV]	Un2 [kV]	Un3 [kV]	Sn12 [MVA]	Sn23 [MVA]	Sn31 [MVA]
1	JIJIGA II TR	132	132	33	15	20	9.6	9.6
2	HARAR II TR1	132	132	66	33	20	9.6	9.6
3	DIRE DAWA I TR	132	132	66	15	20	20	20
4	DIRE DAWA III ATR1	230	225	132	15	37.8	11.34	11.34
5	AWASH 7 KILO TR	132	132	66	16	12	12	4
6	KOKA PP TR1	132	135	10.5	15	18	6	6
7	KALITI I TR1	132	135	45	16	18	12	6
8	SEBETA TR1	132	135	45	16	20	8	8
9	COTOBIE TR2	132	132	45	15	12	12	4
10	KALITI II TR1	132	135	45	16	20	8	8
11	BONGA TR	132	132	33	15	20	9.6	9.6
12	WOLAYITA SODDO TR	132	132	66	15	6	6	6
13	YIRGA ALEM TR	132	132	45	15	12	12	4
14	SHAKISSO TR1	132	132	66	15	6	6	6
15	NEGELE BORENA TR	66	66	33	15	9	4.8	4.8
16	BUTAJITA TR	132	132	33	15	9.6	9.6	9.6
17	TEPI TR	66	66	33	15	9.6	5.04	5.04
18	MIZAN TR	132	132	66	33	20	9.6	9.6
19	FINCHAA TR	230	230	66	13.2	12.02	12.02	24.2
20	BAHIR DAR II TR1	230	230	66	15	6.3	2.7	2.7
21	GONDER TR1	230	230	66	15	16	16	16
22	BAHIR DAR II ATR1	230	230	132	15	50	16.7	16.7
23	DEBRE MARKOS TR1	230	230	66	15	6.3	2.7	2.7
24	AWASH II TR1	132	141.75	15	10.5	4.2	4.2	14
25	COMBOLCHA TR2	132	132	66	16	6	6	12
26	COMBOLCHA TR1	132	132	66	16	6	6	12
27	MELKA WAKENA TR1	132	132	66	15	6	6	6
28	ALAMATA ATR1	230	219.8	132	15	25	15	15
29	ALAMATA TR1	132	132	66	15	9.6	6.4	6.4
30	WOLKITE TR	230	230	66	33	16	16	16
31	GHEDO TR1	230	230	132	15	16	4	4
32	KALITI I TR2	132	135	45	16	18	6	6
33	KALITI I TR3	132	135	45	16	20	20	8
34	GEFARSA TR1	132	132	45	15	15	15	15
35	SEBETA TR2	132	132	45	15	12	4	4
36	KOKA TR1	132	132	45	15	12	4	4
37	SHAKISSO TR2	132	132	66	15	6	6	6

No	Element Name	Net-work Level	Un1 [kV]	Un2 [kV]	Un3 [kV]	Sn12 [MVA]	Sn23 [MVA]	Sn31 [MVA]
38	MELKA WAKENA YTR1	132	132	66	15	6	6	6
39	DIRE DAWA III ATR2	230	225	132	15	37.8	11.34	11.34
40	ALAMATA ATR2	230	219.8	132	15	25	15	15
41	MEKELE ATR1	230	219.8	132	15	25	15	15
42	MEKELE ATR2	230	219.8	132	15	25	15	15
43	HARAR II TR2	132	132	66	33	20	9.6	9.6
44	GHEDO TR2	230	230	132	15	16	4	4
45	AWASH II TR2	132	141.75	15	10.5	6	6	20
46	AWASH III TR1	132	141.75	15	10.5	6	6	20
47	AWASH III TR2	132	141.75	15	10.5	4.2	4.2	14
48	ADWA TR1	132	132	66	15	9.6	6.4	6.4
49	ADWA TR2	132	132	66	15	9.6	6.4	6.4
50	ADIGRAT TR1	132	132	66	15	9.6	6.4	6.4
51	ADIGRAT TR2	132	132	66	15	9.6	6.4	6.4
52	KOKA PP TR2	132	135	10.5	15	18	6	6
53	KOKA PP TR3	132	135	10.5	15	18	6	6
54	BAHIR DAR II ATR2	230	230	132	15	50	16.7	16.7
55	BAHIR DAR II TR2	230	230	66	15	6.3	2.7	2.7
56	DEBRE MARKOS TR2	230	230	66	15	6.3	2.7	2.7
57	GEFARSA TR2	132	135	45	16	18	6	6
58	TEKEZETRAFO	230	230	66	6.6	20	20	20
59	Mekelle Tr1	230	230	132	15	63	63	23
60	Mekelle Tr2	230	230	132	33	63	63	23

