



Addis Ababa University
Addis Ababa Institute of Technology
School of Electrical & Computer Engineering

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the award of the Degree of Master of Science in Electrical Power Engineering*

Dynamic Security Assessment on Ethiopian Existing
Power Network

by

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DECLARATION

I, the undersigned, declare that this thesis work is my original work, has not been presented for a degree in this or any other university, and all sources of materials used for the thesis work have been fully acknowledged.

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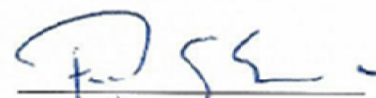
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ABSTRACT

Power system security is an important issue in power system operation and hence the operation of a power system requires regular security assessment. However, presently dynamic security assessments are not being performed on Ethiopian existing power network. Consequently, the power system operators do not have remedial action plans for various contingencies that may occur in the system.

In this thesis work, the dynamic security of the Ethiopian existing power network is assessed using PSS/E software in off-line mode. The Ethiopian existing operational power network model has been extracted from the 2015 planning model and used for simulation studies. This model is validated by checking the models of each element one by one. In addition, the history of generators loading profile has been reviewed and their loading of April 11, 2017 at 19:45 o'clock resulting in the peak operational scenario is selected for the analysis.

The dynamic simulations have been performed considering sever short circuit faults at the 400 kV and the 230 kV parts of the system and the outage of a generator at different power plants one by one. The voltage at 132 kV buses like Awassa, Dilla and Boculuguma doesn't recover to 0.9 pu within 10 seconds for all cases considered in the analysis. In addition, the Sudanese system would be out of synchronism from the Ethiopian system for a short circuit fault on Akaki II-Kaliti I 230 kV line even if the fault is cleared as per the actual protection setting provided that the total tie-line flow is above 148MW. These results confirm that the Ethiopian operational power network was operating at insecure operating point for the operation scenario considered in the analysis.

The frequency response plots for outage of a generator at different power plants depict that the frequency returns near to the normal value despite the outage. This indicates that the primary controllers of the generators which are in operation are working properly; and the remaining generators are jointly capable of covering the lost generation.

Reactive power sources like capacitor banks need to be installed in the Southern Region of the system to improve the voltage profile. The generators need to be re-dispatched in such a way that the total tie-line flow is kept at 148MW and below to keep the Sudanese system in synchronous operation with the Ethiopian system for the operation scenario considered.

Keywords: Power system, Security assessment, Dynamic security, Security criteria

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LIST OF ACRONYMS

AC	: Alternating Current
CB	: Circuit Breaker
CBEMA	: Computer and Business Equipment Manufacturers' Association
CCT	: Critical Clearing Time
DSA	: Dynamic Security Assessment
EAPP	: Eastern Africa Power Pool
EEP	: Ethiopian Electric Power
EEU	: Ethiopian Electric Utility
EHV	: Extra High Voltage
EMS	: Energy Management System
FC	: Filter Capacitor
G	: Generator
HV	: High Voltage
Hz	: Hertz
ICS	: Interconnected System
km	: Kilo Meter
kV	: Kilo Volt
LV	: Low Voltage
ms	: millisecond
MV	: Medium Voltage
MVA	: Mega Volt Amper
MW	: Mega Watt
NERC	: North American Electric Reliability Council
NGCC	: National Grid Control Center
PP	: Power Plant
PSS/E	: Power System Simulator for Engineering
pu/p.u	: Per Unit
S	: Complex Power
SCS	: Self Contained System
SSA	: Steady-State Security Assessment
SVC	: Static Var Compensator
T	: Transformer
TCR	: Thyristor Controlled Reactor
TSC	: Thyristor Switched Capacitor
TSO	: Transmission System Operator
V	: Voltage (Volt)
Var	: Volt Amper Reactive

CHAPTER 1: INTRODUCTION

1.1. Background

An electric power system is a bulk system which consists of generation plants, transmission and sub-transmission systems and distribution lines to supply reliable and good quality electric power to the end users. Provision of reliable and good quality electric power to end users is the overall objective of power system design and operation; and to be reliable it must be secure most of the time.

The operating state of a power system changes from time to time due to many factors like load changing, small and large disturbances and others. The operating states of a power system can be classified into five categories i.e normal state, alert state, emergency state, in extremis state and restorative state as shown in Figure 1.1.

In the normal state, all equipments of the power system will be running in their prescribed limits and all the system variables are within acceptable ranges. In addition, the system should also continue to operate in the normal state even in the case of contingencies. The main focus of the system operator for a 'normal' system is to 'foresee' contingencies (disturbances) and to take preventive control actions, as economically as possible, such that the system integrity and quality of power supply is maintained [1]. In the alert state, the system variables are still within limits and constraints are satisfied. However, the system has been weakened to a level where a contingency may cause an overloading of equipment [2]. Even if the equality (load-generation balance) and inequality (operating) constraints are still maintained, preventive controls should be brought into action to steer the system out of the alert state. If the preventive control fails, or the disturbance is reverse, the system may enter into an emergency state, though the demand is still met by the generation, one or more component or state violates the prescribed operation limits. Emergency control actions should immediately be brought into actions to bring the system back to the normal state. If the emergency control actions also fail, the system may enter in extremis state which is characterized by disintegration of the entire system into smaller islands, or a complete system blackout. Both constraints (equality and inequality constraints) are violated and the system no longer remains intact. The system enters the restorative state if there were any

remaining equipment operating within their total capacity or some equipment had been restarted following the total collapse [2].

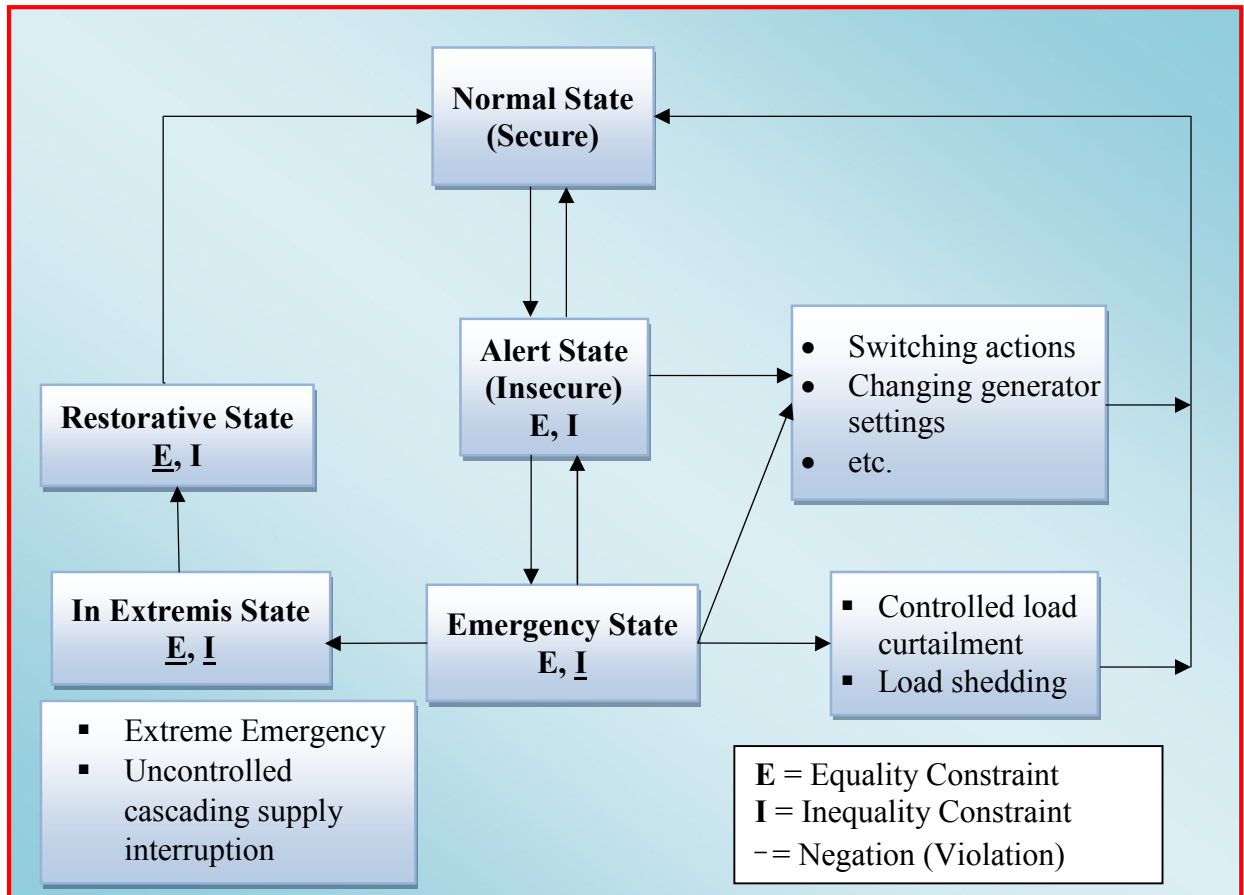


Figure 1.1: Operating states and state transitions of a power system

1.2. Problem Statement

The dynamic performance evaluation of an interconnected power system after the occurrence of a contingency is very important in power system operation. However, currently these analyses are not being performed on Ethiopian existing operational power network either online or off-line modes. Therefore, this thesis assesses the dynamic security of the operational power network in off-line mode considering the occurrence of different contingencies. Based on the findings of this research suitable remedial measures are proposed for insecure system operation.

1.3. Objectives

General Objective

The general objective of this thesis is to assess the dynamic security of the Ethiopian existing operational power network in off-line mode under various contingencies and to propose remedial measures to avoid possible insecurity that may damage the system.

Specific Objectives

The specific objectives of this thesis are:

- To review and analyse the existing power network power flow and dynamic models.
- To assess the current operational conditions.
- To assess and analyse the impact of selected contingencies on the dynamic security of Ethiopian existing power network.
- To investigate possible remedial measures for insecure operation under contingencies.
- To provide recommendations to the findings of this research.

1.4. Literature Review

In relation to this thesis, different works have been reviewed to understand the general procedure of dynamic security assessment.

Reference [2] discussed how a dynamic security assessment is performed considering the case of 330 kV power network of Nigeria.

Reference [3] discussed in detail about the impact of the second Ethiopia-Djibouti power system interconnector on small signal stability, transient stability and frequency stability considering the Ethiopia-Djibouti integrated model of year 2020, 2030 and others. It also clearly indicated the security criteria considered in different analysis.

Reference [4] also discussed the impact of the second Ethiopia-Sudan 500 kV interconnector on the stability of the integrated system of the two counties considering 2020, 2025 and 2030 anticipated operation years.

1.5. Methodology

The following steps have been followed in order to meet the stated objectives and to accomplish this thesis work successfully.

Literature Review

Various literatures on the general area of dynamic security assessment, power system stability, modelling of power system elements using PSS/E have been reviewed. In addition, different reports and operation procedures which deal with the dynamic security criteria of Ethiopian power network have also been reviewed.

Data Collection and Peak Load Condition Creation

First of all, power system elements should be modeled properly with appropriate data to perform various types of analysis on it. The Ethiopian existing operational power network is already modeled on PSS/E but it is found integrated with the planning model. Therefore, the Ethiopian operational power network model is extracted from the planning model with consideration of new operational elements which were not included in the planning model. In short, the operational power network model is checked and any detected discrepancy from the actual system configuration is cleared. Once the model is checked and validated, peak load condition operation scenario on which the analysis is based on is estimated. Usually a state estimator is used in the control centre to process the tele-metered data and to compute the best estimates of the system states. However, currently only some substations are reporting to the load dispatch center and it is difficult to find a complete state data from the energy management system (EMS). For this reason recent peak load data of each substation which is used as input for estimation of peak load operation scenario has been collected from the substations and the load dispatch center, operational planning work unit. Regarding the generators' dispatch, hourly generation output data of 8 months has been reviewed and used.

Dynamic Simulations

Once the data collection and peak load condition operation scenario creation phase is finalized, a dynamic model of the existing operational power network has been adopted and validated. Based on the final valid model, the time-domain dynamic simulations have been performed for selected

contingency lists, which are given below, to investigate their effects on bus voltages, rotor angles and frequency deviations. Then the results of the dynamic simulations have been evaluated based on the N-1 dynamic security criteria of the Ethiopian existing power network to know whether the system is secure or not. Remedial measures have also been proposed for insecure cases. The following lists of contingencies have been selected for analysis in this thesis.

Faults on 400 kV Lines

- Gibe III-Wolaita Sodo 400 kV line
- Wolaita Sodo- Akaki II 400 kV line
- Akaki II-Sebeta II 400 kV line
- Gibe II-Sebeta II 400 kV line
- Gibe II-Old Gibe 400 kV line
- Beles-Bahir Dar II 400 kV line
- Bahir Dar II-Debre Markos 400 kV line
- Debre Markos-Sululta 400 kV line

Faults on the 230 kV Lines

- Akaki II-Kaliti I 230 kV line
- Alamata-Combolcha II 230 kV line
- Ashegoda-Alamata 230 kV line
- Bahir Dar II-Gondar II 230 kV line
- Combolcha II-Cotobie II 230 kV line
- Gibe Old-Ghedo 230 kV line
- Gondar II-Metema 230 kV line
- Kaliti I-Bole Lemi 230 kV line
- Gondar II-Metema 230 kV line
- Kaliti I-Sebeta I 230 kV line
- Mekele-Ashegoda 230 kV line
- Mekele-Mehoni 230 kV line
- Sebeta I-Sebeta II 230 kV line
- Sebeta I-Wolkite 230 kV line
- Tekeze-Mekele 230 kV line
- Wolkite-Gibe Old 230 kV line

Outage of a Single Generating Unit at:

- Gibe III power plant
- Gibe II power plant
- Beles power plant
- Tekeze power plant

The following dynamic security aspects have been checked.

- Bus voltages
- Rotor angles and
- Frequency deviations

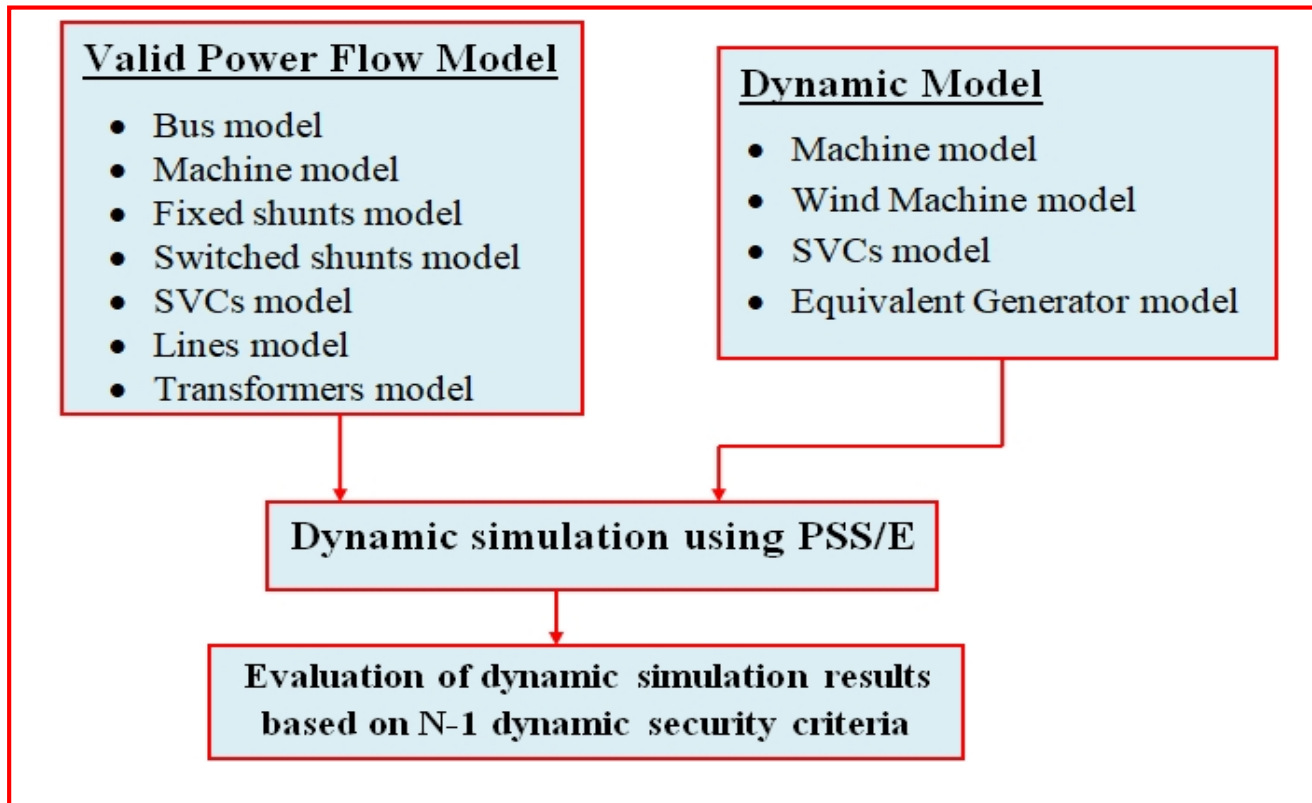


Figure 1. 2: Steps of dynamic security assessment

1.6. Relevance and Scope of the Thesis

Relevance

The off-line DSA analysis is used to predict the performance of the power system after the occurrence of a contingency. The predictions assist the power system operator to adapt correct remedial actions which will ensure the power system to remain at equilibrium points or regain equilibrium points.

Scope

The scope of this thesis includes literature review, system models review and validation, simulation of selected contingencies and assessment of the robustness of the system to survive from such contingencies. In this thesis, only large disturbances have been applied on selected 400 kV and 230 kV lines; and outage of large generators has also been considered for analysis. In addition, the transmission infrastructures which are commissioned and ready to evacuate power from Grand Renaissance to the operational grid are not considered in this research as this power station is not currently operational. The export powers to Sudan and Djibouti are considered in the analysis.

1.7. Organization of the Thesis

This thesis consists of five chapters. The present chapter deals with the background, the problem statement, the objective, the methodology, the literature review and the scope and relevance of the thesis. The next chapter, chapter two, presents the detail architecture and the applicable network security criteria of the existing power network. Chapter three presents the modeling of the existing power network. In chapter four simulation studies and analysis of results are presented using plots and tables. Finally, in chapter five conclusions, recommendations and suggestions for future work are made.

CHAPTER 2: ETHIOPIAN EXISTING POWER NETWORK

2.1. Introduction

The electric power system converts energy from a raw form into electricity, transmits it from the conversion site to a load site, and delivers it to consumers. The power generation and transmission system is not designed to store energy and its operation requires the rate of conversion of energy at the generating plants to be equal, within a very tight tolerance, to the rate of consumption by the loads. The power system does, nevertheless, store some energy in its electrical and mechanical components [5].

The energy stored in the power system, while insignificant in relation to the demands of the loads, is a critical factor in the dynamic behaviour of the system. There are three ways the power system stores energy [5]:

- The inductances and capacitances of the transmission lines, transformers, and shunt devices.
- The rotating inertia of the turbine-generators and motor-driven loads.
- The thermodynamic processes of the power plants, particularly within the boiler drums.

The amount of energy stored by each of these phenomena can be estimated in terms of the length of time its discharge could maintain full-load system power flows; and these times are summarized in Table 2.1.

Phenomenon	Seconds at Full System Power Flow
Electromagnetic and Electrostatic Energy Conversion	10^{-6} to 10^{-3} sec.
Rotating Inertial System	10^{-1} to 10 sec.
Thermodynamic System	10 to 10^3 sec.

Table 2. 1: Characterization of energy storage in terms of time required for full-load power flows to discharge the storage

The transient processes associated with these energy storages generally occur on a time scale that is similar to the discharge times given in Table 2.1. Electrical transients may be expected to arise and disappear within a few milliseconds, while electromechanical transients take several seconds to run, and thermodynamic transients may persist for many minutes; and it is neither practical nor desirable to consider all classes of transients at the same time.

This thesis work is mainly concerned with power system dynamic behaviour associated with the energy stored in the rotating inertias of the system, where transients arise and decay away again within a period of a few seconds.

2.2. Power System Stability

Power system stability may be broadly defined as that property of a power system that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable equilibrium after being subjected to a disturbance [6]. Based on the physical mechanism responsible for power system instability, the power system stability is broadly classified into three as show in Figure 2.1.

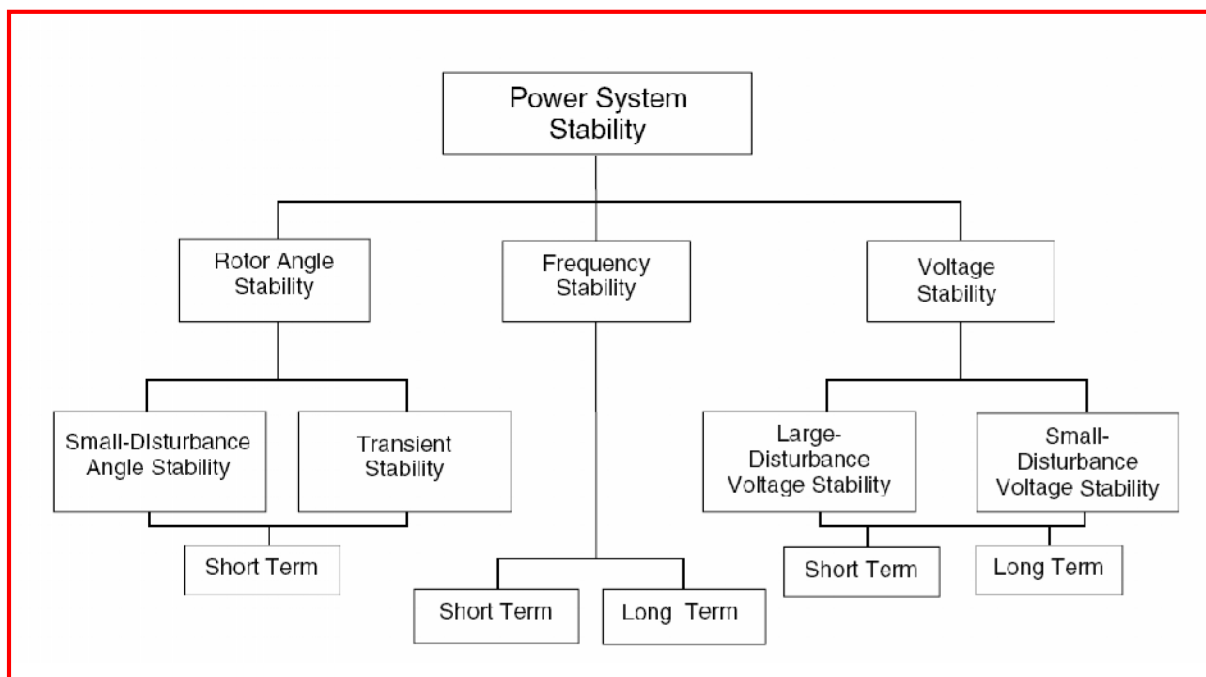


Figure 2. 1: Classification of power system stability

2.2.1. Rotor Angle Stability

The total active electrical power fed into the power system by the generators is always equal to the active power consumed by the loads including the losses in the system. On the other hand there is not always a similar balance between the loads and the power fed into the generators by the prime movers, e.g. the hydro and steam turbines. If such an imbalance develops, the rotating parts of the generators and other rotating machines, will act as energy buffer, and the kinetic energy stored in these will decrease or increase as a result. Rotor angle stability refers to the ability of synchronous machines of a power system to remain in synchronism after such an imbalance.

2.2.2. Frequency Stability

If the total power fed into the system by the prime movers is less than what is consumed by the loads, including losses, this imbalance will influence the frequency of the whole system. As mentioned above, the kinetic energy stored in rotating parts of the synchronous machines and other rotating electrical machines will compensate for the imbalance resulting in a frequency deviation. If the imbalance is not too large, the generators participating in the frequency control will regulate the active power input through their prime movers, and bring back the frequency deviation to acceptable values. If the imbalance is too large, the frequency deviation will be significant with possible serious consequences like activation of under frequency relays. As a last resort the generators are disconnected, making the situation even more serious. This type of instability is called frequency instability and the time scale could be from a few seconds up to several minutes.

2.2.3. Voltage Stability

Voltage stability is the ability of a power system to maintain steady acceptable voltages at all buses in the system under normal operating conditions and after being subjected to a disturbance. A system enters a state of voltage instability when a disturbance, increases in load demand, or change in system condition causes a progressive and uncontrolled drop in voltage. The main factor causing instability is the inability of the power system to meet the demand for reactive power. The heart of the problem is usually the voltage drop that occurs when active power and reactive power flow through inductive reactances associated with the transmission network [6]. A criterion for voltage stability is that, at a given operating condition for every bus in the system, the bus voltage magnitude increases as the reactive power injection at the same bus is increased. A system is voltage unstable if, for at least one bus in the system, the bus voltage magnitude (V) decreases as the reactive power injection (Q) at the same bus is increased. In other words, a system voltage is stable if V - Q sensitivity is positive for every bus and voltage unstable if V - Q sensitivity is negative for at least one bus [6].

2.3. Power System Security

Power system security is an important issue in power system operation. According to the North American Electric Reliability Council (NERC), “power system security is the ability of the electric system to withstand sudden disturbances such as electric short circuits or unanticipated loss of system elements.” In other words, power system security implies the ability of a power system in normal

operation mode to survive a likely disturbance without entering an emergency state. The power system operators should frequently conduct a security assessment to know the performance of their system for disturbances.

Security assessment refers to the analysis and quantification of the degree and risk in a power system's ability to survive imminent disturbances (contingencies) without interruption to customer service [7]. The security assessment of a power system includes steady-state security assessment (SSA) and dynamic security assessment (DSA). Steady-state security assessment (SSA) studies the system steady state operating points between dynamic transitions, whereas dynamic security assessment (DSA) focuses on the security of system dynamics in various timescales, from transients of several seconds to slow dynamics of several minutes or even hours [7]. In short, DSA is an evaluation of the ability of a certain power system to withstand a defined set of contingencies and to survive the transition to an acceptable steady-state condition [8].

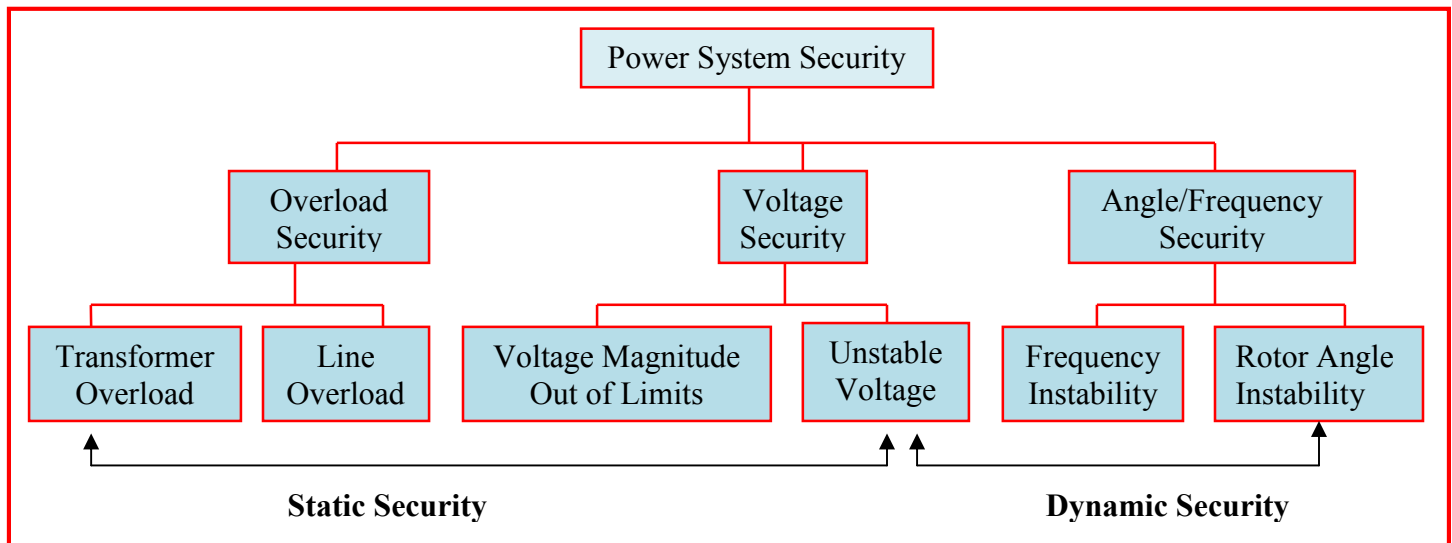


Figure 2. 2: Classification of power system security

In DSA, many security aspects of power systems are assessed, including transmission line thermal loading, voltage, rotor angles and frequency deviations [7]. DSA can be performed either online or off-line. In off-line DSA analysis, detailed time-domain stability analysis is performed for all contingencies and a variety of operating conditions. In most cases, this off-line analysis is used to determine limits of power transfers across important system interfaces. These limits then are used in an operating

environment that is hopefully not significantly different from those conditions considered. On-line DSA is used to supplement (or update) off-line DSA to consider current operating conditions [8].

According to [9], security of a power system is affected by three factors:

- Characteristics of the physical system: the integrated generation, transmission and distribution system and the protection and control systems.
- Business structures of owning and operating entities.
- The regulatory framework.

2.4. Existing Operational Power Network

The Ethiopian existing operational power network is classified into two major sub-systems; namely the self-contained system (SCS) and the interconnected system (ICS). The SCS, with installed capacity of 34MW, delivers power to isolated load centers which are far from the ICS using off-power network small hydro power plants located at Yadot and Dembi and small-scale diesel generators [10].

The Ethiopian Electric Power (EEP), which was set up by council of ministers regulation No.302/2013, is responsible for the construction, operation, maintenance and management of generation stations and transmission network which is above 66 kV voltage level. It is also mandated for bulk sale of electricity to Ethiopian Electric Utility (EEU) and neighboring countries like Sudan and Djibouti. On the other hand EEU is responsible for construction, operation, maintenance and management of the sub-transmission part of the system, 66 kV and 45 kV voltage levels, and medium and low voltage levels, 33 kV, 15 kV and others, and retail of electricity.

2.4.1. Existing Generation Systems

The Ethiopian operational power network consists of 14 hydro power plants, 3 wind farms, 3 standby diesel power plants and 1 geothermal power plant. These power plants are distributed all over the country and are located far away from the big load centers [10]. However, currently the geothermal power plant is non-operational due to low pressure of the thermal fuels. The existing hydro, diesel and geothermal power plants and wind farms are shown with their installed capacity and commissioning/refurbishment year in Table 2.2.

No.	Name of the Existing Power Plant	Type	Installed Capacity (MW)	Commissioning /Rehabilitation Year (G.C)
1	Aba Samuel	Hydro	6.6	2016
2	Awash II	Hydro	32	1966
3	Awash III	Hydro	32	1971
4	Beles	Hydro	460	2010
5	Fincha	Hydro	134	1973
6	Gibe I	Hydro	184	2004
7	Gibe II	Hydro	420	2010
8	Gibe III	Hydro	1870	2016
9	Tekeze	Hydro	300	2009
10	Koka	Hydro	43.2	1960
11	Melka Wakena	Hydro	153	1988/2014
12	Amerti Neshe	Hydro	97	2013
13	Tys Abay II	Hydro	72	2001
14	Tys Abay I	Hydro	12	1964/2000
Sub-Total			3815.8	
14	Adama I	Wind	51	2012
15	Adama II	Wind	153	2015
16	Ashegoda	Wind	120	2012
Sub-Total			324	
17	Aluto Langano	Geothermal	7.3	2007
Sub-Total			7.3	
18	Awash 7Kilo	Diesel	36	2014
19	Dire Dawa	Diesel	40	2014
20	Kaliti I	Diesel	12	2014
Sub-Total			88	
Grand Total			4227.8	

Table 2. 2: Power plants of Ethiopian existing power network

2.4.2. Existing Transmission Network

The existing transmission network which interconnects major power generation plants with load centers consists of the extra high voltage (EHV) and high voltage (HV) transmission lines and medium voltage (MV) sub-transmission lines.

No.	Category of Transmission Line	Voltage Level (kV)	Length of Single Circuit (km)	Length of Double Circuit (km)	Total Length (km)
1	Extra High Voltage	500	0	1240	1240
		400	767.12	912.4	1679.52
		Sub-Total			2919.52
2	High Voltage	230	4344.9	1781.44	6126.34
		132	4752.49	31.96	4784.45
		Sub-Total			10910.79
3	Medium Voltage	66	1850.55	12.69	1863.24
		45	116.01	6	122.01
		Sub-Total			1985.25
Total			11831.07	3963.49	15815.56

Table 2. 3: Summary of transmission lines of Ethiopian existing power network

The 500 kV network which is commissioned but still not be operational is currently limited to a few transmission lines and substations. This includes the interconnection between Grand Renaissance power plant which is under construction and Dedessa and Holeta substations to the west of Addis Ababa.

The 400 kV network includes interconnections between [10]:

- Gibe I/Gibe II power plants and Sebeta II and Wolaita Sodo II substations.
- Gibe III power plant and Wolaita Sodo II, Akaki II (Gelan), Sebeta II, Holeta and Sululta substations.
- Beles power plant and Bahir Dar II, Debre Markos, Gebre Guracha and Sululta substations.

The 230 kV network includes:

- A complete ring around Addis Ababa, including; Sululta, Gefersa, Sebeta and Cotobie II (Legetafo).
- Interconnections between Addis Ababa and power plants to the south east including Koka and Melka Wakena.
- Interconnection between Koka and Dire Dawa and Hurso in the east, with onward interconnection to Djibouti.
- Interconnection between Sebeta I, Wolkitie, Gilgel Gibe, Jimma II, Agaro, Bedele, Metu and Gambela.

- North-Western corridor, including interconnection with Finchaa, Debre Markos, Mota, Tis Abay II and Beles power plants and interconnection to Gondar II and Sudan via Metema/Shehedi.
- Northern corridor including Combolcha II, Alamata, Mehoni, Mekele, Tekeze power plant, Endasilassie and Humera.
- A 230kV Bahir Dar II-Alamata line which interconnects North-Western and Northern corridors.
- A 230kV line between Alaba, Hossaina and Wolkitie constructed to reinforce the Southern corridor.

In the existing operational power network there are a total of about 184 substations across the system; 14 hydro, 4 thermal, 122 transmission and 44 sub-transmission substations as indicated in Table 2.4.

Type of Substation	Voltage Level (kV)	Quantity
Transmission	500	2
	400	9
	230	43
	132	68
Sub-Total		122
Sub-Transmission	66	31
	45	13
Sub-Total		44
Hydro	400	3
	230	5
	132	4
	45	2
Sub-Total		14
Thermal	230	1
	132	1
	15	2
Sub-Total		4
Grand Total		184

Table 2. 4: Summary of Ethiopian existing power network

The 132 kV, 66 kV and 45 kV lines are also used in the operational power network of Ethiopia. The 66 kV and 45 kV lines are phasing out from the system.

Ethiopia is currently interconnected with Djibouti and Sudan at 230 kV voltage level. The Djibouti interconnector comprises a 283 km, 230 kV double circuit line from Hurso in Ethiopia to PK12

substation in Djibouti; and the agreed export from Ethiopia to Djibouti is 60MW firm. The Ethiopian system is also connected to the Sudanese system via a 160 km, 230 kV double circuit line from Metema (Shehedi) in the North West of Ethiopia to Gadarif in Sudan. The agreed export from Ethiopia to Sudan is 100 MW firm.

2.4.2.1. Reactive Power Compensators

Reactive power compensators like static var compensators (SVC), shunt capacitors, line connected reactors and bus connected reactors are installed at various locations across the existing operational power network to maintain coarse voltage at peak and minimum load conditions. The reactive power compensation equipments are detailed in Table 2.5, Table 2.6 and Table 2.7 below.

Static VAR Compensators (SVC)		
Substation		Holeta 500kV
Configuration		TCR+TSC+FC
No.	Item	Rating
1	Rated Power	0-900MVar
2	Step-down Transformer	3x (400/33kV, 315MVA)
3	Thyristor Switched Capacitor (TSC)	3x150MVar
4	Thyristor Controlled Reactor (TCR)	-3x150Mvar
5	Third Harmonic Filter Capacitor (FC)	3x50MVar
6	Fifth Harmonic Filter Capacitor (FC)	3x50MVar
7	Seventh Harmonic Filter Capacitor (FC)	3x50MVar

Table 2. 5: Detail of SVC of Ethiopian existing operational power network

No.	Name of the Line	Voltage Level (kV)	Substation	Fixed or Switchable	Rating (MVar)
1	Cotobie II-Combolcha II	230	Cotobie II and Combolcha II	Switchable	2x15
2	Hurso-Koka line 1	230	Hurso and Koka	Fixed	2x15
3	Hurso-Koka line 2	230	Hurso and Koka	Fixed	2x15
4	Gambela-Metu	230	Gambela and Metu	Switchable	2x15
5	Melka Wakena Yugo-Ramo	230	Melka Wakena Yugo and Ramo	Switchable	2x15
6	Ramo-Gode	230	Ramo and Gode	Switchable	2x15
7	Akaki II-Wolaita Sodo	400	Akaki II and Wolaita Sodo	Fixed	2x90
8	Beles-Grand Renaissance	400	Beles and Grand Renaissance	Fixed	2x45
9	Adigala-Djibouti-PK12	230	Adigala	Fixed	1x15
10	Dire Dawa III-Hurso Line 1	230	Dire Dawa III	Fixed	1x10
11	Dire Dawa III-Hurso Line 2	230	Dire Dawa III	Fixed	1x15
12	Dire Dawa III-Awash 7KL	230	Dire Dawa III	Fixed	1x15
13	Bahir Dar II-Mota	230	Bahir Dar II	Fixed	1x15
14	Bahir Dar II-N.Mewcha Tap	230	Bahir Dar II	Switchable	1x15
15	Debre Markos-Mota	230	Debre Markos	Fixed	1x15
16	Alamata-Ashegoda	230	Alamata	Switchable	1x15
17	Endasilassie-Tekeze	230	Endasilassie	Switchable	1x15
18	Humera-Endasilassie	230	Humera	Switchable	1x15
19	Mekele-Ashegoda	230	Mekele	Switchable	1x15
20	Ditcheto-Semera	230	Ditcheto	Fixed	1x15
21	Adigala-Hurso	230	Hurso	Switchable	1x10
22	Djibouti-PK12-Hurso	230	Hurso	Switchable	1x15
23	Combolcha II-Semera	230	Semera	Switchable	1x15
24	Bahir Dar II-Gondar II Line 1	230	Gondar II	Fixed	1x15
25	Bahir Dar II-Gondar II Line 2	230	Gondar II	Fixed	1x15
26	Gashena Tap-Alamata	230	Alamata	Switchable	1x15
27	Gondar II-Metema Line 1	230	Metema	Fixed	1x15
28	Gondar II-Metema Line 2	230	Metema	Fixed	1x15
29	Awash 7KL-Koka	230	Koka	Fixed	1x15
30	G.Gibe II-G.Gibe (Sekoru)	400	Sekoru	Switchable	1x45
Total number of line connected reactors					38

Table 2. 6: Details of line connected reactors of Ethiopian existing power network

No.	Name of Substation	Voltage Level (kV)	Type of Switched Shunt	Fixed or Switchable	Rating (MVar)
1	Mendi	132	Reactor	Switchable	1x8
2	Combolcha I	132	Reactor	Switchable	1x10
3	Gode	132	Reactor	Switchable	1x20
4	Shakisso	132	Reactor	Switchable	1x6
5	Key Afer	132	Reactor	Switchable	1x10
6	Mizan	132	Reactor	Switchable	1x6
7	Metu	230	Reactor	Switchable	1x15
8	Bahir Dar II	230	Reactor	Switchable	1x15
9	Gondar II	230	Reactor	Switchable	1x15
10	Metema	230	Reactor	Switchable	1x15
11	Endasilassie	230	Reactor	Switchable	1x15
12	Humera	230	Reactor	Switchable	1x30
13	Ditcheto	230	Reactor	Switchable	1x15
14	Semera	230	Reactor	Switchable	1x15
15	Ramo	230	Reactor	Switchable	1x15
16	Gode	230	Reactor	Switchable	1x15
17	Sululta	400	Reactor	Switchable	1x45
18	Bahir Dar II	400	Reactor	Switchable	1x45
19	Debre Markos	400	Reactor	Switchable	1x45
20	Gilgel Gibe (Sekoru)	400	Reactor	Switchable	1x45
21	Dire Dawa III	15	Reactor	Switchable	1x10
22	Alamata	15	Reactor	Switchable	1x15
23	Mekele	15	Reactor	Switchable	1x5
24	Arbaminch	15	Reactor	Switchable	1x5
25	Sebeta II	230	Capacitor	Switchable	1x45
26	Sebeta II	400	Capacitor	Switchable	1x90
27	Akaki II	400	Capacitor	Switchable	1x90
Total number of bus connected switched shunts					27

Table 2. 7: Details of bus connected switched shunts of Ethiopian existing power network

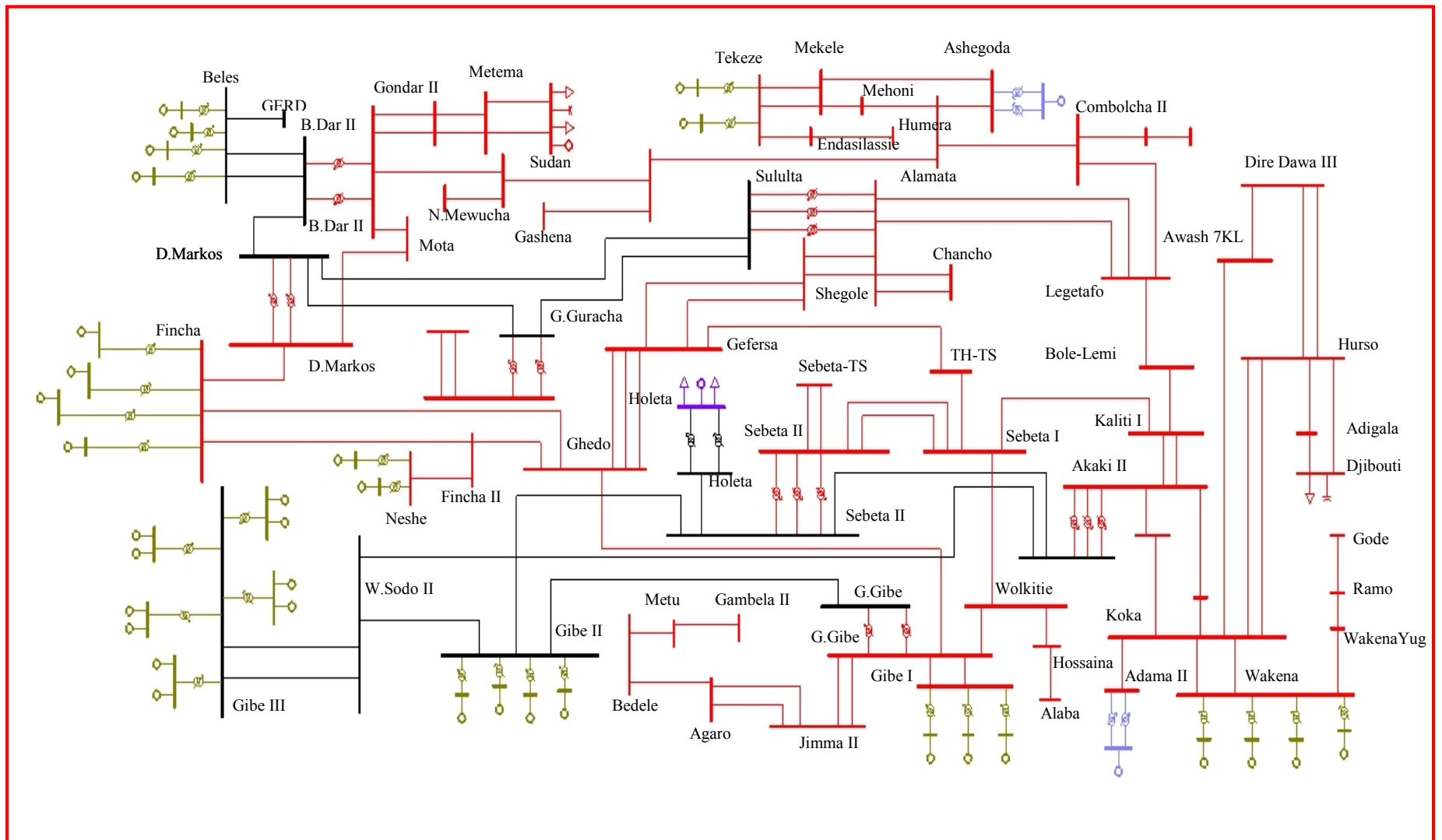
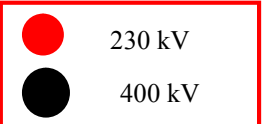


Figure 2. 3: The 400 kV and 230 kV subsystems of Ethiopian existing power network



2.5. Network Security Criteria

The fundamental rule of network operational security is to ensure compliance with the N-1 security criteria to prevent overloading, unacceptable voltage drops, loss of stability, cascade triggers, etc. In power system security assessment study the security criteria need to be defined clearly; but such criteria particularly dynamic voltage security criteria are not clearly defined even in [11]. Therefore, the network security criteria which have been used in this thesis work are adopted from different feasibility study documents. In general the network security criteria are classified as static security criteria and dynamic security criteria.

2.5.1. Static Security Criteria

The static security specifies the security of the network at steady state after the occurrence of an outage of an element, a line, a transformer, a generator, or a load, from the system. The following static voltage security criteria are adopted from [3] and [12] and indicated here in Table 2.8.

Steady State Voltage Security Criteria		
Operating Condition	Voltage (pu)	
	Maximum	Minimum
Normal (N) Operating Condition	1.05	0.95
Single Contingency (N-1) Operating Condition	1.1	0.9

Table 2. 8: Steady state voltage security criteria

The following N and N-1 condition security criteria of lines, cables and transformers are adopted from [3] and indicated below in Table 2.9. As it is clearly indicated in the table below, lines, cables and transformers are allowed to be overloaded up to 10%, 15% and 20% of their nominal power respectively at N-1 steady state condition.

Steady State Security Criteria of Lines, Cables and Transformers			
Operating Condition	Loading of Lines (%)	Loading of Cables (%)	Loading of Transformers (%)
Normal (N) Operating Condition	100	100	100
Single Contingency (N-1) Operating Condition	110	115	120

Table 2. 9: Steady state security criteria of lines, cables and transformers

2.5.2. Dynamic Security Criteria

The dynamic security specifies the ability of a power system to withstand a defined set of contingencies during its transition period from one steady state operating point to another acceptable steady state operating point following a disturbance; line outage, transformer outage, generator tripping, load rejection etc.

The N-1 condition dynamic security criteria of the Ethiopian existing operational power network are adopted from [11], [3] and [4]; and are clearly indicated below. These dynamic security criteria have been used to evaluate the dynamic performance of the Ethiopian existing operational power network from the point of view of:

- transient stability,
- frequency stability and
- transient voltage recovery

2.3.3.2. Transient (Angle) Stability Criteria

The transient stability criteria require that all machines in the system have to remain in synchronism for a three-phase fault occurring anywhere on the meshed parts of the system followed by opening of the most heavily loaded line at the point of fault within the meshed part of the network [10]. Neither sustained nor increasing oscillations of the rotor angle is generated for any machine of the system.

The system should maintain synchronism between plants for a line-to-line fault followed by opening and successful re-closure of the most heavily loaded line at the point of fault within the radial part of the network [10].

The acceptance criteria are shown in [3] as follows:

- No machine losing synchronism;
- No activation of over-voltage or under-voltage, over-frequency or under-frequency relays of the machines;
- Voltage recovery criteria: $V > 0.70$ p.u within 500 ms after fault clearance or $V > 0.90$ p.u after 10 seconds.

2.5.2.3. Frequency Security Criteria

Frequency is a global parameter of a synchronous electric power system and an indicator of the system's ability to balance generation and load as well as to manage disturbances [11]. Under normal operation, the frequency of the EAPP interconnected transmission system shall be normally 50 Hz and shall be controlled between 49.5 and 50.5 Hz ($\pm 1\%$) unless exceptional circumstances prevail. Following a system disturbance such as a load variation, the frequency band is extended to 49.0-51.0 Hz ($\pm 2\%$). If a major generating plant unit is tripped, a major transmission element fails or large loads are suddenly disconnected, the maximum frequency band becomes 48.75-51.25 Hz ($\pm 2.5\%$). If several of the contingencies mentioned previously occur simultaneously, the operating condition is labeled as extreme and the frequency can be below 47.5 Hz or above 51.5 Hz ($-5\%/+3\%$) for up to 20 seconds, and then extreme measures should be taken to restore the system [11]. These figures are summarized in Table 2.10.

Operating Condition	Frequency Limits (Hz)
Under Normal (N) Operating Condition	49.5 to 50.5
Under System Disturbance Condition	49.0 to 51.0
Maximum Band Under System Fault Condition	48.75 to 51.25
Under Extreme System Operation or Fault Condition	<47.5 or >51.5 for up to 20 seconds

Table 2. 10: Frequency limits in the EAPP interconnected transmission system

2.5.2.3. Voltage Security Criteria

The dynamic voltage security criteria are not clearly indicated in [11] and [4]; and for this thesis work these criteria are adopted from [13] and [3]. While [3] defined a voltage recovery criteria as $V > 0.70$ p.u within 500 ms after fault clearance and $V > 0.90$ p.u after 10 seconds, [13] defined it as shown in Table 2.11 below.

For surges and dips outside nominal voltage a typical voltage dip standard, Computer and Business Equipment Manufacturers' Association (CBEMA) curve, which recommends an inverse relationship between the voltages dip magnitude and the corresponding allowable duration where most electrical equipment can typically ride through is recommended [13].

Most high voltage equipments are designed to withstand an overvoltage of up to 1.2 per unit for a sufficiently short duration without incurring an excessive stress. It is for this reason that the allowable temporary overvoltage in [13] is recommended to be 1.2 per unit for maximum 1 second duration. For the temporary under voltage [13] recommended a post-fault voltage recovery to be 0.8 per unit for maximum of 1 second duration taking into account the motor under voltage protection.

Dynamic Voltage Limits	
Description	Dynamic Voltage Excursion (p.u)
Surges and dips outside nominal voltage	Within CBEMA curve
Maximum temporary over voltage	1.2 p.u, for maximum 1 second
Maximum temporary under voltage	0.8 p.u, for maximum 1 second

Table 2. 11: Dynamic voltage limits

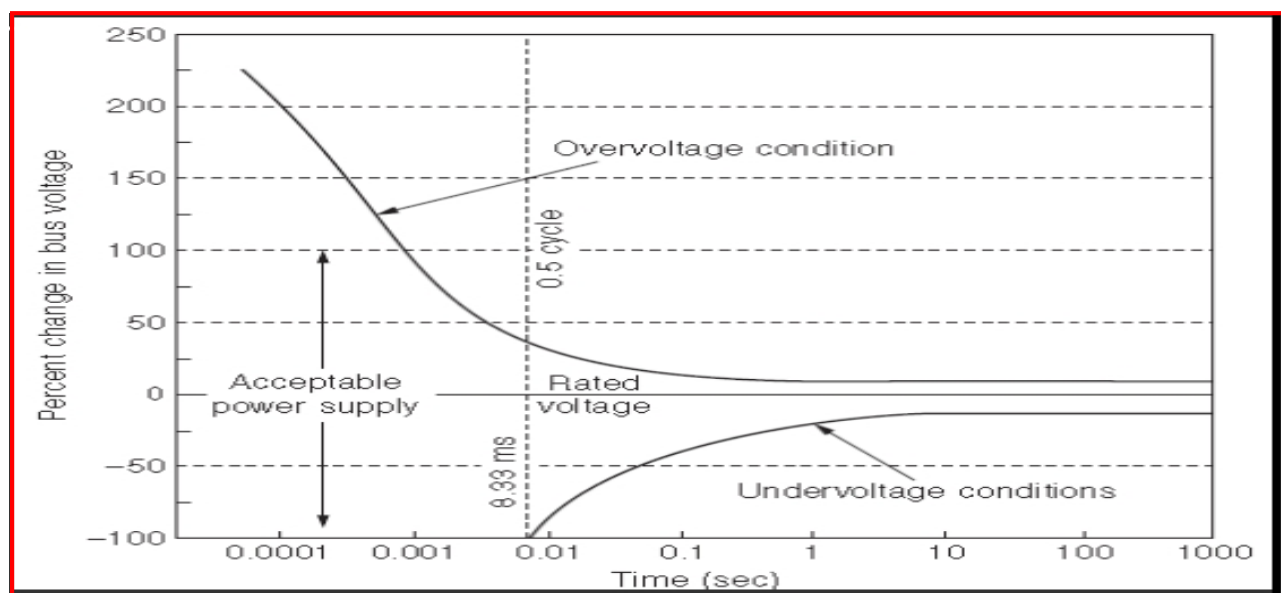


Figure 2. 4: CBEMA curve

2.6. Fault Clearance Times

As per the recommendation of [11], the clearance times for a fault on the EAPP interconnected transmission system or for a fault on the user system at the connection point shall not be longer than:

- 80 ms for faults at 400 kV and 500 kV;
- 100 ms for faults at 230 kV and 220 kV;
- 120 ms for faults at 132 kV and below.

Nothing shall prevent a TSO or user utilising faster fault clearance times; and total fault clearance time shall be from fault inception until arc extinction, which therefore includes relay operation, circuit breaker operation and telecommunication signalling times [11].

However, the actual protection setting data is considered for all the analysis performed in this thesis work. While duration of 200 ms is assigned from the fault inception point of time to the opening of the fault end circuit breaker, actual protection setting is referred for the opening of the far end circuit breaker.

CHAPTER 3: POWER SYSTEM MODELING USING PSS/E

3.1. Introduction

Time-domain dynamic simulations have to be conducted considering different disturbances to perform an offline dynamic security assessment on a power system; and then the simulation results have to be evaluated against the dynamic security criteria. The assumptions considered in the peak load condition creation, the load modeling, and the characteristics of loads in dynamic simulations are presented in this chapter. Activities executed to arrange the Ethiopian existing operational power network model for dynamic simulations are explained in this chapter. The steady-state power flow modeling and the dynamic modeling are presented in section 3.2 and section 3.3 respectively.

3.2. Steady-State Power Flow Model

The steady-state power flow model of a power system is mandatory and fundamental for any type of analysis; load flow, short circuit, contingency, dynamic and small-signal analyses. Therefore, the first phase of the system modeling part is to work with the steady-state power flow model.

The PSS/E software, an advanced power system analysis program developed by Siemens PTI which is selected to be used for analysis in this thesis work, represents the steady-state power system using standard positive-sequence network elements with lumped parameters.

AC transmission lines are modeled as Pi branches with R_{ij} , X_{ij} , B_{ch} elements and provision to connect line shunt reactors as shown in Figure 3.1. Line-connected shunt reactors should be specified by nonzero values as appropriate for the reactor parameters G_{li} , B_{li} , G_{lj} , and B_{lj} .

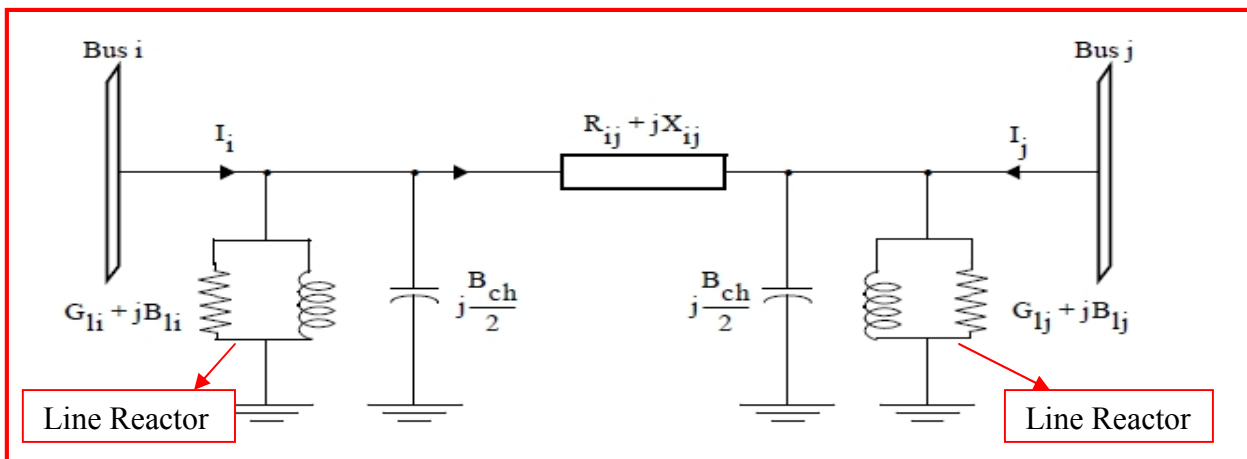


Figure 3. 1: Transmission line equivalent Pi model with line reactors in PSS/E

Fixed or switched capacitors and reactors may be shunt connected to buses to maintain the local or a remote bus voltage within a controlled range. Line series capacitors are modelled as negative-value series reactance.

Transformers are modeled as series branches with R (resistance) and X (reactance) elements where X depends on the tap ratio for transformers with tap changers.

It is normal practice in power flow analysis to assume that distribution system tap changers and voltage regulators have brought customer voltages to nominal values and, hence, loads are treated as constant power (MVA) loads i.e the values of P_{load} and Q_{load} are considered to be constant in any power flow case.

Generators are modeled as generator buses (PV buses), bus type code 2, with reactive capability limits and voltage set-point. Static Var Compensators (SVCs) are also modeled as generators but only with reactive power output; and the active power output is set to zero.

The Ethiopian 2017 existing operational power network model is extracted from the 2015 planning model with appropriate modifications and adjustments. The final 2017 existing operational model is compared with the 2015 planning model in terms of number of power system elements in Table 3.1 below.

Element Name	2017 Existing System Model	2015 Planning Model
	Quantity	Quantity
Buses	541	534
Plants	39	58
Machines	42	58
Equivalent Generator	1	1
Loads	241	295
Fixed Shunts	0	0
Switched Shunts	27	56
Static Var Compensators	1	0
Transmission Lines	250	338
Two Winding Transformers	248	278
Three Winding Transformers	109	95

Table 3. 1: Comparison of 2017 existing operational and 2015 planning models

The models of machines, switched shunts, transmission lines, transformers and a static var compensator have been checked and compared with their actual parameters; and some corrections have been done

specifically with transformers. The load and equivalent generator models of Sudan and a load model of Djibouti have been adopted from Ethiopian master plan study [10].

3.2.1. Peak Load Condition Creation

For the creation of the peak load condition operation scenario, the peak load data of each substation has been collected and then fed into the Ethiopian operational power network model of year 2017. All substations would not be at peak load condition at the same time. Therefore, the collected peak load data has been adjusted equally by a scaling factor of 0.85 called coincidence factor to obtain suitable and more realistic study scenario. The collected peak load data and the adjusted peak load data of the final model which is used for analysis are presented in Appendix C in Table C.1.

In addition to the Ethiopian internal peak load, two additional loads representing the power export towards Sudan and Djibouti are introduced into the study scenario model. The internal peak load data and export amounts have been summarized briefly in Table 3.2 below.

Summary of Ethiopian Internal Peak Load and Export Amounts	
Internal peak load of Ethiopia	2159.13 MW
Internal peak load of Ethiopia adjusted with coincidence factor of 0.85	1835.26 MW
Export amount to Sudan	188.00 MW
Export amount to Djibouti	56.00 MW

Table 3.2: Adjustment of collected peak load data

3.2.2. Loading of Generators

Once the peak load data is introduced into the model and adjusted, the operational generators' loading profile data for eight months is collected from the National Grid Control Center (NGCC) and monthly peak generations is tabulated as shown in Appendix D in Table D.1. As it is clearly indicated there, the highest peak generation was recorded on 11th April 2017 specifically at 19:45 o'clock; and this is selected for loading of the generators considered in the model. The loading of the generators of the specific date and time, on which the highest peak generation has been observed, is shown in Table 3.3.

Name of Power Plant	Number of Generators /Wind Turbines	Installed Capacity (MW)	Maximum Capacity of Each Generator (MW)	Minimum Capacity of Each Generator (MW)	Actual Loading of the Power Plants in the Model (MW)
Beles	4	460	115	30	331.52
Melka Wakena	4	153	30	15	90.00
Finchaa	4	134	Unit IV=20, Others=33	0	108.00
Gilgel Gibe I	3	184	70	20	110.01
Koka	3	42	13	2	10.62
Awash II	2	32	13	3	13.00
Awash III	2	32	Unit I=14, Unit II=8	3	0.00
Gilgel Gibe II	4	420	105	20	340.00
Gilgel Gibe III	10	1870	187	80	870.00
Tekeze	4	300	75	40	112.00
Amerti Neshe	2	97	49	0	20.32
Tis Abay II	2	72	30	27	0.00
Adama Wind I	34	51	1.5	0	26.74
Ashegoda Wind	84	120	1x30 turbines, 1.5x90 turbines	0	85.75
Adma Wind II	102	153	1.5	0	84.69
Aba Samuel	4	6.6	Unit IV=3.15, others=1.15	0	0.00

Table 3. 3: Actual dispatching of power plants in the model

In addition, the Sudanese system is represented in the power flow model as an equivalent generator; and it is loaded at 1320 MW as shown in Figure 3.2. On the other hand, the Djibouti system is represented as a load; and its generators impact is not considered as it is small system compared to the overall system.

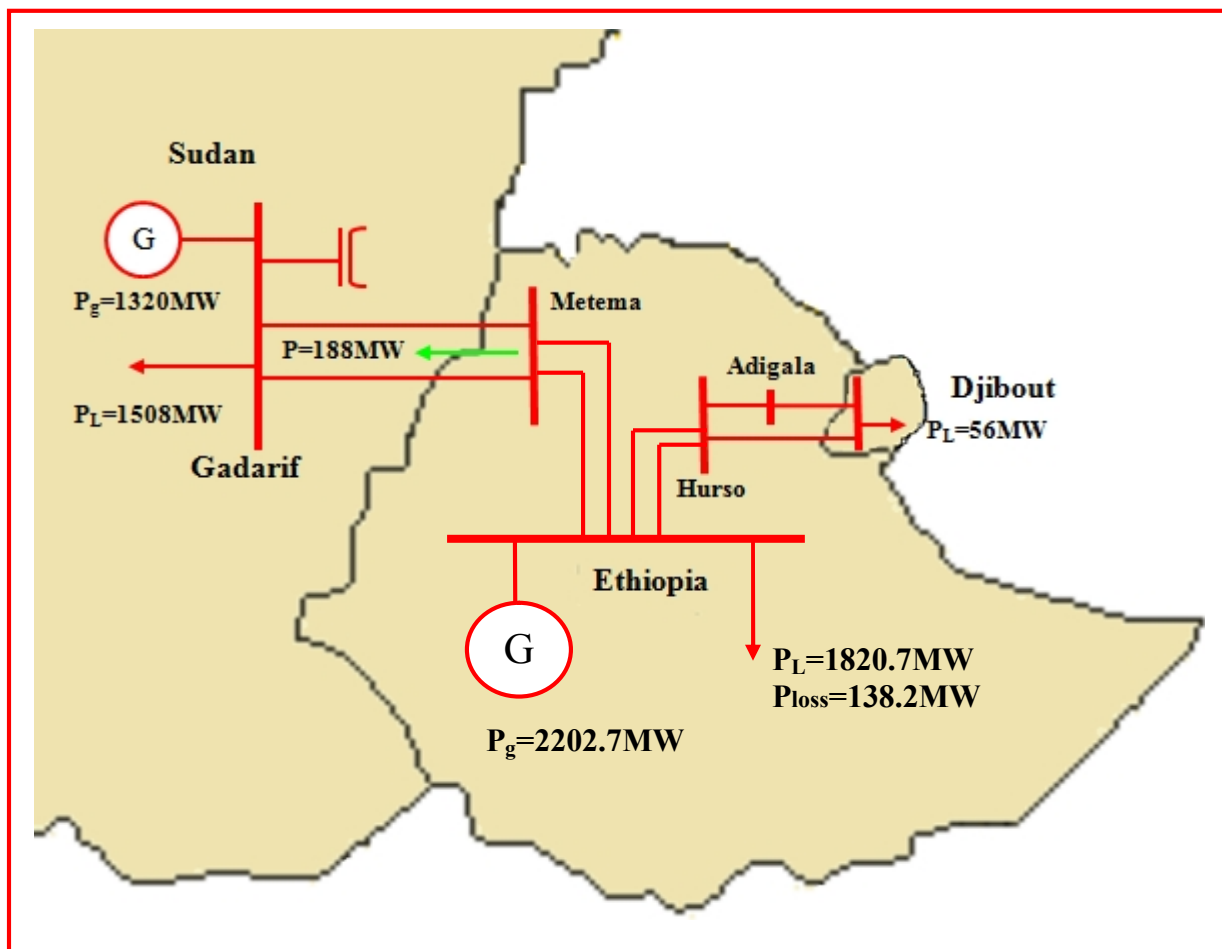


Figure 3. 2: Representation of Sudan and Djibouti systems

3.3. Dynamic Model

The development of the dynamic models of the power system elements, like generators and their control systems, which has great impact on the dynamic behaviour of the system, is important. The dynamic models of these elements of the Ethiopian existing operational power network are adopted from [4], [5] and [10].

3.3.1. Generator Models

All of the operational loaded machines, for which their loading is shown in Table 3.3, are salient pole generators; and they are modeled using GENSAL standard PSS/E dynamic models. On the other hand the synchronous generator model, CSVGN1, is adopted to represent a static Var Compensator (SVC) device.

The representation of GENSAL and CSVGN1 models are shown in Figure 3.3 and Figure 3.4 below respectively.

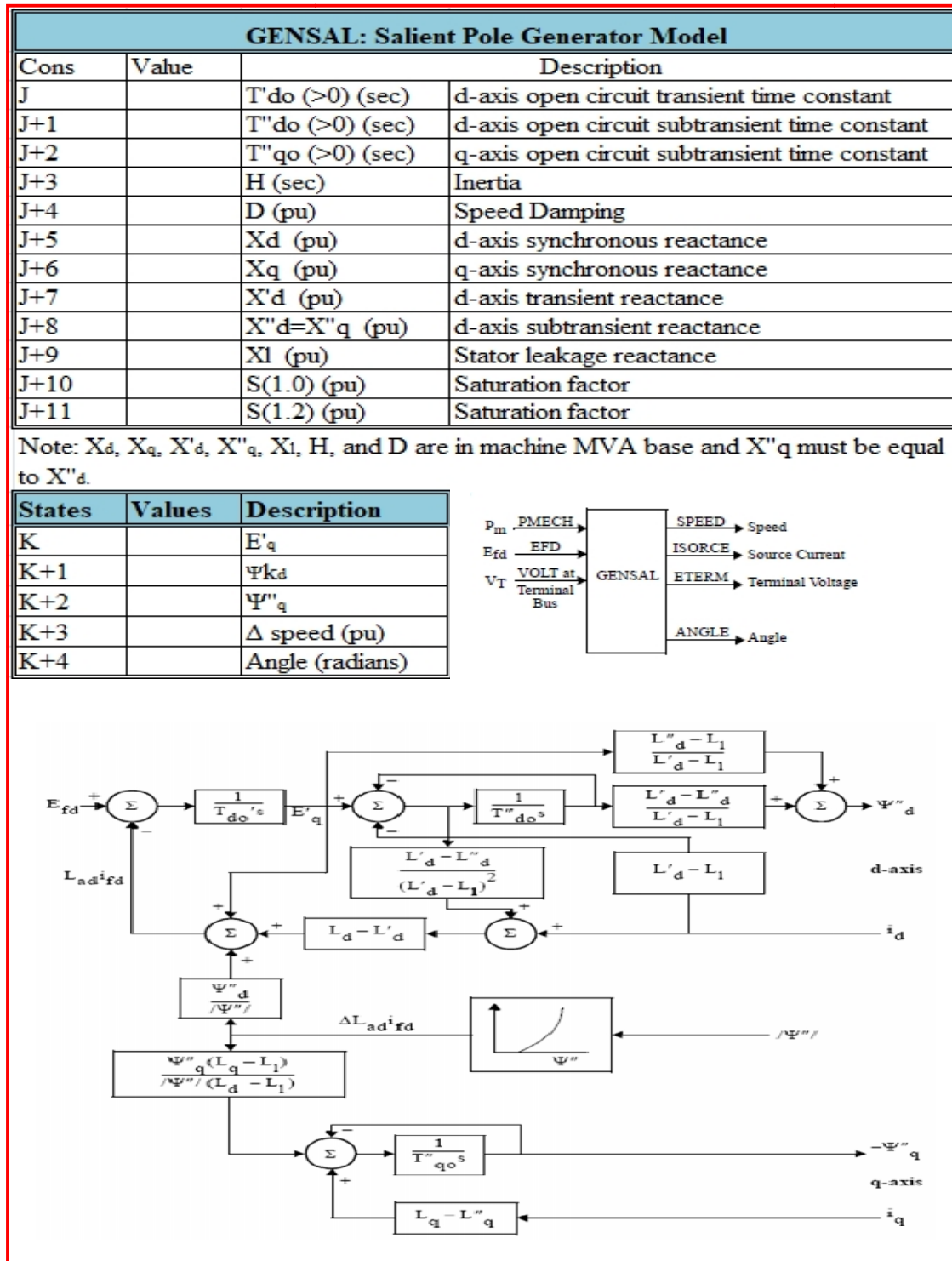


Figure 3. 3: Description of synchronous generator GENSAL model

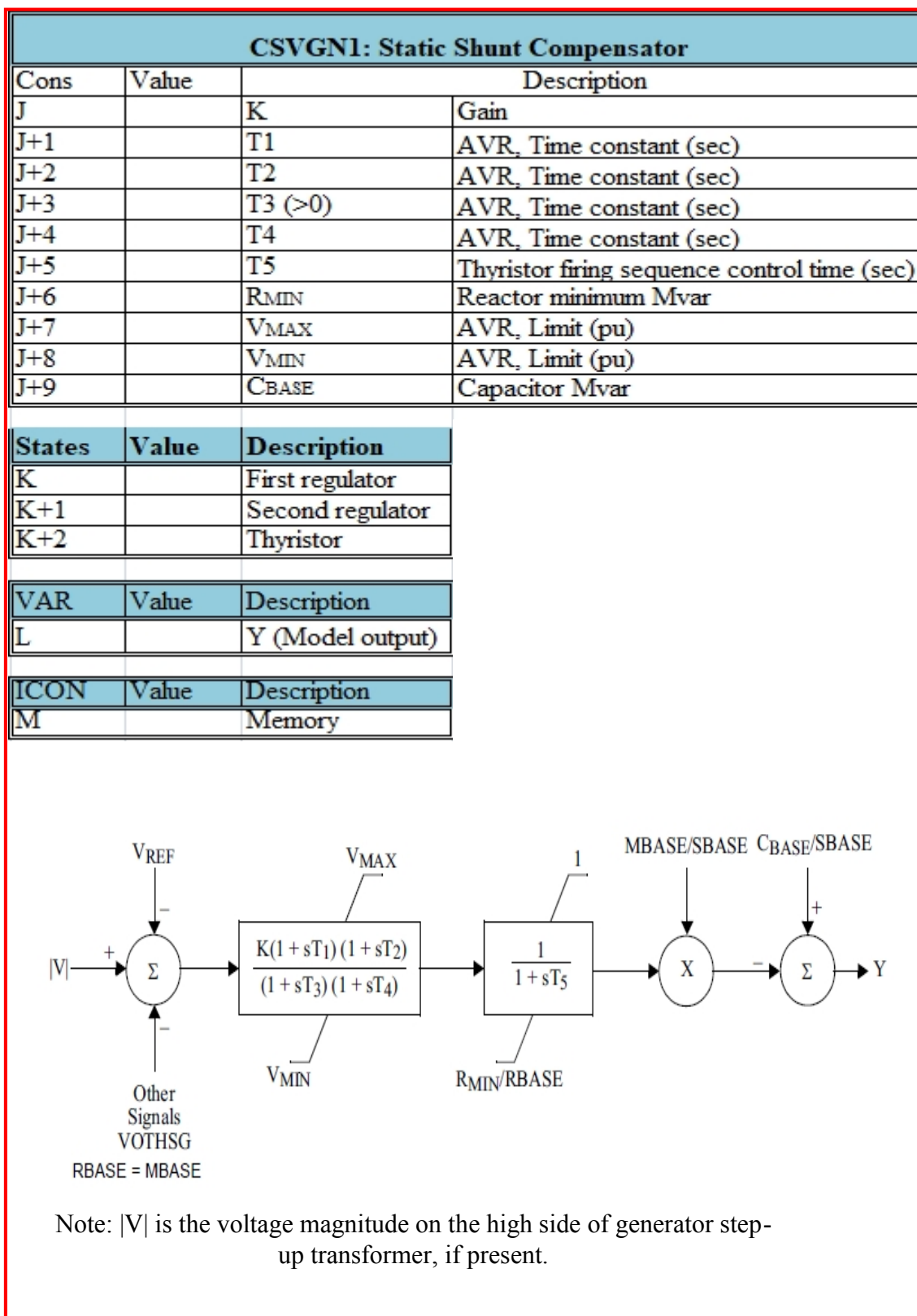


Figure 3. 4: Description of synchronous generator CSVGN1 model

3.3.2. Turbine and Governor Models

For turbine/governor models, the PSS/E standard model HYG0V is used for hydro generators; and all are adopted from [4] and [5]. HYG0V represents a straightforward hydroelectric plant governor, with a simple hydraulic representation of the penstock with unrestricted head race and tail race, and no surge tank. A schematic representation of a HYG0V governor is given in Figure 3.5 below.

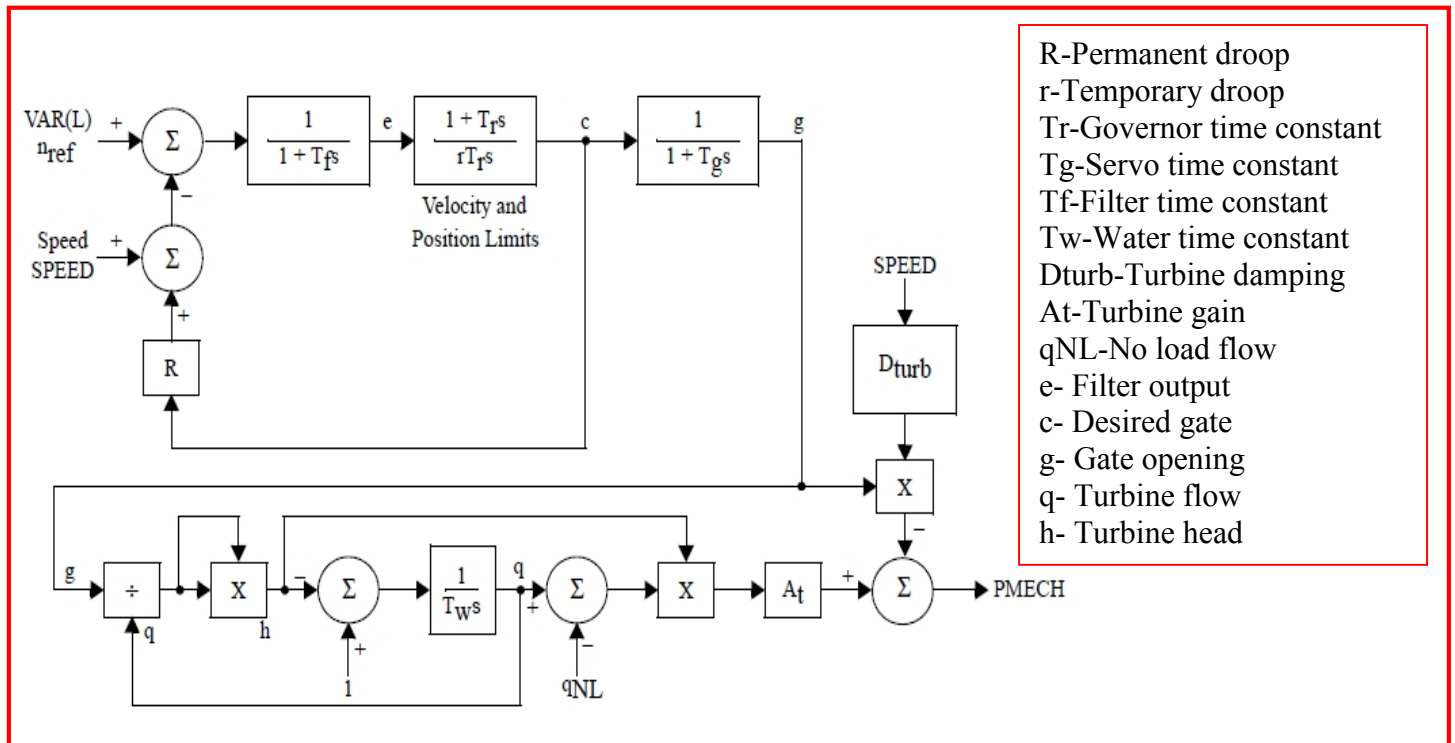


Figure 3. 5: HYG0V governor dynamic model

3.3.3. Excitation System Models

For this thesis work different exciter models are adopted from [4] and [5] in the representation of the Ethiopian existing operational power network. The exciter models which have application in the Ethiopian system can be categorized into about four types; EXST1, SCR, IEEE1 and EXDC2. A schematic representation of the exciters together with a brief description of each of them is give below.

3.3.3.2. EXST1

This model of a potential source controlled rectifier-exciter excitation system is intended to represent systems in which excitation power is supplied through a transformer from the generator terminals (or the unit's auxiliary bus) and is regulated by a controlled rectifier. The maximum exciter voltage available

from such systems is directly related to the generator terminal voltage [4].

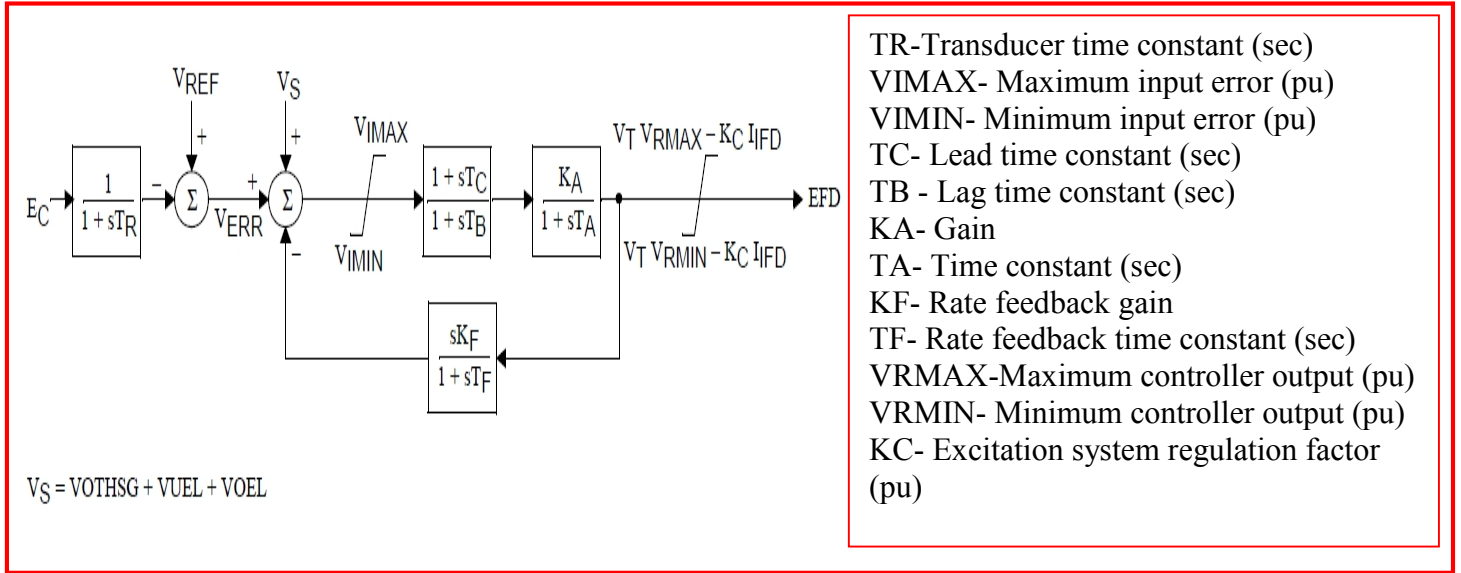


Figure 3. 6: EXST1 exciter dynamic model

3.3.3.3. IEEEEX1

Model IEEEEX1 is widely used to represent systems with shunt dc exciters as well as systems with alternator exciters and uncontrolled shaft-mounted rectifier bridges [4] and [5].

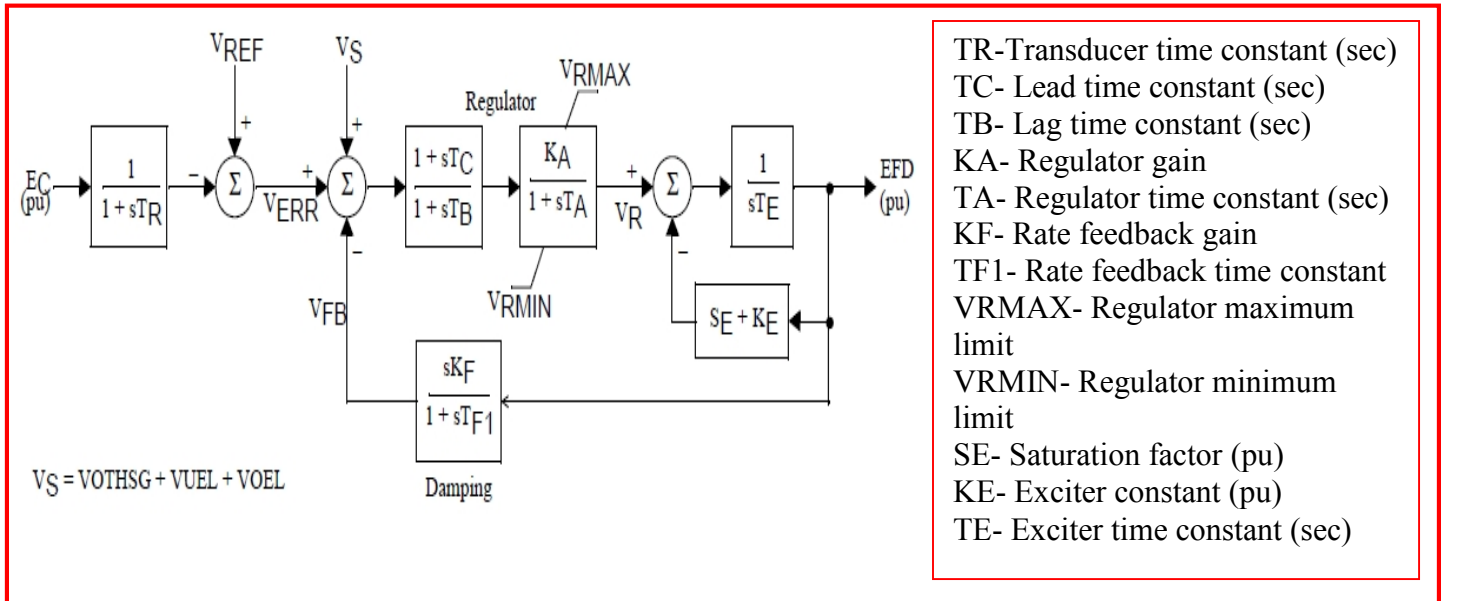


Figure 3. 7: IEEEEX1 exciter dynamic model

3.3.3.3. EXDC2

This model is used to represent systems with shunt dc exciters as well as systems with alternator exciters and uncontrolled shaft-mounted rectifier bridges when the voltage regulator's source of supply is the generator or auxiliary bus voltage [4] and [5].

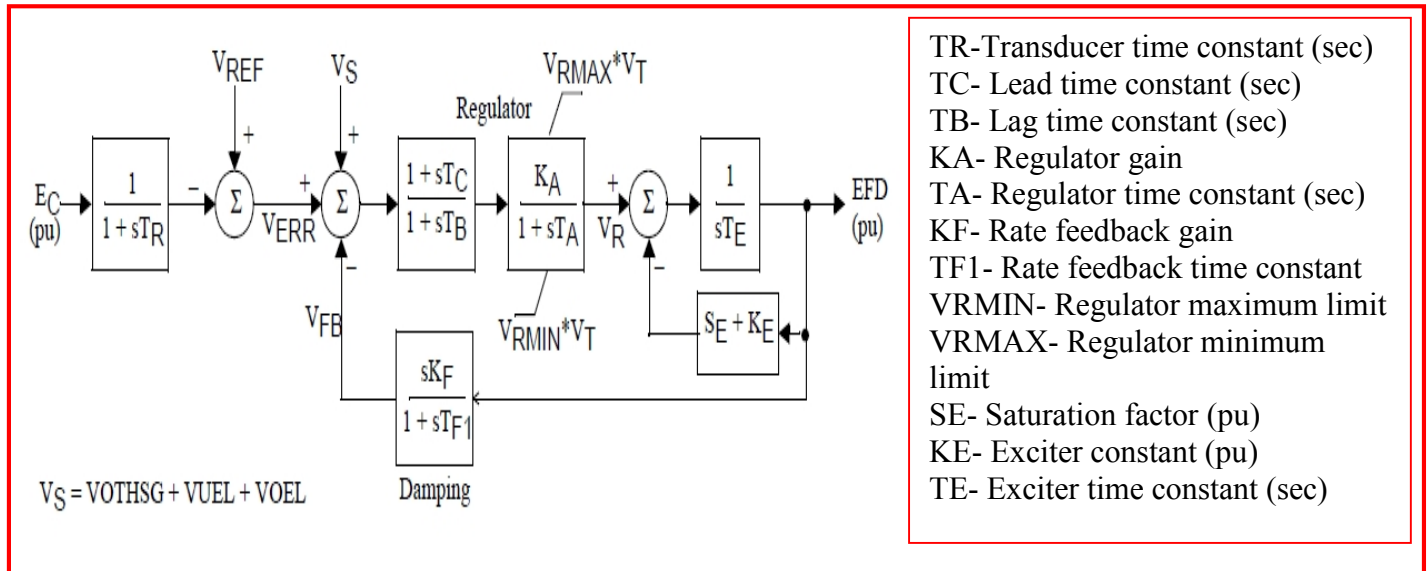


Figure 3. 8: EXDC2 exciter dynamic model

3.3.3.4. SCRX

This model is widely used as a general model to represent systems built with rectifier bridges [4] and [5].

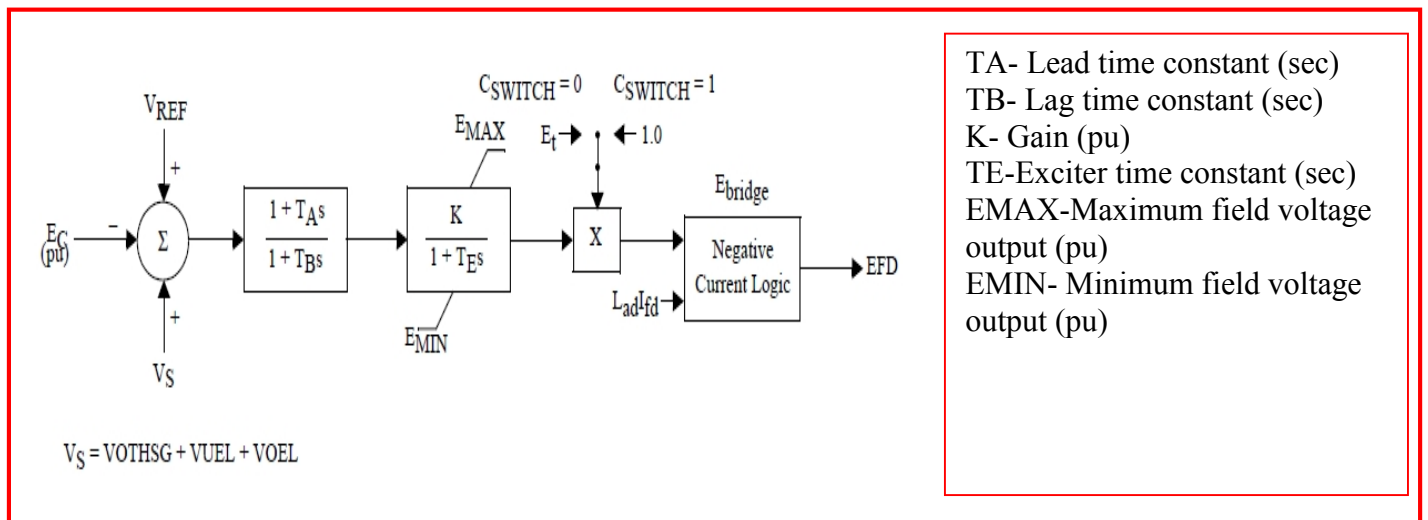


Figure 3. 9: SCRX exciter dynamic model

3.3.4. Wind Farm Models

The dynamic models of the wind farms of the Ethiopian existing system have been adopted from [4] and [5] to represent the wind generators and the associated controls. The wind generators are modeled as WT4G1 and the wind electrical controls are modeled as WT4E1.

3.3.4.1. WT4G1

Model WT4G1 allows representing the asynchronous or synchronous wind generator with full converter interface [4] and [5]; and it is shown in Figure 3.10.

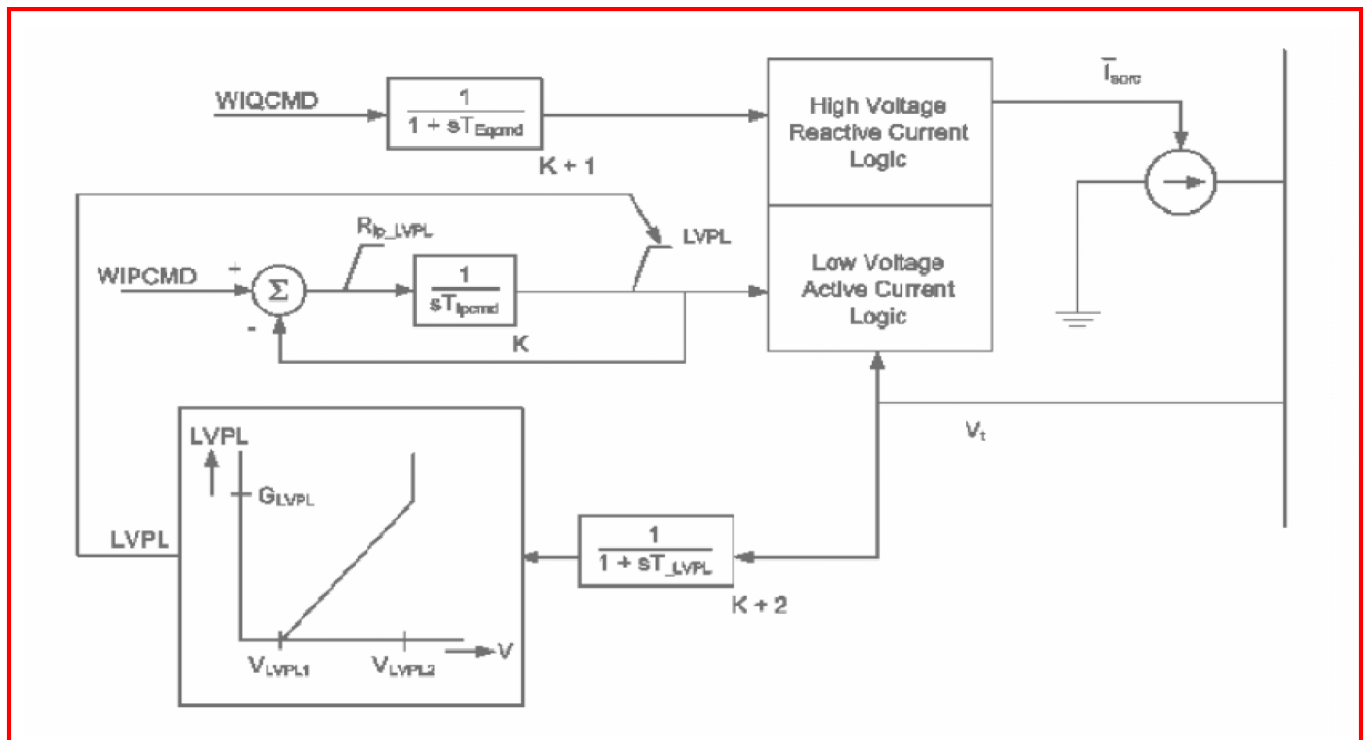


Figure 3. 10: ET4G1 wind generator model

- TIQCcmd, Converter time constant for IQcmd
- TIPcmd, Converter time constant for IPcmd
- VLVPL1, LVPL voltage 1 (Low voltage power logic)
- VLVPL2, LVPL voltage 2
- GLVPL, LVPL gain
- VHVRcr, HVRcr voltage (High voltage reactive current limiter)
- CURHVRcr, HVRcr current (Max. reactive current at VHVRcr)
- RIp_LVPL, Rate of LVACR active current change
- T_LVPL, Voltage sensor for LVACR time constant

3.3.5. Load Models

There are conditions, like short circuit and dynamic conditions, under which voltage excursions can be significant. For such conditions it is not acceptable treating loads as purely constant MVA at reference load value because time delays in distribution voltage-regulating devices prevent them from adjusting customer voltages in the period of interest. Further, loads have frequency dependence. For dynamic studies, therefore, a variety of load models of varying complexity are available. These models recognize, in more detail, the specific characteristics of loads such as lighting, heating and motor loads [4]. However, in this thesis work the following load models are adopted from [4] for the dynamic simulation as there is no precise information about the load characteristics of the Ethiopian existing operational system.

The active power component of the load is modelled as follows in the dynamic simulations.

- 30% is considered as constant impedance.
- 70% is considered as constant current.

The reactive power component of the load is modelled as follows in the dynamic simulations.

- 70% is considered as constant impedance.
- 30% is considered as constant current.

In general, modelling the power of a load as constant impedance means to consider a quadratic dependency from the voltage, instead modelling the power as a constant current means to consider a linear dependency by the voltage. A quadratic dependence by the voltage is typical for motors; and therefore, the hypothesis to consider 30% of the active power load with a quadratic dependence by the voltage means to consider approximately the load is composed by 30% of motors [4].

3.3.6. Dynamic Models of Ethiopian Existing System

The Ethiopian existing operational power network is described in detail for dynamic analysis taking into consideration the generating units and their control systems with a provision of special focus on synchronous machines, turbines, speed governors, excitation systems and voltage controls. The list of models of generating units with their automatic controller models which are included in the PSS/E database are presented in Table 3.4 below. The parameters of the generators, the speed governors, the excitation systems and the voltage regulators could be found in Appendix E in Table E.1 - Table E.8.

Table 3. 4: List of dynamic models of generators and their control systems

Bus Number	Bus Name	Id	Mbase (MVA)	Generator	Exciter	Turbine Governor	Stabilizer
207013	SUDAN-GADARE230	1	3500	GENSAL	None	None	None
507003	HOLETA-500 500	1	900	CSVGN1	None	None	None
907001	BELES-1 15.0	1	133	GENSAL	EXST1	HYGOV	None
907002	T-ABA2-1 10.5	1	40	GENSAL	EXST1	HYGOV	None
907003	TS-ABAY1-1 6.0	1	4.8	GENSAL	EXST1	HYGOV	None
907004	BELES-2 15.0	1	133	GENSAL	EXST1	HYGOV	None
907005	T-ABA2-2 10.5	1	40	GENSAL	EXST1	HYGOV	None
907006	TS-ABAY1-2 6.0	1	4.8	GENSAL	EXST1	HYGOV	None
907007	BELES-3 15.0	1	133	GENSAL	EXST1	HYGOV	None
907008	TS-ABAY1-3 6.0	1	4.8	GENSAL	EXST1	HYGOV	None
907009	BELES-4 15.0	1	133	GENSAL	EXST1	HYGOV	None
908001	FINCHA1 13.8	1	35	GENSAL	SCRX	HYGOV	None
908002	NESHE-1 13.8	1	75	GENSAL	EXDC2	HYGOV	None
908003	FINCHA2 13.8	1	35	GENSAL	SCRX	HYGOV	None
908004	NESHE-2 13.8	1	75	GENSAL	EXDC2	HYGOV	None
908005	FINCHA3 13.8	1	35	GENSAL	EXST1	HYGOV	None
908006	FINCHA4 13.8	1	35	GENSAL	EXST1	HYGOV	None
909001	TEKEZE1 13.8	1	87.6	GENSAL	EXST1	HYGOV	None
909002	TEKEZE4 13.8	1	87.6	GENSAL	EXST1	HYGOV	None
909004	TEKEZE2 13.8	1	87.6	GENSAL	EXST1	HYGOV	None
909005	TEKEZE3 13.8	1	87.6	GENSAL	EXST1	HYGOV	None
911003	AWASH2-1 10.5	1	20	GENSAL	SCRX	HYGOV	None
911004	AWASH3-1 10.5	1	20	GENSAL	SCRX	HYGOV	None
911005	KOKA1 10.5	1	18	GENSAL	IEEEX1	HYGOV	None
911006	KOKA3 10.5	1	18	GENSAL	IEEEX1	HYGOV	None
911007	M-WAKNA1 13.8	1	45	GENSAL	SCRX	HYGOV	None
911008	AWASH2-2 10.5	1	20	GENSAL	SCRX	HYGOV	None
911009	AWASH3-2 10.5	1	20	GENSAL	IEEEX1	HYGOV	None
911010	KOKA2 10.5	1	18	GENSAL	IEEEX1	HYGOV	None
911011	M-WAKNA2 13.8	1	45	GENSAL	SCRX	HYGOV	None
911012	M-WAKNA3 13.8	1	45	GENSAL	SCRX	HYGOV	None
911013	M-WAKNA4 13.8	1	45	GENSAL	SCRX	HYGOV	None
915002	G-GIB2-1 15.0	1	125	GENSAL	EXST1	HYGOV	None
915003	G-GIBE1-1 13.8	1	75	GENSAL	SCRX	HYGOV	None
915004	G-GIB2-2 15.0	1	125	GENSAL	EXST1	HYGOV	None

915005	G-GIBE1-2	13.8	1	75	GENSAL	SCRX	HYGOV	None
915006	G-GIB2-3	15.0	1	125	GENSAL	EXST1	HYGOV	None
915007	G-GIBE1-3	13.8	1	75	GENSAL	SCRX	HYGOV	None
915008	G-GIB2-4	15.0	1	125	GENSAL	EXST1	HYGOV	None
915009	G-GIB 3_1	15.0	1	176.3	GENSAL	EXST1	HYGOV	None
915009	G-GIB 3_1	15.0	2	176.3	GENSAL	EXST1	HYGOV	None
915010	G-GIB3_2	15.0	1	176.3	GENSAL	EXST1	HYGOV	None
915010	G-GIB3_2	15.0	2	176.3	GENSAL	EXST1	HYGOV	None
915011	G-GIB3_3	15.0	1	176.3	GENSAL	EXST1	HYGOV	None
915011	G-GIB3_3	15.0	2	176.3	GENSAL	EXST1	HYGOV	None
915012	G-GIB3_4	15.0	1	176.3	GENSAL	EXST1	HYGOV	None
915012	G-GIB3_4	15.0	2	176.3	GENSAL	EXST1	HYGOV	None
915013	G-GIB3_5	15.0	1	176.3	GENSAL	EXST1	HYGOV	None
915013	G-GIB3_5	15.0	2	176.3	GENSAL	EXST1	HYGOV	None

In addition to the conventional power plants and a static var compensator for which their dynamic models are shown in the above table, the following wind farms are also included in the dynamic model of the Ethiopian existing operational power network. The generator and the electrical control parameters of wind machines could be found in Appendix F in Table F.1 and Table F.2

Table 3. 5: List of dynamic models of wind machines and their control systems

Bus Number	Bus Name	Id	Mbase (MVA)	Generator	Electrical
909006	ASHEGODA-WF 33.0	1	90	WT4G1	WT4E1
909006	ASHEGODA-WF 33.0	2	37.5	WT4G1	WT4E1
911015	ADAMA WF-II 33.0	1	191.3	WT4G1	WT4E1
911016	ADAMA I WF 33.0	1	54	WT4G1	WT4E1

CHAPTER 4: SIMULATION STUDIES AND ANALYSIS OF RESULTS

4.1. Introduction

Once the system modeling issue has been finalized and checked whether it is valid or not, dynamic simulations have been performed for various contingencies considering the operation scenario created. The assumptions considered and the steps followed in the dynamic simulations for faults on the 400 kV and the 230 kV lines and for the outage of a generator are presented in section 4.2, section 4.3 and section 4.4 respectively. In addition, the critical clearing time (CCT) of the lines are also calculated to know the robustness of the Ethiopian existing operational power network and are reported in section 4.5. The system variables like rotor angles, bus voltages and frequency deviations are checked and plotted.

4.2. Dynamic Simulations for Faults on 400 kV Lines

In the dynamic simulations for the occurrence of faults on the 400 kV lines, zone 1 and tele-protection systems are considered to participate in clearing the faults because tele-protection systems are functional for such lines as they are relatively new. The most sever type of faults, a three phase to ground metallic fault with zero fault impedance, is applied at one end of the line for 200 ms and then after 200 ms the fault end CB is assumed to be opened by the action of zone 1 protection system. The fault is completely cleared after 220 ms following the opening of the far end CB by the action of tele-protection system as shown in Figure 4.1 below.

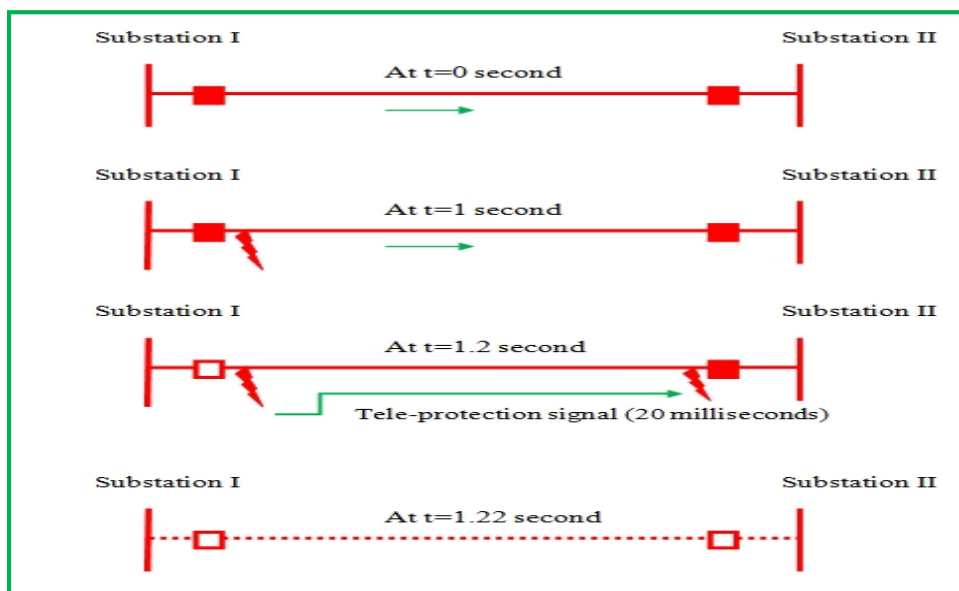


Figure 4. 1: Sequence of events for clearing faults on 400 kV lines

The dynamic simulations have been performed for various faults on the 400 kV lines which are identified in chapter one considering the sequence of events indicated in Figure 4.1 above. The plots below show the simulation results for machine relative angle, bus frequency deviations and bus voltage responses at selected substations for faults considered on selected 400 kV lines. In the simulation process Beles generators are set as a reference machines for angle measurement; and its value is initialized at 26.54 degrees.

The outages of the 400 kV lines didn't cause any of the generators to be out of synchronism from the system as it is clearly seen from the plots shown in Figure 4.2 to Figure 4.22. In addition, the voltage at 400 kV and 230 kV buses and the system frequency have recovered to the normal values as per their security criteria. However, the voltage at Awassa, Dilla and Boculuguma substations doesn't recover to 0.9 pu within 10 seconds as shown in Figures 4.16, 4.19 and 4.22. This shows that the system is operating at insecure point.