A.1 Grid Data

A.1.4 Transmission line Data

Table A.5: Existing Transmission line data of the Ethiopian High Voltage Grid

No	From Bus	To Bus	ℓ(km)	r(ohm /km)	x(ohm/ k m)	c(nF/ km)	y(mho/km)
1	DABAT 66	GONDER I 66	58.4	0.522	0.4192	8.6	0.0000027
2	GONDER I 66	GONDER II 66	4.3	0.522	0.4192	8.6	0.0000027
3	GONDER II 66	WORETA 66	81.8	0.522	0.4192	8.6	0.0000027
4	PAWE 66	DANGLA 66	109	0.5219	0.4231	8.6	0.0000027
5	WORETA 66	BAHRDAR I 66	51.6	0.522	0.4192	8.6	0.0000027
6	DANGLA 66	BAHRDAR II 66	68.6	0.522	0.4192	8.6	0.0000027
7	BAHRDAR II 66	BAHRDAR I 66	4.5	0.522	0.4192	8.6	0.0000027
8	GONDER II 230	BAHRDAR II 230	137	0.0918	0.3205	11.5	0.0000036
9	ALAMATA 230	BAHRDAR II 230	338	0.0918	0.3193	11.5	0.0000036
10	MAYCHEW 66	ALAM 66	48	0.4262	0.4155	8.6	0.0000027
11	SEKOTA 66	ALAM 66	80	0.4262	0.4155	8.6	0.0000027
12	LALIBELA 66	ALAM 66	104.9	0.4262	0.4155	8.6	0.0000027
13	MEKELE 230	ALAMATA 230	140.7	0.0918	0.3193	11.5	0.0000036
14	MEKELE 230	TEKEZE 230	103	0.0739	0.4142	8.9	0.0000028
15	MESSOBO 132	MEK 132	5.1	0.1835	0.4278	8.6	0.0000027
16	MEK 132	ADWA 132	116.7	0.1835	0.4278	8.6	0.0000027
17	ADW 66	ENDASELASE 66	66.4	0.2676	0.4009	8.9	0.0000028
18	TAP WUKR	MEK 132	31	0.1835	0.4278	8.6	0.0000027
19	ADIGRAT 132	TAP WUKR	56.5	0.1835	0.4278	8.6	0.0000027
20	TAP WUKR	WUKRO 132	1.2	0.1835	0.4278	8.6	0.0000027
21	BAHIRDAR II 230	MOTA 230	81.1	0.0597	0.4113	8.9	0.0000028
22	MOTA 230	DEBRMRKOS 230	111.8	0.0597	0.4113	8.9	0.0000028
23	BICHENA 66	DEB MAR 66	65.7	0.5219	0.4231	8.6	0.0000027
24	FINOTSELAM 66	DEB MAR 66	80	0.5219	0.4231	8.6	0.0000027
25	DEBRMRKOS 230	FINCHA 230	95	0.0597	0.4113	8.9	0.0000028
26	FINCH 66	FINCHA SUG I 66	15.4	0.3625	0.4256	8.6	0.0000027
27	FIN SUG II 66	FINCHA SUG I 66	11	0.3625	0.4256	8.6	0.0000027
28	GHEDO 230	FINCHA 230	67.2	0.0671	0.4272	8.6	0.0000027
29	GEFARSA 230	GHEDO 230	133	0.0671	0.4272	8.6	0.0000027
30	ADDIS NRTH 132	GEF 132	11.1	0.1906	0.434	8.3	0.0000026
31	GEF 132	MUGER 132	80	0.1906	0.434	8.3	0.0000026
32	GEF 45	ADISALEM 45	29.6	0.5453	0.411	8.9	0.0000028
33	GEF 66	FICHE 66	96	0.5219	0.4231	8.6	0.0000027
34	SEBETA I 230	GEFARSA 230	10.6	0.0725	0.408	8.9	0.0000028
35	ADDIS EST II 132	ADDIS NRTH 132	9.9	0.1835	0.4237	8.6	0.0000027
36	COTEBE 132	ADDIS EST II 132	5.5	0.1835	0.4237	8.6	0.0000027
37	COT 45	ADDIS EAST I 45	6	0.5451	0.4132	8.6	0.0000027
38	DEBRBRHAN 132	COTEBE 132	107.5	0.1906	0.4333	8.3	0.0000026
39	SHWAROBIT 132	DEBREBRHN 132	57.5	0.1906	0.4333	8.3	0.0000026
40	SEMERA 230	COMBLCH II 230	177.1	0.0918	0.3206	11.5	0.0000036