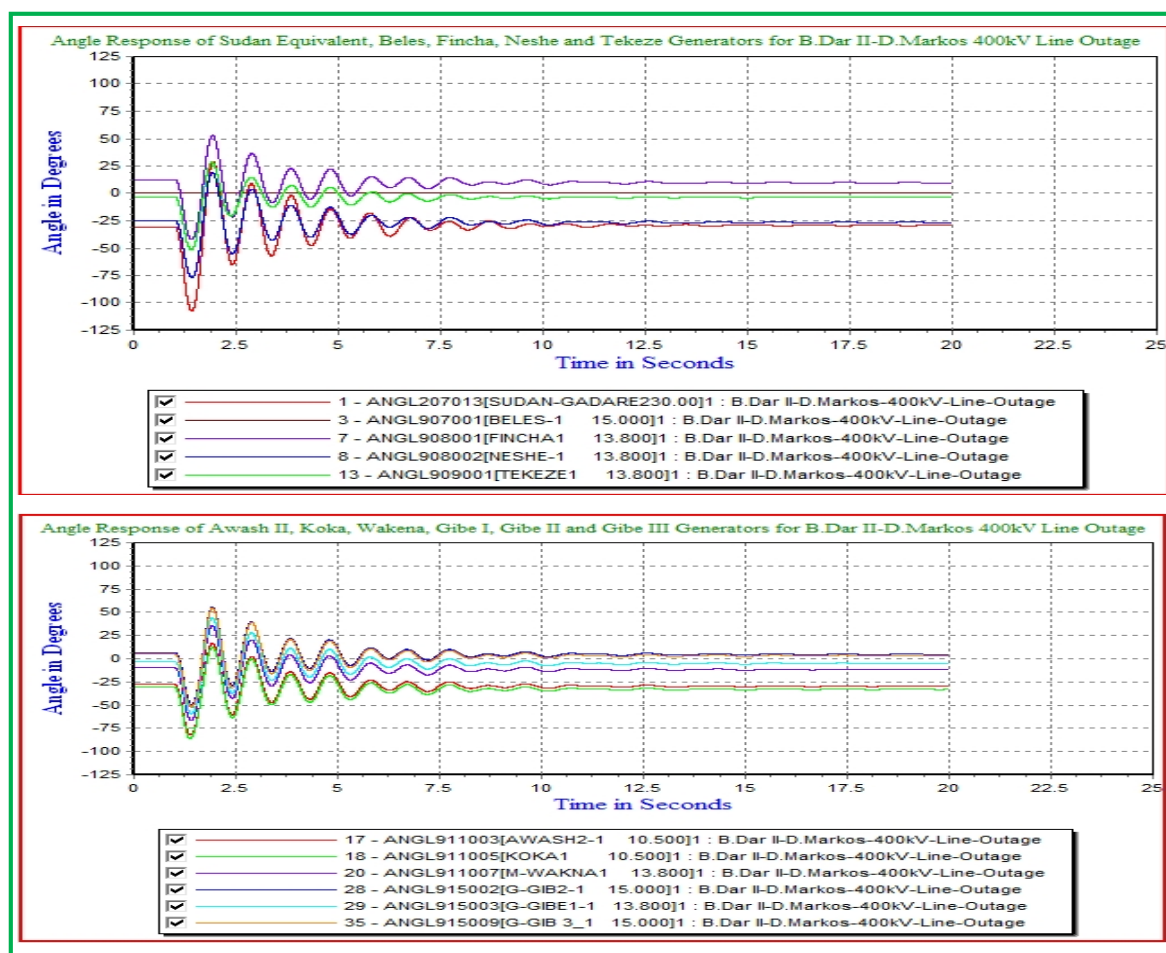


Figure 4. 2: Angle response of generators for B.Dar II-D.Markos 400 kV line outage

The machine angle excursion has relationship with the fault location. As it is possible to see from Figure 4.2 the angle of Fincha generators is larger than the others. This is due to Fincha power plant is electrically nearby the fault location which is at Bahir Dar II substation.

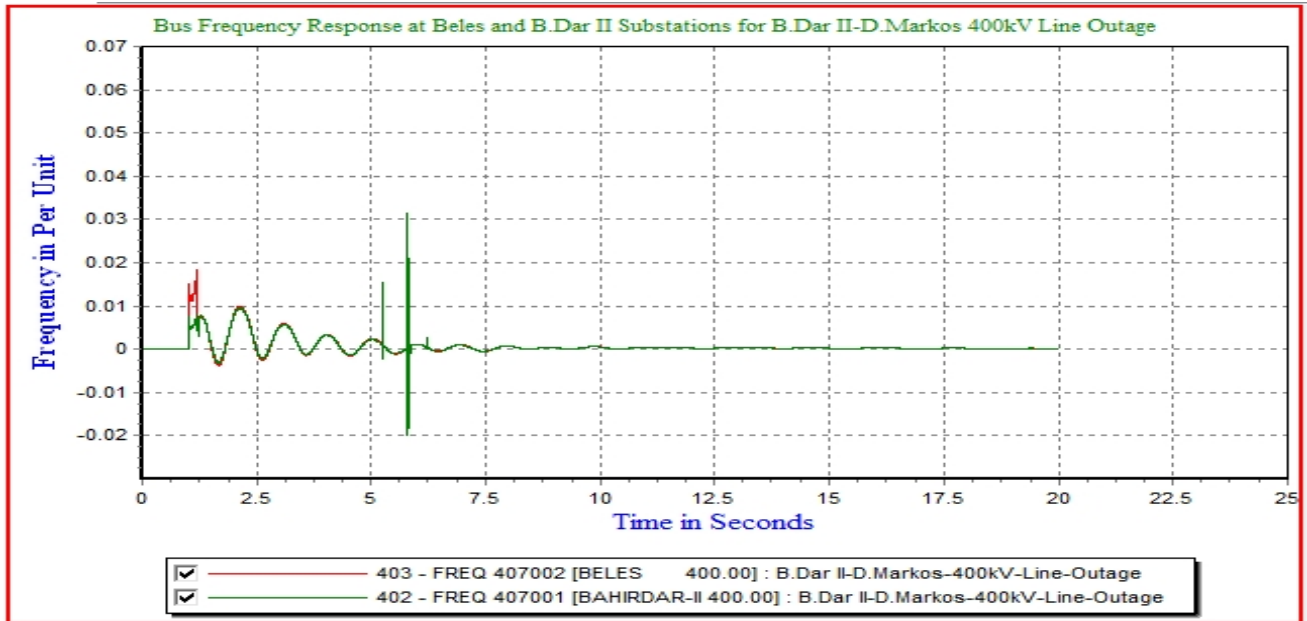


Figure 4. 3: Bus frequency response of substations for B.Dar II-D.Markos 400 kV line outage

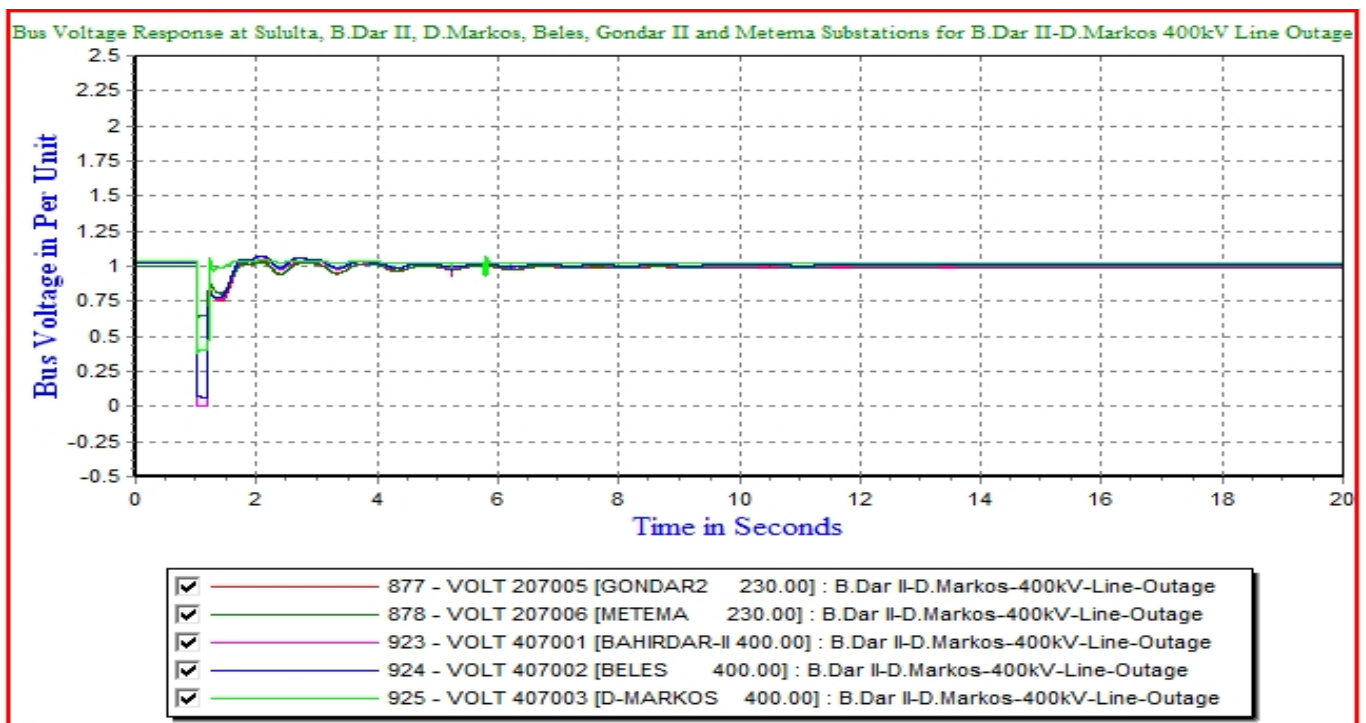


Figure 4. 4: Bus voltage response of substations for B.Dar II-D.Markos 400 kV line outage

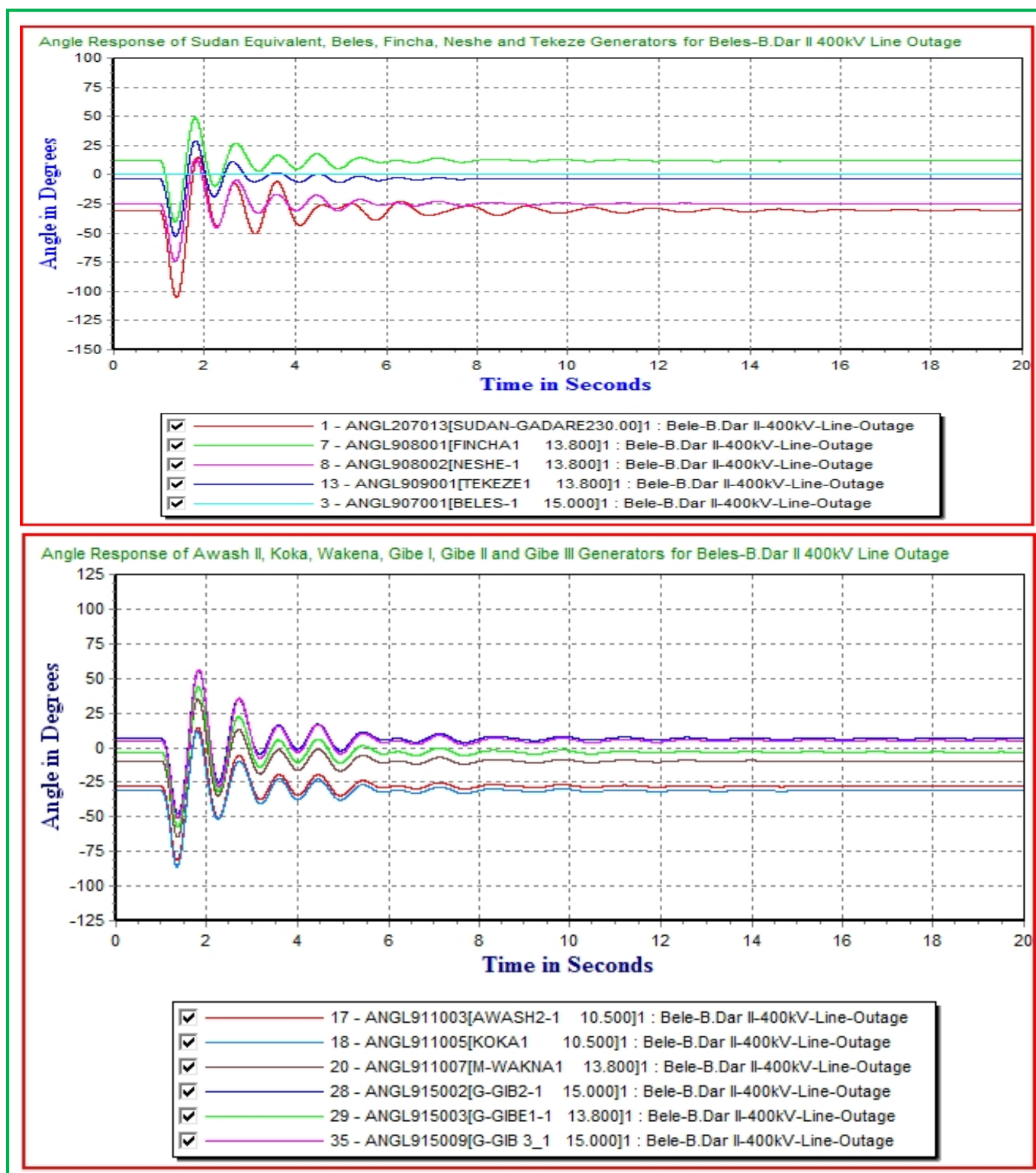


Figure 4. 5: Angle response of generators for Beles-B.Dar II 400 kV line outage

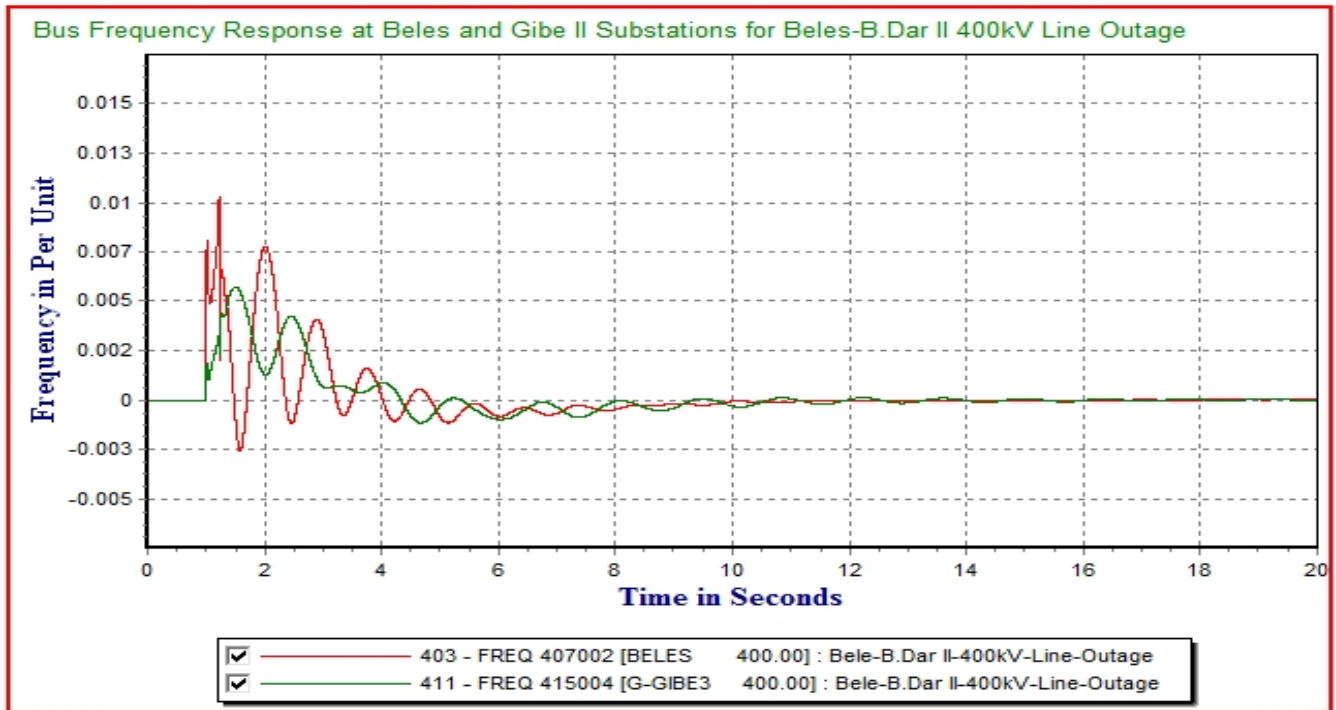


Figure 4. 6: Bus frequency response of substations for Beles-B.Dar II 400 kV line outage

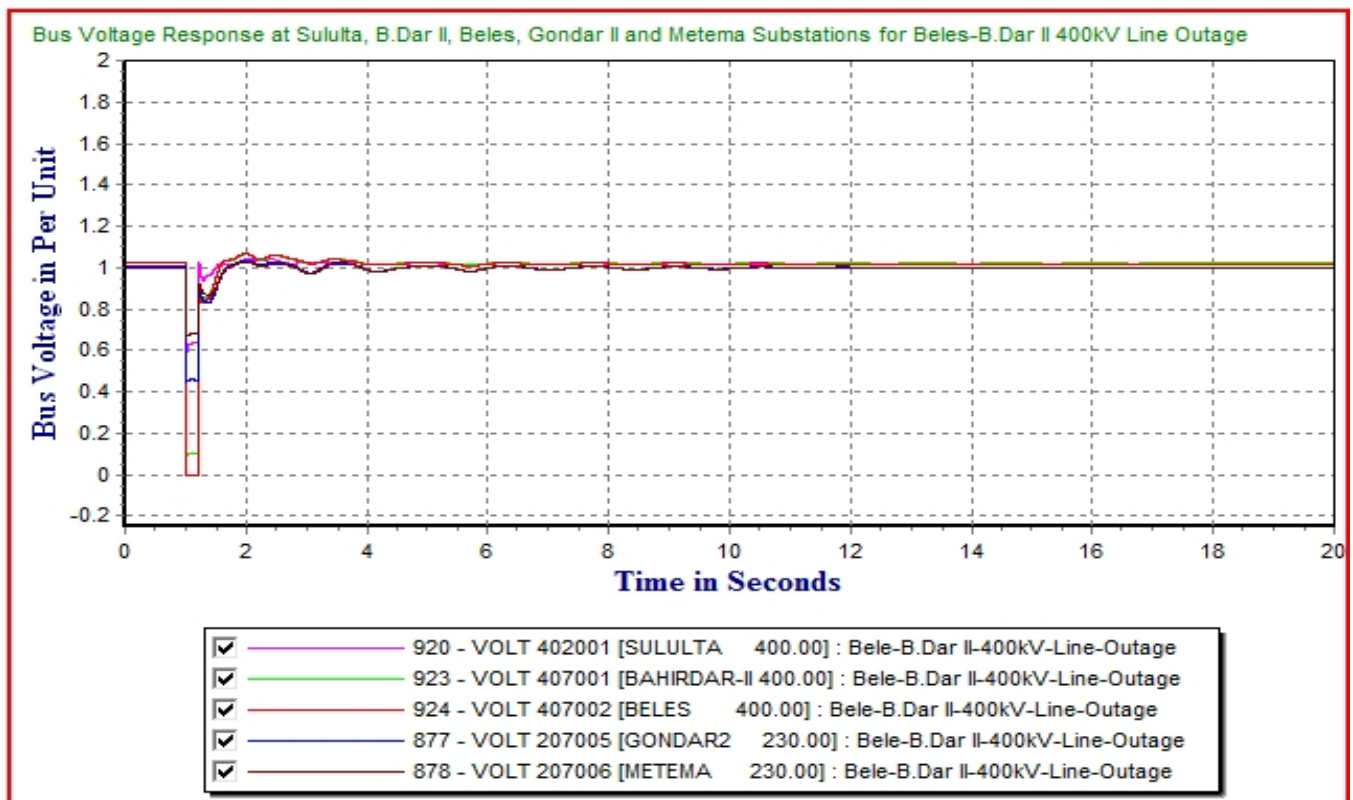


Figure 4. 7: Bus voltage response of substations for Beles-B.Dar II 400 kV line outage

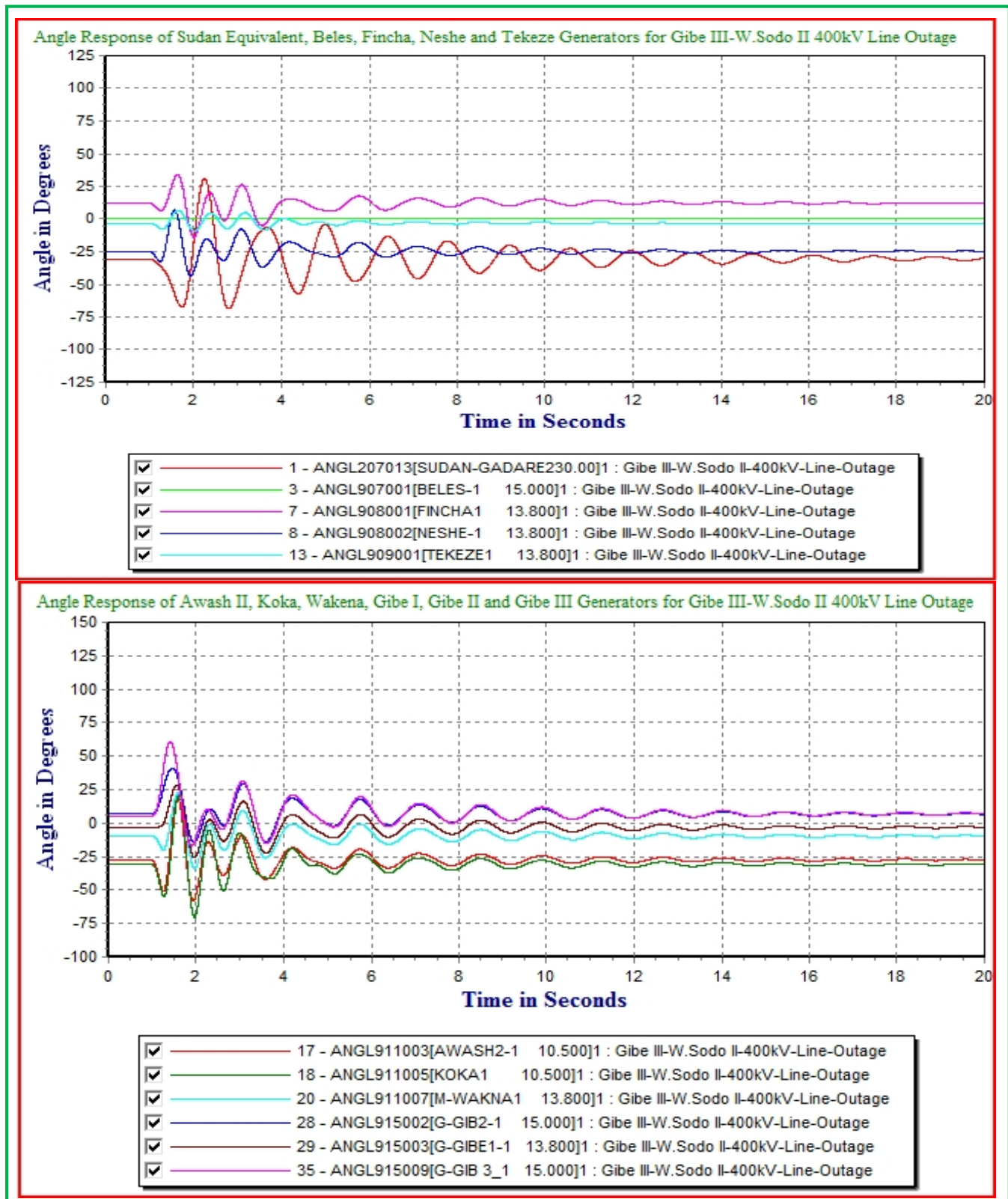


Figure 4. 8: Angle response of generators for Gibe III-W.Sodo II 400 kV line outage

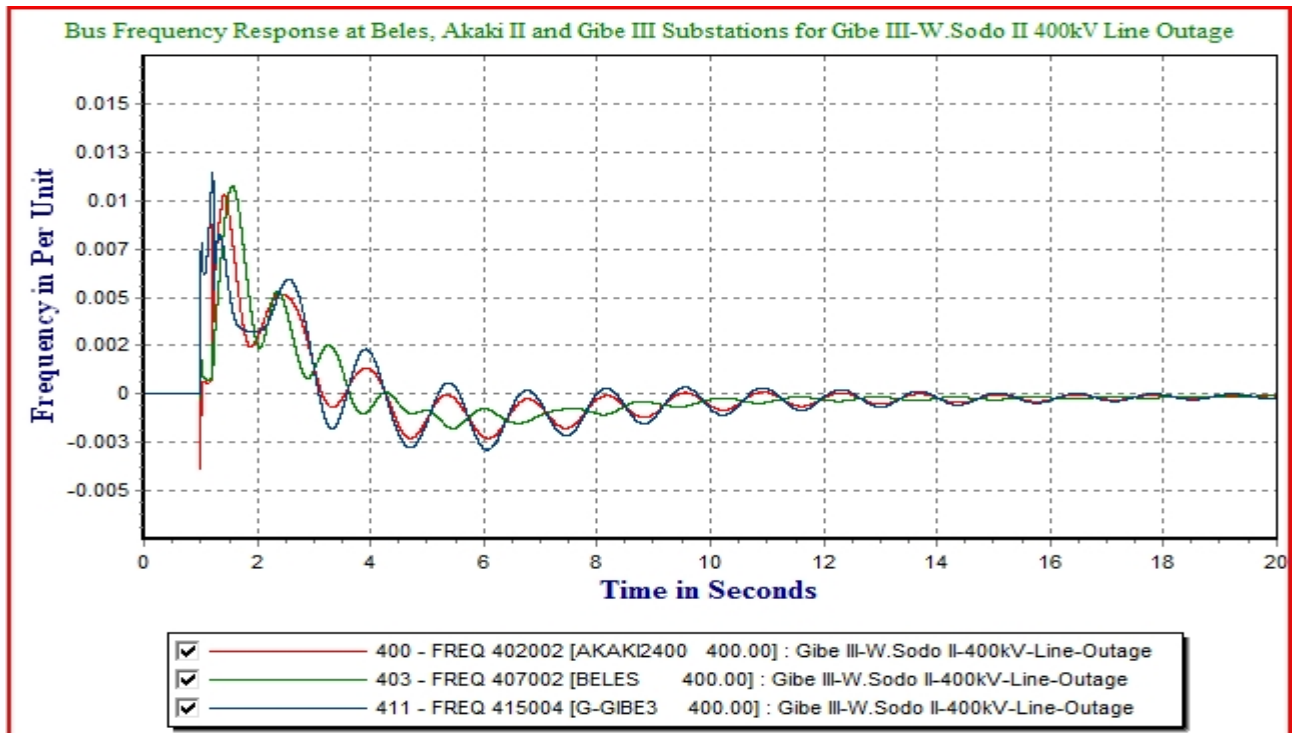


Figure 4. 9: Bus frequency response of substations for Gibe III-W.Sodo II 400 kV line outage

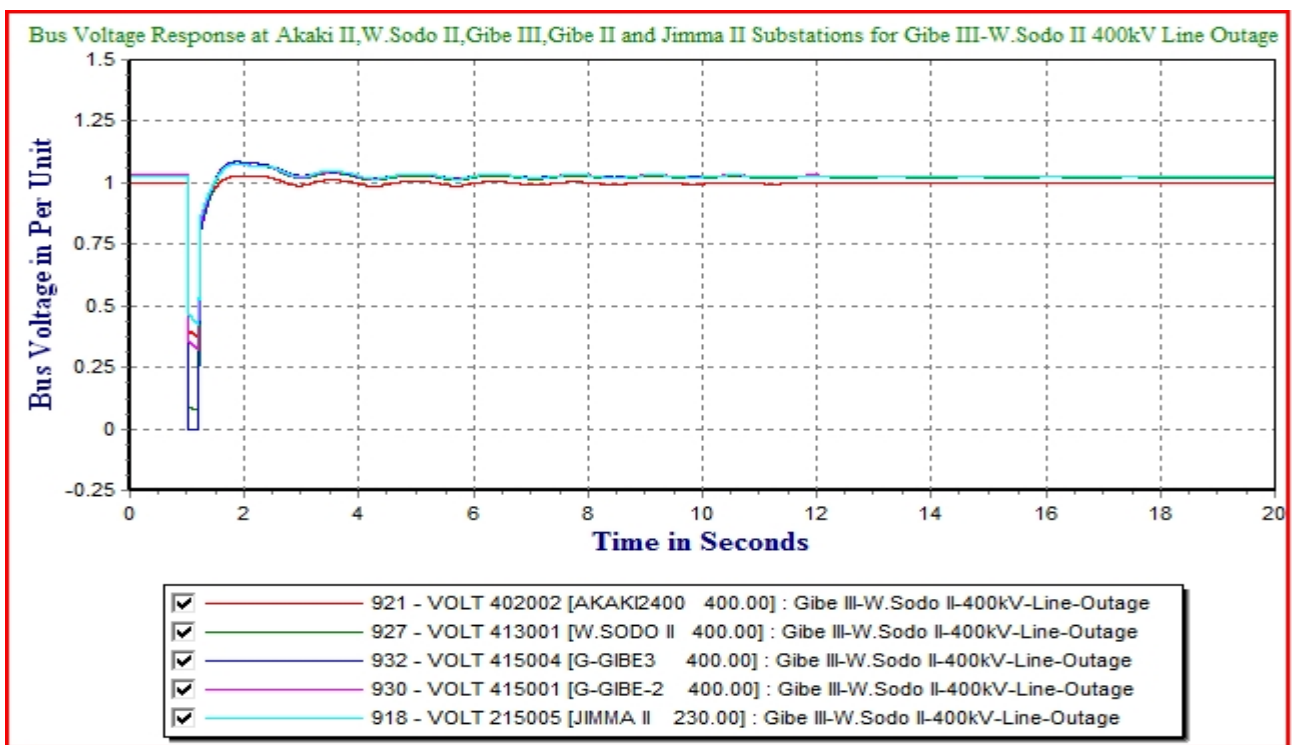


Figure 4. 10: Bus voltage response of substations for Gibe III-W.Sodo II 400 kV line outage

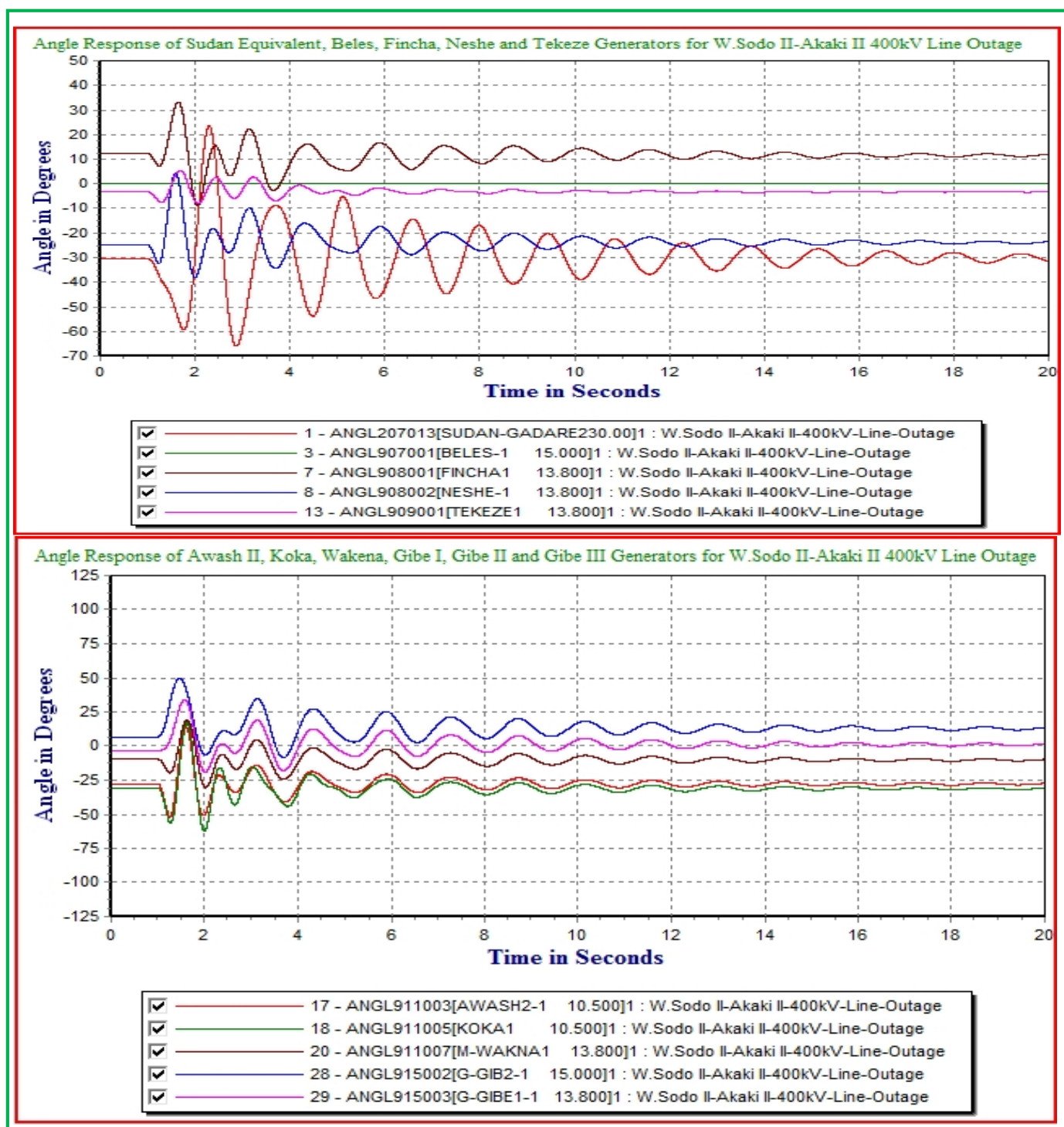


Figure 4. 11: Angle response of generators for W.Sodo II-Akaki II 400 kV line outage

As it is possible to see from Figure 4.11, the angle of machines continues oscillating for long time which indicates that the outage of the W.Sodo II-Akaki II 400kV line would cause the system to be under damped.

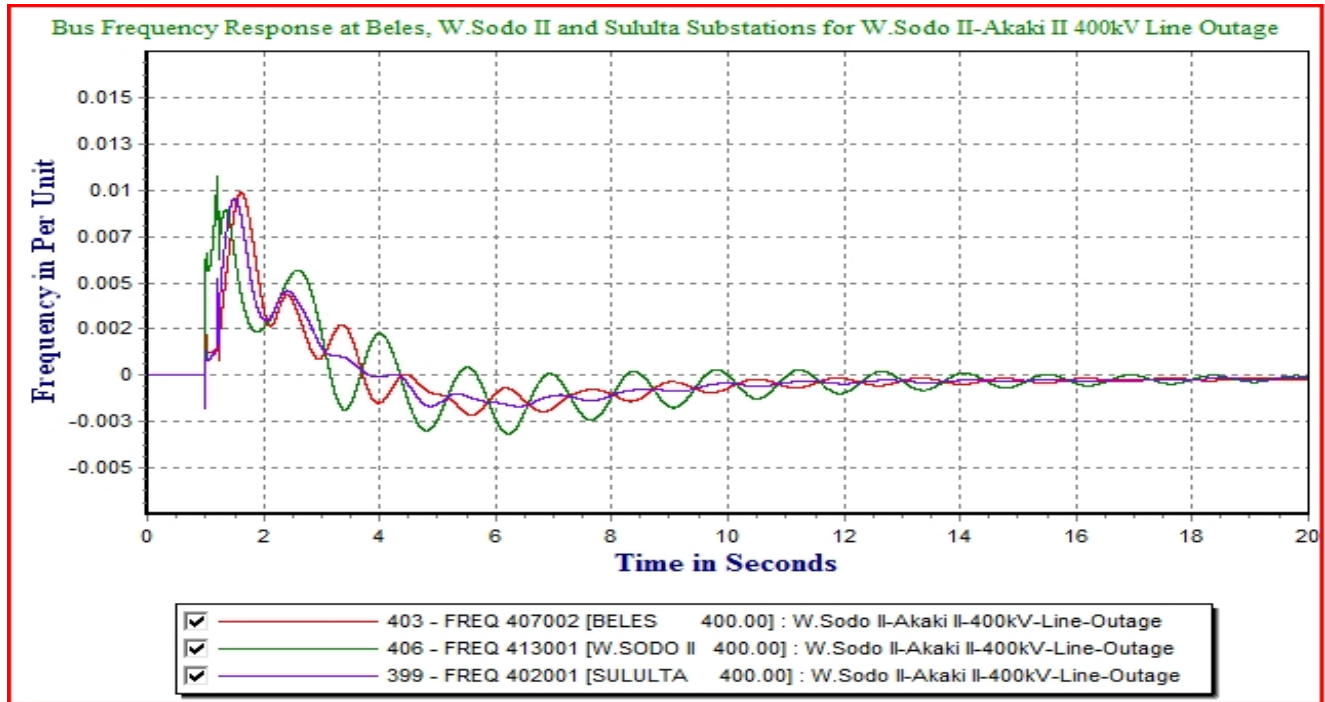


Figure 4. 12: Bus frequency response of substations for W.SodoII-AkakiII 400 kV line outage

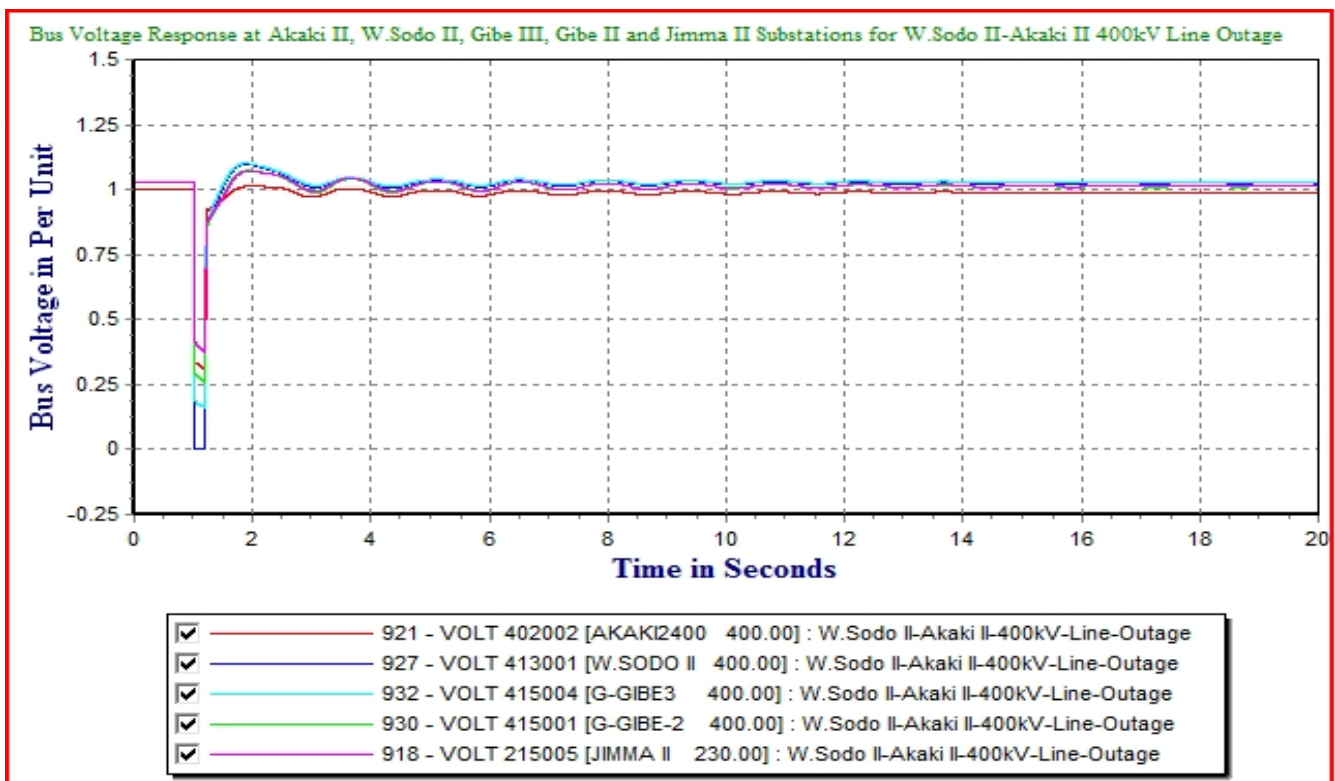


Figure 4. 13: Bus voltage response of substations for W.Sodo II-Akaki II 400 kV line outage

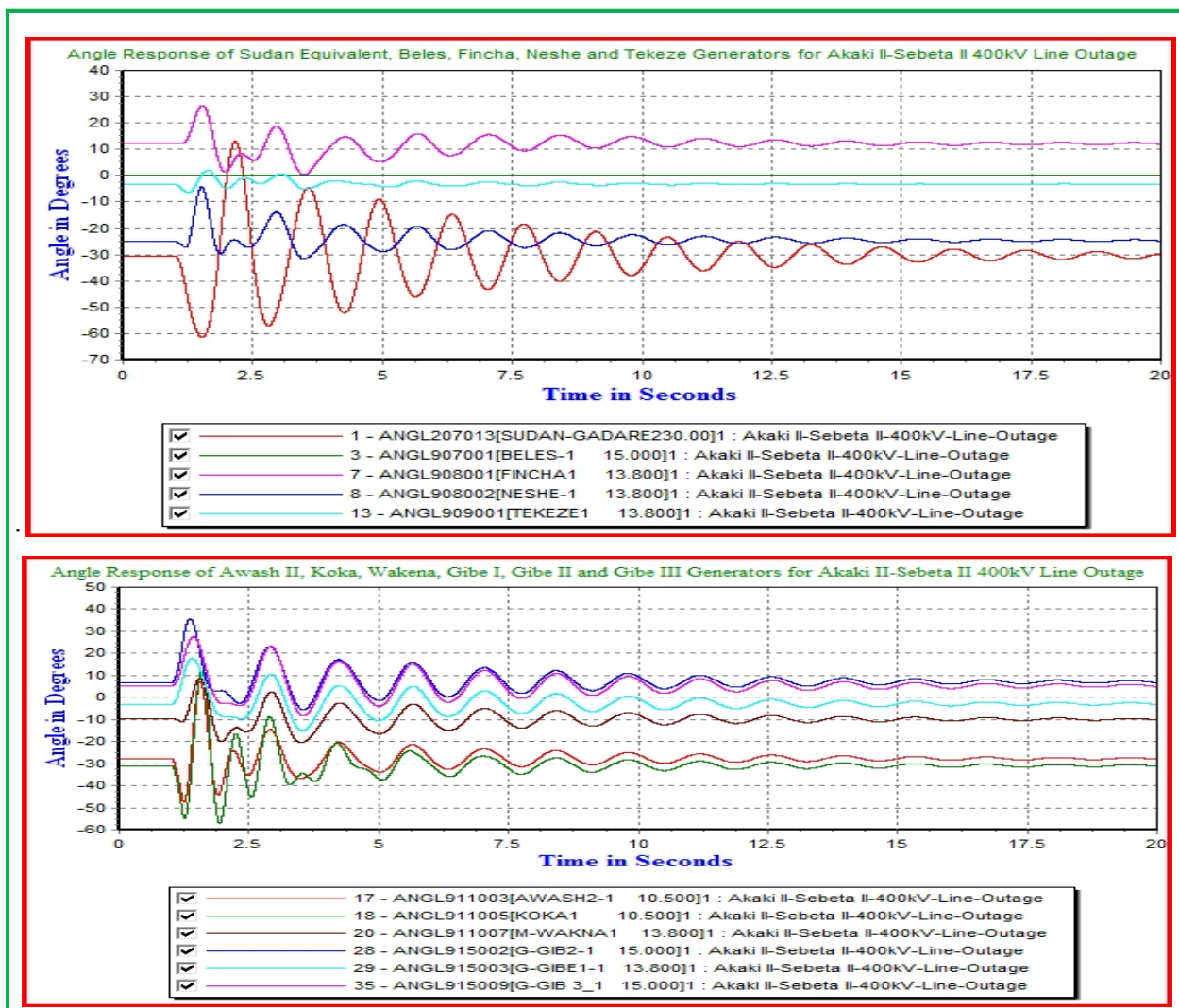


Figure 4. 14: Angle response of generators for Akaki II-Sebeta II 400 kV line outage

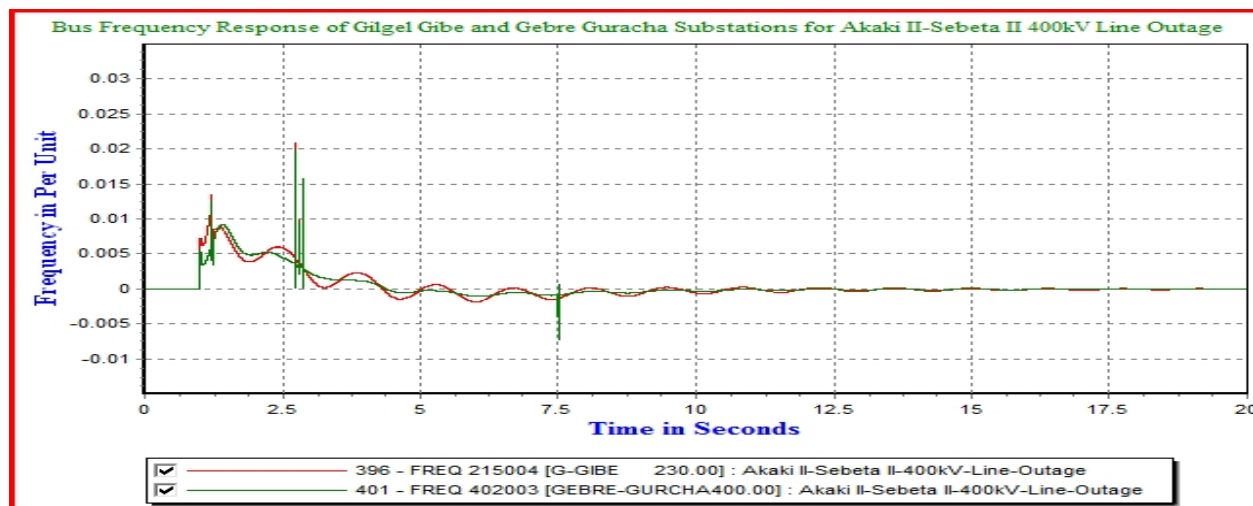


Figure 4. 15: Bus frequency response of substations for Akaki II-Sebeta II 400 kV line outage

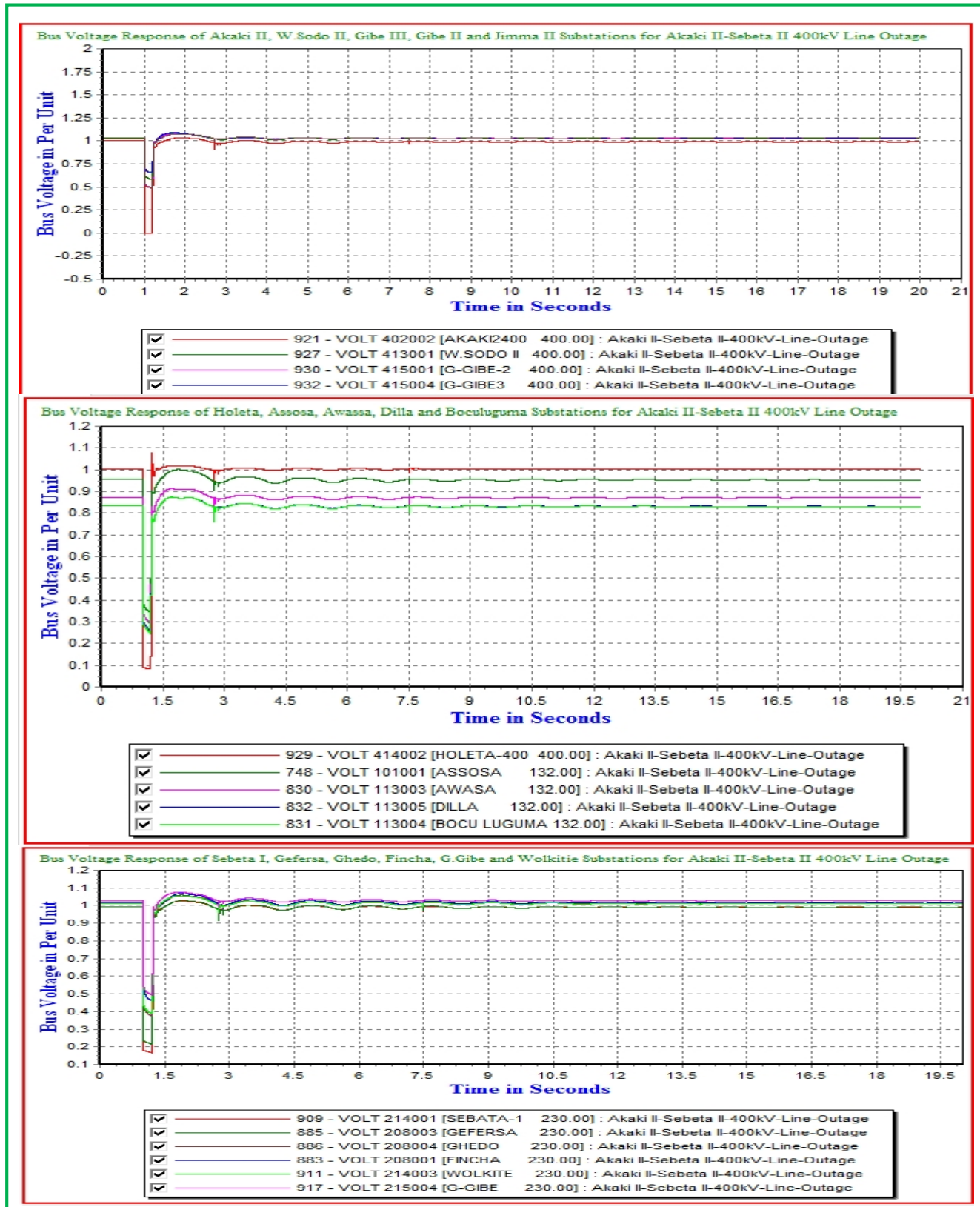


Figure 4. 16: Bus voltage response of substations for Akaki II-Sebeta II 400 kV line outage

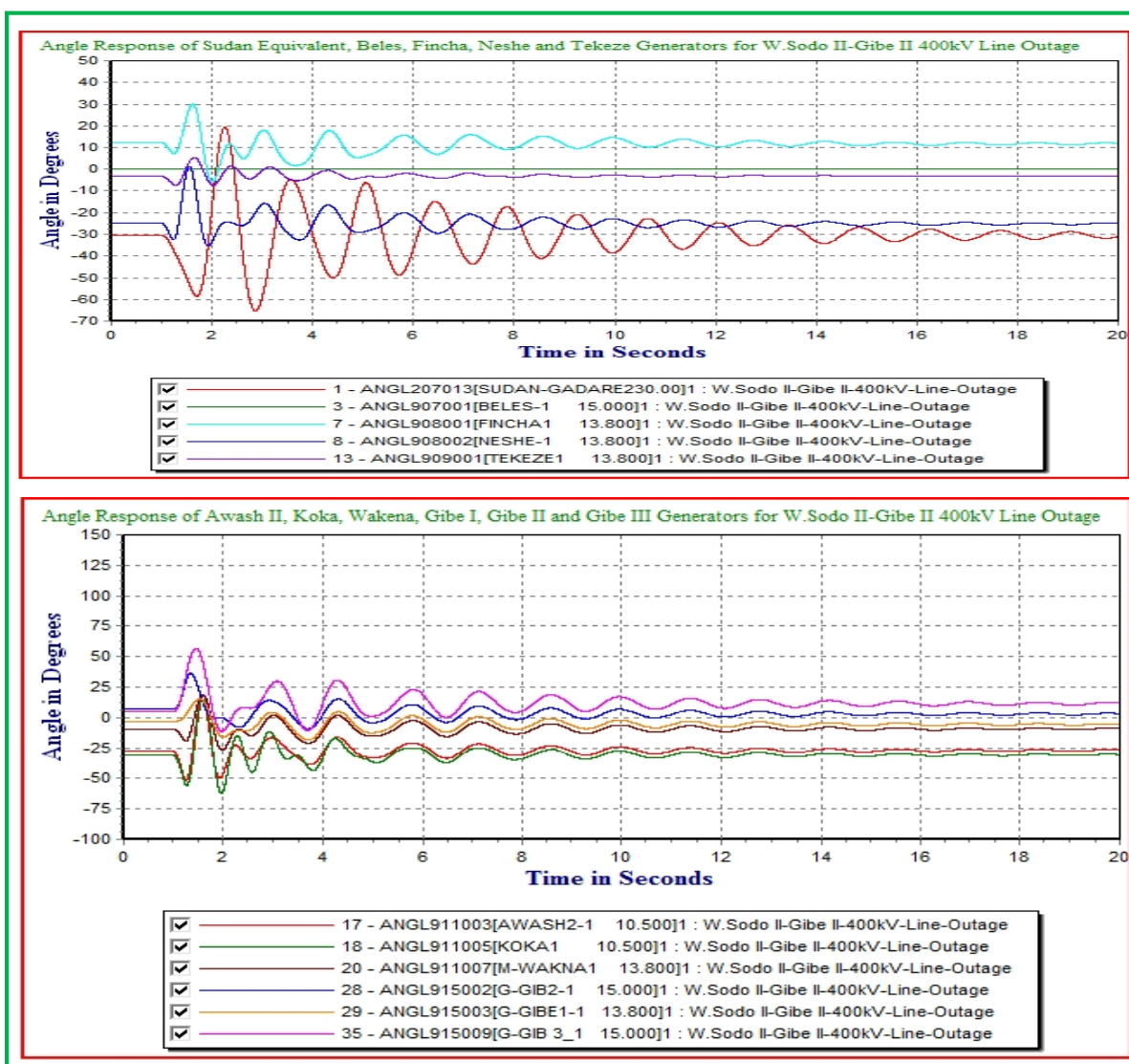


Figure 4. 17: Angle response of generators for W.Sodo II-Gibe II 400 kV line outage