41	DESSIE 66	COMB 66	12.7	0.522	0.4225	8.6	0.0000027
42	DESSIE 66	WOLDIA 66	88	0.5219	0.4231	8.6	0.0000027
43	GHEDO 132	NEKEMT 132	115.9	0.1903	0.4188	8.6	0.0000027
44	NEKEMT 132	GHIMBI 132	84.3	0.1903	0.4188	8.6	0.0000027
45	GHEDO 132	GUDER 132	34	0.194	0.4308	8.3	0.0000026
46	GHEDO 230	GG OLD 230	130.8	0.0725	0.4089	8.9	0.0000028
47	SEBETA I 230	WOLKITE 230	132.5	0.0597	0.4113	8.9	0.0000028
48	SEB I 45A	ADDIS WEST 45	6.8	0.5451	0.4132	8.6	0.0000027
49	SEB I 45B	ADDIS WEST 45	6.2	0.5451	0.4132	8.6	0.0000027
50	SEB I 45A	GEJA 45	23.1	0.5172	0.4093	8.9	0.0000028
51	SEB 66	WOLISO 66	98.6	0.5219	0.4231	8.6	0.0000027
52	WOLISO 66	WOLK 66	39.2	0.4261	0.4142	8.6	0.0000027
53	WOLKITE 230	GG OLD 230	65	0.0597	0.4113	8.9	0.0000028
54	SEB I 132	SEB TAP	0	0.1906	0.434	8.3	0.0000026
55	SEB TAP	GEF 132	14	0.1906	0.434	8.3	0.0000026
56	KALITI I 132	MEKANISA 132	16.2	0.1906	0.434	8.3	0.0000026
57	KALITI I 132	GEF 132	24.7	0.1906	0.434	8.3	0.0000026
58	ADDIS CNTER 132	KALITI I 132	14.3	0.1906	0.433	8.3	0.0000026
59	KALI 45	AKAK S.P FACT 45	6	0.5171	0.4187	8.6	0.0000027
60	NEFAS SILK 45	KALI II 45	3	0.5451	0.4204	8.6	0.0000027
61	KAL NOR TAP	KALITI I 132	1.5	0.1906	0.434	8.3	0.0000026
62	COTEBE 132	KAL NOR TAP	18.6	0.1906	0.434	8.3	0.0000026
63	COTEBE 132	WEREG TAP	2.4	0.1906	0.434	8.3	0.0000026
64	WEREG TAP	KALITI I 132	17.5	0.1906	0.434	8.3	0.0000026
65	WOREGENU 132	WEREG TAP	4.5	0.1906	0.434	8.3	0.0000026
66	KALITI NRTH 132	KAL NOR TAP	0.4	0.1906	0.434	8.3	0.0000026
67	KALITI I 230	SEBETA I 230	14.3	0.0597	0.4113	8.9	0.0000028
68	KALI 45	AKAK S.P FACT 45	6	0.5171	0.4187	8.6	0.0000027
69	KALI 45	ADDIS SOUTH I 45	8.8	0.5451	0.4132	8.6	0.0000027
70	KALI 45	AKAKI I 45	3	0.5451	0.4132	8.6	0.0000027
71	AKAKI I 45	ABA SAMUEL 45	18	0.5451	0.4132	8.6	0.0000027
72	AKAKI I 45	DUKEM 45	15	0.5451	0.4132	8.6	0.0000027
73	DUKEM 45	DEBREZEIT I 45	8.4	0.5451	0.4132	8.6	0.0000027
74	GG OLD 132	GG I 132	2.6	0.1835	0.4486	8.3	0.0000026
75	GG OLD 132	JIMMA 132	71.3	0.1905	0.4373	8.3	0.0000026
76	JIMMA 132	AGARO 132	34.8	0.1905	0.4373	8.3	0.0000026
77	AGARO 132	BEDELE 132	81.5	0.1905	0.4373	8.3	0.0000026
78	JIMMA 132	BONGA 132	102.3	0.1834	0.4229	8.9	0.0000028
79	BONGA 132	MIZAN 132	88.3	0.1834	0.4229	8.9	0.0000028
80	MIZ 66	TEPI 66	30.1	0.4262	0.4131	8.9	0.0000028
81	HOSAINA 132	GG OLD 132	70.6	0.1905	0.4373	8.3	0.0000026
82	HOSAINA 132	ALABA 132	39.6	0.1905	0.4373	8.3	0.0000026
83	ALABA 132	WOLAYTSOD 132	61.8	0.1941	0.4308	8.3	0.0000026
84	WOLAYTSOD 132	ARBAMINCH 132	109.1	0.1905	0.4373	8.3	0.0000026
85	SHASHMENE 132	ALABA 132	63.2	0.1941	0.4308	8.3	0.0000026
86	SHASHMENE 132	AWASA 132	21.6	0.1906	0.4333	8.3	0.0000026
87	AWASA 132	YIRGALEM 132	35.1	0.1906	0.4333	8.3	0.0000026
88	DILLA 45	YIRGA 45	39.7	0.5172	0.4093	8.9	0.0000028
89	DILLA 132	YIRGALEM 132	38.7	0.161	0.4151	8.9	0.0000028

90	HAGERMRAM 132	DILLA 132	94.6	0.161	0.4151	8.9	0.0000028
91	SHAKISSO 132	YIRGALEM 132	133.2	0.1941	0.4308	8.3	0.0000026
92	SHAK 66	NEGELBORNA 66	113.9	0.4261	0.4163	8.6	0.0000027
93	KALITI I 230	KOKA 230	66.4	0.0739	0.4142	8.9	0.0000028
94	KALITI I 230	KOKA 230	66.4	0.0739	0.4142	8.9	0.0000028
95	KALITI I 132	YESU FACT 132	9	0.1836	0.4181	8.9	0.0000028
96	KALITI I 132	ELA TAP	43	0.1906	0.4264	8.6	0.0000027
97	KALITI I 132	DEBREZ TAP	28	0.1906	0.4264	8.6	0.0000027
98	KOKA 132	ELA TAP	23	0.1906	0.4264	8.6	0.0000027
99	KOKA 132	DEBREZ TAP	38	0.1906	0.4264	8.6	0.0000027
100	KOKA 132	YESU FACT 132	58.7	0.1906	0.433	8.3	0.0000026
101	DEBREZ TAP	DEBREZEIT II 132	0	0.1906	0.4333	8.3	0.0000026
102	ELA TAP	ELALA GEDA 132	4.9	0.1906	0.4333	8.3	0.0000026
103	KOKA 230	MELKA WAK 230	163.9	0.0739	0.4142	8.9	0.0000028
104	KOKA 230	MELKA WAK 230	163.9	0.0739	0.4142	8.9	0.0000028
105	KOKA 45	NAZARETH I 45	12	0.5451	0.4132	8.6	0.0000027
106	KOKA 45	MOJO 45	17	0.5451	0.4132	8.6	0.0000027
107	MELK 132	MELK WAK Y 132	5	0.1941	0.4308	8.3	0.0000026
108	MELK WAK Y 132	SHASHEMENE 132	119.2	0.1941	0.4308	8.3	0.0000026
109	ROBE 66	MELK WAK Y 66	72.9	0.4131	0.415	8.6	0.0000027
110	GOBESA 66	MELK WAK Y 66	74.2	0.4261	0.4163	8.6	0.0000027
111	ADAMITULU 132	SHASHMENE 132	76.8	0.1906	0.4333	8.3	0.0000026
112	KOKA 132	AWASH II 132	25	0.1906	0.4264	8.6	0.0000027
113	KOKA 132	WON TAP	7.4	0.1906	0.4264	8.6	0.0000027
114	WON TAP	AWASH II 132	18	0.1906	0.4264	8.6	0.0000027
115	WONJI 132	WON TAP	0.6	0.1906	0.4333	8.3	0.0000026
116	AWASH II 132	ASELA 132	51.2	0.1906	0.4333	8.3	0.0000026
117	ASELA 132	ADAMITULU 132	51	0.1906	0.4333	8.3	0.0000026
118	BUTAJIRA 132	ADAMITULU 132	46.8	0.1835	0.4237	8.6	0.0000027
119	AWASH II 132	AWASH III 132	1.4	0.1906	0.4156	8.9	0.0000028
120	AWASH II 132	AWASH III 132	1.4	0.1906	0.4156	8.9	0.0000028
121	NAZARETH II 132	KOKA 132	11.5	0.1906	0.4273	8.6	0.0000027
122	METH TAP	NAZARETH II 132	88.2	0.1906	0.4273	8.6	0.0000027
123	METHEHARA 132	METH TAP	0	0.1906	0.4273	8.6	0.0000027
124	AWASH 7 KILO 132	METH TAP	29.6	0.1906	0.4273	8.6	0.0000027
125	AMIBARA 66	AWASH 7 66	42.6	0.5219	0.4231	8.6	0.0000027
126	ASEBE TEFERI 132	AWASH 7 KL 132	201.5	0.1906	0.4273	8.6	0.0000027
127	BEDESA 66	ASEBE 66	24	0.5219	0.4231	8.6	0.0000027
128	GONDER II 230	BAHIRDAR II 230	137	0.0918	0.3205	11.5	0.0000036
129	DIRE III 230	KOKA 230	335.1	0.0725	0.4089	8.9	0.0000028
130	DIREDAWA III 132	DIREDAWA I 132	3.7	0.1906	0.4273	8.3	0.0000026
131	DIRE I 66	ALEMAYA 66	27.3	0.542	0.4132	8.6	0.0000027
132	ALEMAYA 66	CHELENKO 66	49.8	0.4261	0.4153	8.6	0.0000027
133	ALEMAYA 66	HAR II 66	16	0.5219	0.4231	8.6	0.0000027
134	HAR II 66	HARAR I 66	2.7	0.4261	0.4208	8.6	0.0000027
135	HAR I 45	BABILE 45	26	0.5171	0.4012	8.9	0.0000028
136	JIJIGA I 45	BABILE 45	93	0.5171	0.4012	8.9	0.0000028
137	DIREDAWA III 132	DIREDAWA II 132	12	0.1906	0.4333	8.3	0.0000026
138	DIREDAWA II 132	HARAR II 132	43.8	0.1835	0.4242	8.6	0.0000027