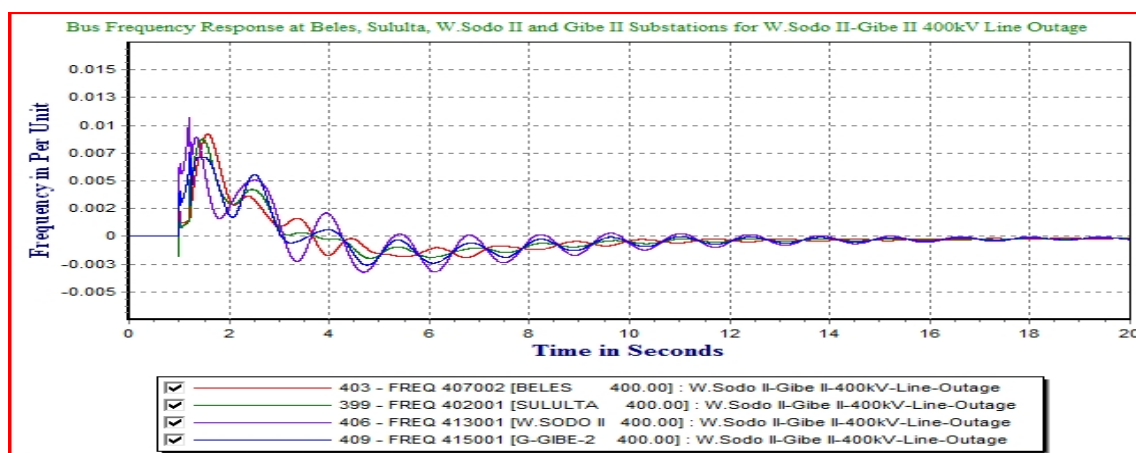


Figure 4. 18: Bus frequency response of substations for W.Sodo-Gibe II 400 kV line outage

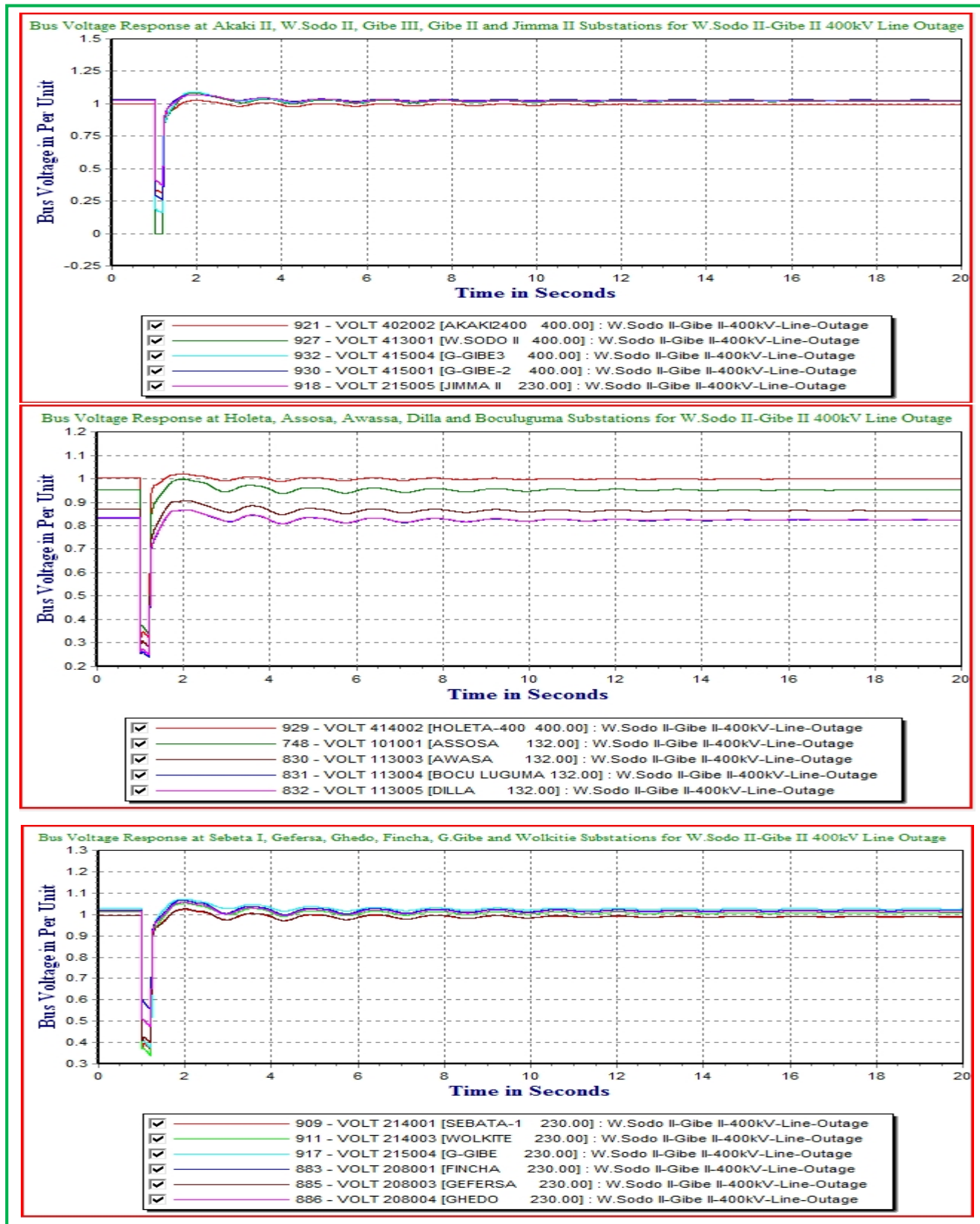


Figure 4. 19: Bus voltage response of substations for W.Sodo II-Gibe II 400 kV line outage

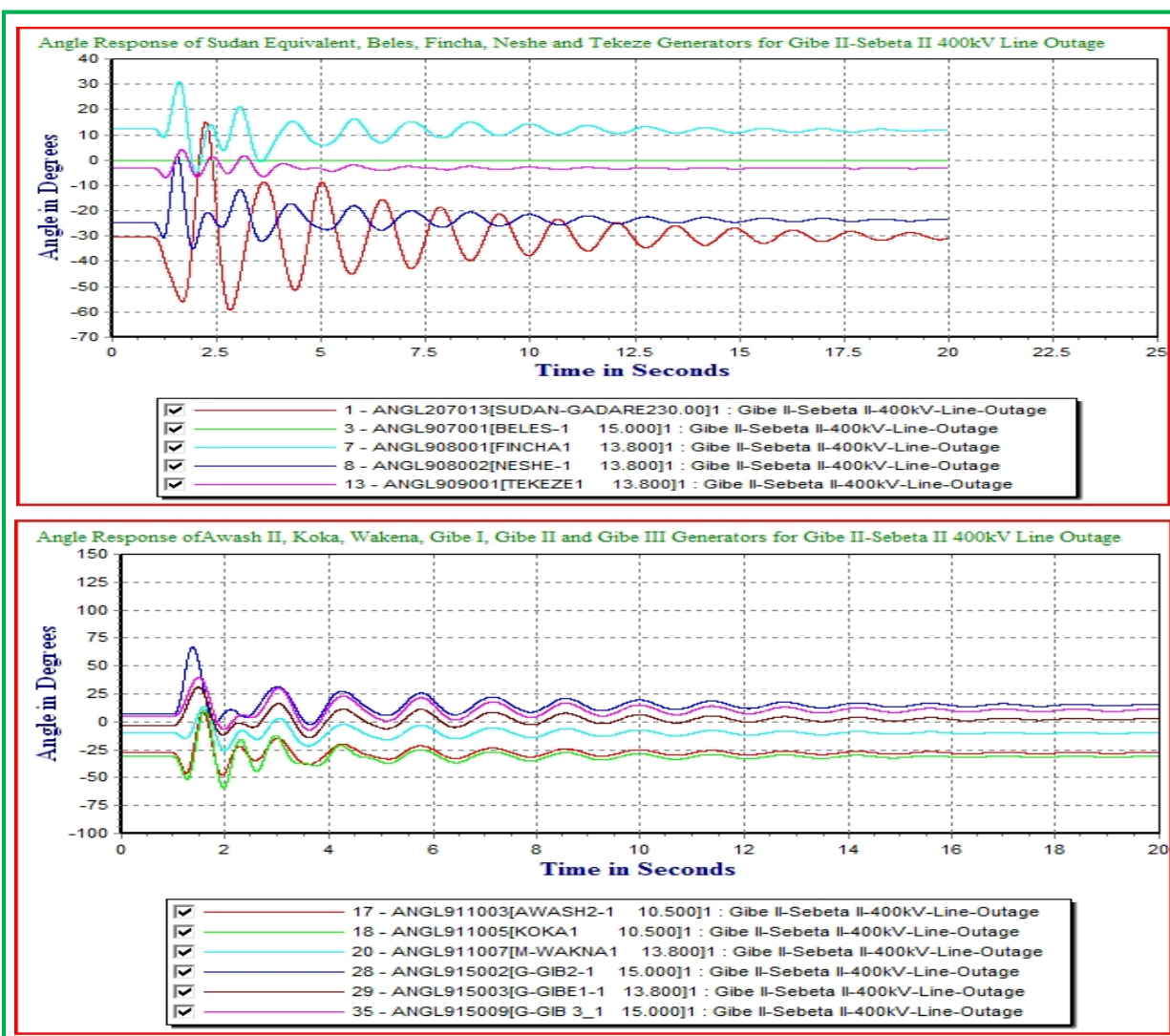


Figure 4. 20: Angle response of generators for Gibe II-Sebeta II 400 kV line outage

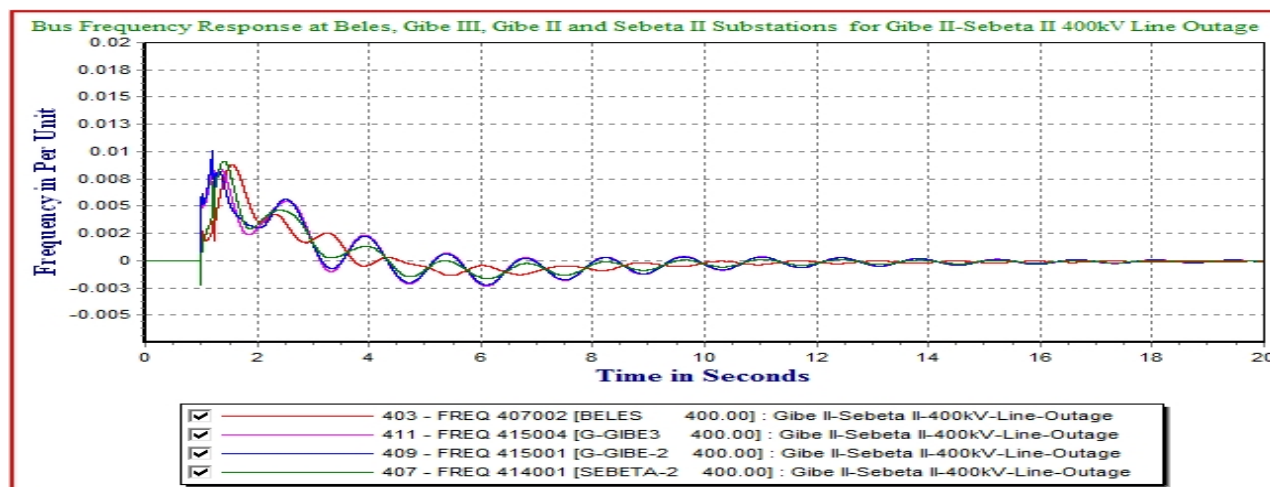


Figure 4. 21: Bus frequency response of substations for Gibe II-Sebeta II 400 kV line outage

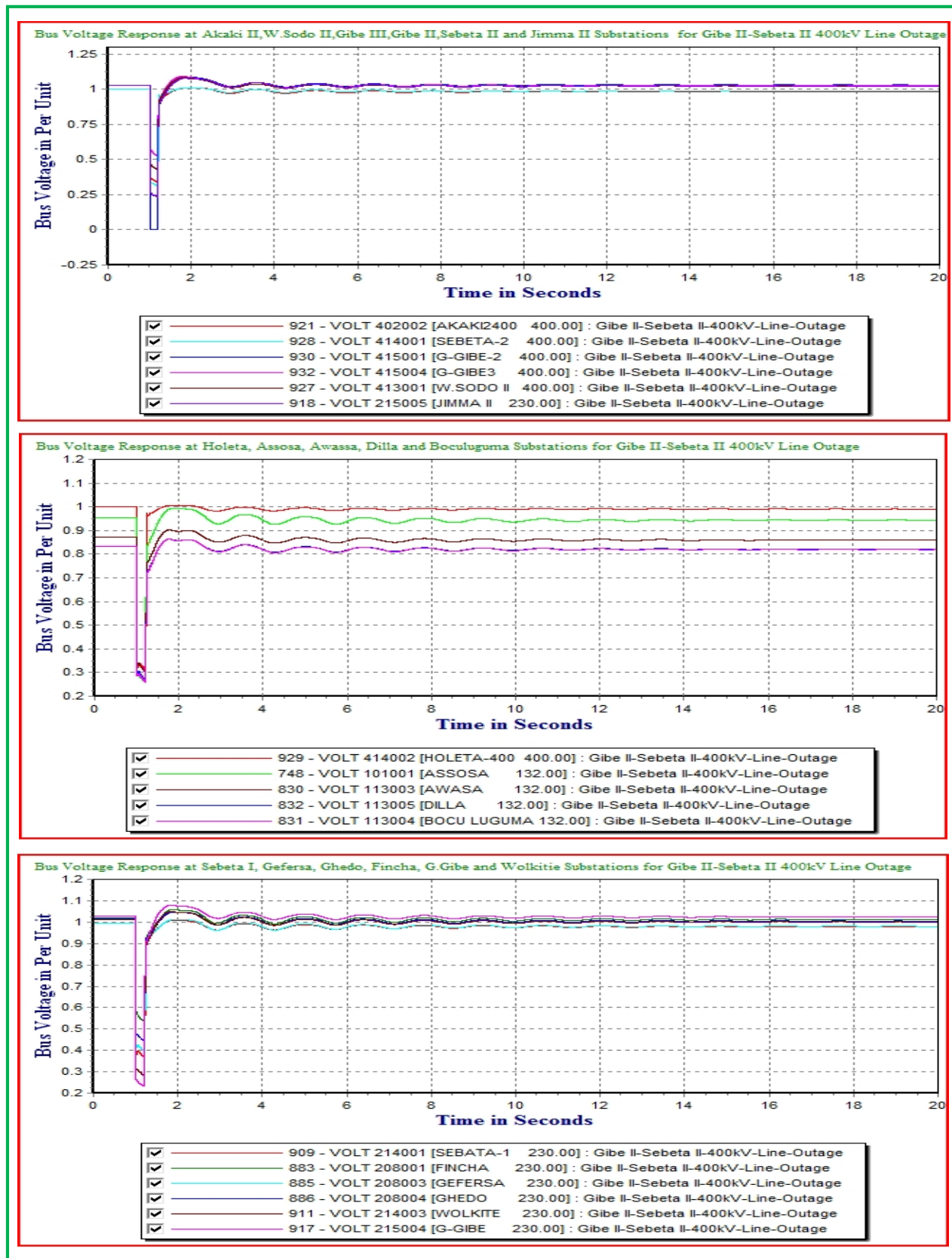


Figure 4. 22: Bus voltage response of substations for Gibe II-Sebeta II 400 kV line outage

The simulation results of the 400 kV line outages are summarized in Table 4.1 below.

Name of the Line	End at which the fault is Applied	Voltage Level (kV)	Line Loading (MW)	Line Loading (%)	Power Flow Direction	Considered Fault Clearing Times (ms)		Angle Response	Frequency Response	Bus Voltage Response
						Fault End CB Opened at	Far End CB Opened at			
Akaki II-Sebeta II	Akaki II	400	86.79	5	To Akaki II	200	220	All machines stay in synchronism for all cases	The system frequency is within the security criteria for all cases.	The voltage at Awassa, Dilla and Boculuguma substations doesn't recover to 0.9 pu within 10 seconds. In general the voltage profile is not good in most parts of the southern region of system.
Bahir Dar II-D.Markos	Bahir Dar II	400	34.23	7	To Debre Markos	200	220			
Beles-Bahir Dar II	Beles	400	149.96	12	To Bahir Dar II	200	220			
D.Markos-Sululta	D.Markos	400	12.1	8	To Sululta	200	220			
Gibe II-Gibe Old	Gibe II	400	223.19	17	To Gibe Old	200	220			
Gibe III-W.Sodo II	Gibe III	400	435	22	To W.Sodo II	200	220			
Gibe II-Sebeta II	Gibe II	400	390.79	29	To Sebeta II	200	220			
W.Sodo II-Akaki II	W.Sodo II	400	481.59	25	To Akaki II	200	220			
W.Sodo II-Gibe II	W.Sodo II	400	276.69	15	To Gibe II	200	220			

Table 4. 1: Summary of simulation results of the 400 kV line outages

4.3. Dynamic Simulations for Faults on 230 kV Lines

The zone 1 and zone 2 protections are considered to participate in clearing the faults for the occurrence of faults on the 230 kV lines. Tele-protection is not considered for 230 kV lines as it is not functional for such lines most of the time due to bad communication system. The most severe type of faults, a three phase to ground metallic fault with zero fault impedance, is applied at one end of the line for 200 ms and then after 200 ms the fault end CB is assumed to be opened by the action of zone 1 protection system. The fault is completely cleared following the opening of the far end CB by the action of zone 2 protection system as per the actual protection setting data. The sequence of events for clearing such type of faults is shown in Figure 4.23 below.

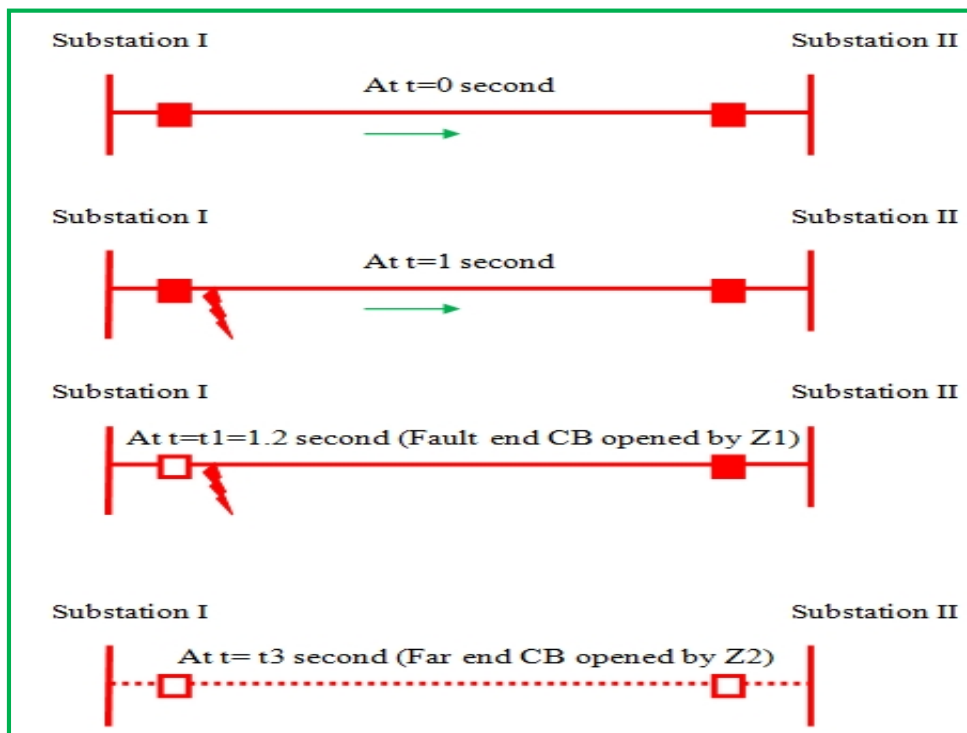


Figure 4. 23: Sequence of events for clearing faults on 230 kV lines

The dynamic simulations have been performed for three phase to ground metallic faults on the 230 kV lines which are identified in chapter one considering the sequence of events indicated in Figure 4.23 above. The plots below show the simulation results for machine relative angle, bus frequency deviations and bus voltage responses at selected substations for faults considered on selected 230 kV lines. In the simulation process Beles generators are set as a reference machines for angle measurement; and its value is initialized at 26.54 degrees.

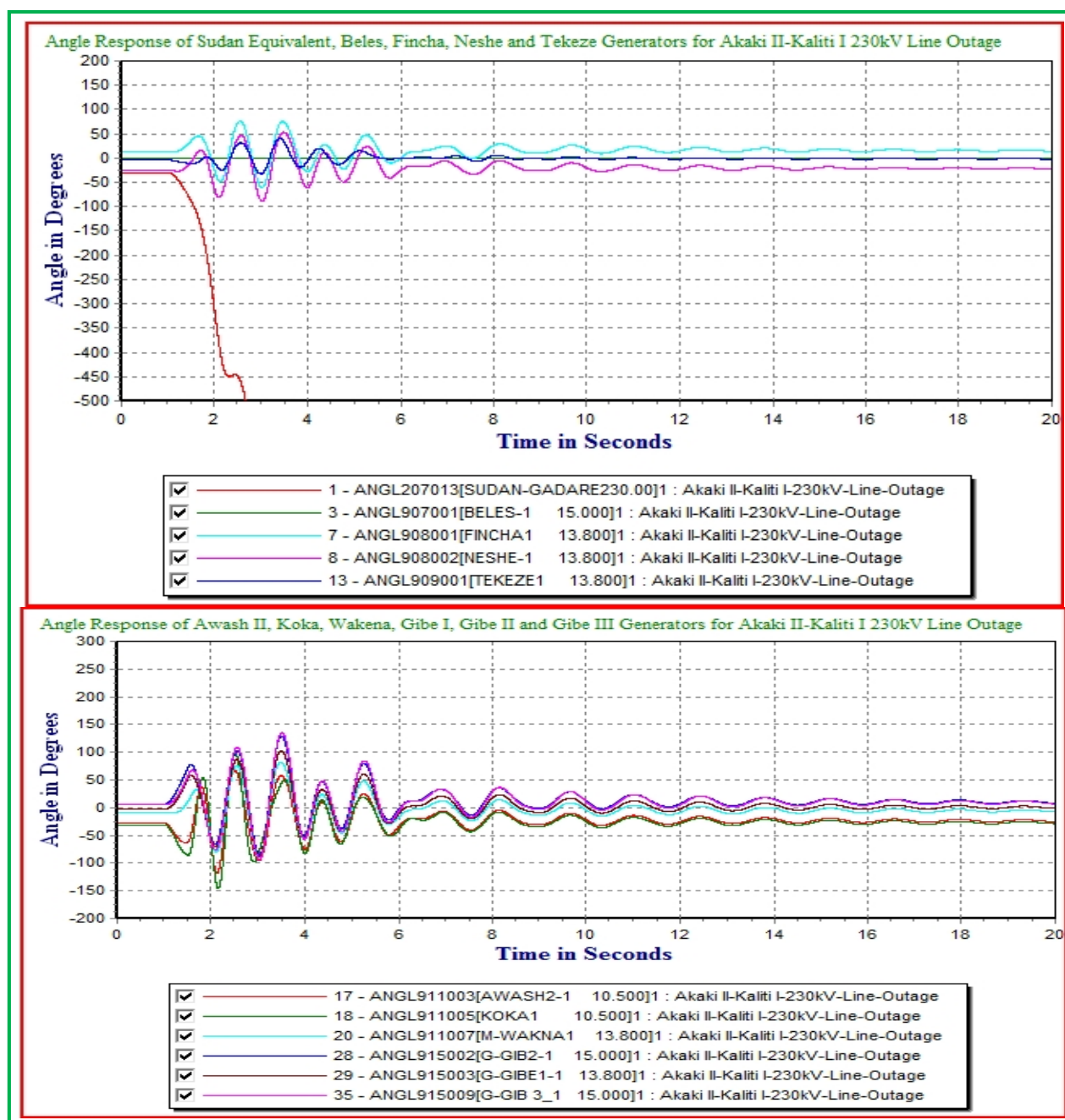


Figure 4. 24: Angle response of generators for Akaki II-Kaliti I 230 kV line outage

It can be seen from the plot of Figure 4.24 above that the system is unstable for the operation scenario considered for a short circuit fault on Akaki II-Kaliti I 230 kV line even if the fault is cleared as per the actual protection setting. This confirms that the Sudanese system will be out of synchronism from the Ethiopian system; and therefore the operating point of the system is insecure.

It is possible to restore the operating point of the system to a secure operating point by changing the generation dispatch and by reducing the total tie-line flow from 188MW to at least 148MW which is still above the scheduled value, 100MW, of April 11, 2017 at 19:45 o'clock. This could be accomplished by increasing the total generation of Sudanese system. As it is clearly indicated in Figure 4.25 below, the system operating point is insecure for the Ethiopia-Sudan total tie-line flow of 149 MW; but it is secure for total tie-line flow of 148MW.

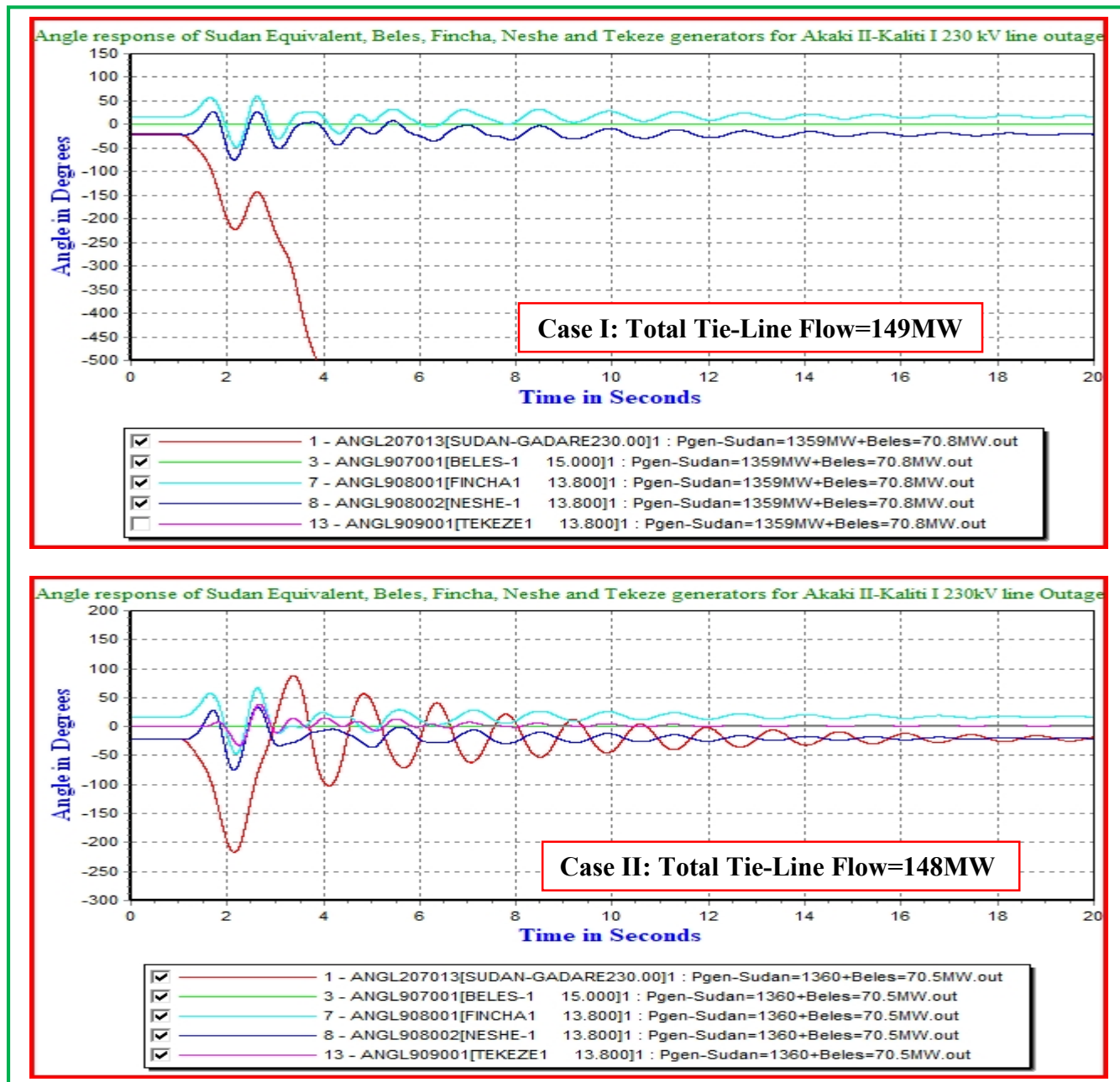


Figure 4. 25: Tie-Line flow limit for the operation scenario considered

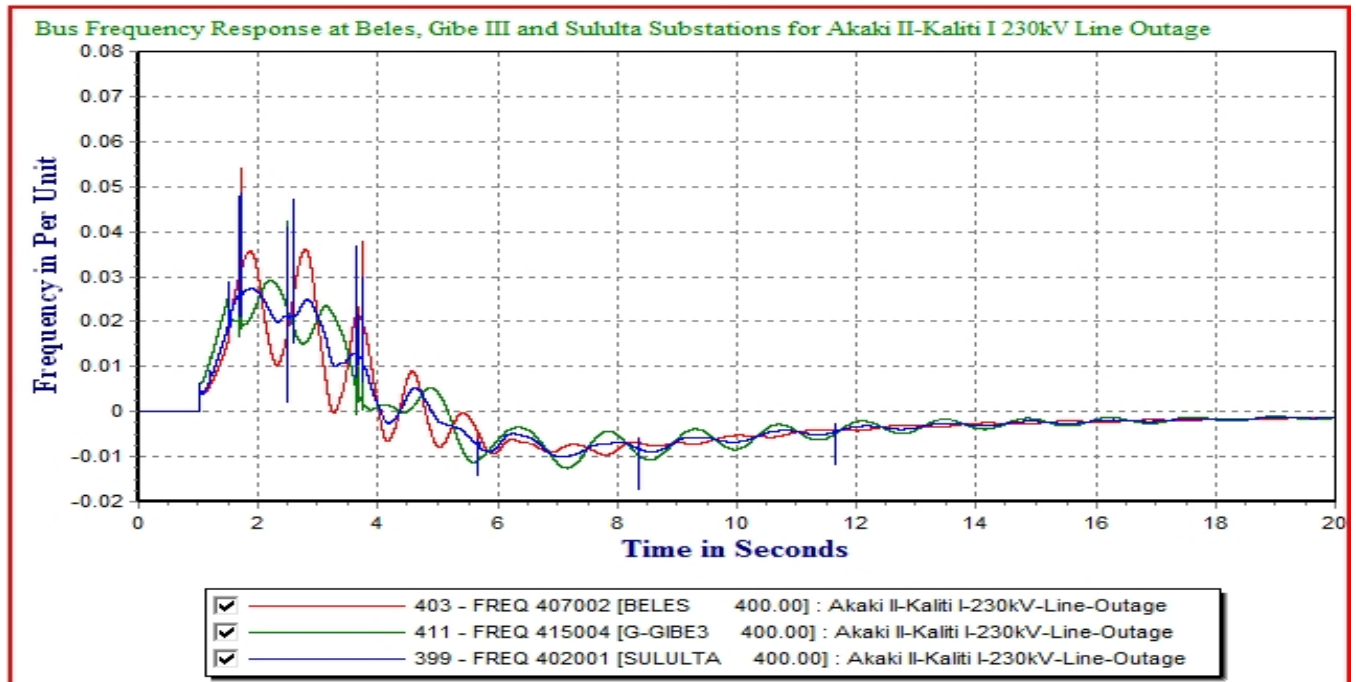


Figure 4. 26: Bus frequency response of substations for Akaki II-Kaliti I 230 kV line outage

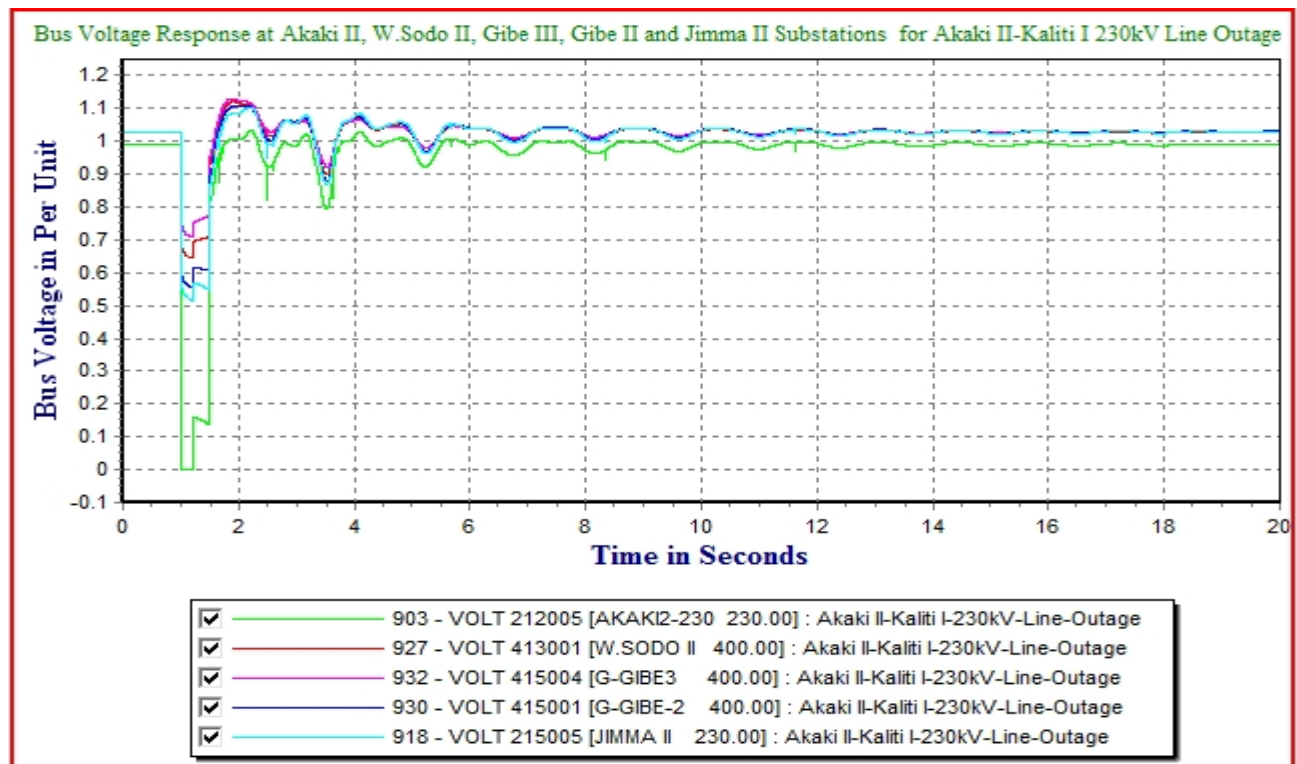


Figure 4. 27: Bus voltage response of substations for Akaki II-Kaliti I 230 kV line outage

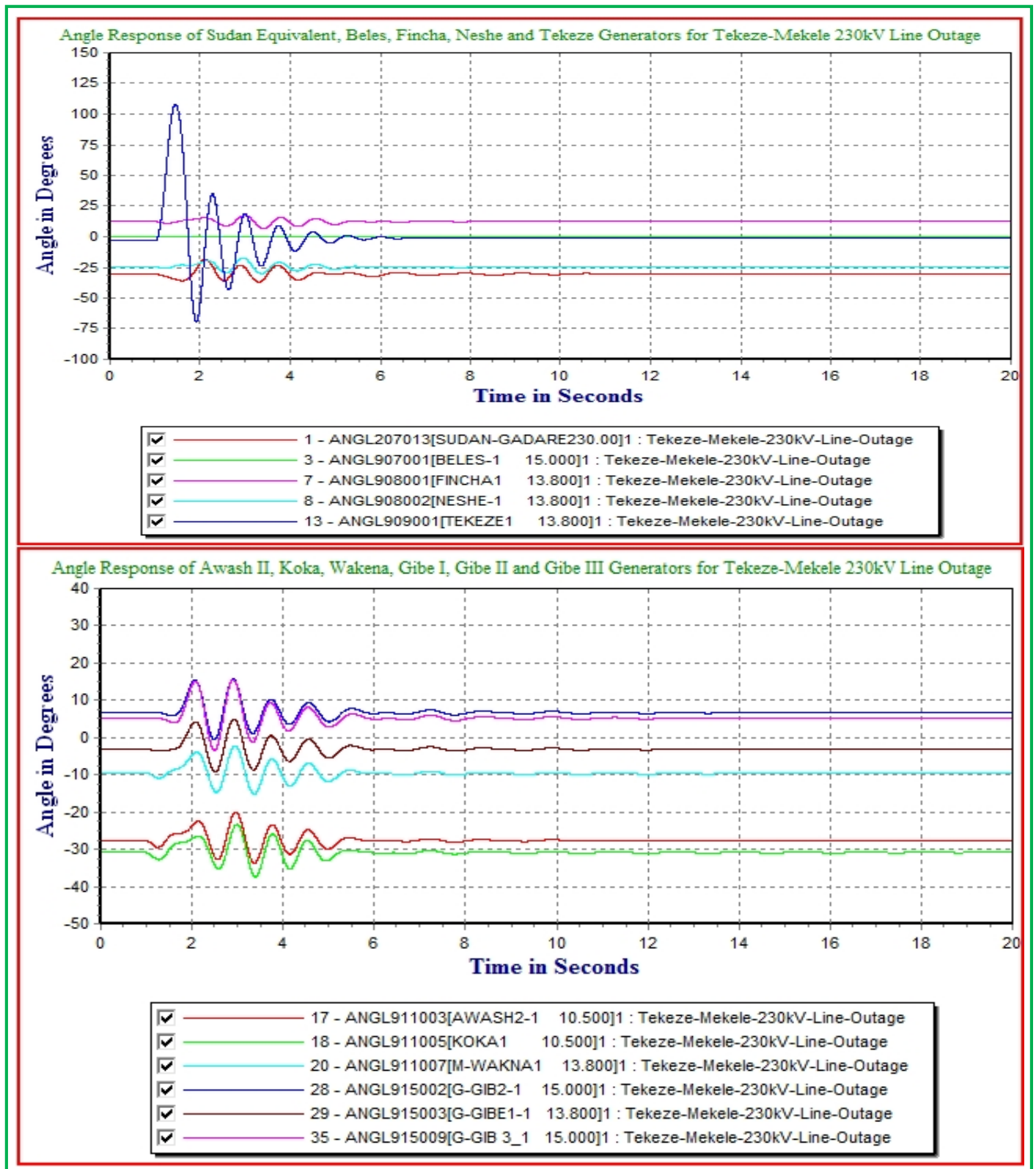


Figure 4. 28: Angle response of generators for Tekeze-Mekele 230 kV line outage

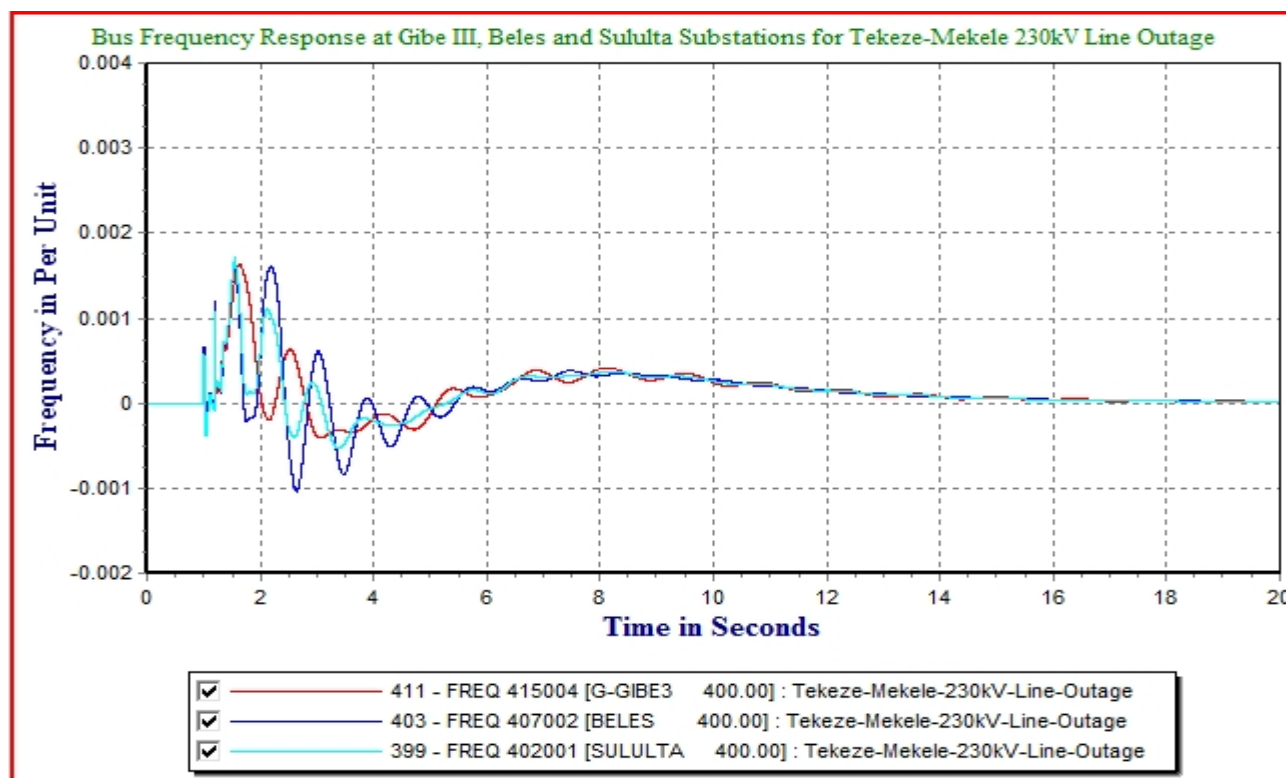


Figure 4. 29: Bus frequency response of substations for Tekeze-Mekele 230 kV line outage

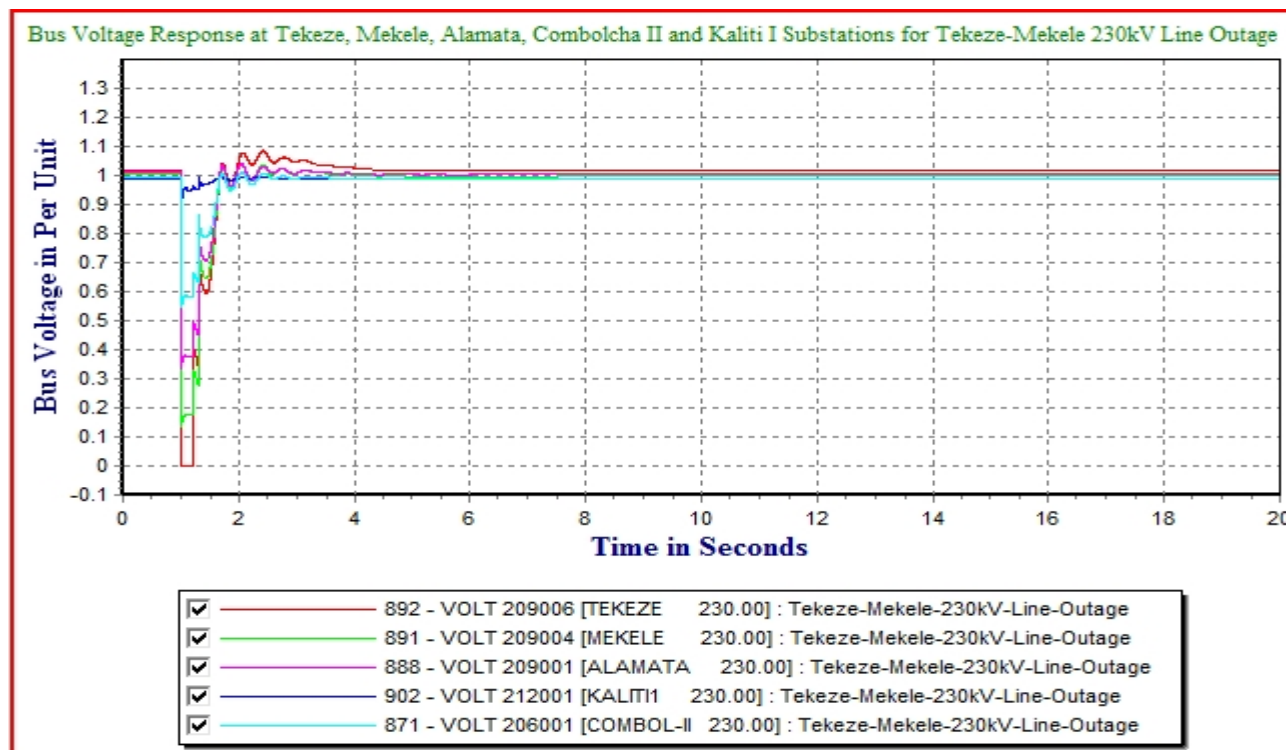


Figure 4. 30: Bus voltage response of substations for Tekeze-Mekele 230 kV line outage

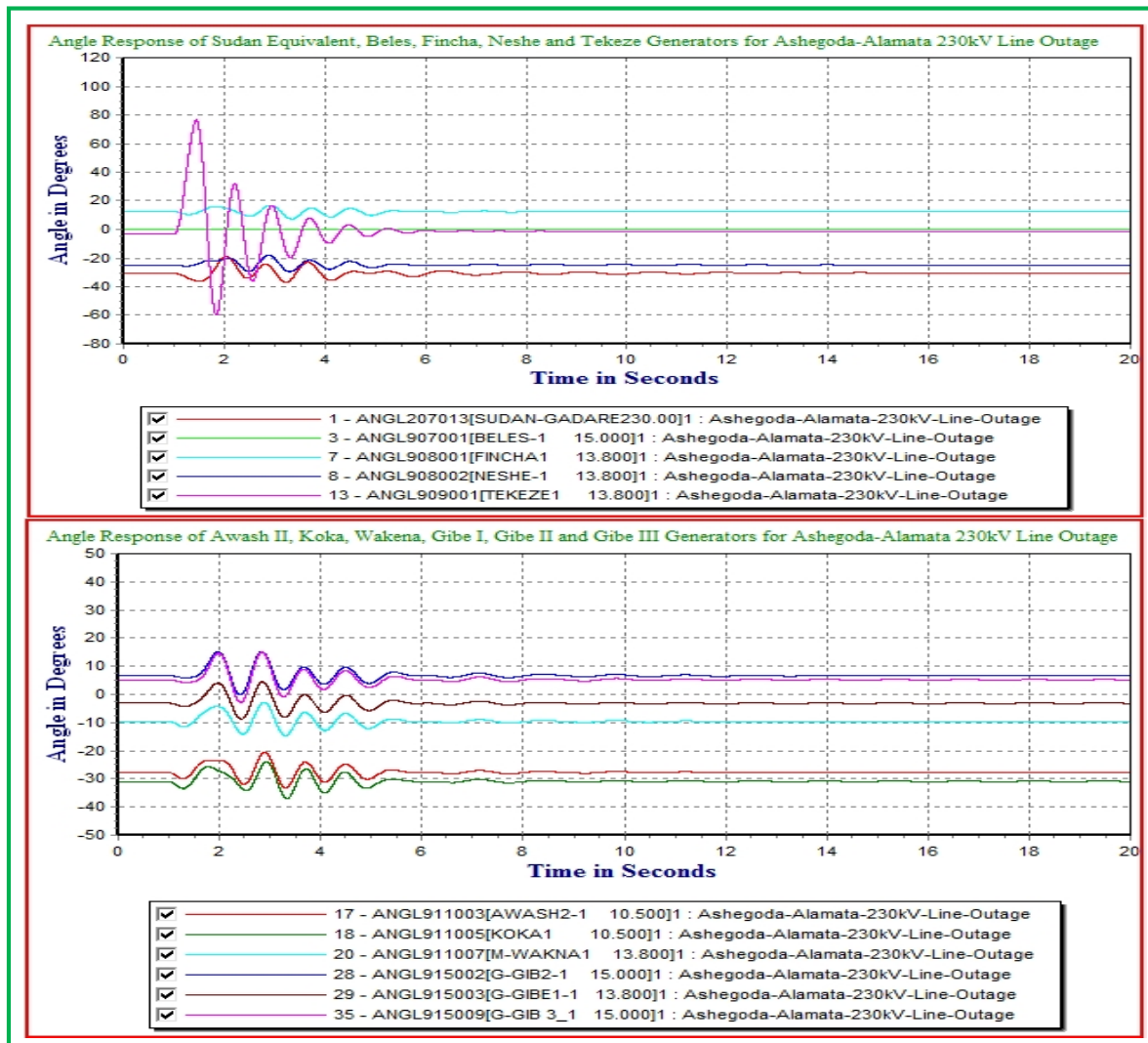


Figure 4. 31: Angle response of generators for Ashegoda-Alamata 230 kV line outage

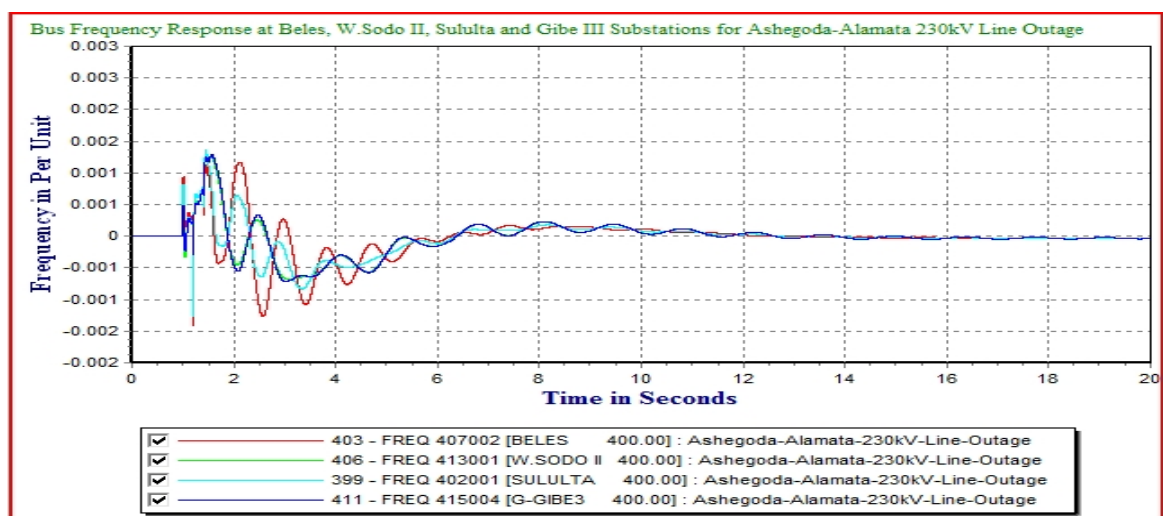


Figure 4. 32: Bus frequency of substations for Ashegoda-Alamata 230 kV line outage

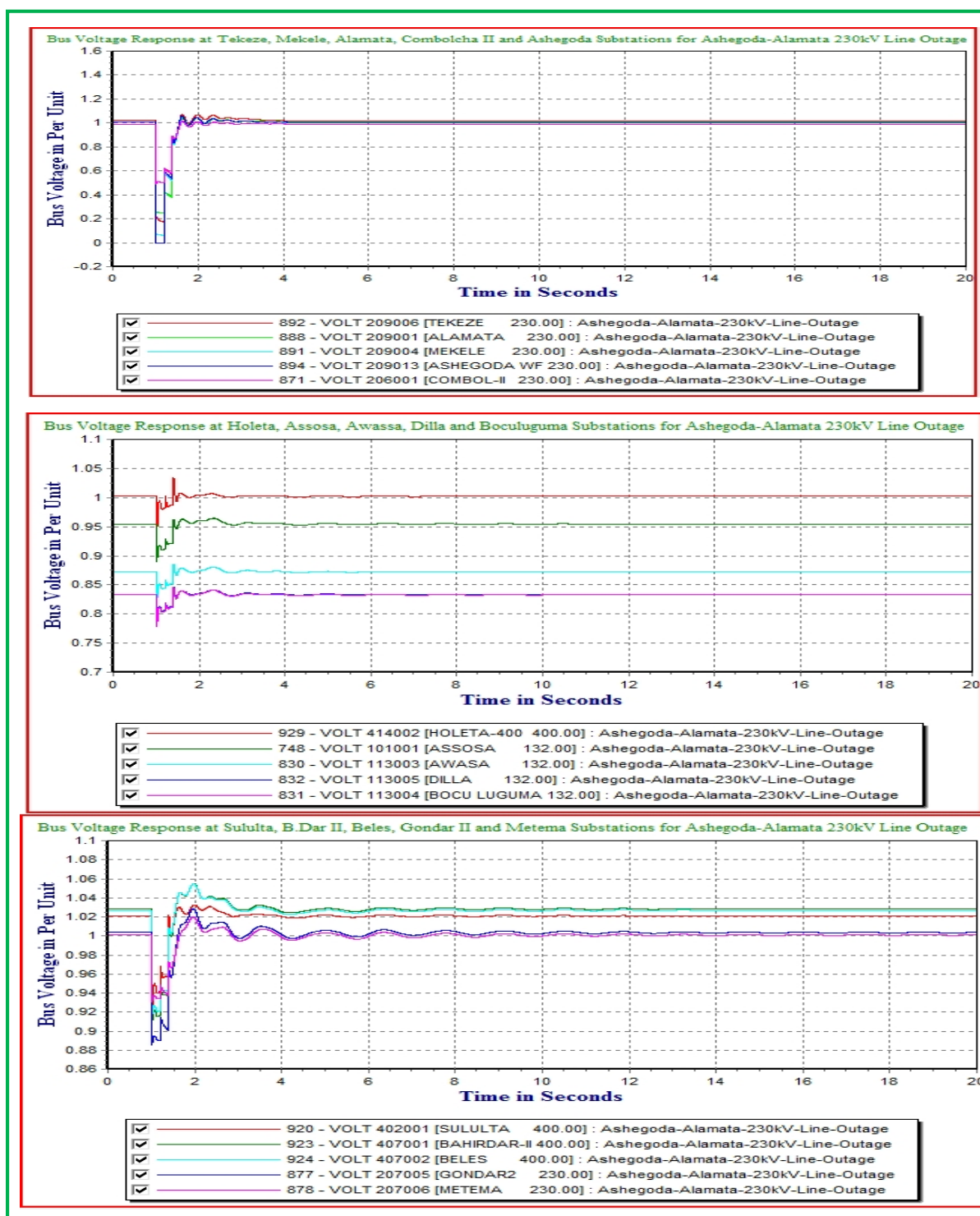


Figure 4. 33: Bus voltage of substations for Ashegoda-Alamata 230 kV line outage

As it is possible to see from Figure 4.28 and Figure 2.31, the angle of Tekeze generators is larger than the others for the faults applied at Tekeze and Mekele substations. This is due to Tekeze power plant is electrically nearby to the fault locations which are at Tekeze and Mekele substations.

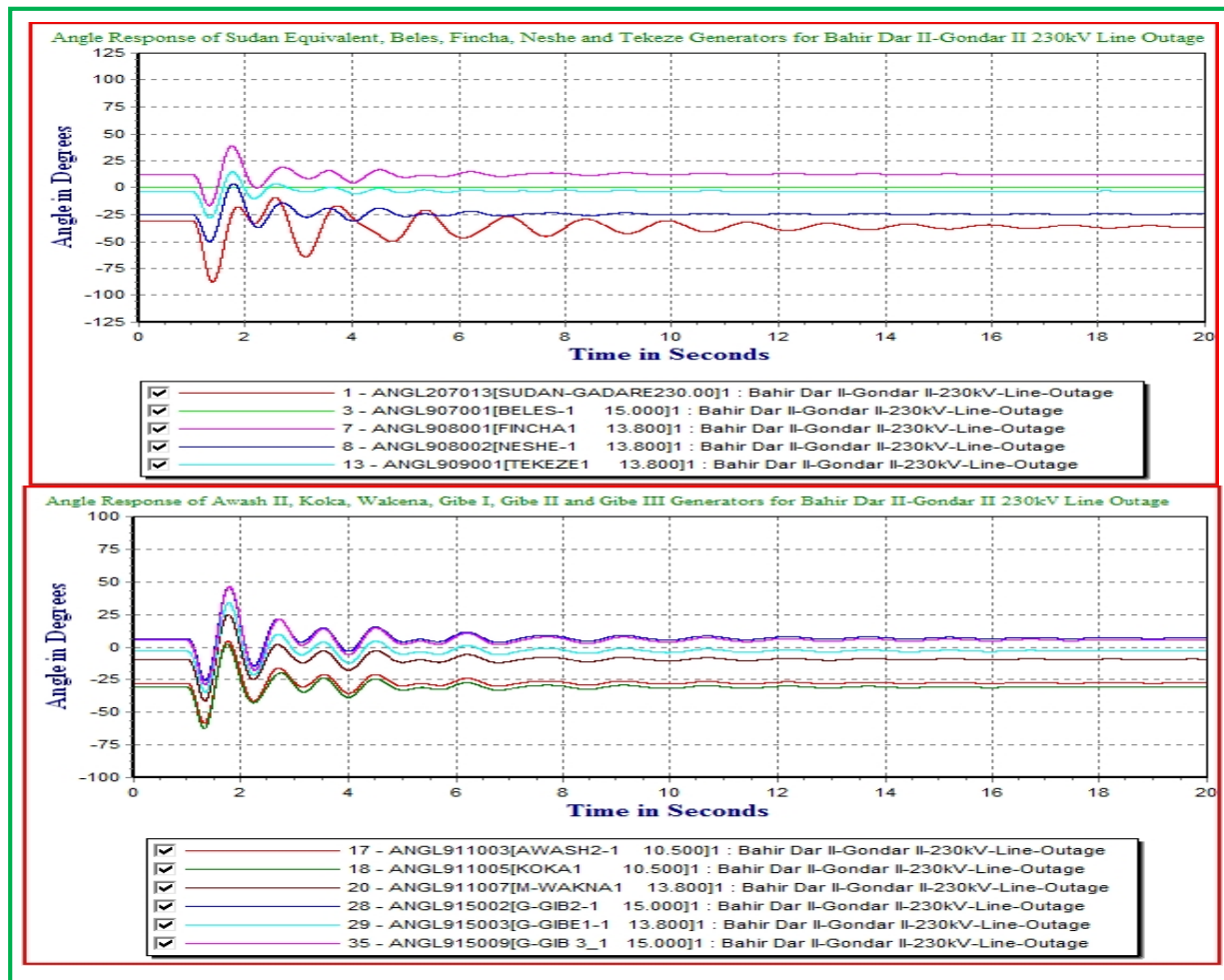


Figure 4. 34: Angle response of generators for B.Dar II-Gondar II 230 kV line outage

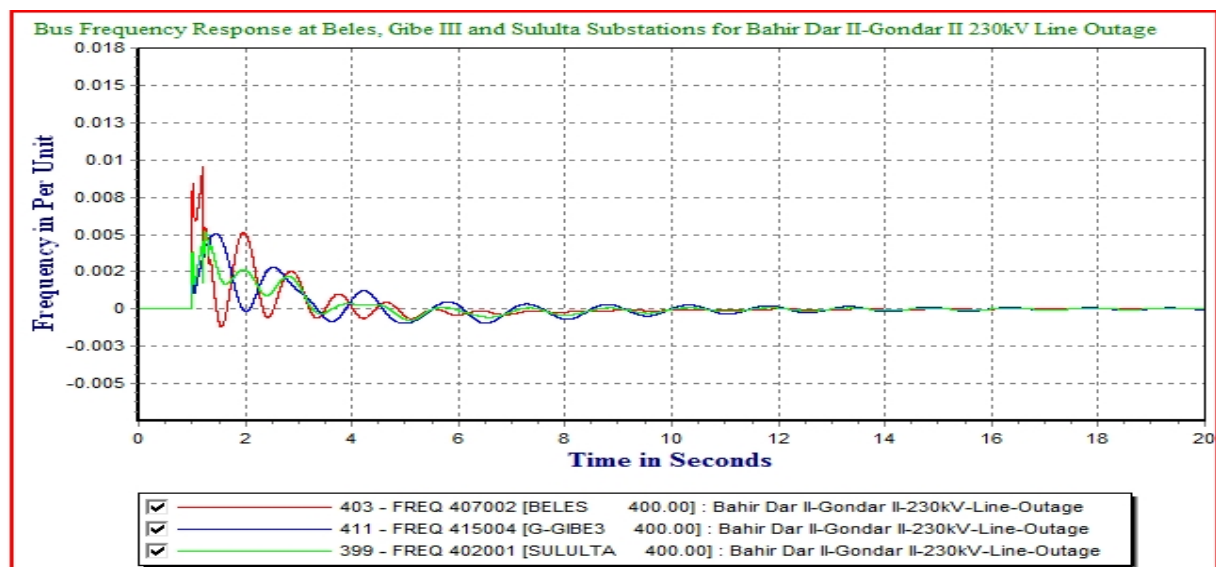


Figure 4. 35: Frequency response of substations for B.Dar II-Gondar II 230 kV line outage

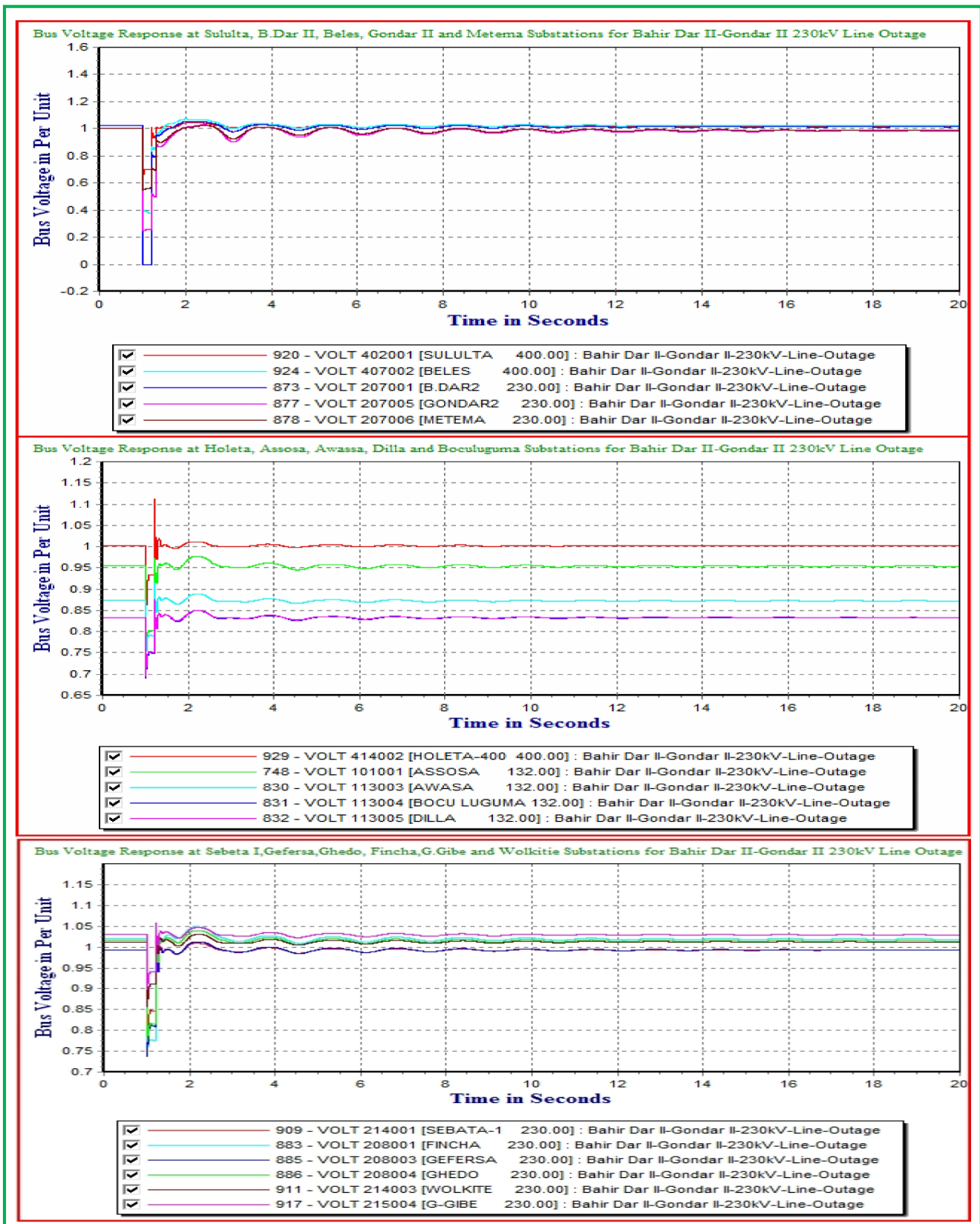


Figure 4. 36: Bus voltage response of substations for B.Dar II-Gondar II 230 kV line outage

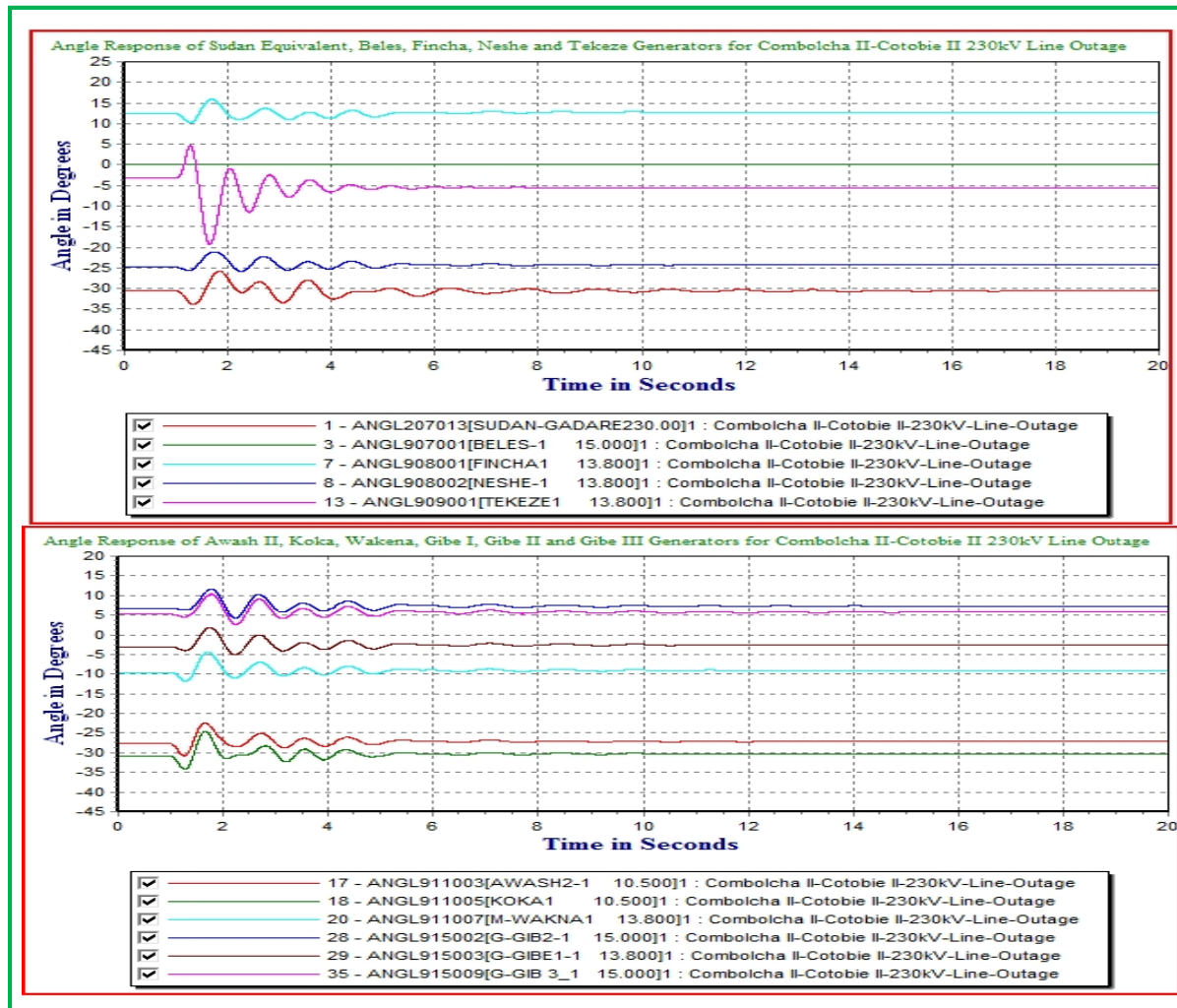


Figure 4. 37: Angle response of generators for Combolcha II-Cotobie II 230 kV line outage

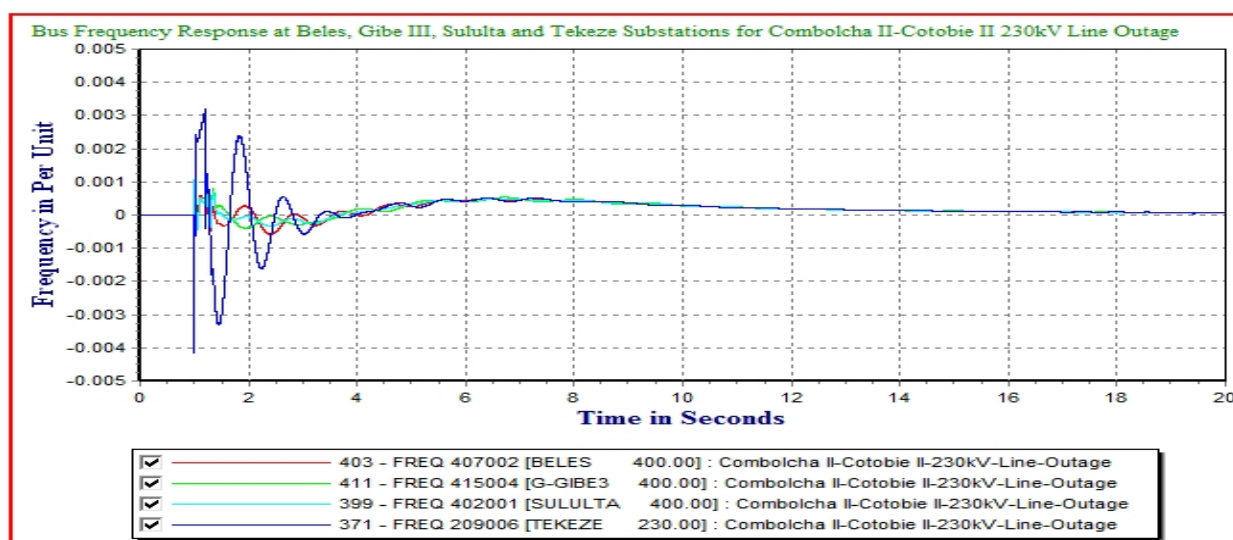


Figure 4. 38: Frequency at substations for Combolcha II-Cotobie II 230kV line outage

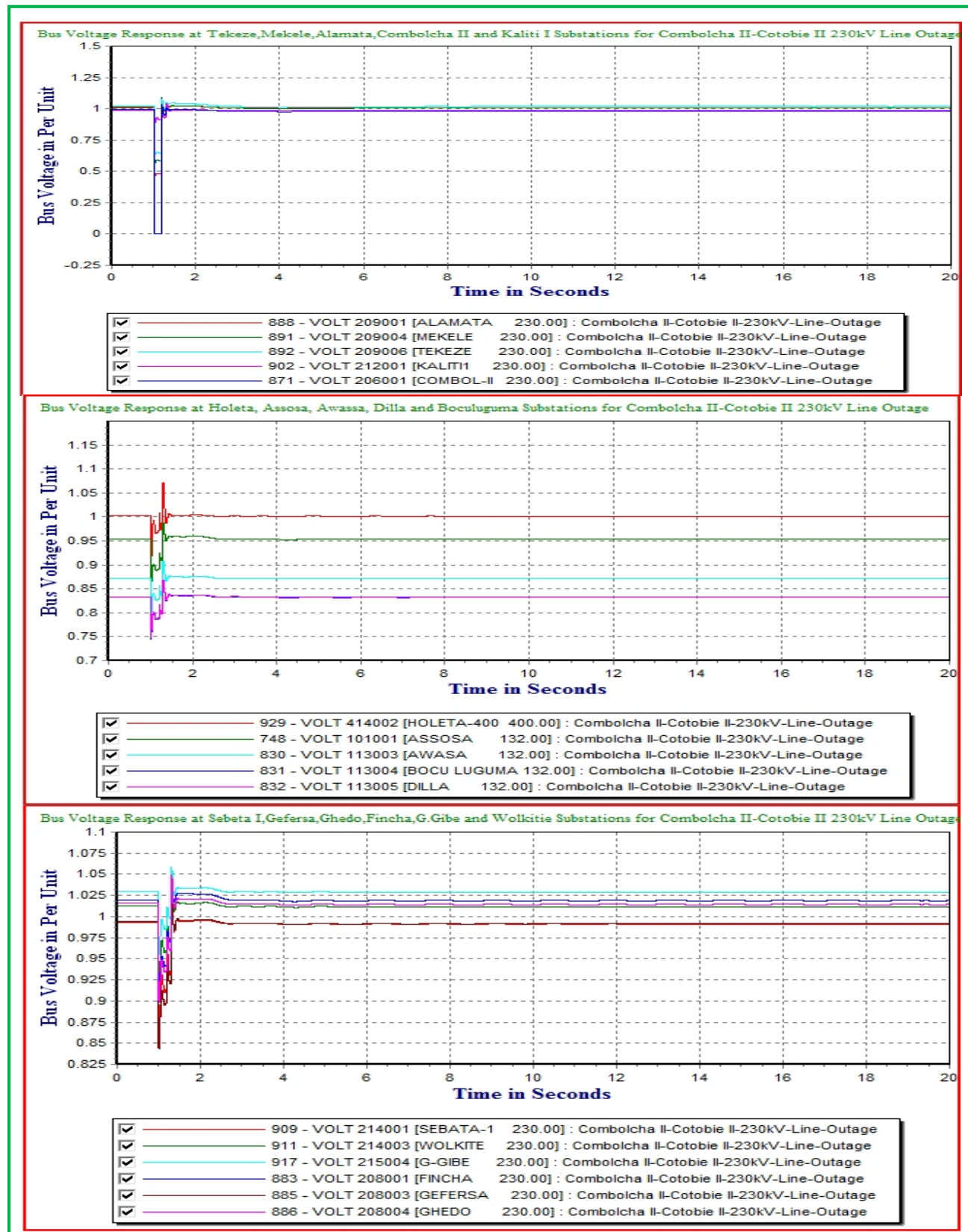


Figure 4. 39: Bus voltage of substations for Combolcha II-Cotobie II 230kV line outage

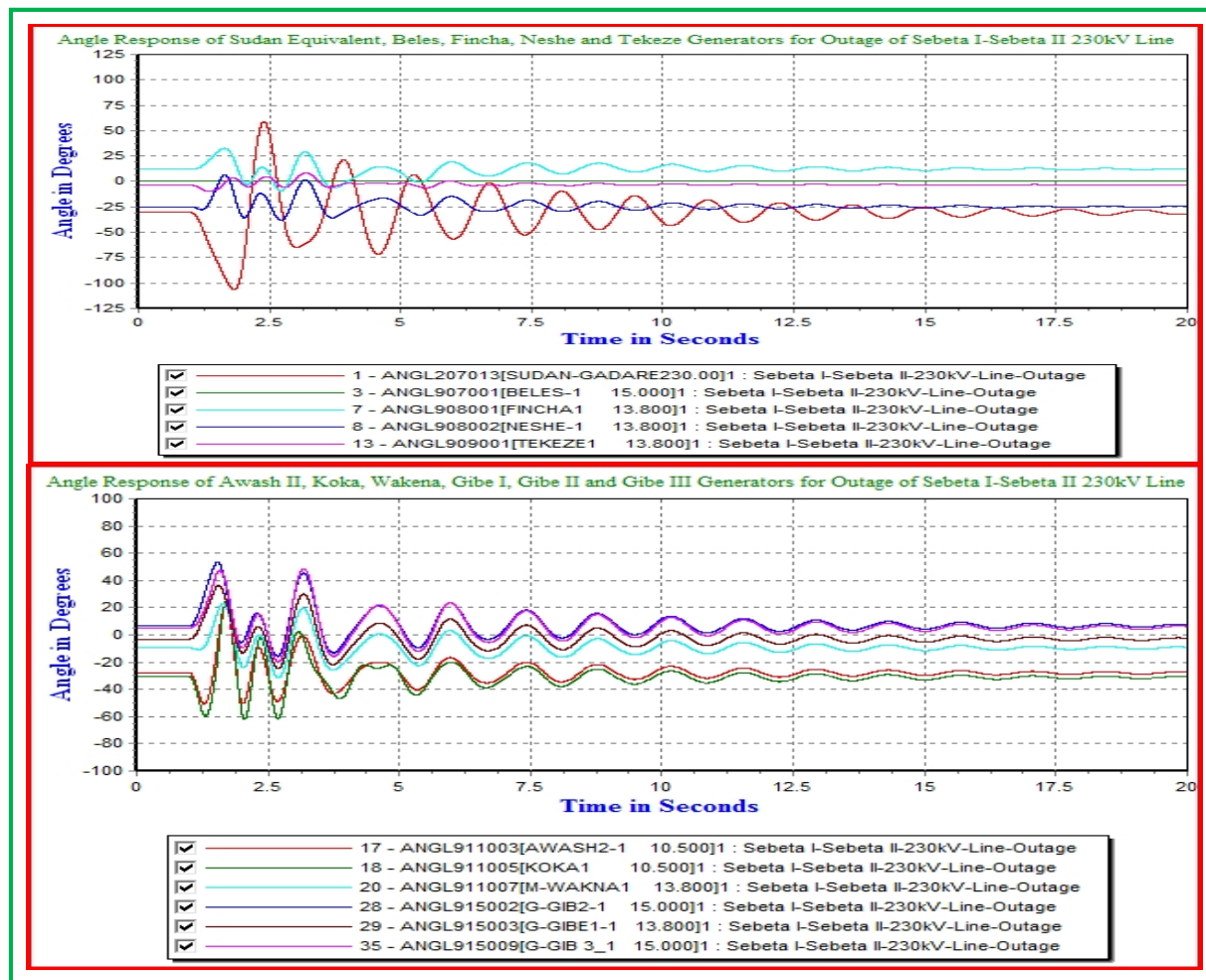


Figure 4. 40: Angle response of generators for Sebeta I-Sebeta II 230kV line outage

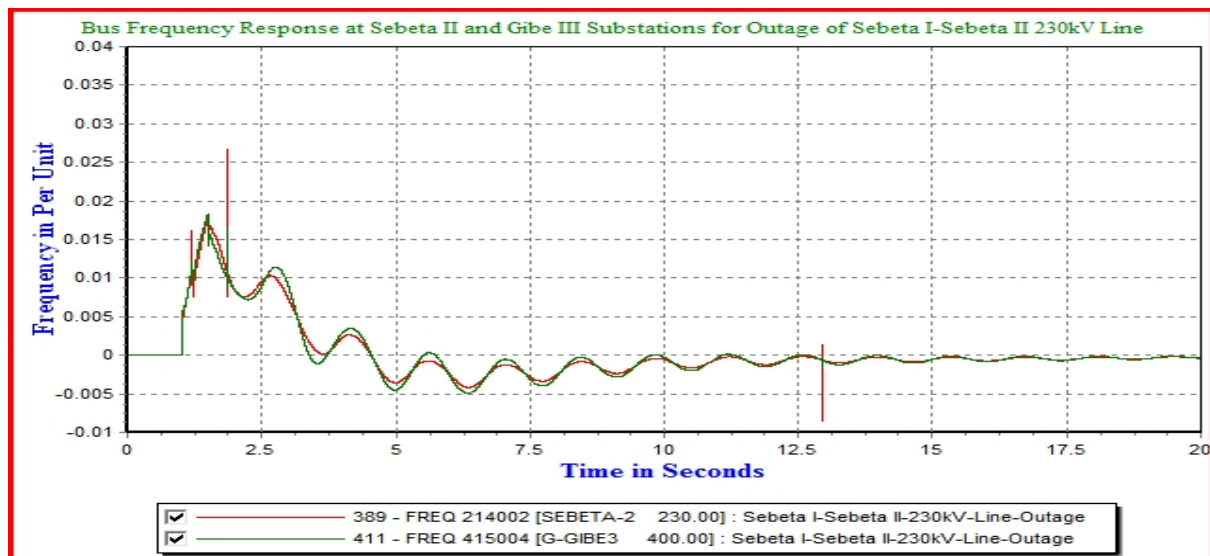


Figure 4. 41: Frequency response of Substations for Sebeta I-Sebeta II 230kV line outage

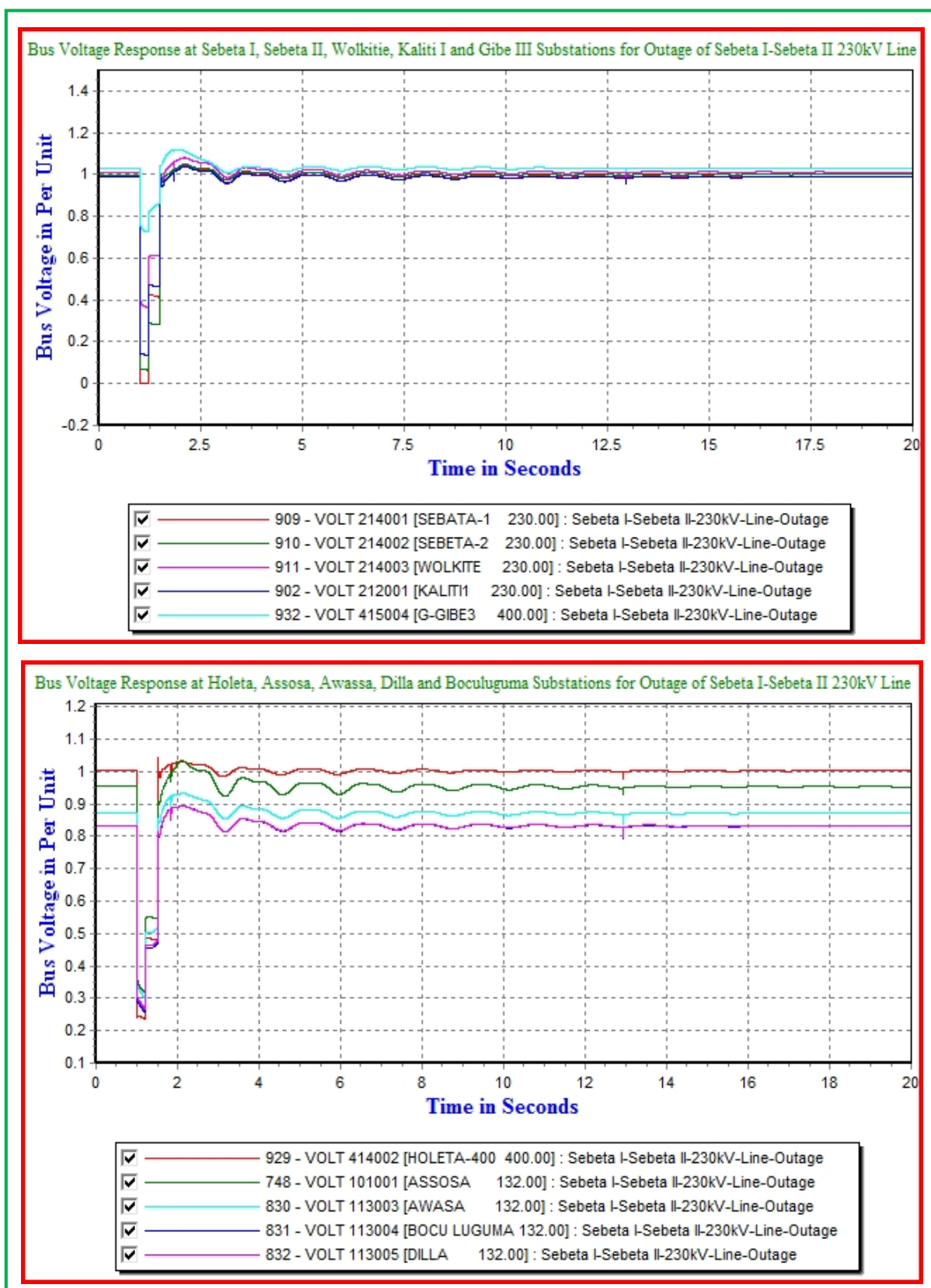


Figure 4. 42: Bus voltage of substations for Sebata I-Sebata II 230kV line outage

The simulation results of the 230 kV line outages are summarized in Table 4.2 below.

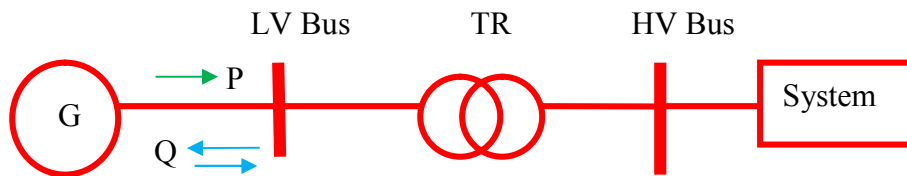
Name of the Line	End at which the fault is Applied	Voltage Level (kV)	Loading (MW)	Loading (%)	Power Flow Direction	Fault Clearing Times (ms)		Angle Response	Frequency Response	Bus Voltage Response
						Fault End CB Opened at	Far End CB Opened at			
Akak II -Kaliti I	Akaki II	230	154.33	57	To kaliti I	200	500	For the outage of Akaki II-Kaliti I 230kV line, the Sudan equivalent generator would be out of synchronism from Ethiopian machines. For the other cases all of the machines are in synchronism.	The system frequency is within the security criteria for all cases considered.	The voltage at Awassa, Dilla and Boculuguma substations doesn't recover to 0.9 pu within 10 seconds. In general, the voltage profile is not acceptable in most parts of the southern region of the system.
Alamata-Combolcha II	Alamata	230	37.4	14	To Combolcha II	200	500			
Ashegoda-Alamata	Ashegoda	230	44.29	16	To Alamata	200	400			
B.Dar II-Gondar II	B.Dar II	230	119.11	30	To Gondar II	200	300			
Combolcha II-Cotobie II	Cotobie II	230	24.19	10	To Combolcha II	200	300			
Gibe Old-Ghedo	Gibe Old	230	113.26	42	To Ghedo	200	400			
Gondar II-Metema	Gondar II	230	102.21	35	To Metema	200	400			
Kaliti I-Bole Lemi	Kaliti I	230	113.11	29	To Bole Lemi	200	500			
Kaliti I-Sebeta I	Kaliti I	230	8.63	14	To Sebeta I	200	500			
Mekele-Ashegoda	Mekele	230	41.39	13	To Mekele	200	400			
Mekele-Mehoni	Mekele	230	34.88	14	To Mehoni	200	300			
Sebeta I-Sebeta II	Sebeta I	230	128.23	47	To Sebeta I	200	500			
Sebeta I-Wolkite	Sebeta I	230	77.45	28	To Sebeta I	200	500			
Tekeze-Mekele	Tekeze	230	47.37	15	To Mekele	200	300			
Wolkite-Gibe Old	Gibe Old	230	106.58	38	To Wolkite	200	500			

Table 4. 2: Summary of simulation results of the 230 kV line outages

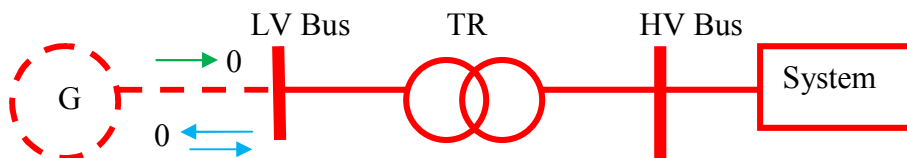
4.4. Dynamic Simulations for Outage of a Generating Unit

In this thesis work, the impact of an outage of a single generator at Gibe III, Beles, Gibe II and other power plants has also been assessed one by one. The following steps have been followed to conduct such analysis.

1. The dynamic simulation is performed for 1 second without disconnecting a generator.



2. At time $t=1$ second, the generator is assumed to be disconnected suddenly for any reason.



3. Then the dynamic simulation is continued to 20 seconds.

The dynamic simulations are performed for the outage of a generator at each power plant turn by turn following the steps indicated above. The plots below show the simulation results of machine relative angle, bus frequency deviations and bus voltage responses at selected substations.

As it is clearly indicated in the frequency response plots in Figure 4.43, Figure 4.46 and Figure 4.49, the frequency returns near to the normal value despite the outage of a generator. This indicates that the primary controllers of the generators which are in operation are working properly; and the remaining generators are jointly capable of covering the lost generation.

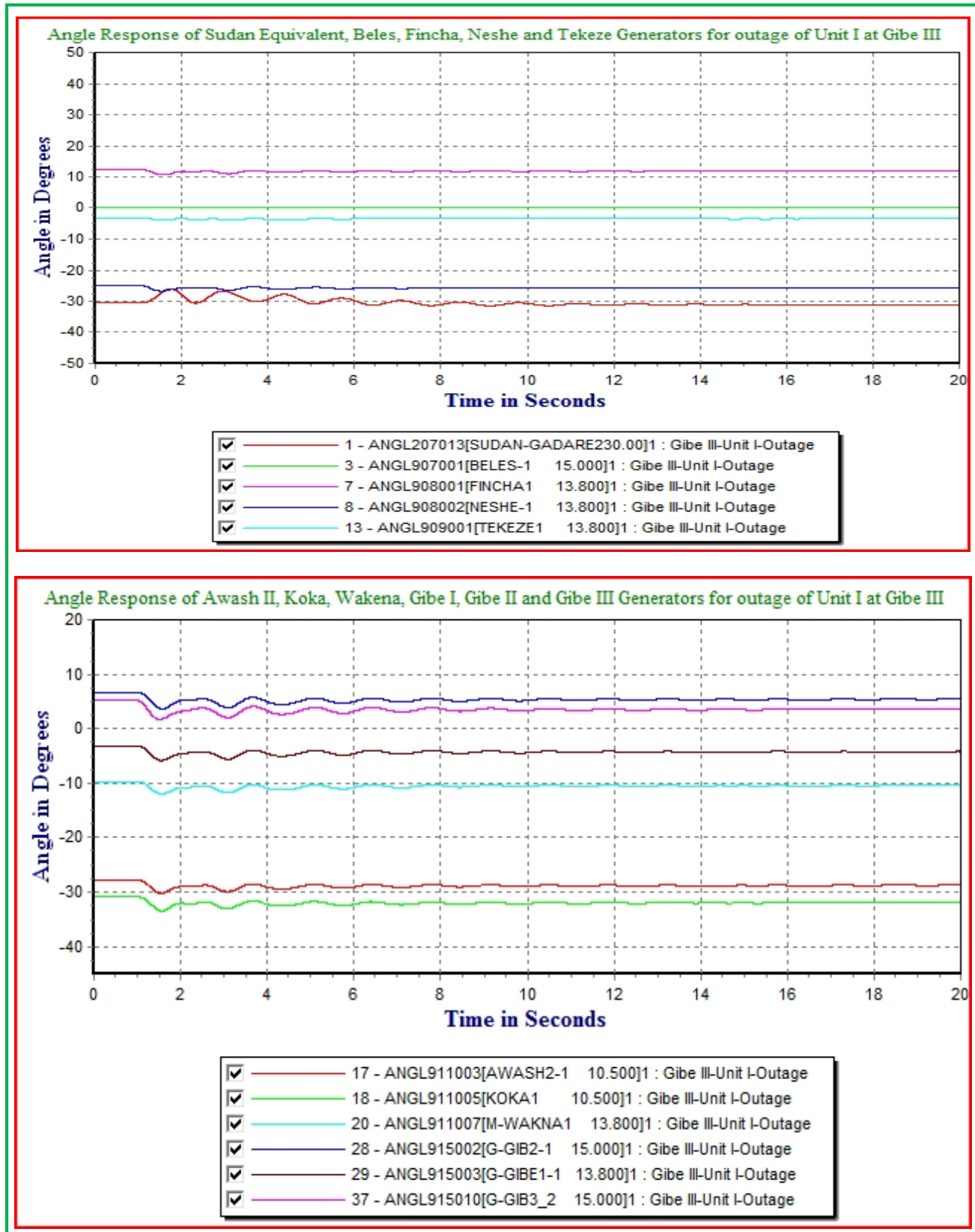


Figure 4. 43: Angle response of generators for outage of Unit I at Gibe III

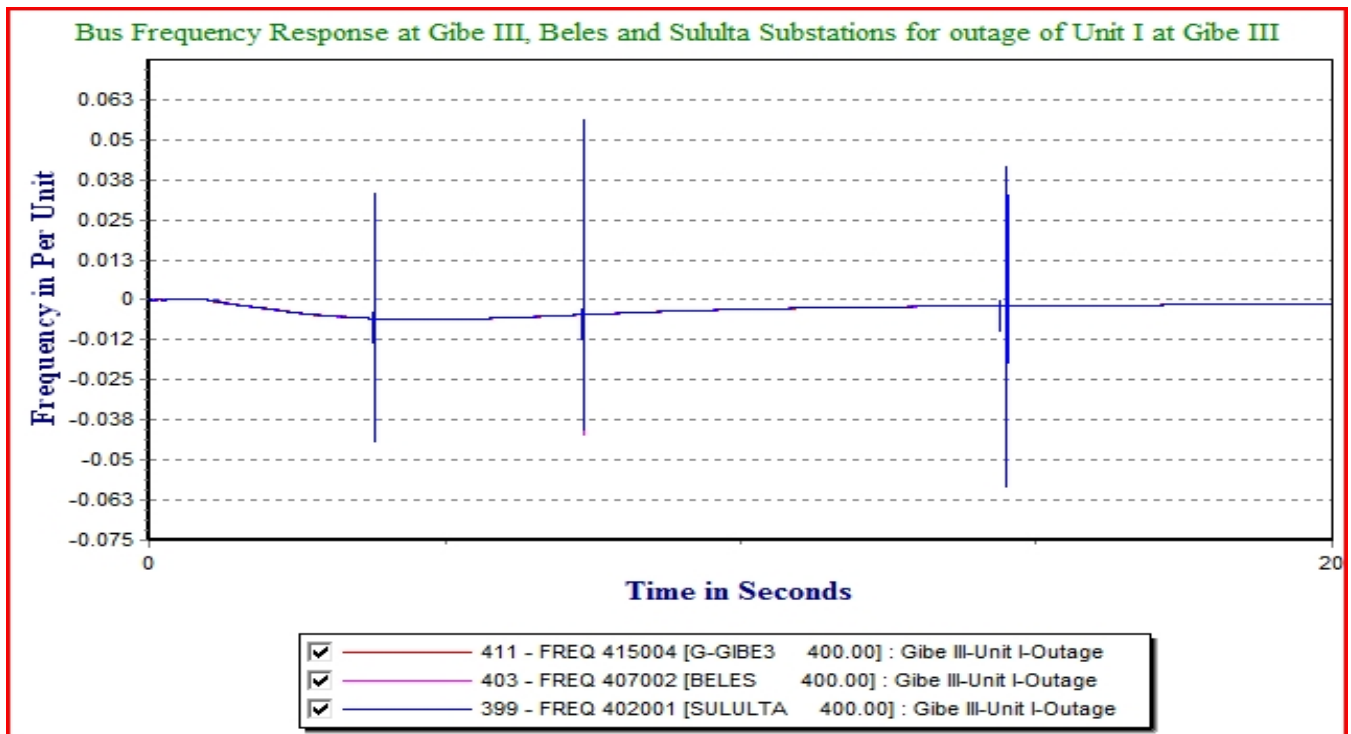


Figure 4. 44: Bus frequency response of substations for outage of Unit I at Gibe III

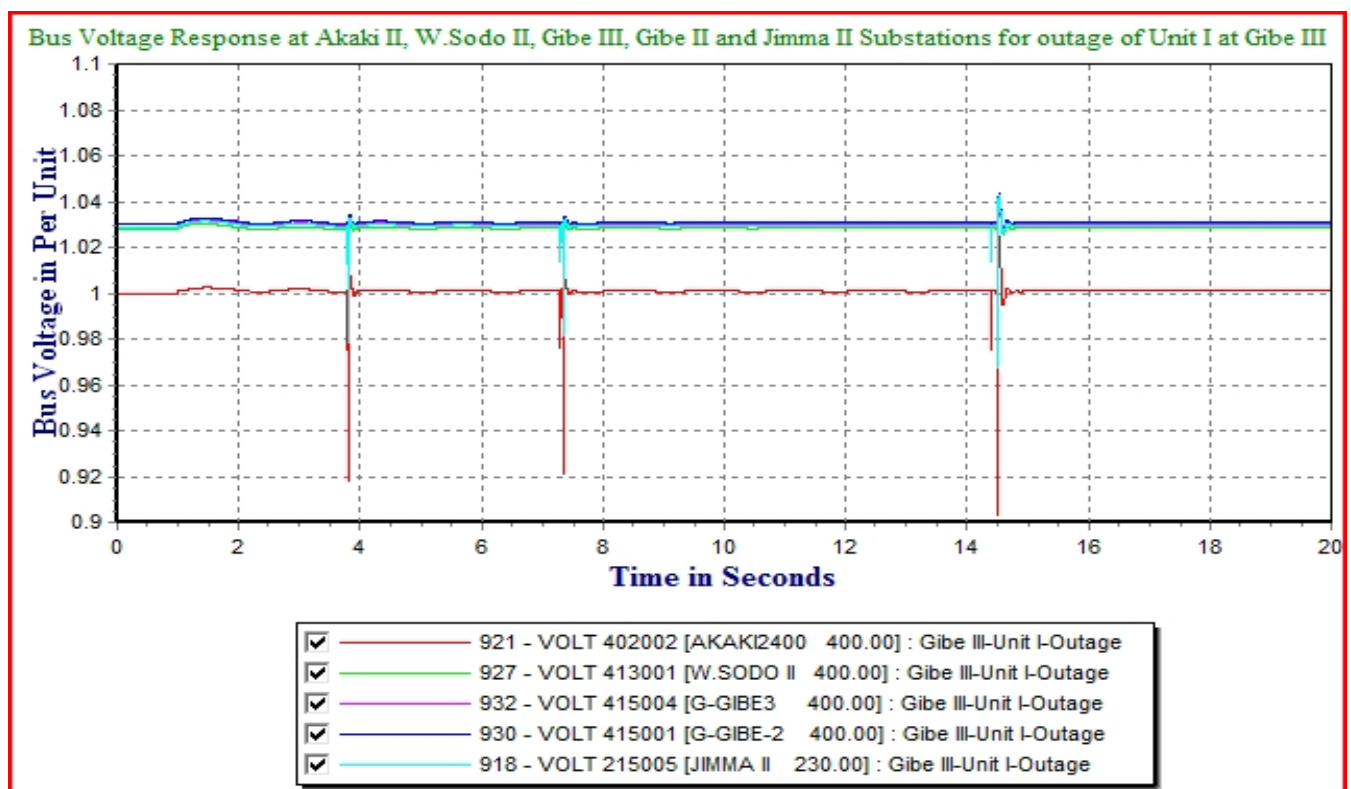


Figure 4. 45: Bus voltage response of substations for outage of Unit I at Gibe II

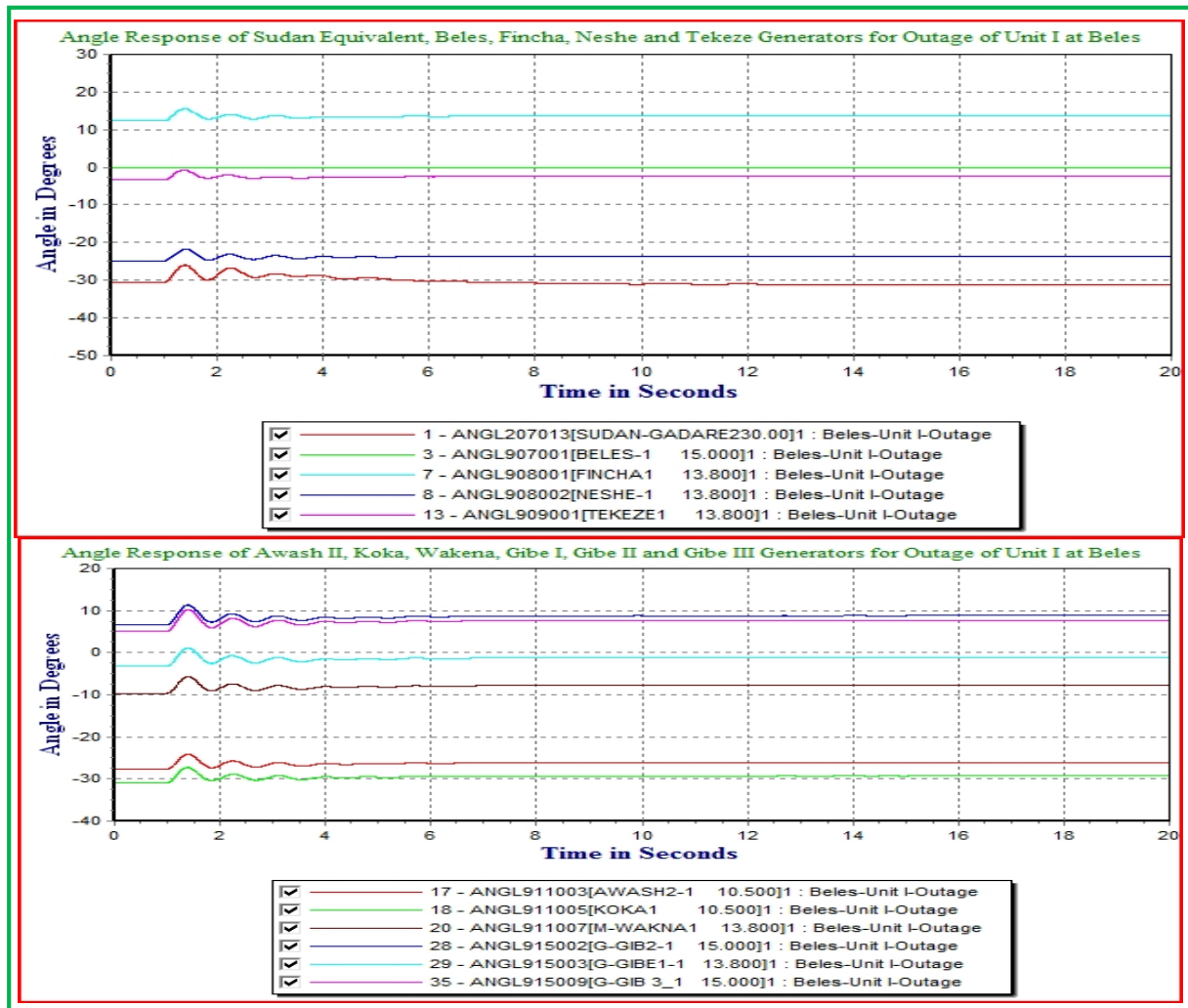


Figure 4. 46: Angle response of generators for outage of Unit II at Beles PP

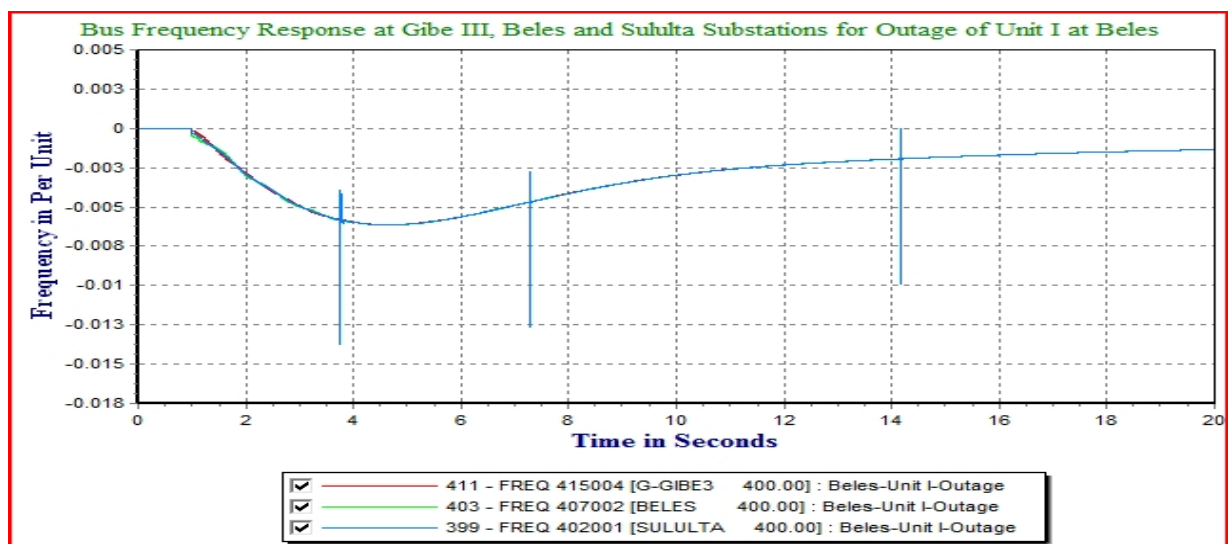


Figure 4. 47: Bus frequency response of substations for outage of Unit II at Beles PP