139	HARAR II 132	JIJIGA II 132	95.1	0.1835	0.4242	8.6	0.0000027
140	MEKELE 230	TEKEZE 230	103	0.0739	0.4142	8.9	0.0000028
141	NEKEMT 132	BEDELE 132	73	0.1625	0.4071	8.9	0.0000028
142	BED 230	METU 230	90.4	0.0919	0.3166	11.5	0.0000036
143	BED 230	METU 230	90.4	0.0919	0.3166	11.5	0.0000036
144	GHIMBI 132	MENDI 132	132	0.1903	0.4188	8.6	0.0000027
145	MENDI 132	ASSOSA 132	84	0.1903	0.4188	8.6	0.0000027
146	COMBLCHA II 230	ALAMATA 230	170.6	0.0919	0.3167	11.5	0.0000036
147	COMB II 132	COMBLCHA I 132	7	0.1941	0.4308	8.3	0.0000026
148	COMB II 132	SHEWAROBT 132	129.5	0.1906	0.4333	8.3	0.0000026
149	BEL 400PP	BAHRD II 400	62.8	0.0209	0.3096	12.1	0.0000038
150	BEL 400PP	BAHRD II 400	62.8	0.0209	0.3096	12.1	0.0000038
151	SULULTA 230	GEFARSA 230	16.9	0.0599	0.4081	9.2	0.0000029
152	GG II 400PP	GG OLD 400	28	0.0375	0.4259	8.6	0.0000027
153	SEBETA II 400	GG II 400PP	185	0.0375	0.4259	8.6	0.0000027
154	SEB II 230	SEBETA I 230	16	0.0597	0.4113	8.9	0.0000028
155	SEB II 230	SEBETA I 230	16	0.0597	0.4113	8.9	0.0000028
156	WOLA 66	SAWLA 66	199.6	0.1941	0.4308	8.3	0.0000026
157	JIMMA 132	ABA 132	53	0.1905	0.4373	8.3	0.0000026
158	SEB TAP	MEKANISA 132	7.8	0.1906	0.434	8.3	0.0000026
159	BAHRD II 400	DEB MAR 400	193.8	0.0209	0.3034	12.1	0.0000038
160	DEB MAR 400	SUL 400	215.9	0.0209	0.3096	11.8	0.0000037
161	GG OLD 230	GILGEL GIBE I 230	2.6	0.0597	0.4113	8.9	0.0000028
162	GG OLD 230	GILGEL GIBE I 230	2.6	0.0597	0.4113	8.9	0.0000028
163	MEKANISA 132	ADIS SOUTH II132	5	0.1906	0.434	8.3	0.0000026
164	MEKELE 230	ALAMATA 230	140.7	0.0918	0.3193	11.5	0.0000036
165	Welayta Sodo 400 kv	Akaki 400	267	0.0206	0.3082	12.5	0.0000028
166	Welayta Sodo 400 kv	Gilgel Gibe 400KV	119	0.019	0.3291	11.1	0.0000037
167	Welayta Sodo 400 kv	Gibe 3 400	51	0.0206	0.3082	12.5	0.0000027
168	Welayta Sodo 400 kv	Gibe 3 400	51.3	0.0189	0.3097	11.8	0.0000028