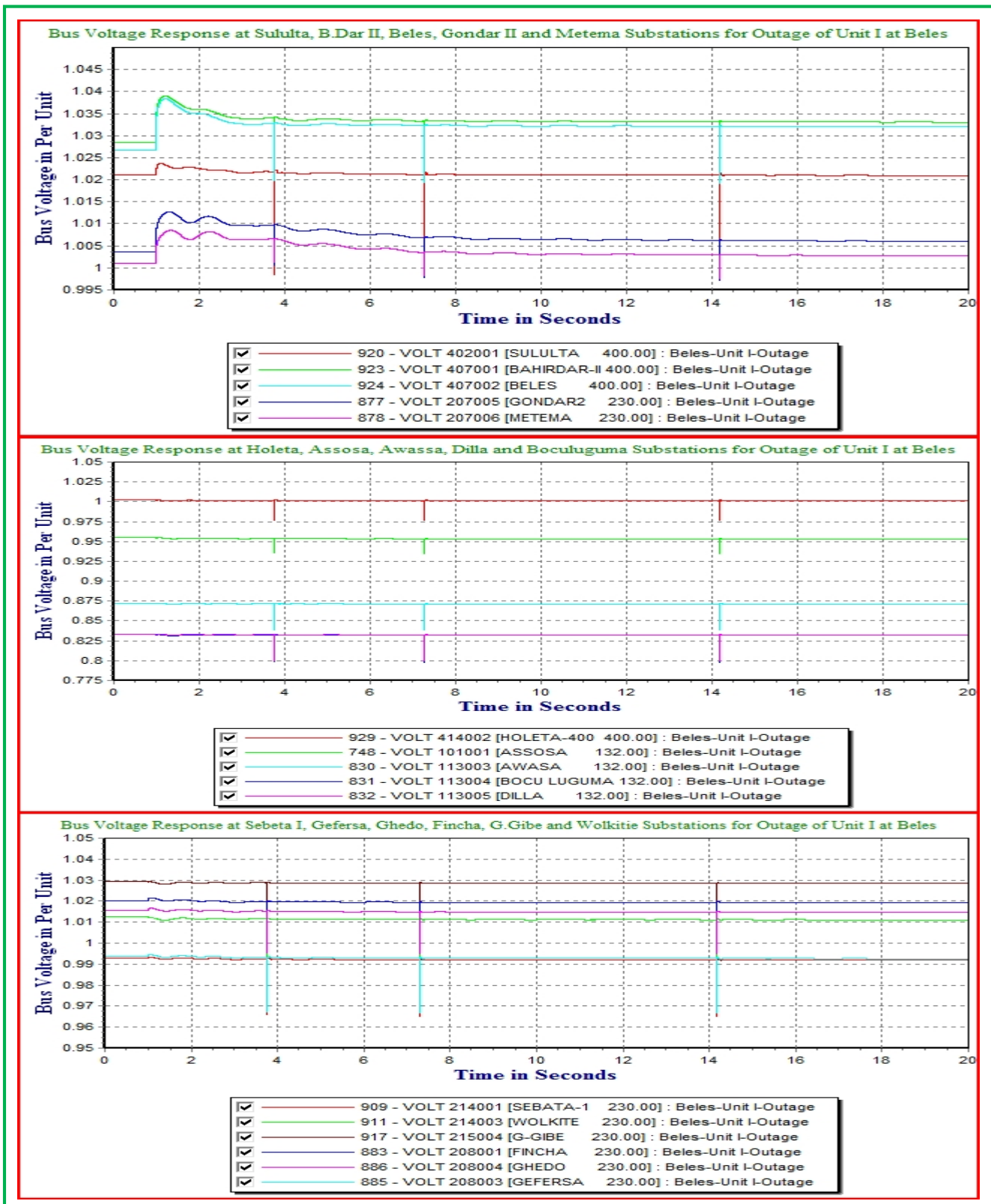


Figure 4. 48: Bus voltage response of substations for outage of Unit II at Beles PP

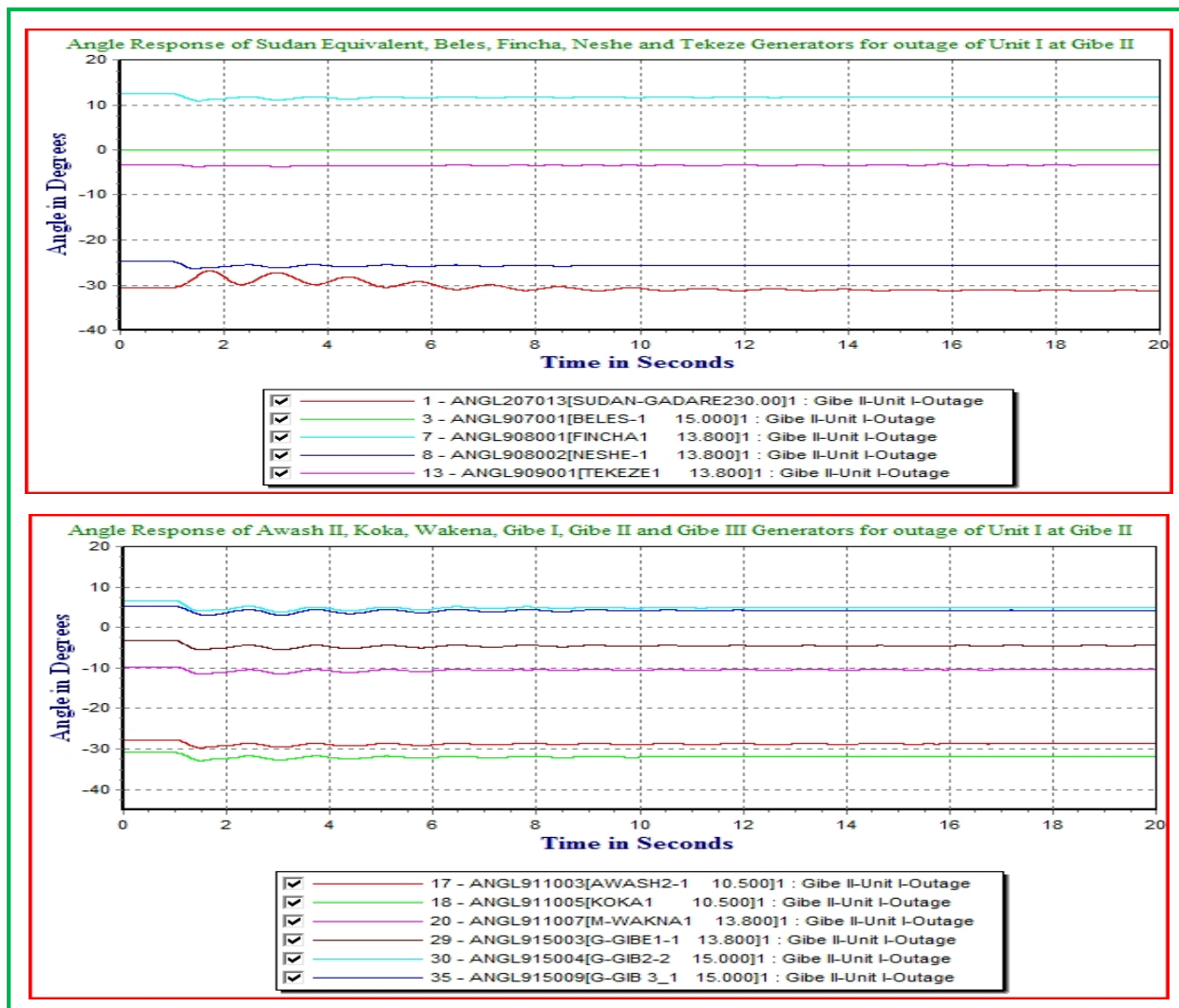


Figure 4. 49: Angle response of generators for outage of Unit I at Gibe II PP

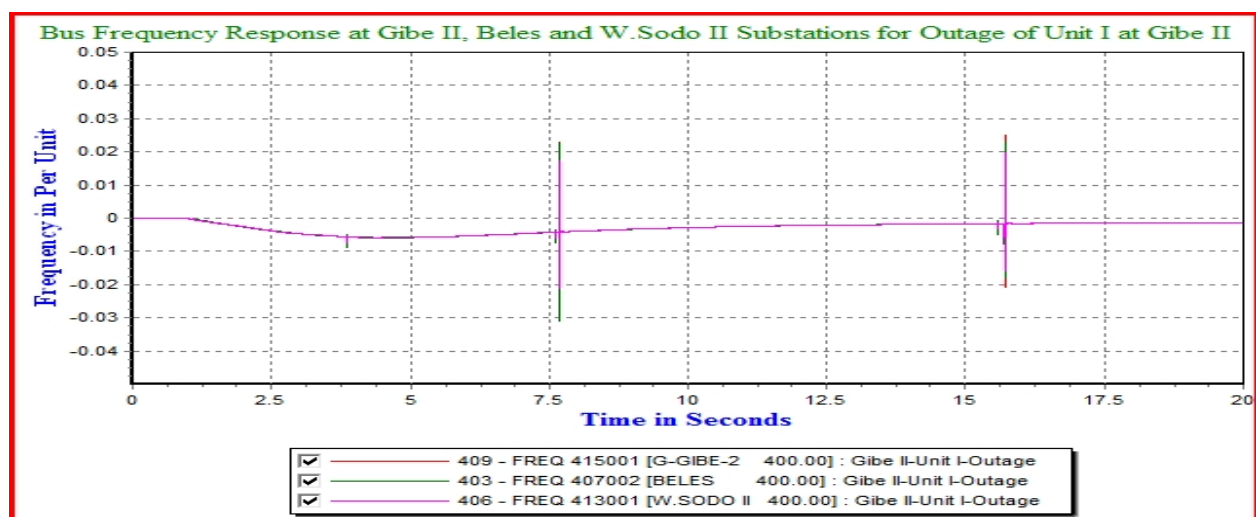


Figure 4. 50: Bus frequency response of substations for outage of Unit I at Gibe II PP

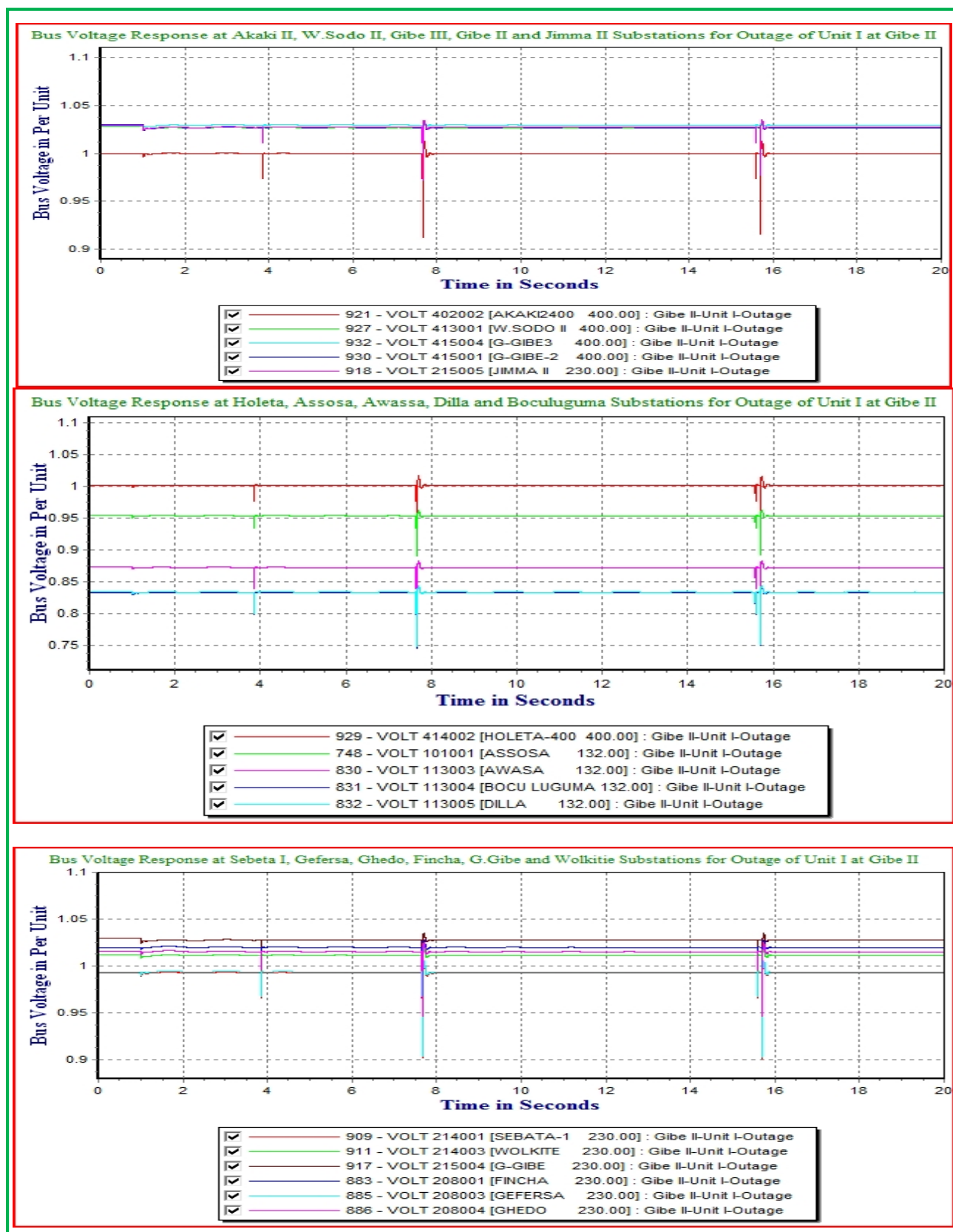


Figure 4. 51: Bus voltage response of substations for outage of Unit I at Gibe II

The simulation results of generator outages at each power plant are summarized in Table 4.3 below.

Disconnected Generator	Total Generation Pre-disturbance (MW)	P _{max} (MW)	Generator Loading (MW)	Lost Generation (%)	Angle Response	Frequency Response	Voltage Response
Gibe III Unit I	2202.70	187.00	87.00	3.95	For the outage of any one of the generators at any power plant, the remaining machines would stay in synchronism.	The system frequency would return to nominal value and it is within the security criteria.	The voltage at Awassa, Dilla and Bocoluguma substations doesn't recover to 0.9 pu within 10 seconds. In general the voltage profile is not good in most parts of the southern region of system.
Beles Unit II	2202.70	117.00	82.90	3.76			
Gibe II Unit I	2202.70	107.00	85.00	3.86			
Tekeze Unit I	2202.70	78.00	56.00	2.54			
Gibe I Unit I	2202.70	70.00	36.67	1.66			
Melka Wakena Unit I	2202.70	38.25	25.50	1.16			
Fincha Unit I	2202.70	33.00	27.00	1.23			
Neshe Unit I	2202.70	48.50	10.16	0.46			
Awash II Unit I	2202.70	18.00	6.50	0.30			
Koka Unit I	2202.70	12.80	3.54	0.16			
Adama II Unit I	2202.70	153.00	84.69	3.84			
Adama I Unit I	2202.70	51.00	26.74	1.21			
Ashegoda Unit I	2202.70	90.00	80.00	3.63			

Table 4. 3: Summary of simulation results for the outage of generators

The frequency overshoot and the bus voltage notches observed in the frequency response and the bus voltage response plots are related with the wind farms. This is confirmed by replacing the wind farms with appropriate load (a negative active load and appropriate reactive load) in such a way that the power flow result would not be changed as shown in Table 4.4 below.

Name of Wind Farm	Machine ID	Active Power Output of Wind Machine (MW)	Reactive Power of Wind Machine (MVar)		Equivalent Load Used to Replace the Wind Machine	
			Magnitude	Direction of Reactive Power Flow	Active Component of the Load (MW)	Reactive Component of the Load (MVar)
Ashegoda	1	80	19.2077	To the generator	-80	19.2077
	2	5.75	1.3806	To the generator	-5.75	1.3806
Adama I	1	26.74	5	To the system	-26.74	-5
Adama II	1	84.69	36.9502	To the generator	-84.69	36.9502

Table 4. 4: Detail of equivalent load introduced into the model to replace wind machines

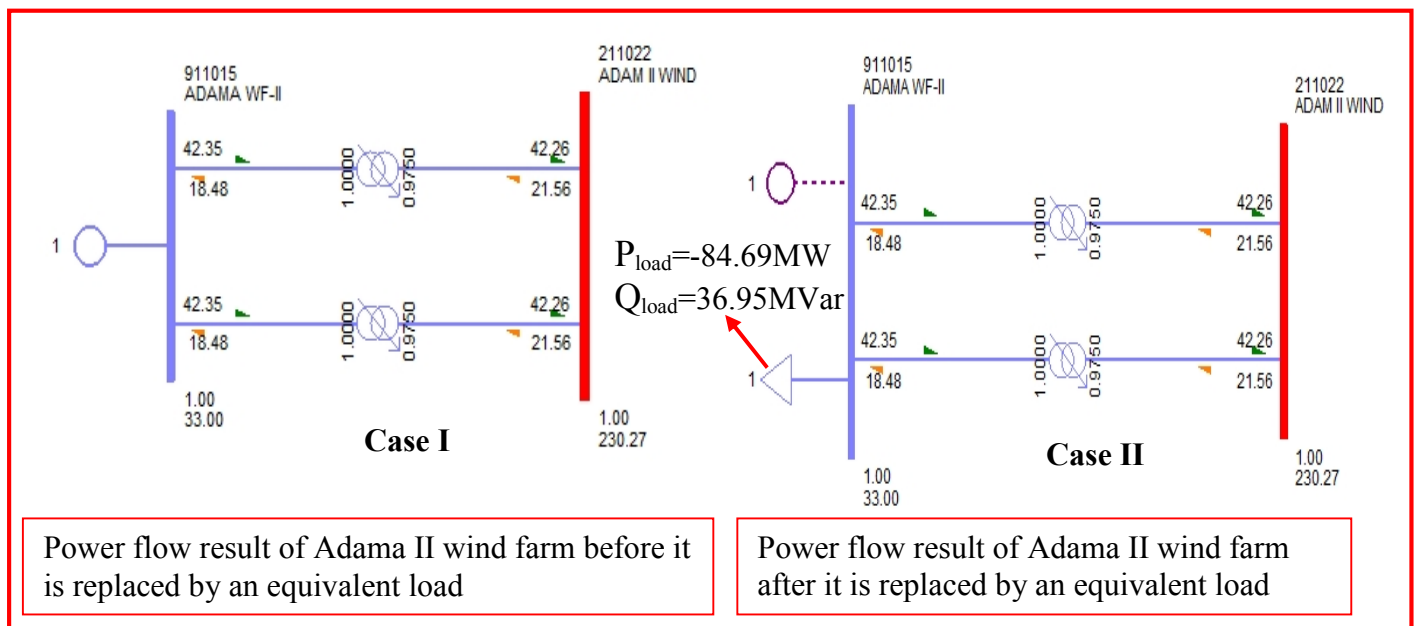


Figure 4. 52: Wind farms replaced by equivalent load in the model

As it is clearly indicated in Table 4.4 and Figure 4.52 above, for the first case the total active power injection from Adama II wind farm to the system is about 84.69 MW; and this wind farm is consuming about 36.95 MVar from the system at the same time. For the second case, the wind farm is replaced by an equivalent load which is injecting about 84.69 MW power into the system and is

consuming about 36.95 MVar from the system. In short, the power flow result is the same for both cases. Once all of the wind farms are replaced by corresponding equivalent loads in similar way, the dynamic simulations have been performed and sample frequency and bus voltage plots which are clear from frequency overshoots and voltage notches are shown in Figure 4.52 and Figure 4.53 respectively below. The simulation result plots confirm that the frequency overshoots and the bus voltage notches observed in the corresponding plots are related with the wind farms.

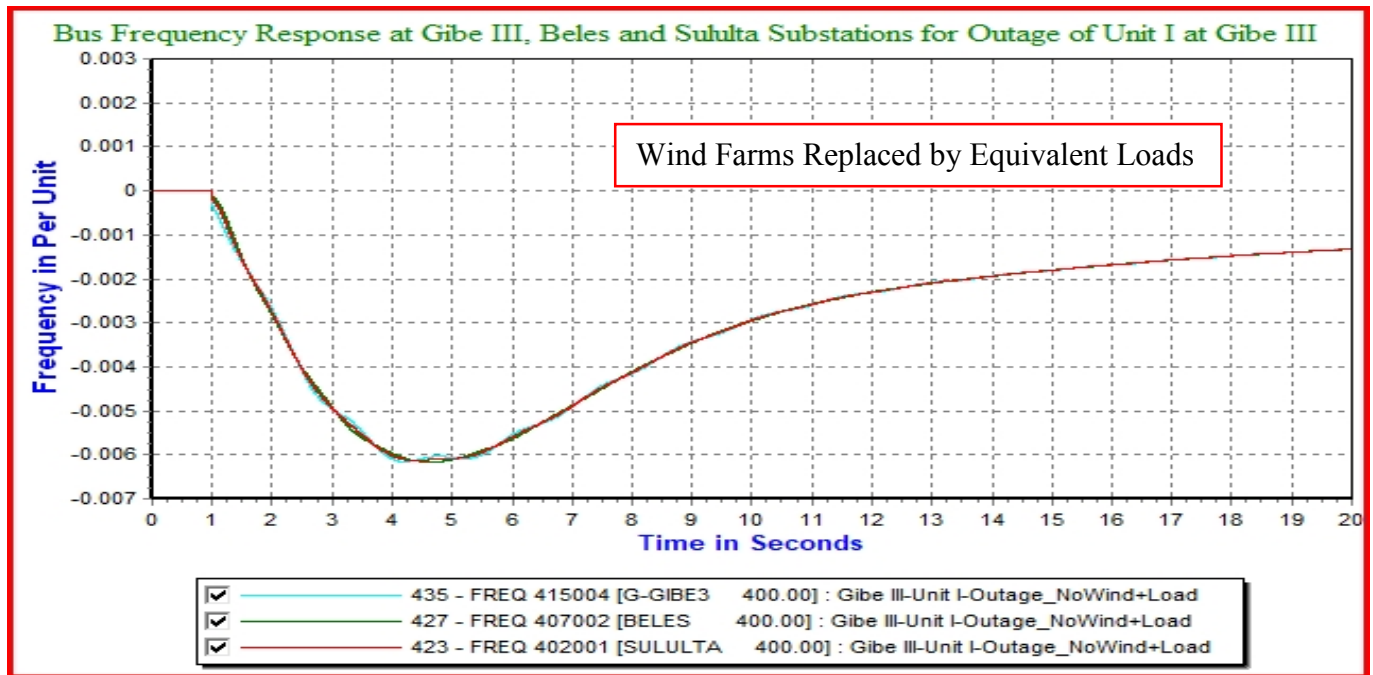


Figure 4. 53: Bus frequency response for outage of Unit I at Gibe III-Wind Farms replaced

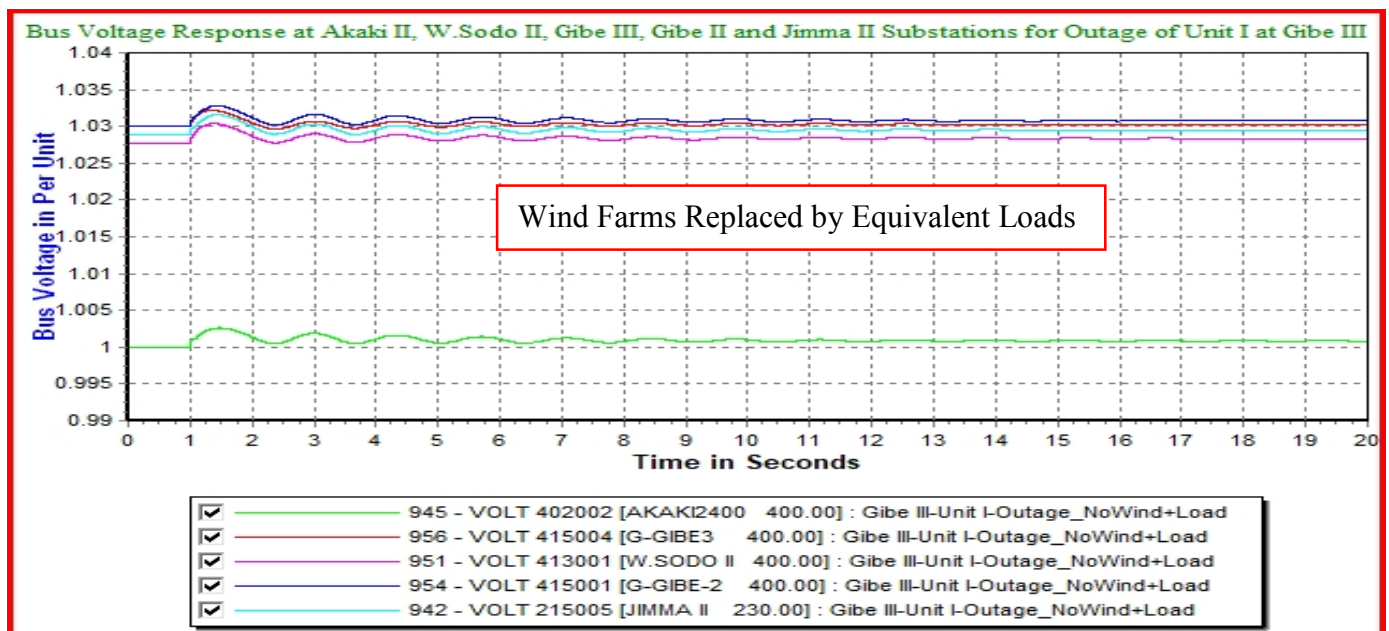


Figure 4. 54: Bus voltage response for outage of Unit I at Gibe III -Wind Farms replaced

In most parts of the Southern Region of the system there are no sufficient reactive power sources. This calls for reactive power transmission over long distance which in turn causes a high voltage drop in the transmission infrastructure and low voltage at the end of the customers in the region. This is checked by performing the simulation taking into account reactive power sources at selected substations of the Southern Region (45MVar capacitor bank at Assela substation and 30MVar capacitor bank at Yirgalem substation). As the simulation result shown in Figure 4.54 depicts the voltage profile is improved in the region after consideration of the capacitor banks.

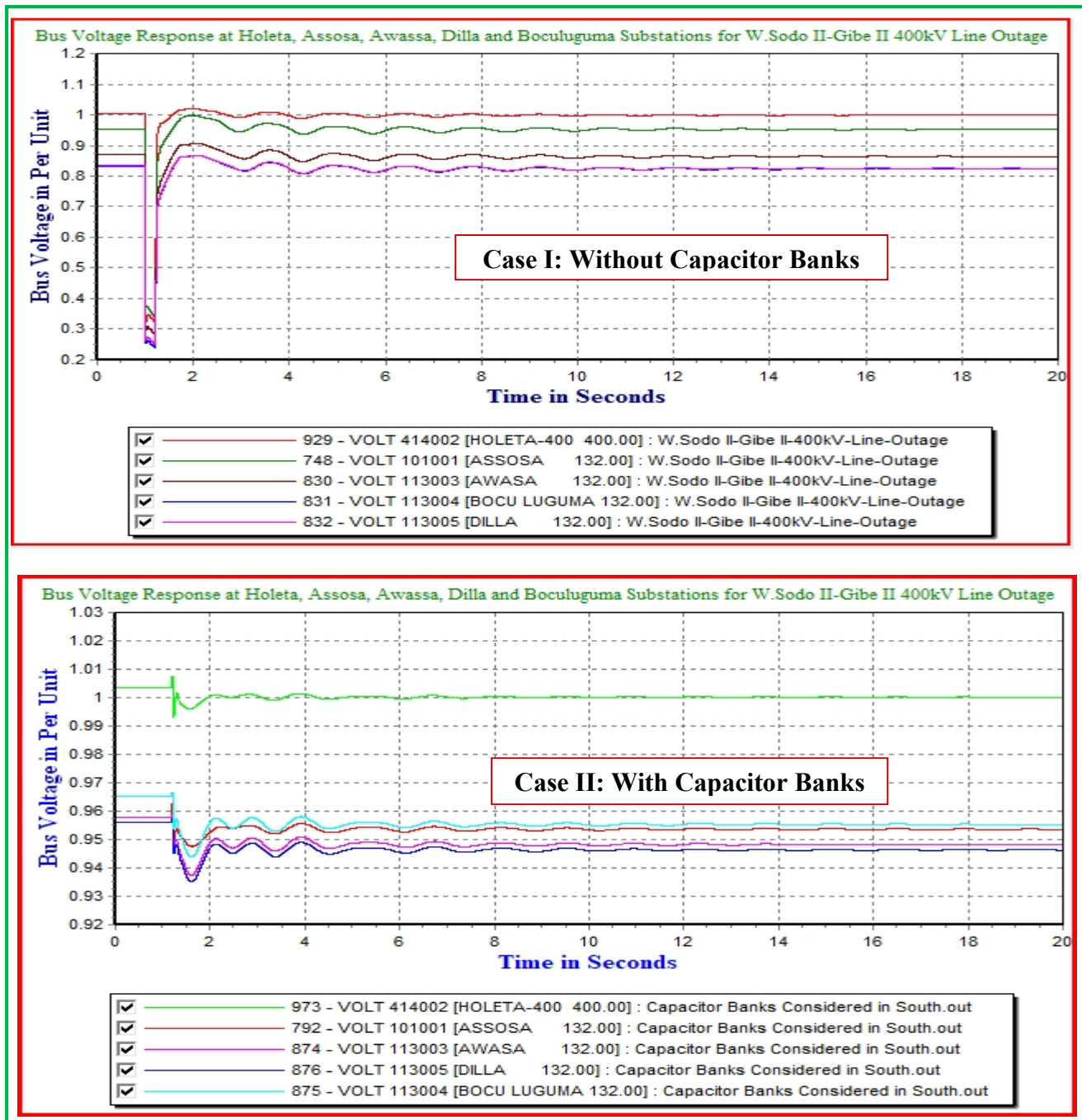


Figure 4. 55: Impact of capacitor banks on bus voltage response in the Southern Region

4.5. Critical Clearing Time (CCT) Calculations

The critical clearing times (CCTs) of the selected lines have also been calculated to see the robustness of the system for the occurrence of a three phase short circuit metallic fault at one end of the line and to check how the actual protection setting is far from the CCT values. The CCT is computed using "trial and error" analysis of the system post disturbance conditions by performing dynamic simulations iteratively with increasing fault duration until the system becomes unstable. The calculated CCT values of the 400 kV and 230 kV lines are reported in Table 4.5 and Table 4.6 respectively below.

Name of Line	Voltage Level (kV)	Loading (MW)	End at which fault is Applied	CCT (ms)	Protection Settings (ms)				
					Zone 1	Tele protection	Zone 2	Zone 3	Zone 4
Akaki II-Sebeta II	400	86.79	Akaki II	411	0	20			
			Sebeta II	421	0	20			
Bahir Dar II-D.Markos	400	34.23	Bahir Dar II	258	0	20	400	600	1000
			D.Markos	413	0	20	400	600	1000
Beles-Bahir Dar II	400	149.96	Beles	298	0	20	400	600	1000
			Bahir Dar II	307	0	20	400	600	1000
D.Markos-Sululta	400	12.1	D.Markos	462	0	20	400	600	1000
			Sululta	497	0	20	400	600	1000
Gibe II-Gibe Old	400	223.19	Gibe II	364	0	20			
			Gibe Old	457	0	20			
Gibe III-W.Sodo II	400	435	Gibe III	312	0	20			
			W.Sodo II	335	0	20			
Gibe II-Sebeta II	400	390.79	Gibe II	357	0	20			
			Sebeta II	421	0	20			
W.Sodo II-Akaki II	400	481.59	W.Sodo II	315	0	20			
			Akaki II	415	0	20			
W.Sodo II-Gibe II	400	276.69	W.Sodo II	336	0	20			
			Gibe II	340	0	20			
D.Markos-G.Guracha	400	29.17	D.Markos	466	0	20			
			G.Guracha	633	0	20			
G.Guracha-Sululta	400	0.68	G.Guracha	633	0	20			
			Sululta	501	0	20			

Table 4. 5: Calculated CCT values of the 400 kV lines and their protection setting

Name of Line	Voltage Level (kV)	Loading (MW)	End at which fault is Applied	CCT (ms)	Protection Settings (ms)				
					Zone 1	Tele protection	Zone 2	Zone 3	Zone 4
Akaki II -Kaliti I	230	154.33	Akaki II	404	0	20	500	800	1100
			Kaliti I	408	0	20	500	800	1100
Alamata-Combolcha II	230	37.4	Alamata	384	0	20	500	100	1200
			Combolcha II	>1200	0	20	300	100	1200
Ashegoda-Alamata	230	44.29	Ashegoda	328	0	20	400	1000	1000
			Alamata	385	0	20	400	1000	1000
Bahir Dar II-Gondar II	230	119.11	Bahir Dar II	402	0	20	300	800	1200
			Gondar II	806	0	20	300	1000	1200
Combolcha II-Cotobie II	230	24.19	Combolcha II	>1200	0	20	300	1000	1200
			Cotobie II	513	0	20	300	1000	1200
Gibe Old-Ghedo	230	113.26	Gibe Old	523	0	20	400	600	800
			Ghedo	615	0	20	400	600	800
Gondar II-Metema	230	102.21	Gondar II	804	0	20	400		
			Metema	>1200	0	20	400		
Kaliti I-Bole Lemi	230	113.11	Kaliti I	408	0	20	500	1500	1500
			Bole Lemi	564	0	20	500	1500	1500
Kaliti I-Sebeta I	230	8.63	Kaliti I	408	0	20	500	1000	1000
			Sebeta I	414	0	20	500	1000	1000
Mekele-Ashegoda	230	41.39	Mekele	295	0	20	400	1000	1000
			Ashegoda	323	0	20	400	1000	1000
Mekele-Mehoni	230	34.88	Mekele	299	0	20	300		
			Mehoni	429	0	20	300		
Sebeta I-Sebeta II	230	128.23	Sebeta I	413	0	20	500		
			Sebeta II	454	0	20	500		
Sebeta I-Wolkitie	230	77.45	Sebeta I	413	0	20	500	2000	3500
			Wolkitie	>1200	0	20	500	2000	3500
Tekeze-Mekele	230	47.37	Tekeze	260	0	20	300	600	1000
			Mekele	296	0	20	300	600	1000
Wolkitie-Gibe Old	230	106.58	Wolkitie	>1200	0	20	500	2000	3500
			Gibe Old	519	0	20	500	2000	3500

Table 4. 6: Calculated CCT values of the 230 kV lines and their protection setting

CHAPTER 5: CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK

5.1. Conclusions

The outages of the 400 kV lines don't cause any of the generators to be out of synchronism from the system; and the voltage at 400 kV and 230 kV buses and the system frequency have recovered to the values what their security criteria recommends. However, the voltage at 132 kV buses like Awassa, Dilla and Boculuguma doesn't recover to 0.9 pu within 10 seconds. In general, the voltage profile is not acceptable in most parts of the Southern Region of the system. This area is far from the reactive power sources; and this causes the reactive power to be transmitted long distance which is not possible practically. This results in under voltage problem in the Southern Region of the system. This shows that the system is operating at insecure operating point. On the other hand the Sudanese system would be out of synchronism from the Ethiopian system for occurrence of a short circuit fault on Akaki II-Kaliti I 230 kV line even if the fault is cleared as per the actual protection setting. This confirms that again the system is operating at insecure operating point.

In addition, the zone 2 protection setting of many 400 kV and 230 kV lines is higher than their CCT calculated values. This shows that if a fault occurs on one of those lines while zone 1 and tele-protection systems are out of service for any reason, the system may go to the in extremis state.

The frequency response plots after outage of a generator at different power plants depicts that the frequency returns near to the normal value despite the outage. This indicates that the primary controllers of the generators which are in operation are working properly and the remaining generators are jointly capable of covering the lost generation.

5.2. Recommendations

The voltage profile is not acceptable in most parts of the Southern Region of the system. Therefore, Ethiopian Electric Power need to install reactive power sources like capacitor banks near to the reactive power demand.

The load dispatch center need to re-dispatch the generators in such a way that the total tie-line flow is kept at 148MW and below to keep the Sudanese system in synchronous operation with the Ethiopian system for the operation scenario considered.

The zone 2 protection setting of 400 kV and 230 kV lines considered in this thesis work is higher than their CCT calculated values.

Therefore, Ethiopian Electric Power need to consider revising the zone 2 protection setting of those lines taking into account a good safety margin.

5.3. Suggestions for Future Work

The dynamic security assessment done in this study is based on the assumption that the protection and control systems are going to work as they are supposed to. However, a comprehensive security assessment should also include cases like failure of protection and control systems. A follow-up study should also consider such cases in addition to extreme and multiple contingencies brought about by weather or human error.

The detailed modeling should also include protection and control systems. Measures, such as improved control or improved protection or improved coordination of the operation of these, should be identified that can minimize the chances of extreme contingencies. Moreover a plan to deal with extreme contingencies should be developed and deployed at the control center. A well-planned and rehearsed plan for quick restoration of the system should be developed for the event that all defensive plans fail.

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APPENDICES

Appendix A: Parameters of Transmission Lines

The transmission lines data used in the Ethiopian existing power network PSS/E model of year 2017 is given in Table A.1 to Table A.6.

Table A. 1: Parameters of the 500 kV lines

Name of the Line	Type of Circuit	Type of Conductor	Length [km]	Positive Sequence Data			Zero sequence Data			Rating [MVA]
				R(pu)	X (pu)	B (pu)	R(pu)	X(pu)	B (pu)	
Grand Renaissance-Dedessa	Double	Condor	345	0.003	0.035	3.876027	0.038	0.118	2.2572	3041
Grand Renaissance-Dedessa	Double	Condor	345	0.003	0.035	3.876027	0.038	0.118	2.2572	3041
Dedessa-Holeta	Double	Condor	275	0.003	0.028	3.089586	0.03	0.094	1.7992	3041
Dedessa-Holeta	Double	Condor	275	0.003	0.028	3.089586	0.03	0.094	1.7992	3041

Table A. 2: Parameters of the 400 kV lines

Name of the Line	Type of Circuit	Type of Conductor	Length [km]	Positive Sequence Data			Zero sequence Data			Rating [MVA]
				R (pu)	X (pu)	B (pu)	R(pu)	X (pu)	B (pu)	
Gibe III-W.Sodo	Double	Twin Aster 851	50	0.001	0.0081	0.35653	0.0085	0.0269	0.21272	1973
W.Sodo-Akaki II	Double	Twin Aster 851	267	0.0055	0.0432	1.90389	0.0454	0.1438	1.13591	1973
Akaki II-Sebeta II	Single	Twin Aster 851	33	0.0007	0.0057	0.22078	0.0062	0.0161	0.15909	1973
Sebeta II-Gibe II	Single	Twin Aster 851	183.5	0.00284	0.03776	1.04419	0.03363	0.09511	0.78563	1341
Gibe II-W.Sodo	Single	Twin Aster 851	119	0.0025	0.0207	0.79593	0.0225	0.0579	0.5737	1973
Sebeta II-Holeta	Double	Twin Aster 851	18	0.0004	0.0029	0.12835	0.0031	0.0097	0.07658	1973
Gibe II-G.Gibe	Single	Twin Aster 851	27.89	0.00043	0.00574	0.15868	0.00511	0.01445	0.11939	1341
Beles-B.Dar II	Double	Twin Aster 851	62.8	0.00096	0.01216	0.37713	0.01035	0.03583	0.23811	1341
B.Dar II-D.Markos	Single	Twin Aster 851	193.73	0.003	0.03986	1.10239	0.0355	0.10041	0.82942	1341

D.Markos-Sululta	Double	Twin Aster 851	215.6	0.00334	0.04436	1.22684	0.03951	0.11175	0.92306	1341
D.Markos-G.Guracha	Double	Twin Aster 851	87.5	0.0014	0.018	0.4979	0.016	0.0454	0.3746	1341
G.Guracha-Sululta	Double	Twin Aster 851	131.5	0.002	0.0271	0.7483	0.0241	0.0682	0.563	1341
Sululta-Holeta	Double	Twin Aster 851	31	0.0006	0.005	0.22105	0.0053	0.0167	0.13188	1973
Akaki II-Holeta	Double	Twin Aster 852	49	0.001	0.0079	0.349	0.0083	0.0264	0.20846	1973
Beles-GERD	Single	Twin Aster 853	210	0.0044	0.0366	1.40458	0.0396	0.1022	1.01241	1973

Table A. 3: Parameters of the 230 kV lines

Name of the Line	Type of Circuit	Type of Conductor	Length [km]	Positive Sequence Data			Zero sequence Data			Rating [MVA]
				R (pu)	X (pu)	B (pu)	R (pu)	X (pu)	B (pu)	
Kaliti I-Sebeta I	Single	Mallard	14.26	0.0023	0.011264	0.02069	0.008789	0.03046	0.01384	274
Kaliti I-Akaki II	Double	Twin Ash	4	0.0007	0.003094	0.005952	0.002392	0.008764	0.003914	274
Akaki II-Dukem Tap	Double	Twin Ash	64	0.0104	0.049503	0.095224	0.038272	0.14022	0.062623	74
Dukem Tap-Koka	Double	Twin Ash	33	0.0054	0.025525	0.0491	0.019734	0.072301	0.03229	74
Kaliti I-Bole Lemi	Single	Twin Ash	30.4	0.0065	0.018239	0.058577	0.019754	0.061329	0.035509	402
Bole Lemi-Legetafo	Single	Twin Ash	8.5	0.0018	0.0051	0.016378	0.005523	0.017148	0.009928	402
Legetafo-Combolcha II	Single	Twin Ash	286.89	0.0578	0.176833	0.53458	0.188108	0.563027	0.32674	318
Combolcha II-Alamata	Single	Twin Ash	168	0.034126	0.101275	0.32526	0.10758	0.340539	0.19717	318
Alamata-Ashegoda	Single	Twin Ash	123.69	0.024939	0.07624	0.230477	0.081101	0.242744	0.140871	318
Ashegoda-Mekele	Single	Twin Ash	19	0.003831	0.011711	0.035404	0.012458	0.037288	0.021639	318
Mekele-Tekeze	Double	Twin Ash	105	0.021228	0.062997	0.20232	0.066919	0.211828	0.12265	318
Tekeze-Enda Silassie	Single	Twin Ash	159.55	0.032245	0.09569	0.30732	0.101648	0.321761	0.1863	318
EndaSilassie-Humera	Single	Twin Ash	319	0.068473	0.19139	0.614675	0.207286	0.643555	0.37261	402
Alamata-Mehoni	Single	Twin Ash	42	0.008491	0.025198	0.080926	0.026767	0.084729	0.049056	318
Mehoni-Mekele	Double	Twin Ash	123.69	0.020217	0.059995	0.192681	0.063731	0.201736	0.116799	318
Combolcha II-Semera	Single	Twin Ash	177	0.0357	0.109099	0.329813	0.116055	0.347366	0.201593	318
Semera-Dicheto	Single	Twin Ash	55	0.0111	0.033901	0.10248	0.036062	0.107938	0.06264	318
Alamata-Gashena TP	Single	Twin Ash	102.3	0.0206	0.063056	0.19062	0.067076	0.200766	0.11651	318
Gashena TP-Gashena	Single	Twin Ash	1	0.0002	0.000616	0.00186	0.000656	0.001963	0.00114	318

GashnaTP-N.Mewcha TP	Single	Twin Ash	102.3	0.0206	0.063056	0.19062	0.067076	0.200766	0.11651	318
N.Mewucha Tap-B.Dar II	Single	Twin Ash	136.4	0.027501	0.084074	0.25416	0.089435	0.267687	0.15535	318
N.Mewcha-N.MewchaTP	Single	Twin Ash	1	0.00020	0.00062	0.00186	0.00066	0.00196	0.00114	318
B.Dar II-Mota	Single	Yew	83	0.012781	0.066429	0.12006	0.050467	0.178159	0.08039	280
B.Dar II-Gondar II	Double	Twin Ash	136.97	0.029325	0.084425	0.255224	0.091517	0.268806	0.155997	318
Gondar II-Shehedi	Double	Twin Ash	165	0.033358	0.098995	0.31793	0.105159	0.332873	0.19273	318
Shehedi-Gadarif	Double	Twin Ash	160	0.0343	0.096	0.3083	0.104	0.3228	0.18689	402
Mota-D.Markos	Single	Yew	11.76	0.017209	0.089447	0.16166	0.067955	0.239892	0.10825	280
D.Markos-Fincha	Single	Yew	95.15	0.014652	0.076154	0.13763	0.057855	0.204239	0.09216	280
Fincha-Fincha II	Single	Twin Ash	8.3	0.001673	0.005116	0.01547	0.005442	0.016289	0.00945	318
Fincha-Ghedo	Single	ACAR	67.2	0.010041	0.053852	0.09704	0.04055	0.144299	0.06501	284
Fincha II-Ghedo	Single	Twin Ash	69.72	0.014058	0.042977	0.12992	0.045717	0.136837	0.07941	318
Ghedo-G.Gibe	Single	Mallard	130	0.021099	0.102687	0.1886	0.080127	0.277685	0.12617	274
Ghedo-Gefersa	Single	Yew	133	0.020486	0.106479	0.19244	0.080894	0.285569	0.12886	280
Ghedo-Gefersa	Double	Yew	133	0.020486	0.106479	0.19244	0.080894	0.285569	0.12886	280
Gefersa-Shegole	Double	Twin Ash	8.73	0.001765	0.005238	0.016823	0.005564	0.017612	0.010196	318
Sululta-Shegole	Double	Twin Ash	8	0.001617	0.0048	0.015417	0.005099	0.016139	0.009344	318
Gibe I-G.Gibe	Double	Mallard	5	0.000814	0.003867	0.00744	0.00299	0.010955	0.00489	274
G.Gibe-Wolkitie	Single	Yew	70	0.010779	0.056025	0.10125	0.042563	0.150255	0.0678	280
Wolkitie-Sebeta I	Single	Yew	136	0.020942	0.108849	0.196714	0.082694	0.291924	0.131726	280
Gefersa-Torhailoch TS	Single	Mallard	3.3	0.000573	0.002553	0.00491	0.002009	0.00723	0.003229	274
Sebeta I-Torhailoch TS	Single	Mallard	7.5	0.001302	0.005801	0.011158	0.004566	0.016432	0.007338	274
Sebeta I-Sebeta II	Double	Yew	16	0.002472	0.012543	0.023734	0.009435	0.035222	0.015617	280
G.Gibe-Jimma II	Double	Twin Ash	65.6	0.014081	0.039358	0.126403	0.042627	0.132342	0.076624	402
Jimma II-Agaro	Double	Twin Ash	38.7	0.008307	0.023219	0.07457	0.025147	0.078074	0.045204	402
Agaro-Bedele	Double	Twin Ash	42	0.009015	0.025198	0.080929	0.027292	0.084731	0.049058	402
Bedele-Metu	Double	Twin Ash	90.49	0.018245	0.055777	0.16862	0.059333	0.17759	0.10306	318
Metu-Gambela II	Double	Twin Ash	140	0.029974	0.086293	0.26087	0.093542	0.274753	0.159448	318
Wolkitie-Hossaina	Single	Twin Ash	89.3	0.019119	0.055043	0.166398	0.059666	0.175253	0.101705	318
Hossaina-Alaba	Single	Twin Ash	39.4	0.008435	0.024285	0.073416	0.026325	0.077323	0.044873	402
Sululta-Legetafo	Double	Twin Ash	21	0.0045	0.0126	0.04046	0.0136	0.0424	0.02453	402

Sululta-Chancho	Double	Twin Ash	15	0.0032	0.009	0.0289	0.0097	0.0303	0.01752	402
Wakena-Koka	Double	Redwing	163.86	0.029689	0.127801	0.24166	0.100994	0.360063	0.15934	257
Wakena-Wakena Yugo	Single	Twin Ash	5	0.001073	0.003	0.009635	0.003249	0.010087	0.00584	402
Wakena Yugo-Ramo	Single	Twin Ash	222.39	0.047736	0.133429	0.428524	0.144511	0.448658	0.259767	402
Ramo-Gode	Single	Twin Ash	295.96	0.063526	0.177565	0.570273	0.192313	0.597067	0.345694	402
Koka-Adama II	Single	Twin Ash	10.5	0.0022	0.0065	0.01957	0.007	0.0206	0.01196	402
Koka-Hurso	Double	Mallard	315	0.054691	0.24365	0.468647	0.191767	0.690145	0.308204	274
Koka-Awash7KL	Single	Mallard	129.32	0.02245	0.10003	0.19240	0.07873	0.28333	0.12653	274
Awash7KL-D.Dawa III	Single	Mallard	205	0.03559	0.15857	0.30499	0.12480	0.44914	0.20058	274
D.Dawa III-Hurso	Double	Mallard	28.5	0.00612	0.01710	0.05492	0.01852	0.05750	0.03329	402
Hurso-Adigala	Single	Twin Ash	131	0.02805	0.08075	0.24410	0.08753	0.25709	0.14920	402
Adigala-PK12	Single	Twin Ash	156	0.03340	0.09616	0.29068	0.10423	0.30615	0.17767	402
Hurso-PK12	Single	Twin Ash	300.86	0.06437	0.18551	0.56060	0.20108	0.59044	0.34267	402
Fincha II-Neshe PP	Single	Twin Ash	29.25	0.00590	0.01803	0.05450	0.01918	0.05740	0.03331	318
Sebeta II-Sebeta TS	Double	Yew	1.4	0.00022	0.00110	0.00208	0.00083	0.00308	0.00137	280
D.Birhane-Cotobie II	Single	Tiger	100	0.14955	0.243534	0.0467	0.301362	0.685015	0.02881	82