A.1 Grid Data

A.1.5 Bus bar Data

Table A.6: Existing bus bar data (above 45KV) of the Ethiopian High Voltage Grid

No	Network Level	Name	Short Name	Node Type	Uref [kV]	Ustart [kV]	Inter-nal Node
1	132	DIRE DAWA III 132 BB1	N50	Busbar	132	132	Busbar
2	132	AWASH 7 KILO 132	N120	Busbar	132	132	Busbar
3	66	AWASH 7 KILO 66	66AW7K	Busbar	66	66	Busbar
4	66	AMIBARA 66	66AMIB	Busbar	66	66	Busbar
5	66	ASEBE TEFERI 66	66ASEB	Busbar	66	66	Busbar
6	66	BEDESA 66	66BEDES	Busbar	66	66	Busbar
7	132	METEHARA TP	N164	Busbar	132	132	Busbar
8	132	NAZRETH II 132	N165	Busbar	132	132	Busbar
9	132	KOKA 132 BB1	N166	Busbar	132	132	Busbar
10	45	KOKA 45	45KOKA	Busbar	45	45	Busbar
11	45	MODJO 45	45MODJ	Busbar	45	45	Busbar
12	45	NAZRETH I 45	45NAZR1	Busbar	45	45	Busbar
13	132	AWASH II 132 BB1	N190	Busbar	0	132	Busbar
14	132	WONJI 132	N191	Busbar	0	132	Busbar
15	132	AWASH III 132 BB1	N192	Busbar	0	132	Busbar
16	132	KALITI I 132 BB1	N203	Busbar	132	132	Busbar
17	132	KALITI II 132	N204	Busbar	0	132	Busbar
18	45	KALITI I 45 BB1	45B1KAL1	Busbar	45	45	Busbar
19	45	AKAKI S.P FACTORY 45	45AKFA	Busbar	45	45	Busbar
20	45	ADDIS SOUTH I 45	45ASSO1	Busbar	45	45	Busbar
21	45	AKAKI I 45	45AKAK1	Busbar	45	45	Busbar
22	45	ABA SAMUEL 45	45ABSA	Busbar	45	45	Busbar
23	45	DUKEM 45	45DUKE	Busbar	45	45	Busbar
24	45	DEBRE ZEIT I 45	45DEZE1	Busbar	0	45	Busbar
25	132	GEFARSA 132 BB1	N241	Busbar	0	132	Busbar
26	132	ADDIS NORTH 132	N242	Busbar	0	132	Busbar
27	132	SEBETA I 132	N243	Busbar	132	132	Busbar
28	230	SEBETA 230 BB1	SEBI230	Busbar	230	230	Busbar
29	45	SEBETA 45B	45BSEBE	Busbar	0	45	Busbar
30	45	ADDIS WEST 45	45ADWE	Busbar	45	45	Busbar
31	45	SEBETA 45A	45ASEBE	Busbar	45	45	Busbar
32	66	SEBETA 66	66SEBE	Busbar	66	66	Busbar
33	66	WOLISSO 66	66WOLI	Busbar	66	66	Busbar
34	66	WOLKITE 66	66WOLK	Busbar	66	66	Busbar
35	132	MEKANISSA 132	N273	Busbar	0	132	Busbar
36	45	GEDJA 45	45GEDJ	Busbar	0	45	Busbar

37	230	WOLKITE 230 BB1	WOLKITE	Busbar	230	230	Busbar
38	230	GILGEL GIBE I 230	GGI230PP	Busbar	230	230	Busbar
39	132	ADDIS CENTER 132	132ADCE	Busbar	0	132	Busbar
40	132	ADDIS EAST II 132	132ADEA2	Busbar	0	132	Busbar
41	132	COTOBIE 132	N288	Busbar	0	132	Busbar
42	132	WEREGENU 132	N289	Busbar	132	132	Busbar
43	132	KALITI NORTH 132	N290	Busbar	0	132	Busbar
44	132	DEBRE BIRHAN 132	N294	Busbar	0	132	Busbar
45	132	SHOA ROBIT 132	N295	Busbar	0	132	Busbar
46	132	COMBOLCHA 132	N296	Busbar	132	132	Busbar
47	132	DEBRE ZEIT II 132	N300	Busbar	132	132	Busbar
48	132	ELALA GEDA 132	N301	Busbar	0	132	Busbar
49	132	YESU FACTORY 132	N304	Busbar	0	132	Busbar
50	45	ADDIS EAST I 45	45ADEA1	Busbar	0	45	Busbar
51	45	KALITI II 45	45KALI2	Busbar	0	45	Busbar
52	45	NEFAS SILK 45	45NEFA	Busbar	45	45	Busbar
53	132	ASELA 132	N367	Busbar	132	132	Busbar
54	132	ADAMITULU 132	132ADAM	Busbar	0	132	Busbar
55	132	BUTAJIRA 132	N369	Busbar	0	132	Busbar
56	132	SHASHEMENE 132	N375	Busbar	0	132	Busbar
57	132	SHAKISSO 132	N376	Busbar	0	132	Busbar
58	132	MELKA WAKENA 132	N378	Busbar	0	132	Busbar
59	132	AWASA 132	N379	Busbar	0	132	Busbar
60	132	YIRGA ALEM 132	N380	Busbar	132	132	Busbar
61	132	WOLAYITA SODO 132	N384	Busbar	0	132	Busbar
62	132	ARBAMINCH 132	N385	Busbar	0	132	Busbar
63	132	BONGA 132	N386	Busbar	0	132	Busbar
64	132	JIMMAI I 132	Jimma 2	Busbar	0	132	Busbar
65	132	AGARO 132	N388	Busbar	0	132	Busbar
66	132	NEKEMTE 132	N389	Busbar	0	132	Busbar
67	132	BEDELE 132	N390	Busbar	132	132	Busbar
68	132	MIZAN 132	N392	Busbar	132	132	Busbar
69	132	GHIMBI 132	N393	Busbar	0	132	Busbar
70	132	GHEDO 132	N399	Busbar	0	132	Busbar
71	132	GUDER 132	N401	Busbar	0	132	Busbar
72	132	GILGEL GIBE OLD 132 BB1	GGOLD132	Busbar	132	132	Busbar
73	132	HOSAINA 132	N404	Busbar	0	132	Busbar
74	132	MUGER 132	N406	Busbar	0	132	Busbar
75	132	GIGEL GIBE I 132	N415	Busbar	0	132	Busbar
76	230	DEBRE MARKOS 230	N418	Busbar	230	230	Busbar
77	230	FINCHAA 230	N420	Busbar	230	230	Busbar
78	230	GHEDO 230	Ghdeo230	Busbar	230	230	Busbar
79	66	SOR 66	66SOR	Busbar	66	66	Busbar
80	66	METU 66	66METU	Busbar	66	66	Busbar
81	66	WOLAYITA SODDO 66	66WOSO	Busbar	66	66	Busbar
82	45	YIRGA ALEM 45	45YIRG	Busbar	0	45	Busbar
83	45	DILLA I 45	45DILLA1	Busbar	45	45	Busbar
84	66	SHAKISSO 66	66SHAK	Busbar	0	66	Busbar