Table A. 4: Parameters of the 132 kV lines

Name of the Line	Type of Circuit	Type of Conductor	Length [km]	Positive Sequence Data			Zero sequence Data			Rating [MVA]
				R (pu)	X (pu)	B (pu)	R (pu)	X (pu)	B (pu)	
Kaliti I-Gefersa	Single	Tiger	24.75	0.0370	0.0603	0.0116	0.0746	0.1695	0.0071	82
Kaliti I-Addis Center	Single	Tiger	14.35	0.0215	0.0349	0.0067	0.0432	0.0983	0.0041	82
Kaliti II-Kaliti II GIS	Single	Tiger	4	0.0060	0.0097	0.0019	0.0121	0.0274	0.0012	82
Kaliti I-Kaliti II GIS	Single	Tiger	3	0.0045	0.0073	0.0014	0.0090	0.0206	0.0009	82
Kaliti II-Nifas Silk	Double		3	0.0006	0.0036	0.0289	0.0013	0.0023	0.0289	100
Kaliti I-Mekanissa	Single	Tiger	16.16	0.0242	0.0394	0.0076	0.0487	0.1107	0.0047	82
Sebeta I-Gefersa	Single	Tiger	21.9	0.0328	0.0533	0.0102	0.0660	0.1500	0.0063	82
Sebeta I-Mekanissa	Single	Tiger	8.81	0.0132	0.0215	0.0041	0.0266	0.0604	0.0025	82
Mekanissa-A.South II	Single	Ash	5	0.0061	0.0122	0.0024	0.0137	0.0343	0.0015	91
Gefersa-Menilik TS	Single	Tiger	7.11	0.0106	0.0173	0.0033	0.0214	0.0487	0.0020	82

Menilik TS-A.North	Single	Tiger	4	0.0060	0.0097	0.0019	0.0121	0.0274	0.0012	82
Kaliti I-K.North TP	Single	Tiger	1.5	0.0022	0.0037	0.0007	0.0045	0.0103	0.0004	82
K.North TP-Cotobie I	Single	Tiger	19	0.0284	0.0463	0.0088	0.0573	0.1302	0.0055	82
K.North TP-K.North	Single	Tiger	0.44	0.0007	0.0011	0.0002	0.0013	0.0030	0.0001	82
Kaliti I-Akaki II	Single	Tiger	4	0.0060	0.0097	0.0019	0.0121	0.0274	0.0012	82
Kaliti I-Akaki II	Single	Tiger	4	0.0060	0.0097	0.0019	0.0121	0.0274	0.0012	82
Kaliti I-Akaki II	Single	Tiger	4	0.0060	0.0097	0.0019	0.0121	0.0274	0.0012	82
Akaki II-Yesu	Single	Tiger	5	0.0075	0.0122	0.0023	0.0151	0.0343	0.0014	82
Akaki II-E.Geda TP	Single	Tiger	39.3	0.0588	0.0957	0.0184	0.1184	0.2692	0.0113	82
E.Geda-E.Geda TP	Single	Tiger	4.9	0.0073	0.0119	0.0023	0.0148	0.0336	0.0014	82
Akaki II-D.Zeit IITP	Single	Tiger	24.5	0.0366	0.0597	0.0114	0.1184	0.2692	0.0113	82
D.Zeit II-D.Zeit II TP	Single	Tiger	0.1	0.0002	0.0002	0.0000	0.0003	0.0007	0.0000	82
Koka-E.Geda TP	Single	Tiger	23.8	0.0356	0.0580	0.0111	0.0717	0.1630	0.0069	82
Koka-D.Zeit II TP	Single	Tiger	38.6	0.0577	0.0940	0.0180	0.1163	0.2644	0.0111	82
Koka Yesu	Single	Tiger	58.7	0.0878	0.1430	0.0274	0.1769	0.4021	0.0169	82
Yesu-Kanoria TP	Single	Tiger	8	0.0120	0.0195	0.0037	0.0241	0.0548	0.0023	82
Kanoria TP-Koka	Single	Tiger	50.7	0.0758	0.1235	0.0237	0.1528	0.3473	0.0146	82
Kanoria TP-Kanoria	Single	Tiger	1	0.0015	0.0024	0.0005	0.0030	0.0069	0.0003	82
Koka-W.Pulp TP	Single	Tiger	7.36	0.0110	0.0179	0.0034	0.0222	0.0504	0.0021	82
W.Pulp TP-Awash II	Single	Tiger	17.99	0.0269	0.0438	0.0084	0.0542	0.1232	0.0052	82
Koka-Awash II	Single	Tiger	25.35	0.0379	0.0617	0.0118	0.0764	0.1737	0.0073	82
W.Pulp TP-W.Pulp	Single	Tiger	0.6	0.0009	0.0015	0.0003	0.0018	0.0041	0.0002	82
Awash II-Awash III	Single	Tiger	1.45	0.0022	0.0035	0.0007	0.0043	0.0101	0.0004	82
Assela-Wonji SGR TP	Single	Tiger	25.6	0.0383	0.0623	0.0120	0.0771	0.1754	0.0074	82
Awash II-Wonji SGR TP	Single	Tiger	25.6	0.0383	0.0623	0.0120	0.0771	0.1754	0.0074	82
Wonji SGR-WonjSGR TP	Single	Tiger	4	0.0060	0.0097	0.0019	0.0121	0.0274	0.0012	82
Assela-Adamitulu	Single	Tiger	50.96	0.0762	0.1241	0.0238	0.1536	0.3491	0.0147	82
Adamitulu-Shashemene	Single	Tiger	76.83	0.1149	0.1871	0.0359	0.2315	0.5263	0.0221	82
Shashemene-Wakena Yugo	Single	Ostrich	119.2	0.1537	0.2893	0.0560	0.3346	0.8155	0.0345	89
Shashemene-Alaba	Single	Ostrich	63.23	0.0815	0.1535	0.0297	0.1775	0.4326	0.0183	89
Shashemene-Awassa	Single	Tiger	21.6	0.0323	0.0526	0.0101	0.0651	0.1480	0.0062	82

Wakena Yugo-Yadot	Single	Ash	167	0.2043	0.4088	0.0786	0.4578	1.1461	0.0483	91
Awassa-Yirgalem	Single	Tiger	35.09	0.0525	0.0855	0.0164	0.1057	0.2404	0.0101	82
Yirgalem-Dilla	Single	Ash	40	0.0489	0.0979	0.0188	0.1097	0.2745	0.0116	91
Yirgalem-Shakisso	Single	Tiger	133.2	0.1992	0.3244	0.0622	0.4014	0.9125	0.0384	82
Dilla-H.Mariam	Single	Ash	94	0.1150	0.2301	0.0442	0.2467	0.6176	0.0261	91
H.Mariam-Boculuguma	Single	Ash	170	0.2080	0.4161	0.0800	0.4462	1.1170	0.0471	91
Adamitulu-Butajira	Single	Ash	46.78	0.0572	0.1145	0.0220	0.1283	0.3210	0.0135	91
Alaba-Hossaina	Single	Ostrich	39.6	0.0511	0.0961	0.0186	0.1112	0.2709	0.0115	89
Alaba-W.Sodo II	Single	Ostrich	61.81	0.0797	0.1500	0.0291	0.1735	0.4229	0.0179	89
W.Sodo I-A.Minch	Single	Ostrich	109.1	0.1407	0.2649	0.0513	0.3064	0.7466	0.0316	89
W.Sodo I-W.Sodo II	Single	Ostrich	5	0.0064	0.0121	0.0024	0.0140	0.0342	0.0014	89
W.Sodo I-Sawla	Single	Ash	111	0.1358	0.2717	0.0523	0.3043	0.7618	0.0321	91
Hossaina-Gibe Old	Single	Ostrich	70.62	0.0911	0.1714	0.0332	0.1983	0.4832	0.0204	89
Gibe I-Gibe Old	Single	Ostrich	2.6	0.0034	0.0063	0.0012	0.0073	0.0178	0.0008	89
Ghedo-Guder	Single	Ostrich	33.99	0.0438	0.0825	0.0160	0.0954	0.2326	0.0098	89
Ghedo-Nekemte	Single	Ostrich	115.9	0.1494	0.2813	0.0545	0.3254	0.7929	0.0335	89
Nekemte-Ghimbi	Single	Ostrich	84.29	0.1087	0.2046	0.0396	0.2367	0.5767	0.0244	89
Ghimbi-Mendi	Single	Ash	130	0.1591	0.3182	0.0612	0.3564	0.8922	0.0376	91
Mendi-Gidami	Single	Ash	150	0.1949	0.3672	0.0706	0.4226	1.0294	0.0434	115
Nekemte-Gidayana	Single	Ash	93.59	0.1145	0.2291	0.0441	0.2566	0.6423	0.0271	91
Nekemte-Bedele	Single	Ash	116	0.1419	0.2840	0.0546	0.3180	0.7961	0.0336	91
Mendi-Assossa	Single	Ash	80	0.0979	0.1958	0.0377	0.2193	0.5490	0.0232	91
Mekele-Mesobo	Single	Ostrich	5.1	0.0065	0.0123	0.0024	0.0142	0.0346	0.0015	89
Mekele-Wukro TP	Single	Ostrich	31	0.0400	0.0753	0.0146	0.0871	0.2124	0.0090	89
Wukro TP-Wukro	Single	Ostrich	1.17	0.0015	0.0028	0.0006	0.0033	0.0080	0.0003	89
Wukro TP-Adigrat	Single	Ostrich	56.55	0.0729	0.1372	0.0266	0.1588	0.3869	0.0164	89
Mekele-Adwa	Single	Ostrich	116.7	0.1505	0.2833	0.0549	0.3278	0.7987	0.0338	89
Combolcha II-Combolcha I	Single	Ash	11	0.0086	0.0171	0.0033	0.0192	0.0480	0.0020	91
Combolcha II-Kemissie	Single	Tiger	38	0.0568	0.0925	0.0177	0.1145	0.2603	0.0109	82
Kemissie-Shewa Robit	Single	Tiger	87	0.1301	0.2119	0.0406	0.2622	0.5960	0.0251	82
Shewa Robit-D.Birhane	Single	Tiger	57.49	0.0860	0.1400	0.0269	0.1733	0.3938	0.0166	82

D.Birhane-Cotobie II	Single	Tiger	100	0.1496	0.2435	0.0467	0.3014	0.6850	0.0288	82
Cotobie I-Weregenu TP	Single	Tiger	2.5	0.0037	0.0061	0.0012	0.0075	0.0171	0.0007	82
Cotobie I-Ayat GIS	Single	Tiger	4	0.0060	0.0097	0.0019	0.0121	0.0274	0.0012	82
Cotobie II-Ayat GIS	Single	Tiger	4	0.0060	0.0097	0.0019	0.0121	0.0274	0.0012	82
Weregenu-Weregenu TP	Single	Tiger	4.5	0.0067	0.0110	0.0021	0.0136	0.0308	0.0013	82
Weregenu TP-Kaliti I	Single	Tiger	19	0.0284	0.0463	0.0088	0.0573	0.1302	0.0055	82
Cotobie I-Addis East II	Single	Ash	5.46	0.0067	0.0134	0.0026	0.0150	0.0375	0.0016	91
Combolcha I-Akista	Single	Ash	106	0.1297	0.2595	0.0499	0.2906	0.7275	0.0307	91
Akista-A.Ketema	Single	Ash	150.2	0.1838	0.3677	0.0707	0.4118	1.0307	0.0435	91
Jimma I-Jimma II	Single	Ash	3	0.0037	0.0073	0.0014	0.0082	0.0206	0.0009	91
Jimma II-Aba	Single	Ash	44	0.0538	0.1077	0.0207	0.1206	0.3020	0.0127	92
Jimma I-Bonga	Single	Ash	102.3	0.1253	0.2490	0.0488	0.2732	0.7128	0.0315	91
Bonga-Mizan	Single	Ash	88.3	0.1080	0.2162	0.0416	0.2421	0.6060	0.0256	91
Gibe Old-Jimma I	Single	Ostrich	71.32	0.0920	0.1731	0.0335	0.2002	0.4880	0.0206	89
Tis Abay II-B.Dar II	Double	Ash	28.96	0.0355	0.0705	0.0138	0.0774	0.2019	0.0089	91
Bedele-Nekemte	Single	Ash	116	0.1419	0.2840	0.0546	0.3180	0.7961	0.0336	91
Jijiga II-Harar III	Single	Ash	95	0.1234	0.2326	0.0447	0.2676	0.6520	0.0275	91
Harar III-D.Dawa II	Single	Ash	43.8	0.0569	0.1072	0.0206	0.1234	0.3006	0.0127	91
Harar III-Fik	Single	Ash	153.9	0.1883	0.3767	0.0724	0.4219	1.0562	0.0446	91
D.Dawa II-D.Dawa III	Single	Tiger	12.43	0.0186	0.0303	0.0058	0.0375	0.0851	0.0036	82
D.Dawa III-D.Dawa I	Single	Tiger	3.67	0.0055	0.0089	0.0017	0.0111	0.0252	0.0011	82
D.Dawa III-D.Dawa DS	Single	Tiger	3.6	0.0047	0.0088	0.0017	0.0101	0.0247	0.0010	82
Adama I WF-Nazreth II	Single	Tiger	12	0.0068	0.0158	0.0031	0.0139	0.0493	0.0020	82
Metehara-Metehara TP	Single	Tiger	0	0.0000	0.0001	0.0000	0.0000	0.0001	0.0000	82
Nazreth II-Metehara TP	Single	Tiger	88.24	0.1320	0.2149	0.0412	0.2659	0.6044	0.0254	82
Koka-Nazreth II	Single	Tiger	11.48	0.0172	0.0280	0.0054	0.0346	0.0787	0.0033	82
Awash 7KL-Metehara TP	Single	Tiger	29.6	0.0443	0.0721	0.0138	0.0892	0.2029	0.0085	82
Gefersa-Derba TP	Ash	Single	62	0.0759	0.1518	0.0292	0.1700	0.4255	0.0180	91
Muger-Derba TP	Ash	Single	18	0.0220	0.0441	0.0085	0.0493	0.1235	0.0052	91
Derba TP-Derba Cement	Ash	Single	49.45	0.0605	0.1211	0.0233	0.1356	0.3394	0.0143	91
DangoteTP-DangoteCMNT	Ash	Single	40	0.0489	0.0979	0.0188	0.1097	0.2745	0.0116	91

Sululta-Dangote CMNT	Ash	Single	62	0.0806	0.1518	0.0292	0.1747	0.4255	0.0180	115
A.East II-Cotobie I	Ash	Single	5.46	0.0067	0.0134	0.0026	0.0150	0.0375	0.0016	91
A.East II-A.North	Ash	Single	9.94	0.0122	0.0243	0.0047	0.0272	0.0682	0.0029	91

Table A. 5: Parameters of the 66 kV lines

Name of the Line	Type of Circuit	Type of Conductor	Length [km]	Positive Sequence Data			Zero sequence Data			Rating [MVA]
				R (pu)	X (pu)	B (pu)	R (pu)	X (pu)	B (pu)	
B.Dar II-B.Dar I	Single	Merlo	4.52	0.0640	0.0433	0.0005	0.0838	0.1513	0.0003	24
Bahir Dar II-Dangila	Single	Merlo	68.6	0.9715	0.6574	0.0081	1.2721	2.2967	0.0048	24
Bahir Dar I-Woreta	Single	Merlo	51.62	0.7310	0.4947	0.0061	0.9572	1.7282	0.0036	24
Woreta-Gondar II	Single	Merlo	87	1.2320	0.8338	0.0103	1.6133	2.9127	0.0061	24
Gondar I-Gondar II	Single	Merlo	4.31	0.0610	0.0413	0.0005	0.0799	0.1443	0.0003	24
Gondar I-Dabat	Single	Merlo	58.41	0.8271	0.5598	0.0069	1.0832	1.9555	0.0041	24
Dangila-Pawie	Single	Merlo	109	1.5436	1.0446	0.0129	2.0213	3.6492	0.0077	24
D.Markos-Bitchena	Single	Merlo	65.7	0.9304	0.6296	0.0078	1.2183	2.1996	0.0046	24
D.Markos-F.Selam	Single	Merlo	80	1.1329	0.7667	0.0095	1.4835	2.6783	0.0056	24
Alamata-Sekota	Single	Quail	80	0.9219	0.7693	0.0096	1.2725	2.6810	0.0057	27
Alamata-Lalibela	Single	Quail	104.86	1.2083	1.0083	0.0125	1.6679	3.5141	0.0074	27
Alamata-Maychew	Single	Quail	48	0.5531	0.4616	0.0057	0.7635	1.6086	0.0034	27
Combolcha I-Dessie	Double	Merlo	12.69	0.1797	0.1216	0.0015	0.2353	0.4249	0.0009	24
Dessie-Woldia	Single	Merlo	88	1.2462	0.8433	0.0104	1.6319	2.9462	0.0062	24
Adwa-Shire	Single	Penguin	66.4	0.4824	0.6162	0.0082	0.7734	2.2029	0.0048	36
Hara III-Alemaya II	Single	Quail	19	0.2189	0.1827	0.0023	0.3022	0.6367	0.0013	27
Alemaya II-Chelenko	Single	Quail	49.82	0.5741	0.4791	0.0060	0.7924	1.6696	0.0035	27
Harar III-Harar II	Single	Merlo	7	0.0991	0.0671	0.0008	0.1298	0.2344	0.0005	24
Awash 7KL-Nuraera	Single	Merlo	103	1.4586	0.9871	0.0122	1.9100	3.4484	0.0073	24
Awash 7KL-Amibara	Single	Merlo	42.6	0.6033	0.4083	0.0051	0.7900	1.4262	0.0030	24
A.Teferi-Bedessa	Single	Merlo	24	0.3399	0.2300	0.0028	0.4451	0.8035	0.0017	24
Mizan-Tepi	Single	Quail	30.15	0.3474	0.2899	0.0036	0.4796	1.0104	0.0021	27

Metu-Sor	Single	Merlo	24	0.3399	0.2300	0.0028	0.4451	0.8035	0.0017	24
Metu-Gambela I	Single	Merlo	146	2.0675	1.3992	0.0173	2.7074	4.8880	0.0103	24
Gambela I-Dembidolo	Single	Merlo	64	0.9063	0.6133	0.0076	1.1868	2.1427	0.0045	24
Gambela II-Gambela I	Single	Merlo	2	0.0283	0.0192	0.0002	0.0371	0.0670	0.0001	24
Wolkitie-Wolisso	Single	Quail	39.17	0.4514	0.3767	0.0047	0.6230	1.3127	0.0028	27
Wakena Yugo-Gobessa	Single	Quail	74.2	0.8550	0.7135	0.0089	1.1802	2.4866	0.0052	27
Wakena Yugo-B.Robe	Single	ACSR 70/12	72.89	0.8168	0.6922	0.0088	1.1363	2.4340	0.0052	27
Shakisso-N.Borena	Single	Quail	113.9	1.3125	1.0953	0.0136	1.8117	3.8170	0.0081	27
Gefersa-Fitche	Single	Merlo	96	1.3595	0.9200	0.0114	1.7802	3.2140	0.0068	24
Fincha-FinchaSGR I	Single	Racoon	11	0.1081	0.1045	0.0013	0.1563	0.3673	0.0008	30
FinchaSGR I-FinchaSGR II	Single	Racoon	15.4	0.1514	0.1463	0.0019	0.2189	0.5143	0.0011	30

Table A. 6: Parameters of the 45 kV lines

Name of the Line	Type of Circuit	Type of Conductor	Length [km]	Positive Sequence Data			Zero sequence Data			Rating [MVA]
				R (pu)	X (pu)	B (pu)	R (pu)	X (pu)	B (pu)	
Harar I-Babile	Single	Merlo	24	0.7311	0.4886	0.00134	0.95754	1.74033	0.00079	17
Akaki-Kaliti I	Single	Raven	3	0.0889	0.0623	0.00017	0.11720	0.21882	0.00010	17
Kaliti I-Akaki SP	Double	Merlo	6	0.1828	0.1243	0.00033	0.22558	0.43680	0.00018	17
Sebeta I-A.West I	Single	Raven	6.81	0.2018	0.1415	0.00038	0.26605	0.49672	0.00022	17
Sebeta I-A.West II	Single	Raven	6.2	0.1837	0.1289	0.00034	0.24222	0.45223	0.00020	17
Sebeta I-Gedja	Single	Merlo	23	0.7006	0.4682	0.00129	0.91764	1.66782	0.00076	17
Gefersa-A.Alem	Single	Raven	29.64	0.8783	0.616	0.00164	1.15797	2.16195	0.00097	17
Koka-Modjo	Single	Raven	17.4	0.5156	0.3616	0.00096	0.67978	1.26916	0.00057	17
Cotobie-A.East I	Single	Raven	5.96	0.1766	0.1239	0.00033	0.23285	0.43472	0.00020	17

Appendix B: Parameters of Transformers

The parameters of transformers used in the Ethiopian existing power network PSS/E model of year 2017 are given in Table B.1 to Table B.2.

Table B. 1: Parameters of the two winding transformers

Substation Name	Type of Transformer (kV/kV)	Id	R (pu)	X (pu)	Rating (MVA)	Magnetizing G (watts)	Magnetizing B (pu)	Winding MVA Base	R01 (pu)	X01 (pu)
Mendi	132/33	1	0.0059	0.137	20	0	0	25	0.0047	0.1090
A.East II	132/15	1	0.0033	0.081	20	15000	0.00226	20	0.0026	0.0650
A.East II	132/15	2	0.0034	0.081	20	15030	0.00214	20	0.0027	0.0650
Cotobie I	132/15	1	0.007	0.12	12	11800	0.00249	12	0.0056	0.0960
Cotobie I	132/15	1	0.0046	0.103	25	21300	0.002	25	0.0037	0.0820
Sululta	132/230	1	0.0021	0.076	33	30000	0.004	63	0.0017	0.0610
Sululta	132/230	2	0.0021	0.076	33	30000	0.004	63	0.0017	0.0610
Sululta	132/66	1	0.0047	0.109	20	0	0	20	0.0038	0.0870
B.Weregenu	132/15	1	0.003843	0.099926	40	0	0	40	0.0031	0.0799
B.Weregenu	132/15	2	0.003843	0.099926	40	0	0	40	0.0031	0.0799
Cotobie II	132/230	1	0.00365	0.135	125	20000	0.0028	125	0.0038	0.0960
Cotobie II	132/230	2	0.00365	0.135	125	20000	0.0028	125	0.0038	0.0960
Cotobie II	132/15	1	0.004163	0.099913	31.5	21890	0.004	31.5	0.0033	0.0799
Cotobie II	132/15	2	0.004163	0.099913	31.5	21890	0.004	31.5	0.0033	0.0799
Ayat GIS	132/15	1	0.0034	0.081	20	15030	0.00214	20	0.0027	0.0650
Ayat GIS	132/15	2	0.0034	0.081	20	15030	0.00214	20	0.0027	0.0650
D.Dawa I	132/15	3	0.004163	0.099913	31.5	21890	0.004	31.5	0.0033	0.0799
D.Dawa I	132/15	4	0.004163	0.099913	31.5	21890	0.004	31.5	0.0033	0.0799
Fik	132/33	1	0.0047	0.109	20	0	0	20	0.0038	0.0870
Hurso	132/230	1	0.00365	0.135	125	0	0	125	0.0029	0.1080
Hurso	132/230	2	0.00365	0.135	125	0	0	125	0.0029	0.1080
A.Ketema	132/33	1	0.0064	0.08	12	0	0	9.6	0.0051	0.0640

Shewa Robit	132/15	1	0.0085	0.08	6.3	5600	0.00225	6.3	0.0068	0.0640
Combolcha II	132/230	1	0.0047	0.12	63	0	0	63	0.0038	0.0960
A.North	132/15	1	0.0043	0.098	20	17900	0.002	20	0.0034	0.0790
A.North	132/15	2	0.0043	0.098	20	17900	0.002	20	0.0034	0.0790
Geferssa	132/230	1	0.00365	0.135	125	20000	0.0028	125	0.0027	0.1650
Geferssa	132/230	2	0.00365	0.135	125	20000	0.0028	125	0.0027	0.1650
Geferssa	132/230	3	0.00365	0.135	125	20000	0.0028	125	0.0027	0.1650
Geferssa	132/230	4	0.00365	0.135	125	20000	0.0028	125	0.0027	0.1650
Geferssa	132/15	1	0.0036	0.097	31.5	18354	0.00081	25	0.0029	0.0780
Ghedo	132/33	1	0.0064	0.08	9.6	0	0	9.6	0.0051	0.0640
Guder	132/15	1	0.0061	0.079	12	0	0	12	0.0049	0.0630
Guder	132/15	2	0.0061	0.079	12	0	0	12	0.0049	0.0630
Muger	132/15	1	0.0069	0.119	12	13000	0.0053	12	0.0055	0.0950
Muger	132/15	2	0.0069	0.119	12	13000	0.0053	12	0.0055	0.0950
Menilik TS	132/15	1	0.003633	0.079917	25	0	0	25	0.0029	0.0639
Menilik TS	132/15	2	0.003633	0.079917	25	0	0	25	0.0029	0.0639
Adigrat	132/33	1	0.0064	0.08	12	0	0	9.6	0.0051	0.0640
Alamata	132/33	1	0.0034	0.105	20	20380	0.0019	20	0.0027	0.0840
Mosobo	132/6.3	1	0.0038	0.08	20	13000	0.0025	16	0.0031	0.0640
Mosobo	132/6.3	1	0	0.1	45	0	0	45	0.0019	0.0680
Wukiro	132/15	1	0.0031	0.081	20	18258	0.00312	20	0.0025	0.0650
Mekele-IDL	132/230	1	0.0032	0.119	63	30000	0.004	63	0.0025	0.0950
Awash-7KL	132/230	1	0.00365	0.135	125	18192	0.00079	125	0.0029	0.1080
Awash-7KL	132/230	2	0.00365	0.135	125	18192	0.00079	125	0.0029	0.1080
Adamitulu	132/15	5	0.003633	0.079917	25	0	0	25	0.0029	0.0639
Assela	132/15	1	0.0069	0.119	25	13000	0.0053	12	0.0055	0.0950
Awash II	132/15	1	0.0031	0.082	25	18258	0.00312	20	0.0025	0.0650
E.Geda	132/15	1	0.007	0.12	12	11592	0.0021	12	0.0056	0.0960
Metehara	132/15	1	0.004	0.099	20	0	0	18	0.0032	0.0790
Nazret II	132/15	1	0.0036	0.097	20	19090	0.0011	20	0.0029	0.0780
Nazret II	132/15	2	0.0036	0.097	20	19090	0.0011	20	0.0029	0.0780

M.Wakena Yugo	132/230	1	0.0032	0.119	54	30000	0.004	63	0.0025	0.0950
M.Wakena Yugo	132/230	2	0.0032	0.119	54	30000	0.004	63	0.0026	0.0952
Wonji Pulp	132/15	1	0.0047	0.08	20	14700	0.00779	16	0.0037	0.0640
Adama I	132/33	1	0.0075	0.15	63	20000	0.0028	63	0.0075	0.1241
Wonji SGR	132/11	1	0.0059	0.137	25	0	0	25	0.0047	0.1090
A.Center	132/15	6	0.0046	0.103	31.5	21300	0.002	25	0.0037	0.0820
A.Center	132/15	8	0.0046	0.103	31.5	21300	0.002	25	0.0037	0.0820
A.South II	132/15	1	0.0036	0.097	20	19090	0.0011	20	0.0029	0.0780
A.South II	132/15	2	0.0036	0.097	20	19090	0.0011	20	0.0029	0.0780
D.Zeit II	132/15	3	0.0036	0.097	20	19090	0.0011	20	0.0029	0.0780
D.Zeit II	132/15	1	0.0046	0.103	25	21300	0.002	25	0.0037	0.0820
D.Zeit II	132/15	2	0.0046	0.103	25	21300	0.002	25	0.0037	0.0820
Kaliti I	132/230	1	0.00365	0.135	125	20000	0.0028	125	0.0027	0.1650
Kaliti I	132/230	2	0.00365	0.135	125	20000	0.0028	125	0.0027	0.1650
Kaliti I	132/230	3	0.00365	0.135	125	20000	0.0028	125	0.0027	0.1650
K.North	132/15	3	0.004163	0.099913	31.5	0	0	31.5	0.0033	0.0799
K.North	132/15	4	0.004163	0.099913	31.5	0	0	31.5	0.0033	0.0799
Kaliti II	132/15	2	0.003633	0.079917	20	0	0	25	0.0029	0.0639
Kaliti II	132/15	3	0.003633	0.079917	20	0	0	25	0.0029	0.0639
Mekanisa	132/15	6	0.0036	0.079	16	17340	0.002	16	0.0028	0.0630
Mekanisa	132/15	1	0.0058	0.12	40	18546	0.00083	40	0.0047	0.0960
Yesu	132/15	1	0.0066	0.086	10	0	0	10	0.0053	0.0690
Yesu	132/15	6	0.0046	0.103	25	21300	0.002	25	0.0037	0.0820
Akaki II	132/230	1	0.00365	0.135	125	0	0	125	0.0029	0.1080
Akaki II	132/230	2	0.00365	0.135	125	0	0	125	0.0029	0.1080
Akaki II	132/230	3	0.00365	0.135	125	0	0	125	0.0029	0.1080
Akaki II	132/15	3	0.003791	0.109935	50	11909	0.0044	50	0.0030	0.0879
Akaki II	132/15	1	0.004163	0.099913	31.5	0	0	31.5	0.0033	0.0799
Nefasilk	132/15	2	0.004163	0.099913	31.5	0	0	31.5	0.0033	0.0799
Dangote	132/11	1	0.0059	0.137	25	0	0	25	0.0047	0.1090
Dangote	132/11	2	0.0059	0.137	25	0	0	25	0.0047	0.1090

Kanoria	132/11	1	0.0036	0.079	16	17340	0.002	16	0.0028	0.0630
Kaliti II GIS	132/15	1	0.003633	0.079917	25	0	0	25	0.0029	0.0639
Kaliti II GIS	132/15	2	0.003633	0.079917	25	0	0	25	0.0029	0.0639
Arbaminch	132/15	1	0.0035	0.078	16	12132	0.00483	16	0.0028	0.0620
Arbaminch	132/15	2	0.003995	0.0799	20	0	0	20	0.0032	0.0639
Alaba	132/15	2	0.003633	0.079917	16	0	0	20	0.0029	0.0639
Awassa	132/15	3	0.004163	0.099913	25	0	0	31.5	0.0033	0.0799
Awassa	132/15	4	0.004163	0.099913	25	0	0	31.5	0.0033	0.0799
Beculuguma	132/33	1	0.0059	0.137	20	0	0	25	0.0047	0.1090
Hossaina	132/230	1	0.003547	0.109943	63	0	0	63	0.0028	0.0880
Hossaina	132/230	2	0.003547	0.109943	63	0	0	63	0.0028	0.0880
Shashemene	132/15	1	0.0035	0.081	20	15460	0.00134	20	0.0028	0.0640
Shakisso	132/33	1	0.0059	0.137	20	0	0	25	0.0047	0.1090
W.Sodo II	132/400	1	0.00293	0.135	250	0	0	250	0.0023	0.1080
W.Sodo II	132/15	2	0.0034	0.079	40	19044	0.00252	20	0.0027	0.0630
Yadot	132/33	1	0.0047	0.109	20	0	0	20	0.0038	0.0870
Key Afer	132/33	1	0.003995	0.0799	20	0	0	20	0.0032	0.0639
W.Sodo I	132/66	1	0.0069	0.119	25	13000	0.0053	12	0.0055	0.0950
W.Sodo I	132/15	1	0.0036	0.079	16	17340	0.002	16	0.0028	0.0630
Sebeta I	132/230	1	0.00365	0.135	125	20000	0.0028	125	0.0027	0.1650
Sebeta I	132/230	2	0.00365	0.135	125	20000	0.0028	125	0.0027	0.1650
Sebeta I	132/230	3	0.00365	0.135	125	20000	0.0028	125	0.0027	0.1650
Sebeta I	132/15	1	0.0058	0.12	50	18546	0.00083	40	0.0047	0.0960
Sebeta I	132/15	2	0.0058	0.12	50	18546	0.00083	40	0.0047	0.0960
Alaba	132/15	1	0.0045	0.1	25	0	0	25	0.0036	0.0800
Agaro	132/230	1	0.003547	0.109943	63	0	0	63	0.0028	0.0880
Bedele	132/230	1	0.003869	0.119938	63	0	0	63	0.0031	0.0960
Bedele	132/15	2	0.0069	0.119	12	13000	0.0053	12	0.0055	0.0950
Bedele	132/33	1	0.0047	0.109	20	0	0	20	0.0038	0.0870
G.Gibe	132/15	1	0.0085	0.081	6.3	5600	0.00225	6.3	0.0068	0.0640
G.Gibe I	132/230	1	0.0039	0.117	30	11840	0.00052	40	0.0031	0.0936

Gida Ayana	132/33	1	0.0047	0.109	20	0	0	20	0.0038	0.0870
Gida Ayana	132/33	2	0.0047	0.109	20	0	0	20	0.0038	0.0870
Jimma I	132/15	1	0.0036	0.079	16	17340	0.002	16	0.0028	0.0630
Nekempte	132/15	1	0.0035	0.08	20	18913	0.00237	20	0.0028	0.0640
Nekempte	132/33	1	0.0034	0.079	20	19044	0.00252	20	0.0027	0.0630
Jimma II	132/230	1	0.003547	0.109943	63	0	0	63	0.0028	0.0880
Jimma II	132/230	2	0.003547	0.109943	63	0	0	63	0.0028	0.0880
Jimma II	132/15	1	0.0047	0.109	20	0	0	20	0.0038	0.0870
Sululta	230/400	1	0.0018	0.121	133	80000	0.00049	250	0.0014	0.0960
Sululta	230/400	2	0.0018	0.121	133	80000	0.00049	250	0.0014	0.0960
Sululta	230/400	3	0.0018	0.121	133	80000	0.00049	250	0.0014	0.0960
Bole Lemi	230/400	1	0.00365	0.135	125	0	0	125	0.0029	0.1080
Bole Lemi	230/33	2	0.00365	0.135	125	0	0	125	0.0029	0.1080
G.Guracha	230/400	1	0.00293	0.135	250	0	0	250	0.0023	0.1080
G.Guracha	230/400	2	0.00293	0.135	250	0	0	250	0.0023	0.1080
G.Guracha	230/33	1	0.003791	0.109935	50	0	0	50	0.0030	0.0879
G.Guracha	230/33	2	0.003791	0.109935	50	0	0	50	0.0030	0.0879
Adigala	230/33	1	0.0035	0.078	20	22474	0.00137	20	0.0028	0.0630
B.Dar II	230/400	3	0.00293	0.135	133	0	0	250	0.0023	0.1080
B.Dar II	230/400	4	0.00293	0.135	133	0	0	250	0.0023	0.1080
D.Markos	230/400	1	0.0018	0.121	133	0	0	250	0.0014	0.0960
D.Markos	230/400	2	0.0018	0.121	133	0	0	250	0.0014	0.0960
Metema	230/33	1	0.0041	0.124	20	17790	0.0019	20	0.0033	0.0990
Mota	230/33	1	0.003	0.084	20	20960	0.00306	20	0.0024	0.0670
Fincha	230/13.8	1	0.0027	0.069	40.3	45700	0.0073	24.2	0.0021	0.0560
Fincha	230/13.8	1	0.0027	0.069	40.3	45700	0.0073	24.2	0.0021	0.0560
Fincha	230/13.8	1	0.0027	0.069	40.3	45700	0.0073	24.2	0.0021	0.0560
Fincha	230/13.8	1	0.0027	0.069	40.3	45700	0.0073	24.2	0.0021	0.0920
Neshe	230/13.8	1	0.0062	0.124	60	0	0	60	0.0050	0.0990
Neshe	230/13.8	1	0.0062	0.124	60	0	0	60	0.0050	0.0990
Humera	230/33	1	0.0076	0.13	20	0	0	20	0.0061	0.1040

Tekeze	230/13.8	1	0.0032	0.135	90	54500	0.0026	90	0.0026	0.1080
Tekeze	230/13.8	1	0.0032	0.135	90	54500	0.0026	90	0.0026	0.1080
Ashegoda	230/33	1	0	0.1	65	0	0	113	0.0000	0.0800
Ashegoda	230/33	2	0	0.1	65	0	0	113	0.0000	0.0800
Dicheto	230/33	1	0.0041	0.124	20	17790	0.0019	20	0.0033	0.0990
Semera	230/33	1	0.0041	0.124	20	17790	0.0019	20	0.0033	0.0990
Wakena	230/13.8	1	0	0.1	47	0	0	45	0.0038	0.0880
Wakena	230/13.8	1	0.0048	0.11	45	45000	0.005	45	0.0038	0.0880
Wakena	230/13.8	1	0.0048	0.11	45	45000	0.005	45	0.0038	0.0880
Wakena	230/13.8	1	0.0048	0.11	45	45000	0.005	45	0.0038	0.0880
Adama II	230/33	1	0.00361	0.12995	90	0	0	90	0.0029	0.1040
Adama II	230/33	2	0.00361	0.12995	90	0	0	90	0.0029	0.1040
Akaki II	230/400	1	0.00293	0.135	500	0	0	500	0.0023	0.1080
Akaki II	230/400	2	0.00293	0.135	500	0	0	500	0.0023	0.1080
Akaki II	230/400	3	0.00293	0.135	500	0	0	500	0.0023	0.1080
Dukem TP II	230/33	1	0.003547	0.109943	63	0	0	63	0.0028	0.0880
Dukem TP II	230/33	1	0.003547	0.109943	63	0	0	63	0.0028	0.0880
Sebeta II	230/400	1	0.0018	0.121	133	80000	0.00049	250	0.0014	0.0960
Sebeta II	230/400	2	0.0018	0.121	133	80000	0.00049	250	0.0014	0.0960
Sebeta II	230/400	3	0.00293	0.135	250	0	0	250	0.0023	0.1080
Sebeta II	230/33	1	0.0075	0.099	25	20700	0.0011	20	0.0060	0.0790
Torhailoch TS	230/15	1	0.003633	0.079917	25	0	0	25	0.0029	0.0639
Torhailoch TS	230/15	2	0.003633	0.079917	25	0	0	25	0.0029	0.0639
Gibe I	230/13.8	1	0.0021	0.088	73	33880	0.005	51	0.0017	0.0700
Gibe I	230/13.8	1	0.0021	0.088	73	33880	0.005	51	0.0017	0.0700
Gibe I	230/13.8	1	0.0021	0.088	73	33880	0.005	51	0.0017	0.0700
G.Gibe	230/400	1	0.0018	0.121	133	80000	0.00049	250	0.0014	0.0960
G.Gibe	230/400	2	0.0018	0.121	133	80000	0.00049	250	0.0014	0.0960
Beles	400/15	1	0.0022	0.135	133	80000	0.0008	133	0.0017	0.1080
Beles	400/15	1	0.0022	0.135	133	80000	0.0008	133	0.0017	0.1080
Beles	400/15	1	0.0022	0.135	133	80000	0.0008	133	0.0017	0.1080

Beles	400/15	1	0.0022	0.135	133	80000	0.0008	133	0.0017	0.1080
Holeta	400/500	6	0.00293	0.135	750	0	0	750	0.0023	0.1080
Holeta	400/500	7	0.00293	0.135	750	0	0	750	0.0023	0.1080
G.Gibe II	400/15	1	0.0023	0.144	125	65352	0.0008	125	0.0018	0.1150
G.Gibe II	400/15	1	0.0023	0.144	125	65352	0.0008	125	0.0018	0.1150
G.Gibe II	400/15	1	0.0023	0.144	125	65352	0.0008	125	0.0018	0.1150
G.Gibe II	400/15	1	0.0023	0.144	125	65352	0.0008	125	0.0018	0.1150
Gibe III	400/15	1	0	0.1	441	0	0	441	0.0000	0.0800
Gibe III	400/15	1	0	0.1	441	0	0	441	0.0000	0.0800
Gibe III	400/15	1	0	0.1	441	0	0	441	0.0000	0.0800
Gibe III	400/15	1	0	0.1	441	0	0	441	0.0000	0.0800
Gibe III	400/15	1	0	0.1	441	0	0	441	0.0000	0.0800
Alemaya II	66/15	1	0.0059	0.071	6.3	5380	0.0018	6.3	0.0047	0.0570
Alemaya II	66/33	1	0.0052	0.065	9.6	0	0	9.6	0.0042	0.0520
A.Teferi	66/33	1	0.0048	0.081	12	0	0	12	0.0038	0.0650
A.Teferi	66/15	1	0.0084	0.067	3	0	0	3	0.0067	0.0540
A.Teferi	66/15	2	0.0071	0.057	1.5	0	0	1.5	0.0057	0.0460
Chelenko	66/33	4	0.005322	0.079823	9.6	0	0	9.6	0.0043	0.0639
Chelenko	66/15	1	0.0052	0.065	6.3	0	0	6.3	0.0042	0.0520
Harar II	66/15	1	0.006	0.082	6.3	6830	0.0062	6.3	0.0048	0.0660
Harar II	66/15	2	0.006	0.082	6.3	6830	0.0062	6.3	0.0048	0.0660
Harar II	66/15	3	0.006	0.082	6.3	6830	0.0062	6.3	0.0048	0.0660
Harar III	66/15	1	0.0058	0.072	9.6	8299.998	0.0013	9.6	0.0046	0.0580
Gambela	66/15	1	0.006	0.082	6.3	6830	0.0062	6.3	0.0048	0.0660
Metu	66/33	1	0.0054	0.075	6.3	6500	0.007	6.3	0.0043	0.0600
Dessie	66/15	1	0.006965	0.069653	12	3600	0.004	12	0.0056	0.0557
Dessie	66/15	2	0.006965	0.069653	12	3600	0.004	12	0.0056	0.0557
Lalibela	66/15	1	0.0048	0.068	6.3	5380	0.0018	6.3	0.0038	0.0550
Sekota	66/15	1	0.0048	0.068	6.3	5380	0.0018	6.3	0.0038	0.0550
B.Dar I	66/45	1	0.0027	0.034	9.6	4077	0.002	9	0.0022	0.0270
B.Dar II	66/33	1	0.0052	0.065	9.6	0	0	9.6	0.0042	0.0520

Bitchena	66/15	3	0.005322	0.079823	9.6	0	0	9	0.0043	0.0639
Bitchena	66/15	4	0.005322	0.079823	9.6	0	0	9	0.0043	0.0639
Dangla	66/15	1	0.006	0.082	6.3	6830	0.0062	6.3	0.0048	0.0660
Dangla	66/15	2	0.006	0.082	6.3	6830	0.0062	6.3	0.0048	0.0660
D.Markos	66/33	4	0.005322	0.079823	9.6	0	0	9	0.0043	0.0639
F.Selam	66/15	3	0.005322	0.079823	9.6	0	0	9	0.0043	0.0639
F.Selam	66/15	4	0.005322	0.079823	9.6	0	0	9	0.0043	0.0639
Gondar I	66/15	1	0.0067	0.074	6.3	6247.998	0.0073	6.3	0.0053	0.0590
Woreta	66/15	1	0.0067	0.074	6.3	6214	0.0076	6.3	0.0053	0.0590
Woreta	66/15	4	0.0067	0.074	6.3	6214	0.0076	6.3	0.0053	0.0590
Fincha SGII	66/15	1	0.0073	0.071	7	5111	0.00186	7	0.0058	0.0570
Fincha SGII	66/15	1	0.005322	0.079823	9.6	0	0	9.6	0.0043	0.0639
Fincha SGII	66/15	1	0.005322	0.079823	16	0	0	16	0.0043	0.0639
Adwa	66/15	1	0.006965	0.069653	12	3600	0.004	12	0.0056	0.0557
Maychew	66/15	1	0.004698	0.079862	12	0	0	12	0.0038	0.0639
Endasilassie	66/33	1	0.0054	0.08	6.3	0	0	6.3	0.0043	0.0640
Amibara	66/15	1	0.0093	0.069	3	5500	0.013	3	0.0074	0.0560
B.Robe	66/15	1	0.0078	0.066	6	6281	0.0127	6	0.0062	0.0530
B.Robe	66/15	2	0.005322	0.079823	9.6	0	0	9.6	0.0043	0.0639
Gobessa	66/33	1	0.0054	0.075	6.3	6500	0.007	6.3	0.0043	0.0600
Woliso	66/15	1	0.0063	0.064	3	3319.998	0.0071	3	0.0050	0.0520
Woliso	66/15	2	0.0063	0.064	3	3319.998	0.0071	3	0.0050	0.0520
Woliso-33	66/33	1	0.0052	0.065	9.6	0	0	9.6	0.0042	0.0520
Wolkitie	66/15	1	0.009	0.09	6.3	7112	0.002	6.3	0.0072	0.0720
Mizan	66/15	1	0.006	0.082	6.3	6830	0.0062	6.3	0.0048	0.0660
A.East I	45/15	2	0.0051	0.073	6	8899.998	0.00662	6	0.0041	0.0580
A.East I	45/15	1	0.0051	0.072	12	8449.996	0.00673	6	0.0041	0.0580
Babilie	45/15	1	0.009	0.059	3	2500	0.0082	3	0.0072	0.0470
Hara I	45/15	1	0.0059	0.071	6.3	5120	0.0016	6.3	0.0047	0.0570
B.Dar I	45/15	1	0.0064	0.07	4.8	0	0	4.8	0.0051	0.0560
B.Dar I	45/15	2	0.0064	0.07	4.8	0	0	4.8	0.0051	0.0560

Modjo	45/15	1	0.00563	0.061	12	9720	0.0041	9	0.0043	0.0490
Akaki	45/15	1	0.0046	0.06	12	9870	0.0049	9	0.0037	0.0480
Akaki SP	45/15	1	0.008	0.08	6	9000	0.01	6	0.0064	0.0640
Akaki SP	45/15	2	0.008	0.08	6	9000	0.01	6	0.0064	0.0640
Dukem	45/15	1	0.0082	0.06	3	3690	0.0106	3	0.0066	0.0480
Dukem	45/15	2	0.0082	0.06	3	3692.999	0.0106	3	0.0066	0.0480
A.Wset I	45/15	1	0.0047	0.06	12	9720	0.0041	9	0.0037	0.0480
A.West II	45/15	1	0.00563	0.061	12	9720	0.0041	9	0.0043	0.0490
Gedja	45/15	2	0.00563	0.061	12	9720	0.0041	9	0.0043	0.0490

Table B. 2: Parameters of the three winding transformers

Name of Substation	Rated Voltage of Windings (kV/kV/kV)	Ratings of Windings (MVA/MV A/MVA)	Id	W1-2 R(pu)	W1-2 X(pu)	W2-3 R(pu)	W2-3 X(pu)	W3-1 R(pu)	W3-1 X(pu)	W1-2 MVA Base	W2-3 MVA Base	W3-1 MVA Base	R01 (pu)	X01 (pu)	R02 (pu)	X02 (pu)	R03 (pu)	X03 (pu)
Assosa	132/33/15	25/12/12.0	1	0.004	0.1056	0.0042	0.0648	0.0041	0.1767	25	12	25	-0.0013	0.2946	0.0173	0.1278	0.0177	0.4122
Ghimbi	132/33/15	25/12.5/12.5	1	0.004	0.1056	0.0042	0.0648	0.0041	0.1767	25	12	25	-0.0013	0.2946	0.0173	0.1278	0.0177	0.4122
Cotobie I	132/45/15	16/16/5.3	1	0.00798	0.119755	0.001	0.015327	0.002193	0.049995	12	12	4	0.056496	1.060054	0.010004	-0.062096	-0.001671	0.189821
D.Birhane	132/33/15	16/8/8.0	1	0.003917	0.084	0.002394	0.0216	0.001886	0.0682	16	16	16	0.010653	0.408125	0.013828	0.116875	0.001134	0.018125
D.Birhane	132/33/15	25/20/20	1	0.00773	0.17	0.00473	0.104	0.001	0.065	20	16	20	0.007044	0.2625	0.031606	0.5875	-0.002044	0.0625
Suhulta	132/33/15	50/25/25	1	0.00344	0.1032	0.005893	0.1768	0.00232	0.0696	50	25	25	-0.003707	-0.1112	0.010587	0.3176	0.012987	0.3896
A.Teferi	132/66/15	25/15/10	1	0.0031	0.0657	0.0021	0.0229	0.0024	0.0693	25	15	25	0.004	0.193667	0.0084	0.069133	0.0056	0.083533
A.Teferi	132/66/15	25/15/10	2	0.0031	0.0657	0.0021	0.0229	0.0024	0.0693	25	15	25	0.004	0.193667	0.0084	0.069133	0.0056	0.083533
Harar III	132/66/33	25/25/12	1	0.00384	0.079908	0.0017	0.02402	0.0024	0.068918	20	9.6	9.6	0.013246	0.433614	0.005954	-0.034074	0.011754	0.284282
Harar III	132/66/33	25/25/12	2	0.00379	0.07991	0.00167	0.023942	0.00239	0.069239	20	9.6	9.6	0.013225	0.435697	0.005725	-0.036147	0.011671	0.285542
Hurso	132/33/15	50/25/25	1	0.05249	1.04869	0.151245	3.02122	0.09125	1.82272	100	100	100	-0.003753	-0.074905	0.056243	1.123595	0.095003	1.897625
Jijiga II	132/33/15	25/25/12	1	0.004	0.0833	0.0018	0.021517	0.002394	0.068158	20	9.6	20	0.00661	0.266577	0.01339	0.149923	0.00536	0.074213
Combolcha I	132/66/15	40/20/20	8	0.003846	0.10004	0.0025	0.05002	0.005	0.1	40	20	20	0.011058	0.25	-0.001443	0	0.013942	0.25
Combolcha I	132/66/15	40/20/20	9	0.003846	0.10004	0.0025	0.05002	0.005	0.1	40	20	20	0.011058	0.25	-0.001443	0	0.013942	0.25
Shewa Robit	132/33/15	16/16/8	1	0.003917	0.084	0.002394	0.0216	0.001886	0.0682	16	16	16	0.010653	0.408125	0.013828	0.116875	0.001134	0.018125
Kemissie	132/33/15	25/25/12	2	0.004	0.0833	0.0018	0.021517	0.002394	0.068158	20	9.6	20	0.00661	0.266577	0.01339	0.149923	0.00536	0.074213
Derba	132/33/6.3	50/5/45	1	0.00455	0.1	0.006	0.06	0.00682	0.15	50	5	45	-0.047872	-0.333333	0.056972	0.533333	0.063028	0.666667
Derba	132/33/6.3	50/5/45	2	0.00455	0.1	0.006	0.06	0.00682	0.15	50	5	45	-0.047872	-0.333333	0.056972	0.533333	0.063028	0.666667
Gefersa	132/66/15	25/25/25	1	0.00451	0.078671	0.00359	0.056887	0.00456	0.14753	20	20	20	0.0137	0.423285	0.00885	-0.02993	0.0091	0.314365