85	66	NEGELE BORENA 66	66NEBO	Busbar	0	66	Busbar
86	230	TEKEZE 230	TEK230	Busbar	0	66	Busbar
87	66	TEKEZE66KV	TEK66	Busbar	0	66	Busbar
88	6.6KV	TEKEZE6.6KV	TEKEZE6.	Busbar	0	66	Busbar
89	132	DILLA 132KV	DILLA132	Busbar	0	66	Busbar
90	132	HAGEREMARIAM132KV	N1734	Busbar	0	66	Busbar
91	33	HAGEREMARIAM33KV	N1735	Busbar	0	66	Busbar
92	33	YIRGALEM33KV	N1736	Busbar	0	66	Busbar
93	15	YIRGALEM15B	N1739	Busbar	0	66	Busbar
94	33	DILLA33KV	N1740	Busbar	0	66	Busbar
95	15	DILLA15B	N1741	Busbar	0	66	Busbar
96	132	AKISTA 132	N1745	Busbar	0	66	Busbar
97	33	AKISTA33	N1746	Busbar	0	66	Busbar
98	66	AKISTA66	N1747	Busbar	0	66	Busbar
99	132	MENDI132	N1749	Busbar	0	66	Busbar
100	132	ASSOSA132	N1750	Busbar	0	66	Busbar
101	400	Gilgel Gibe 400KV	GG2 400K	Busbar	400	400	Busbar
102	400	GG OLD 400KV	GG OLD 4	Busbar	400	400	Busbar
103	230	GG OLD 230KV	GGOLD 23	Busbar	230	230	Busbar
104	400	Akaki 400	Akaki 2	Busbar	400	400	Busbar
105	230	Akaki 230	Akaki 2	Busbar	0	230	Busbar
106	400	Welayta Sodo 400 kv	Welyta 4	Busbar	400	400	Busbar
107	132	Welyat sodo 132 new	welyta 1	Busbar	0	132	Busbar
108	132	Akaki II 132	Akaki 13	Busbar	132	132	Busbar
109	400	Gibe 3 400	Gibe 3	Busbar	400	400	Busbar
110	132	Jimma I	JimI	Busbar	0	132	Busbar
111	230	METU230KV	METU230	Busbar	230	230	Busbar
112	230	Gambela 230kv	Gam230	Busbar	230	230	Busbar

A.1 Grid Data

A.1.6 Shunt reactor Data

Table A.7: Existing shunt reactor data of the Ethiopian High Voltage Grid

No	Name	Network Level	Sn [MVA]	Un [kV]
1	Dire dawa III 132 bb1	132	8	132
2	Dire dawa III 15	15	5	15
3	Dire dawa III 15	15	5	15
4	Combolcha 132	132	10	132
5	Bedele 15	15	5	15
6	Agaro 15	15	5	15
7	Bonga 132	132	6	132
8	Arbaminch 15	15	5	15
9	Shakisso 132	132	6	132
10	Shashemene 132	132	12	132
11	Bahir dar ii 230 bb1	230	15	230
12	Shr bahir dar II alamata	230	15	230
13	Shr2 alamata bahir dar II	230	15	230
14	Shr1 alamata bahir dar II	230	15	230
15	Shr gonder II bahir dar II	230	15	230
16	Shr bahir dar ii mota	230	15	230
17	Shr debre markos mota	230	15	230
18	Dire dawa III 230	230	15	230
19	Koka 230	230	15	230
20	Mekele 15	15	5	15
21	Mekele shr	230	15	230
22	Alamata 15c	15	7.5	15
23	Alamata 15b	15	7.5	15
24	Mizan 132	132	5	132
25	Mekele 132	132	12	132
26	Mendi132	132	8	132
27	Bahir dar 400kv	400	40	400
28	Sululta 400KV	400	45	400
29	Endeselase230kv	230	15	230
30	Humera230kv	230	15	230
31	Humera230kv	230	15	230
32	Semera230kv	230	15	230
33	Decheto230kv	230	15	230
34	Gg old 400kv	400	45	400
35	Adigala	230	10	230
36	Shehedi	230	15	230
37	Gonder II 230	230	15	230
38	Hurso 230	230	15	230

39	Koka 230	230	15	230
40	Hurso 230	230	15	230
41	Koka 230	230	15	230
42	Hurso 230	230	15	230
43	Hurso 230	230	15	230
44	Gambella-metu	230	15	230
45	Gambela-metu	230	15	230
46	Metu230kv	230	15	230
47	D/markos 400kv	400	45	400
48	Key Afer132KV	132	10	132
49	Ramo	230	15	230
50	Ramo	230	15	230
51	Gode	230	15	230