Gefersa	132/45/15	35/10/25	1	0.00477	0.114301	0.0022	0.014939	0.00228	0.057054	18	6	6	0.013917	0.668461	0.012583	-0.033456	0.024083	0.282439
Gefersa	132/33/15	30/15/15	1	0.004	0.1056	0.0042	0.0648	0.0041	0.1767	25	12	25	-0.0013	0.2946	0.0173	0.1278	0.0177	0.4122
Muger	132/33/15	35/10/25	1	0.004	0.1	0.004	0.063	0.004	0.176	28	8	28	-0.010714	0.099107	0.025	0.258036	0.025	0.529464
Adigrat	132/66/15	20/12/8.0	2	0.003846	0.10004	0.0025	0.05002	0.005	0.1	20	12	8	0.011058	0.25	-0.001443	0	0.013942	0.25
Adigrat	132/66/15	20/12/8.0	8	0.003846	0.10004	0.0025	0.05002	0.005	0.1	20	12	8	0.011058	0.25	-0.001443	0	0.013942	0.25
Adwa	132/66/15	40/20/20	3	0.003846	0.10004	0.0025	0.05002	0.005	0.1	40	20	20	0.011058	0.25	-0.001443	0.0001	0.013942	0.25
Alamat	132/66/15	40/20/20	2	0.003846	0.10004	0.0025	0.05002	0.005	0.1	40	20	20	0.011058	0.25	-0.001443	0.0001	0.013942	0.25
Mekele	132/33/15	16/16/8	1	0.003917	0.084	0.002394	0.0216	0.001886	0.0682	16	16	8	0.010653	0.408125	0.013828	0.116875	0.001134	0.018125
Awash 7KL	132/66/15	12/12/4.0	1	0.007059	0.12	0.001188	0.0202	0.003935	0.0669	12	12	4	0.073652	1.252084	-0.014828	-0.252084	0.02473	0.420418
Adamitulu	132/33/15	12/12/6.3	1	0.005488	0.0878	0.000062	0.001	0.005	0.08	12	12	6	0.053854	0.861667	-0.008125	-0.13	0.008646	0.138333
Assela	132/33/15	25/12.5/12.5	1	0.00182	0.04	0.00167	0.025106	0.00313	0.068809	20	9.6	20	0.003677	0.141262	0.005423	0.058738	0.011973	0.202783
Awash II	132/33/15	16/16/8	1	0.003917	0.084	0.002394	0.0216	0.001886	0.0682	16	16	16	0.010653	0.408125	0.013828	0.116875	0.001134	0.018125
Awash II	132/15/10.5	20/6/20.0	1	0.001318	0.029	0.002682	0.059	0.003318	0.073	4.2	4.2	14	-0.004383	-0.096429	0.035768	0.786905	0.028084	0.617857
Awash II	132/15/10.5	20/6/20.0	1	0.001864	0.041	0.003545	0.084	0.004727	0.104	6	6	20	-0.002197	-0.098333	0.033257	0.781667	0.025833	0.618333
Koka	132/45/15	25/12.5/12.5	1	0.00569	0.095332	0.00799	0.049053	0.00966	0.185449	12	12	12	0.030667	0.965534	0.01675	-0.1711	0.049833	0.579875
Koka	132/10.5/15	18/18/6	1	0.005	0.096	0.005	0.08	0.004	0.039	18	18	18	0.011111	0.152778	0.016667	0.380555	0.011111	0.063889
Koka	132/10.5/15	18/18/6	1	0.005	0.096	0.005	0.08	0.004	0.039	18	18	18	0.011111	0.152778	0.016667	0.380555	0.011111	0.063889
Koka	132/10.5/15	18/18/6	1	0.005	0.096	0.005	0.08	0.004	0.039	18	18	18	0.011111	0.152778	0.016667	0.380555	0.011111	0.063889
Wakena Yugo	132/66/15	30/15.0/15.0	1	0.095455	0.100024	0.120588	0.050012	0.005882	0.1	24	12	12	-0.287032	0.408334	0.668851	-0.008333	0.336048	0.424999
Wakena Yugo	132/66/15	30/15.0/15.0	1	0.095455	0.100024	0.120588	0.050012	0.005882	0.1	24	12	12	-0.287032	0.408334	0.668851	-0.008333	0.336048	0.424999
Kaliti I	132/45/15	22/22/7.3	1	0.005	0.113	0.002	0.016	0.003	0.059	18	18	18	0.016667	0.433333	0.011111	0.194444	0	-0.105556
Kaliti I	132/45/15	22/22/7.3	2	0.005	0.113	0.002	0.016	0.003	0.059	18	18	18	0.016667	0.433333	0.011111	0.194444	0	-0.105556
Arbaminch	132/33/15	16/16/8	1	0.003917	0.084	0.002394	0.0216	0.001886	0.0682	16	16	16	0.010653	0.408125	0.013828	0.116875	0.001134	0.018125

Awassa	132/33/15	25/16/16.0	1	0.004	0.1056	0.0042	0.0648	0.0041	0.1767	25	12	25	-0.0013	0.2946	0.0173	0.1278	0.0177	0.4122
Dilla	132/33/15	25/25/12.5	2	0.004167	0.1	0.002941	0.05	0.005263	0.1	25	25	12.5	0.00931	0.236111	0.00458	0.097222	0.019929	0.319444
Hageremariam	132/33/15	25/25/12.5	1	0.004167	0.1	0.002941	0.05	0.005263	0.1	25	25	12.5	0.00931	0.236111	0.00458	0.097222	0.019929	0.319444
Hossaina	132/15/33	25/12.5/12.5	1	0.004	0.1056	0.0042	0.0648	0.0041	0.1767	25	12	25	-0.0013	0.2946	0.0173	0.1278	0.0177	0.4122
Shashemene	132/15/33	25/12.5/12.5	1	0.004	0.1056	0.0042	0.0648	0.0041	0.1767	25	12	25	-0.0013	0.2946	0.0173	0.1278	0.0177	0.4122
Sawla	132/66/33	25/25/16	1	0.00574	0.12625	0.00839	0.18464	0.01783	0.39228	25	25	25	0.03036	0.66778	-0.0074	-0.16278	0.04096	0.90134
Shakisso	132/66/15	6/6/6.0	1	0.0082	0.101068	0.00708	0.0708	0.00775	0.1504	6	6	6	0.073917	1.505566	0.06275	0.1789	0.05525	1.001099
Shakisso	132/66/15	6/6/6.0	2	0.00816	0.10057	0.00708	0.0708	0.00775	0.1504	6	6	6	0.073583	1.501416	0.062417	0.17475	0.055583	1.005249
Shakisso	132/66/15	25/12/12.0	3	0.095455	0.1	0.120588	0.05	0.005882	0.1	25	12	12	-0.287032	0.408334	0.668852	-0.008333	0.336048	0.424999
Yirgalem	132/33/15	25/25/12.5	5	0.005249	0.103	0.004125	0.064	0.003042	0.176	20	10	20	0.000103	0.3775	0.026142	0.1375	0.015107	0.5025
W.Sodo I	132/33/15	25/12.5/12.5	1	0.004	0.1056	0.0042	0.0648	0.0041	0.1767	25	12	25	-0.0013	0.2946	0.0173	0.1278	0.0177	0.4122
Butajira	132/33/15	25/12/12.0	1	0.00182	0.04	0.00167	0.025106	0.00313	0.068809	20	9.6	20	0.003677	0.141262	0.005423	0.058738	0.011973	0.202783
Sebeta I	132/45/15	25/25/12.5	2	0.005	0.113	0.002	0.016	0.003	0.059	18	18	18	0.016667	0.433333	0.011111	0.194444	0	-0.105556
Agaro	132/33/15	16/16/8	1	0.003917	0.084	0.002394	0.0216	0.001886	0.0682	16	16	16	0.010653	0.408125	0.013828	0.116875	0.001134	0.018125
Bonga	132/33/15	25/25/12.0	1	0.0038	0.0859	0.002	0.0511	0.0026	0.1519	20	9.6	20	0.005583	0.328354	0.013417	0.101146	0.007417	0.431146
Jimma I	132/33/15	16/16/8	1	0.003917	0.084	0.002394	0.0216	0.001886	0.0682	16	16	16	0.010653	0.408125	0.013828	0.116875	0.001134	0.018125
Mizan	132/66/33	25/12/12.0	1	0.006348	0.086086	0.002912	0.02479	0.004021	0.072539	20	9.6	9.6	0.021646	0.463908	0.010094	-0.033478	0.020239	0.291707
Chanco	230/132/15	125/125/37.5	1	0.0025	0.1	0.00125	0.05	0.003846	0.1	125	125	37.5	0.005628	0.153333	-0.003628	-0.073333	0.004628	0.113333
Chanco	230/132/15	125/125/37.5	2	0.0025	0.1	0.00125	0.05	0.003846	0.1	125	125	37.5	0.005628	0.153333	-0.003628	-0.073333	0.004628	0.113333
Fitch II	230/66/15	40/0/20	1	0.003846	0.10004	0.0025	0.05002	0.005	0.1	40	20	20	0.011058	0.25	-0.001442	0.0001	0.013942	0.25
Fitch II	230/66/15	40/0/20	2	0.003846	0.10004	0.0025	0.05002	0.005	0.1	40	20	20	0.011058	0.25	-0.001443	0.0001	0.013942	0.25
D.Dawa III	230/132/15	63/63/18.9	1	0.002547	0.0764	0.001243	0.0373	0.002113	0.0634	63	18.9	18.9	0.004323	0.129683	-0.00028	-0.008413	0.006859	0.205767
D.Dawa III	230/132/15	63/63/18.9	2	0.002547	0.0764	0.001243	0.0373	0.002113	0.0634	63	18.9	18.9	0.004323	0.129683	-0.00028	-0.008413	0.006859	0.205767
Gambela II	132/66/33	40/20/20	1	0.003846	0.10004	0.0025	0.05002	0.005	0.1	40	20	20	0.011058	0.25	-0.001443	0.0001	0.013942	0.25

Metu	132/66/33	40/20/20	1	0.008036	0.225	0.002929	0.082	0.004929	0.138	40	20	20	0.015045	0.42125	0.005045	0.14125	0.009598	0.26875
B.Dar II	230/132/15	63/63/21	1	0.00389	0.093329	0.00469	0.046665	0.0042	0.082753	50	16.7	16.7	0.002423	0.201377	0.005357	-0.014719	0.022727	0.29415
B.Dar II	230/132/15	63/63/21	2	0.00389	0.093329	0.00469	0.046665	0.0042	0.082753	50	16.7	16.7	0.002423	0.201377	0.005357	-0.014719	0.022727	0.29415
B.Dar II	230/66/15	63/40/23	1	0.005	0.1	0.007	0.14	0.004	0.08	63	40	23	0.003914	0.078278	0.004023	0.080452	0.013477	0.269548
D.Markos	230/66/15	63/40/23	3	0.003226	0.1	0.001923	0.05	0.004762	0.1	63	40	23	0.010509	0.234256	-0.005388	-0.075526	0.010196	0.200526
D.Markos	230/66/15	63/40/23	4	0.003226	0.1	0.001923	0.05	0.004762	0.1	63	40	23	0.010509	0.234256	-0.005388	-0.075526	0.010196	0.200526
Gashena	230/33/15	30/20/10	1	0.00554	0.1219	0.00153	0.0337	0.00543	0.1195	30	20	30	0.014458	0.318083	0.004008	0.08825	0.003642	0.08025
Gondar II	230/66/15	40/20/20	1	0.003286	0.046604	0.003202	0.039972	0.002914	0.090153	40	20	20	0.009369	0.302453	0.011169	-0.011178	0.008844	0.261003
N.Mewucha	230/33/15	30/20/10	8	0.00554	0.1219	0.00153	0.0337	0.00797	0.1195	30	20	10	0.018692	0.318083	-0.000225	0.08825	0.007875	0.08025
Fincha	230/66/15	12/12/8.0	1	0	0.04702	0	0.01293	0.00868	0.068895	12.02	12.02	8	0.05425	0.572399	-0.05425	-0.181218	0.05425	0.288788
Ghedo	230/132/15	63/63/21	1	0.00389	0.093329	0.00469	0.046665	0.0042	0.082753	50	16.7	16.7	0.002423	0.201377	0.005357	-0.014719	0.022727	0.29415
Alamata	230/132/15	63/40/23	1	0.001333	0.04	0.0025	0.075	0.003	0.09	63	40	23	0.002754	0.082609	0.00058	0.017391	0.01029	0.308696
Alamata	230/132/15	63/40/23	2	0.001333	0.04	0.0025	0.075	0.003	0.09	63	40	23	0.002754	0.082609	0.00058	0.017391	0.01029	0.308696
Endasilassie	230/66/15	40/20/20	1	0.006429	0.18	0.002286	0.064	0.004036	0.113	40	20	20	0.012411	0.3475	0.003661	0.1025	0.007768	0.2175
Mekele	230/132/15	125/125/73.5	1	0.0025	0.1	0.00125	0.05	0.003846	0.1	125	125	37.5	0.005628	0.153333	-0.003628	-0.073333	0.004628	0.113333
Mekele	230/132/15	125/125/73.5	2	0.0025	0.1	0.00125	0.05	0.003846	0.1	125	125	37.5	0.005628	0.153333	-0.003628	-0.073333	0.004628	0.113333
Mehoni	230/33/15	63/40/23	1	0.003226	0.1	0.001923	0.05	0.004762	0.1	63	40	23	0.010508	0.234256	-0.005388	-0.075526	0.010196	0.200526
Mehoni	230/33/15	63/40/23	2	0.003226	0.1	0.001923	0.05	0.004762	0.1	63	40	23	0.010508	0.234256	-0.005388	-0.075526	0.010196	0.200526
Ramo	230/132/33	63/63/23	1	0.005	0.1	0.007	0.14	0.0004	0.08	63	63	23	-0.003912	0.078278	0.011849	0.080452	0.005651	0.269548
Gode	230/132/33	63/63/23	1	0.005	0.1	0.007	0.14	0.0004	0.08	63	63	23	-0.003912	0.078278	0.011849	0.080452	0.005651	0.269548
Alaba	230/132/15	63/40/23	1	0.001333	0.04	0.0025	0.075	0.003	0.09	63	40	23	0.002754	0.082609	0.00058	0.017391	0.01029	0.308696
Alaba	230/132/15	63/40/23	2	0.001333	0.04	0.0025	0.075	0.003	0.09	63	40	23	0.002754	0.082609	0.00058	0.017391	0.01029	0.308696
Wolkite	132/66/33	40/20/20	2	0.003846	0.10004	0.0025	0.05002	0.005	0.1	40	20	20	0.011058	0.25	-0.001442	0.0001	0.013942	0.25
G.Gibe	230/132/33	40/40/12	1	0.004179	0.117	0.011036	0.309	0.016821	0.471	40	40	40	0.012455	0.34875	-0.002009	-0.05625	0.029598	0.82875

G.Gibe	230/132/33	40/40/12	2	0.004179	0.117	0.011036	0.309	0.016821	0.471	40	40	40	0.012455	0.34875	-0.002009	-0.05625	0.029598	0.82875
Fiche	66/33/15	12/12/8.0	1	0.005488	0.0878	0.000062	0.001	0.005	0.08	12	12	8	0.053858	0.861667	-0.008125	-0.13	0.008642	0.138333
Fiche	66/33/15	12/12/8.0	2	0.005488	0.0878	0.000062	0.001	0.005	0.08	12	12	8	0.053858	0.861667	-0.008125	-0.13	0.008642	0.138333
Bedessa	66/33/15	8.4/8.4/4	1	0.006667	0.1	0.00333	0.05	0.009091	0.1	8.4	8.4	8.4	0.073976	0.892857	0.005393	0.297619	0.03425	0.297619
Dembidolo	66/33/15	12/12/6.3	1	0.003869	0.0889	0.002121	0.0517	0.002683	0.1587	9.6	9.6	9.6	0.023078	1.020312	0.017224	-0.094271	0.00487	0.632813
Dabat	66/33/15	12/12/6.3	1	0.003869	0.0889	0.002121	0.0517	0.002683	0.1587	9.6	9.6	9.6	0.023078	1.020312	0.017224	-0.094271	0.00487	0.632813
Gondar II	66/33/15	8.3/8.3/8.3	1	0.005488	0.0696	0.000062	0.001	0.005	0.064	6.3	6.3	6.3	0.082746	1.052381	0.004365	0.052381	-0.003381	-0.036508
Bale Robie	66/33/15	8.4/8.4/4	1	0.006667	0.1	0.00333	0.05	0.009091	0.1	8.4	8.4	8.4	0.073976	0.892857	0.005393	0.297619	0.03425	0.297619
Nuraera	66/33/15	12/12/6.3	1	0.003869	0.0889	0.002121	0.0517	0.002683	0.1587	9.6	9.6	9.6	0.023078	1.020313	0.017224	-0.094271	0.00487	0.632812
N.Borena	66/33/15	12/6/6.0	1	0.00561	0.0842	0.0018	0.027	0.01011	0.1517	12	6	12	0.0505	0.757917	-0.00375	-0.05625	0.03375	0.50625
Tepi	66/33/15	12/12/6.3	1	0.003869	0.073298	0.002121	0.040645	0.002683	0.125671	9.6	5.04	5.04	0.025726	1.225272	0.014576	-0.461752	0.027508	1.268201
Addisalem	45/33/15	12/6.3/12	1	0.005488	0.0878	0.000062	0.001	0.005	0.08	12	12	6	0.053854	0.861667	-0.008125	-0.13	0.008646	0.138333
Akista	132/66/33	25/12.0/25	1	0.001	0.103195	0.0015	0.06398	0.0046	0.1779	20	9	20	0.005667	0.347293	-0.000667	0.168682	0.017333	0.542207
Fincha II	230/33/15	20/10/10.0	1	0	0.1	0	0.05	0	0.1	100	100	100	0	0.075	0	0.025	0	0.025
D.Dawa III	132/33/15	16/16/8.0	1	0.003917	0.084	0.002394	0.0216	0.001886	0.0682	16	16	16	0.010653	0.408125	0.013828	0.116875	0.001134	0.018125
Sebeta I	132/45/15	25/25/12.5	1	0.005	0.113	0.002	0.016	0.003	0.059	18	18	18	0.016667	0.433333	0.011111	0.194444	0	-0.105556
Dangila	66/33/15	12/12/6.3	1	0.003869	0.0889	0.002121	0.0517	0.002683	0.1587	9.6	9.6	9.6	0.023078	1.020312	0.017224	-0.094271	0.00487	0.632813
Amibara	66/33/15	8.4/8.4/4	1	0.006667	0.1	0.00333	0.05	0.009091	0.1	8.4	8.4	8.4	0.073976	0.892857	0.005393	0.297619	0.03425	0.297619

Appendix C: Peak Load Data of Substations

The collected peak load data of each substation and corresponding load values in the final model after being adjusted by a coincidence factor is reported in Table C.1.

Table C. 1: Collected peak load data and its adjusted values in the final model

Name of Substation	Voltage level of the load bus (kV)	Collected peak load data		Adjusted peak load data in the final model			
		P _{load} (MW)	Calculated Q _{load} (Mvar)	P _{load} (MW)	Q _{load} (Mvar)	Load ID	Scalable
Aba	15	1.8	0.864	1.5086	0.7242	1	Yes
Adamitulu	15	14	6.72	11.7334	5.6329	1	Yes
Adamitulu	33	6	2.88	5.0286	2.4141	1	Yes
Addis Alem	15	7.95	3.816	6.6629	3.1987	1	Yes
Addis Center	15	56	26.88	46.9336	22.5315	1	Yes
Addis East I	15	5.6	2.688	4.6934	2.2532	1	Yes
Addis East II	15	6	2.88	5.0286	2.4141	1	Yes
Addis East II	15	44	21.12	36.8764	17.7034	1	Yes
Addis North	15	46	22.08	38.5526	18.5081	1	Yes
Addis South II	15	46	24.96	38.5526	20.9221	1	Yes
Addis West I	15	10	4.8	8.381	4.0235	1	Yes
Addis West II	15	9.7	4.656	8.1296	3.9028	1	Yes
Adigala	33	0.6	0.288	0.5029	0.2414	1	Yes
Adigrat	15	8	3.8744	6.7048	3.2476	1	Yes
Adigrat	33	7	3.3901	5.8667	2.8417	1	Yes
Adwa	15	16	7	13.4096	5.8676	1	Yes
Adwa	15	4	1.92	3.3524	1.6094	1	Yes
Agaro	15	6.84	3.283	5.7326	2.7519	1	Yes
Agaro	33	2.184	1.048	1.8304	0.8785	1	Yes
Akaki	15	9.6	4.608	8.0458	3.8625	1	Yes
Akaki II	15	34.101	16.37	28.58	13.7218	1	Yes
Akaki SP	15	8.38	4.0224	7.0233	3.3717	1	Yes
Akista	33	14.08	6.7584	11.8004	5.6651	1	Yes
Alaba	15	8.3	3.984	6.9562	3.3395	1	Yes
Alamata	33	0.2	0	0.1676	0	1	Yes
Alamata	15	8	3.84	6.7048	3.2188	1	Yes
Alem Ketema	33	4.2	2.016	3.52	1.6899	1	Yes
Alemaya	15	4	1.92	3.3524	1.6094	1	Yes
Alemaya	33	2	0.96	1.6762	0.8047	1	Yes
Amibara	15	2.25	1.08	1.8857	0.9053	1	Yes
Amibara	33	1.94	0.9312	1.6259	0.7806	1	Yes
Arba Minch	15	9.8	4.704	8.2134	3.943	1	Yes
Arba Minch	33	2.4	1.152	2.0114	0.9656	1	Yes
Asebe Teferi	15	4.063	1.9678	3.4052	1.6495	1	Yes
Asebe Teferi	33	0.0325	0.0157	0.0272	0.0132	1	Yes

Asebe Teferi	15	0	0	0	0	1	Yes
Assela	15	16	7.68	13.4096	6.4376	1	Yes
Assela	33	1	0.48	0.8381	0.4023	1	Yes
Assosa	33	4	1.92	3.3524	1.6094	1	Yes
Assosa	15	3.7	1.628	3.101	1.3646	1	Yes
Awash 7kilo	15	2.87	1.3776	2.4053	1.1547	1	Yes
Awash II	15	12.132	5.82	10.1678	4.8785	1	Yes
Awash II	33	0.4	0.192	0.3352	0.1609	1	Yes
Awash II	33	0.571	0.274	0.4786	0.2297	1	Yes
Awassa	15	20	9.6	16.762	8.047	1	Yes
Awassa	33	1.103	0.53	0.9244	0.4443	1	Yes
Ayat GIS	15	2	0.96	1.6762	0.8047	1	Yes
Babilie	15	1.8	0.864	1.5086	0.7242	1	Yes
Bahir Dar I	15	7	3.36	5.8667	2.8164	1	Yes
Bahir Dar II	15	5.5585	2.6681	4.6586	2.2365	1	Yes
Bahir Dar II	15	22.763	10.9264	19.0779	9.1588	1	Yes
Bahir Dar II	33	0.4367	0.2096	0.366	0.1757	1	Yes
Bale Robie	15	6.7	3.216	5.6153	2.6957	1	Yes
Bale Robie	33	3.6	1.728	3.0172	1.4485	1	Yes
Bedele	15	5.2	2.496	4.3581	2.0922	1	Yes
Bedele	33	2.4	1.152	2.0114	0.9656	1	Yes
Bedessa	33	3.7445	1.8136	3.1383	1.5202	1	Yes
Bitchena	15	7.76	3.72	6.5036	3.1182	1	Yes
Boculuguma	33	2.5	1.2	2.0952	1.0059	1	Yes
Bole-Lemi	33	9.7907	4.7418	8.2056	3.9747	1	Yes
Bole-Lemi	33	33.504	16.2269	28.08	13.6018	2	Yes
Bonga	15	2.294	1.101	1.9226	0.9229	1	Yes
Bonga	33	1.456	0.699	1.2203	0.5859	1	Yes
Butajira	15	5.65	2.712	4.7353	2.2733	1	Yes
Butajira	33	3.154	1.514	2.6434	1.2691	1	Yes
Chelenko	33	3.6556	1.7705	3.0638	1.4841	1	Yes
Chelenko	15	2	0.96	1.6762	0.8047	1	Yes
Combolcha I	15	16	7.68	13.4096	6.4376	1	Yes
Cotobie	15	4.103	1.97	3.4387	1.6513	1	Yes
Cotobie	15	26.47	12.71	22.1845	10.6539	1	Yes
Cotobie II	15	54	25.92	45.2574	21.7268	1	Yes
Dabat	33	0.44	0.2112	0.3688	0.177	1	Yes
Dabat	15	3.97	1.9056	3.3273	1.5973	1	Yes
Dangila	15	6	2.88	5.0286	2.4141	1	Yes
Dangila	33	2.34	1.1232	1.9612	0.9415	1	Yes
Dangote Cement	11	40	19.2	33.524	16.094	1	Yes
Debre Birhane	33	13	5	10.8953	4.1911	1	Yes
Debre Birhane	15	8.2	3.9713	6.8724	3.3288	1	Yes
Debre Birhane	33	6	2.88	5.0286	2.4141	1	Yes
Debre Markos	15	11.03	5.29	9.2442	4.4342	1	Yes
Debre Markos	33	0.5	0.24	0.419	0.2012	1	Yes
Debre Zeit II	15	16.89	8.1072	14.1555	6.7957	1	Yes

Debre Zeit II	15	17.664	8.4787	14.8042	7.1071	1	Yes
Debre Zeit II	15	15.92	7.6416	13.3425	6.4054	1	Yes
Dembidolo	15	3.1	1.488	2.5981	1.2473	1	Yes
Dembidolo	33	1	0.48	0.8381	0.4023	1	Yes
Derba	33	6.16	2.96	3.8848	1.7964	1	Yes
Derba	6.3	50		30	14.4	1	No
Dessie	66	1.46	0.7071	1.2236	0.5927	1	Yes
Dessie	15	12.243	5.9297	10.261	4.9704	1	Yes
Dicheto	33	1.0136	0.4864	1.0136	0.4864	1	Yes
Dilla	15	8.823	4.235	7.3945	3.5499	1	Yes
Dilla	33	1.165	0.5592	0.9764	0.4687	1	Yes
Dire Dawa DS	132	0.0766	0.0371	0.0642	0.0311	1	Yes
Dire Dawa I	132	23.224	14.148	19.464	11.8592	1	Yes
Dire Dawa I	15	21.484	10.312	18.0057	8.6438	1	Yes
Dire Dawa III	33	4.853	2.329	4.0673	1.9522	1	Yes
Dukem	15	1.3098	0.6344	1.0977	0.5318	1	Yes
East Industry Z	33	14.56	6.9888	12.2027	5.8582	1	Yes
East Industry Z	33	8.83	4.2384	7.4004	3.5527	1	Yes
Elala Geda	15	7.94	3.81	6.6545	3.1936	1	Yes
Fik	33	0.5	0.24	0.419	0.2012	1	Yes
Fincha Sugar	15	3.4927	1.6916	2.9272	1.4179	1	Yes
Fincha Sugar II	15	3	1.44	2.5143	1.207	1	Yes
Fincha Sugar II	11	1	0.48	0.8381	0.4023	1	Yes
Finchaa	15	3.5628	1.7255	2.986	1.4464	1	Yes
Finchaa II	15	2.426	1.1645	2.0332	0.9761	1	Yes
Finote Selam	15	8.73	4.2	7.3166	3.5206	1	Yes
Fitche	66	12.149	5.884	10.1819	4.9321	1	Yes
Fitche	66	15.551	7.5315	13.0329	6.3131	2	Yes
Fitche	15	3.97	1.906	3.3273	1.5977	1	Yes
Fitche	33	1.96	0.941	1.6427	0.7888	1	Yes
Fitche	15	6.1554	2.9812	5.1588	2.4989	1	Yes
Gambela I	15	3.5	1.68	2.9333	1.4082	1	Yes
Gambela II	33	0	0	0	0	1	Yes
Gashena	33	5.3616	2.5967	4.4936	2.1766	1	Yes
Gedja	15	4	1.92	3.3524	1.6094	1	Yes
Gefersa	15	26	12.48	21.7906	10.4611	1	Yes
Gefersa	15	7.95	3.82	6.6629	3.202	1	Yes
Gefersa	15	11	5.28	9.2191	4.4258	1	Yes
Ghedo	15	6	2.88	5.0286	2.4141	1	Yes
Ghedo	33	3	1.44	2.5143	1.207	1	Yes
Ghimbi	15	3.4	1.632	2.8495	1.368	1	Yes
Ghimbi	33	5.8	2.784	4.861	2.3336	1	Yes
Gida Ayana	33	4.3	2.064	3.6038	1.7301	1	Yes
Gilgel Gibe	15	3	1.44	2.5143	1.207	1	Yes
Gilgel Gibe	33	1.6	0.768	1.341	0.6438	1	Yes
Ginchi	45	5.62	2.7	4.7101	2.2632	1	Yes
Gobessa	33	6.1	2.928	5.1124	2.4543	1	Yes

Gode	33	1	0.48	0.8381	0.4023	1	Yes
Gondar I	15	4.79	2.3	4.0145	1.9279	1	Yes
Gondar II	33	4.11	1.9905	3.4446	1.6685	1	Yes
Gondar II	15	17	8.2331	14.2477	6.9012	1	Yes
G.Renaissance	400	37	4.8	30.7322	14.7516	1	No
Guder	15	10	4.8	8.381	4.0235	1	Yes
Hageremariam	33	7.3	3.504	6.1181	2.9371	1	Yes
Harar II	15	5.3939	2.6124	4.5206	2.1898	1	Yes
Harar III	33	1.4	0.672	1.1733	0.5633	1	Yes
Harar III	15	1.98	0.953	1.6594	0.7988	1	Yes
Holeta	500	23.642	11.4502	19.814	9.5979	1	Yes
Holeta	500	4.7384	2.2949	3.9712	1.9236	1	Yes
Hosaina	15	9.88	4.7424	8.2804	3.9752	1	Yes
Hosaina	33	1.165	0.5592	0.9764	0.4687	1	Yes
Humera	33	3.6907	1.7875	3.0932	1.4983	1	Yes
Hurso	15	0.44	0.212	0.3688	0.1777	1	Yes
Jijiga II	33	11	5.28	9.2191	4.4258	1	Yes
Jijiga II	15	1	0.48	0.8381	0.4023	1	Yes
Jimma I	15	12	5.76	10.0572	4.8282	1	Yes
Jimma I	33	7	3.36	5.8667	2.8164	1	Yes
Jimma I	15	6	2.88	5.0286	2.4141	1	Yes
Jimma II	15	0	0	0	0	1	Yes
Kaliti I	15	12.41	5.9568	10.4008	4.9931	1	Yes
Kaliti II	15	30.9	14.832	25.8973	12.4326	1	Yes
Kaliti II	15	35.29	16.94	29.5765	14.1996	1	Yes
Kaliti II-GIS	15	1	0.48	0.8381	0.4023	1	Yes
Kaliti North	15	13	6.24	10.8953	5.2305	1	Yes
Kanoria	11	7	3.36	5.8667	2.8164	1	Yes
Kemissie	33	2.7	1.3076	2.2629	1.0961	1	Yes
Kemissie	15	3.2	1.5498	2.6819	1.2991	1	Yes
Key Afer	33	2.04	0.9792	1.7097	0.8208	1	Yes
Koka	15	8	3.84	6.7048	3.2188	1	Yes
Lalibela	15	4.5	2.1793	3.7714	1.8268	1	Yes
Maychew	15	5	2.4215	4.1905	2.0298	1	Yes
Mehoni	33	0	0	0	0	1	Yes
Mehoni	15	5	2.4215	4.1905	2.0298	1	Yes
Mekanisa	15	9.573	4.595	8.0231	3.8517	1	Yes
Mekele	33	5	2.4215	4.1905	2.0298	1	Yes
Mekele	15	30	14.529	25.143	12.1786	1	Yes
Wakena Yugo	15	5.16	2.4768	4.3246	2.0761	1	Yes
Mendi	33	5	2.4	4.1905	2.0117	1	Yes
Menilik-TS	15	1	0.48	0.8381	0.4023	1	Yes
Menilik-TS	15	11	5.28	7.5429	3.6211	2	Yes
Mesobo	6.3	15	7.2645	12.5715	6.0893	1	Yes
Mesobo	6.3	25	12.1075	20.9525	10.1488	1	Yes
Metahara	15	3.5	1.68	2.9333	1.4082	1	Yes
Metema	33	2.36	1.1429	1.9779	0.958	1	Yes

Metu	33	6.4	3.072	5.3638	2.575	1	Yes
Metu	33	1	0.48	0.8381	0.4023	1	Yes
Mizan	33	1.31	0.6288	1.0979	0.5271	1	Yes
Mizan	15	3.309	1.5883	2.7733	1.3314	1	Yes
Modjo	15	6.4	3.072	5.3638	2.575	1	Yes
Mota	33	4.85	2.328	4.0648	1.9514	1	Yes
Muger	15	15	7.2	12.5715	6.0352	1	Yes
Muger	15	14	6.72	11.7334	5.6329	1	Yes
Muger	33	3	1.44	3.8848	1.7964	1	Yes
Nazreth II	15	42	20.16	35.2002	16.8987	1	Yes
N.Mewucha	33	2	0.9686	1.6762	0.8119	1	Yes
Nefasilk	15	49	23.52	41.0669	19.7151	1	Yes
N.Borena	33	1.4	0.672	1.1733	0.5633	1	Yes
N.Borena	15	2.4	1.152	2.0114	0.9656	1	Yes
Nekempt	15	7.5	3.6	6.2857	3.0176	1	Yes
Nekempt	33	3	1.44	2.5143	1.207	1	Yes
Nuraera	15	4.2	2.016	3.52	1.6899	1	Yes
Nuraera	33	2.9	1.392	2.4305	1.1668	1	Yes
Pawie	66	4	1.92	3.3524	1.6094	1	Yes
Ramo	33	2	0.96	1.6762	0.8047	1	Yes
Sawla	33	2.72	1.3056	2.2796	1.0944	1	Yes
Sebeta I	15	78.9	37.87	66.126	31.7436	1	Yes
Sebeta I	15	7.96	3.82	6.6713	3.202	1	Yes
Sebeta II	33	17.47	8.386	14.6416	7.0294	1	Yes
Sebeta-TS	230	6.43	3	3.4668	1.6793	1	Yes
Sekota	15	4.5	2.1793	3.7714	1.8268	1	Yes
Semera	33	9	4.32	7.5429	3.6211	1	Yes
Shakisso	15	8	3.84	6.7048	3.2188	1	Yes
Shakisso	33	1	0.48	0.8381	0.4023	1	Yes
Shashemene	15	14	6.72	11.7334	5.6329	1	Yes
Shashemene	15	6	2.88	5.0286	2.4141	1	Yes
Shashemene	33	1	0.48	0.8381	0.4023	1	Yes
Shewa Robit	15	5.3	2.3	4.4419	1.9279	1	Yes
Shewa Robit	33	5.4	2.5	4.5257	2.0956	1	Yes
Endasilassie	33	5.28	2.5571	4.4252	2.1434	1	Yes
Endasilassie	15	11	4.843	9.2191	4.0595	1	Yes
Sululta	66	12	5.76	10.0572	4.8282	1	Yes
Sululta	15	25	12	20.9525	10.0587	1	Yes
Sululta	33	6	2.88	5.0286	2.4141	1	Yes
Tepi	15	3	1.44	2.5143	1.207	1	Yes
Tepi	33	0.01	0.0004	0.0084	0.0003	1	Yes
Tis Abay II	132	26	12.48	21.7906	10.4611	1	Yes
TorhailochTS	15	8	3.84	6.7048	3.2188	1	Yes
TorhailochTS	15	0.8	0.384	0.6705	0.3219	1	Yes
Weregenu	15	57.35	27.53	48.065	23.0764	1	Yes
Wolaita Sodo I	66	3	1.5	2.5143	1.2573	1	Yes
Wolaita Sodo I	15	4.2	2.016	3.52	1.6899	1	Yes

Wolaita Sodo I	15	10.5	5.04	8.8	4.2247	1	Yes
Wolaita Sodo I	33	1.1	0.528	0.9219	0.4426	1	Yes
Woliso	15	9.86	4.733	8.2637	3.9673	1	Yes
Woliso	33	2.717	1.304	2.2771	1.093	1	Yes
Wolkitie	33	5.34	2.5632	4.4755	2.1485	1	Yes
Wolkitie	15	3.198	1.535	2.6802	1.2867	1	Yes
Wonji Pulp	15	12	5.76	10.0572	4.8282	1	Yes
Wonji Sugar	11	9	4.32	7.5429	3.6211	1	Yes
Woreta	15	6	2.88	5.0286	2.4141	1	Yes
Wukro	15	8	3.8744	6.7048	3.2476	1	Yes
Yadot	33	2	0.96	1.6762	0.8047	1	Yes
Yesu	15	5	2.4	4.1905	2.0117	1	Yes
Yesu	15	9	4.32	7.5429	3.6211	1	Yes
Yirgalem	15	7.4	3.552	6.2019	2.9774	1	Yes
Yirgalem	33	2.2	1.056	1.8438	0.8852	1	Yes
Djibouti-PK12	230	56	26.88	56	26.88	1	No
Sudan Gadarif	230	138	66.24	138	66.24	2	No
Sudan-Gadarif	230	1370	180	1370	180	1	No

Appendix D: Monthly Peak Hour Loading of Generators

The history of monthly peak hour loading of generators, export amount and total demand of the system are detailed in Table D.1 to D.2.

Table D. 1: Monthly peak hour loading of generators

Date	Time	Beles		Melka Wakena		Finchaa		Gilgel Gibe I		Koka		Awash II	
		Schedule	Actual	Schedule	Actual	Schedule	Actual	Schedule	Actual	Schedule	Actual	Schedule	Actual
29-Sep-16	19:15	435.00	420.60	50.00	40.00	120.00	114.00	170.00	180.00	10.00	5.20	10.50	4.80
03-Oct-16	19:00	435.00	398.70	50.00	40.00	120.00	62.00	170.00	180.00	10.00	5.10	10.40	5.20
29-Nov-16	18:45	200.00	418.80	90.00	53.00	120.00	110.00	120.00	110.00	10.00	13.00	10.20	12.10
19-Dec-16	19:15	435.00	391.20	90.00	53.00	120.00	90.00	120.00	170.00	10.00	12.80	10.50	12.00
17-Jan-17	19:45	435.00	428.40	90.00	90.00	120.00	108.00	120.00	80.00	10.00	12.30	10.20	8.00
21-Feb-17	19:45	435.00	416.90	60.00	60.00	120.00	107.00	120.00	110.00	12.00	10.20	10.20	12.70
09-Mar-17	20:00	435.00	431.60	60.00	60.00	120.00	115.00	120.00	110.00	12.00	10.80	10.10	12.80
11-Apr-17	19:45	435.00	331.60	60.00	90.00	120.00	108.00	120.00	110.00	12.00	10.60	10.20	13.00

Date	Time	Awash III		Gilgel Gibe II		Gilgel Gibe III		Tekeze		Amerti Neshe		Tis Abay II	
		Schedule	Actual	Schedule	Actual	Schedule	Actual	Schedule	Actual	Schedule	Actual	Schedule	Actual
29-Sep-16	19:15	7.50	6.10	350.00	350.00	700.00	806.20	40.00	60.15	0.00	0.00	0.00	0.00
03-Oct-16	19:00	7.40	5.90	350.00	300.00	700.00	824.80	40.00	51.21	0.00	0.00	0.00	0.00
29-Nov-16	18:45	7.30	8.20	300.00	340.00	850.00	801.10	40.00	56.21	15.00	15.68	0.00	0.00
19-Dec-16	19:15	7.50	7.70	350.00	330.00	850.00	747.90	40.00	111.82	15.00	20.42	0.00	0.00
17-Jan-17	19:45	7.30	12.70	350.00	200.00	850.00	847.50	40.00	112.61	15.00	40.25	0.00	0.00
21-Feb-17	19:45	7.30	0.00	350.00	300.00	710.00	803.40	110.00	110.38	20.00	20.13	0.00	0.00
09-Mar-17	20:00	0.00	0.00	350.00	300.00	710.00	808.20	110.00	110.91	20.00	20.76	0.00	0.00
11-Apr-17	19:45	0.00	0.00	350.00	340.00	710.00	869.30	110.00	111.48	20.00	20.32	0.00	0.00

Date	Time	Adama Wind I		Ashegoda Wind		Adama Wind II		Aba Samuel		ICS Total	
		Schedule	Actual	Schedule	Actual	Schedule	Actual	Schedule	Actual	Schedule	Actual
29-Sep-16	19:15	12.34	0.84	43.11	22.69	73.33	0.00	0.00	0.00	2021.78	2010.58
03-Oct-16	19:00	11.55	21.07	42.02	30.22	74.13	87.00	0.00	0.00	2020.50	2011.20
29-Nov-16	18:45	10.20	20.14	49.05	71.20	71.36	87.92	6.60	2.36	1899.71	2119.71
19-Dec-16	19:15	12.34	36.50	43.11	86.24	73.33	116.66	6.6	3.00	2183.38	2189.24
17-Jan-17	19:45	16.03	21.71	34.52	66.13	77.40	100.06	6.6	2.99	2182.05	2130.65
21-Feb-17	19:45	18.88	30.03	37.80	63.64	89.76	99.69	6.6	2.86	2107.54	2146.93
09-Mar-17	20:00	18.03	31.16	37.73	87.83	86.77	100.06	6.6	2.75	2096.23	2201.87
11-Apr-17	19:45	18.88	26.74	37.80	85.75	89.76	84.69	6.6	2.86	2100.24	2204.34

Table D. 2: Monthly peak hour exports and total demand

Date	Time	Export Power to Sudan (MW)		Export to Djibouti (MW)		Total Load of Djibouti (MW)		Total Power Export (MW)		Local Load Forecast (MW)	Total Load Forecast (MW)	Local Demand Met (MW)		Total Demand (MW)
		Schedule	Actual	Line1	Line2	Schedule	Actual	Schedule	Actual			Schedule	Actual	
29-Sep-16	19:15	100.00	120.00	74.00	0.00	90.00	74.00	190.00	194.0	1671.43	1861.43	1831.78	1816.6	2010.58
03-Oct-16	19:00	100.00	152.00	65.00	0.00	90.00	65.00	190.00	217.0	1556.44	1746.44	1830.50	1794.2	2011.20
29-Nov-16	18:45	100.00	128.00	50.40	0.00	90.00	50.40	190.00	178.4	1805.42	1995.42	1709.71	1941.3	2119.71
19-Dec-16	19:15	100.00	164.00	47.70	0.00	90.00	47.70	190.00	211.7	1949.53	2139.53	1993.38	1977.5	2189.24
17-Jan-17	19:45	100.00	160.00	47.30	0.00	90.00	47.30	190.00	207.3	1837.50	2027.50	1992.05	1923.4	2130.65
21-Feb-17	19:45	100.00	136.00	48.80	0.00	90.00	48.80	190.00	184.8	1663.28	1853.28	1917.54	1962.1	2146.93
09-Mar-17	20:00	100.00	248.00	50.40	0.00	90.00	50.40	190.00	298.4	1810.74	2000.74	1906.23	1903.5	2201.87
11-Apr-17	19:45	100.00	188.00	0.00	55.90	90.00	55.90	190.00	243.9	2083.93	2273.93	1910.24	1960.4	2204.34

Appendix E: Parameters of Generation System

The parameters of generators, governors and exciters are given in Table E.1 to Table E.8.

Table E. 1: Generator dynamic parameters for model Type GENSAL

Bus Number	Bus Name	I d	Mbase (MVA)	T'do (>0)	T''do (>0)	T''qo (>0)	Inertia H	Speed Damping D	Xd	Xq	X'd	X''d = X''q	X1	S(1.0)	S(1.2)
207013	GADAREF 230	1	3500	10.00	0.12	0.120	1.01	0.15	1.03	1.20	0.80	1.00	0.50	0.080	0.400
907001	BELES-1 15.0	1	133	9.20	0.13	0.100	3.14	0.00	1.03	0.70	0.31	0.25	0.20	0.090	0.500
907002	T-ABA2-1 10.5	1	40	7.10	0.12	0.12	2.50	0.50	1.00	0.60	0.29	0.37	0.14	0.080	0.400
907003	TS-ABAY1-1 6	1	4.8	5.40	0.05	0.050	2.00	0.50	1.21	0.70	0.30	0.18	0.15	0.080	0.400
907004	BELES-2 15.0	1	133	9.20	0.13	0.100	3.14	0.00	1.03	0.70	0.31	0.25	0.20	0.090	0.500
907005	T-ABA2-2 10.5	1	40	7.10	0.12	0.120	2.50	0.50	1.0	0.60	0.29	0.37	0.14	0.080	0.400
907006	TS-ABAY1-2 6	1	4.8	5.40	0.05	0.050	2.00	0.50	1.21	0.70	0.30	0.18	0.15	0.080	0.400
907007	BELES-3 15.0	1	133	9.20	0.130	0.100	3.14	0.00	1.03	0.70	0.31	0.25	0.20	0.090	0.500
907008	TS-ABAY1-3 6	1	4.8	5.40	0.050	0.050	2.00	0.50	1.21	0.70	0.30	0.18	0.15	0.080	0.400
907009	BELES-4 15	1	133	9.20	0.130	0.100	3.14	0.00	1.03	0.70	0.31	0.25	0.20	0.090	0.500
908001	FINCHA1 13.8	1	35	7.39	0.045	0.057	3.04	0.00	0.96	0.90	0.23	0.12	0.10	0.090	0.250
908002	NESHE-1 13.8	1	75	5.40	0.100	0.200	2.51	0.00	0.70	0.47	0.34	0.17	0.15	0.169	0.500
908003	FINCHA2 13.8	1	35	7.39	0.045	0.057	3.04	0.00	0.96	0.90	0.23	0.12	0.10	0.090	0.250
908004	NESHE-2 13.8	1	75	5.40	0.100	0.200	2.51	0.00	0.70	0.47	0.34	0.17	0.15	0.169	0.500
908005	FINCHA3 13.8	1	35	7.39	0.045	0.057	3.04	0.00	0.96	0.90	0.23	0.12	0.10	0.090	0.250
908006	FINCHA4 13.8	1	35	7.39	0.045	0.057	3.04	0.00	0.96	0.90	0.23	0.12	0.10	0.090	0.250
909001	TEKEZE1 13.8	1	87.6	6.47	0.100	0.200	2.60	0.00	1.00	0.60	0.29	0.17	0.10	0.090	0.500
909002	TEKEZE4 13.8	1	87.6	6.47	0.100	0.200	2.60	0.00	1.00	0.60	0.29	0.17	0.10	0.090	0.500
909004	TEKEZE2 13.8	1	87.6	6.47	0.100	0.200	2.60	0.00	1.00	0.60	0.29	0.17	0.10	0.090	0.500
909005	TEKEZE3 13.8	1	87.6	6.47	0.100	0.200	2.60	0.00	1.00	0.60	0.29	0.17	0.10	0.090	0.500
911003	AWASH2-1 0.5	1	20	5.40	0.075	0.071	2.61	0.00	1.04	0.66	0.35	0.16	0.10	0.143	0.319

911004	AWASH3-1 10.5	1	20	5.40	0.075	0.071	2.61	0.00	1.04	0.66	0.35	0.16	0.10	0.143	0.319
911005	KOKA1 10.5	1	18	5.40	0.065	0.050	2.61	0.00	0.7	0.66	0.34	0.24	0.20	0.169	0.500
911006	KOKA3 10.5	1	18	5.40	0.065	0.050	2.61	0.00	0.7	0.66	0.34	0.24	0.20	0.169	0.500
911007	WAKNA1 13.8	1	45	6.00	0.09	0.17	2.63	0.00	1.00	0.70	0.25	0.17	0.10	0.09	0.50
911008	AWASH2-2 10.5	1	20	5.40	0.08	0.07	2.61	0.00	1.04	0.66	0.35	0.16	0.10	0.14	0.32
911009	AWASH3-2 10.5	1	20	5.40	0.08	0.07	2.61	0.00	1.04	0.66	0.35	0.16	0.10	0.14	0.32
911010	KOKA2 10.5	1	18	5.40	0.07	0.05	2.61	0.00	0.70	0.66	0.34	0.24	0.20	0.17	0.50
911011	WAKNA2 13.8	1	45	6.00	0.09	0.17	2.63	0.00	1.00	0.70	0.25	0.17	0.10	0.09	0.50
911012	WAKNA3 13.8	1	45	6.00	0.09	0.17	2.63	0.00	1.00	0.70	0.25	0.17	0.10	0.09	0.50
911013	WAKNA4 13.8	1	45	6.00	0.09	0.17	2.63	0.00	1.00	0.70	0.25	0.17	0.10	0.09	0.50
915002	G-GIB2-1 15.0	1	125	9.20	0.13	0.10	3.14	0.00	1.03	0.70	0.31	0.22	0.10	0.09	0.50
915003	G-GIBE1-1 13.8	1	75	9.50	0.06	0.11	2.80	0.00	1.22	0.70	0.23	0.16	0.09	0.09	0.25
915004	G-GIB2-2 15.0	1	125	9.20	0.13	0.10	3.14	0.00	1.03	0.70	0.31	0.22	0.10	0.09	0.50
915005	G-GIBE1-2 13.8	1	75	9.50	0.06	0.11	2.80	0.00	1.22	0.70	0.23	0.16	0.09	0.09	0.25
915006	G-GIB2-3 15.0	1	125	9.20	0.13	0.10	3.14	0.00	1.03	0.70	0.31	0.22	0.10	0.09	0.50
915007	G-GIBE1-3 13.8	1	75	9.50	0.06	0.11	2.80	0.00	1.22	0.70	0.23	0.16	0.09	0.09	0.25
915008	G-GIB2-4 15.0	1	125	9.20	0.13	0.10	3.14	0.00	1.03	0.70	0.31	0.22	0.10	0.09	0.50
915009	G-GIB 3_1 15.0	1	176.25	9.20	0.12	0.12	3.14	0.50	1.03	0.70	0.31	0.22	0.14	0.08	0.40
915009	G-GIB 3_1 15.0	2	176.25	9.20	0.12	0.12	3.14	0.50	1.03	0.70	0.31	0.22	0.14	0.08	0.40
915010	G-GIB3_2 15.0	1	176.25	9.20	0.12	0.12	3.14	0.50	1.03	0.70	0.31	0.22	0.14	0.08	0.40
915010	G-GIB3_2 15.0	2	176.25	9.20	0.12	0.12	3.14	0.50	1.03	0.70	0.31	0.22	0.14	0.08	0.40
915011	G-GIB3_3 15.0	1	176.25	9.20	0.12	0.12	3.14	0.50	1.03	0.70	0.31	0.22	0.14	0.08	0.40
915011	G-GIB3_3 15.0	2	176.25	9.20	0.12	0.12	3.14	0.50	1.03	0.70	0.31	0.22	0.14	0.08	0.40
915012	G-GIB3_4 15.0	1	176.25	9.20	0.12	0.12	3.14	0.50	1.03	0.70	0.31	0.22	0.14	0.08	0.40
915012	G-GIB3_4 15.0	2	176.25	9.20	0.12	0.12	3.14	0.50	1.03	0.70	0.31	0.22	0.14	0.08	0.40
915013	G-GIB3_5 15.0	1	176.25	9.20	0.12	0.12	3.14	0.50	1.03	0.70	0.31	0.22	0.14	0.08	0.40
915013	G-GIB3_5 15.0	2	176.25	9.20	0.12	0.12	3.14	0.50	1.03	0.70	0.31	0.22	0.14	0.08	0.40

Table E. 2: Parameters of the in-service generators

Bus Name	P _{max} (MW)	P _{min} (MW)	Q _{max} (Mvar)	Q _{min} (Mvar)	M _{base} (MVA)	R Source (pu)	X Source (pu)	Positive R (pu)	Sub- transient X (pu)	Transient X (pu)	Synchronous X (pu)	Negative R (pu)	Negative X (pu)	Zero R (pu)	Zero X (pu)
BELES-1	117	0	70.1	-41.5	133	0.01	0.25	0.00	0.25	0.25	0.25	0.00	0.25	0.00	0.25
BELES-2	117	0	70.1	-41.5	133	0.01	0.25	0.00	0.25	0.25	0.25	0.00	0.25	0.00	0.25
BELES-3	117	0	70.1	-41.5	133	0.01	0.25	0.00	0.25	0.25	0.25	0.00	0.25	0.00	0.25
BELES-4	117	0	70.1	-41.5	133	0.01	0.25	0.00	0.25	0.25	0.25	0.00	0.25	0.00	0.25
FINCHA1	33.3	0	18.4	-10.9	35	0.01	0.12	0.01	0.12	0.12	0.12	0.01	0.12	0.01	0.12
NESHE-1	48.5	0	39.5	-23.4	75	0.00	0.17	0.00	0.17	0.17	0.17	0.00	0.17	0.00	0.17
FINCHA2	33.3	0	18.4	-10.9	35	0.01	0.12	0.01	0.12	0.12	0.12	0.01	0.12	0.01	0.12
NESHE-2	48.5	0	39.5	-23.4	75	0.00	0.17	0.00	0.17	0.17	0.17	0.00	0.17	0.00	0.17
FINCHA3	33.3	0	18.4	-10.9	35	0.01	0.12	0.01	0.12	0.12	0.12	0.01	0.12	0.01	0.12
FINCHA4	33.3	0	18.4	-10.9	35	0.01	0.12	0.01	0.12	0.12	0.12	0.01	0.12	0.01	0.12
TEKEZE1	78.03	0	46.1	-27.4	87.6	0.00	0.17	0.00	0.17	0.17	0.17	0.00	0.17	0.00	0.17
TEKEZE2	78.03	0	46.1	-27.4	87.6	0.00	0.17	0.00	0.17	0.17	0.17	0.00	0.17	0.00	0.17
ASHEGODA	90	0	47.4	-28.1	90	0.02	0.23	0.02	0.23	0.23	0.23	0.02	0.23	0.02	0.23
ASHEGODA	30	0	19.8	-11.7	37.5	0.02	0.23	0.02	0.23	0.23	0.23	0.02	0.23	0.02	0.23
AWASH2-1	18	0	10.5	-6.2	20	0.00	0.16	0.00	0.16	0.16	0.16	0.00	0.16	0.00	0.16
KOKA1	12.8	0	9.5	-5.6	18	0.01	0.24	0.00	0.24	0.24	0.24	0.00	0.24	0.00	0.24
KOKA3	12.8	0	9.5	-5.6	18	0.01	0.24	0.00	0.24	0.24	0.24	0.00	0.24	0.00	0.24
WAKNA1	38.25	0	23.7	-14.1	45	0.00	0.17	0.00	0.17	0.17	0.17	0.00	0.17	0.00	0.17
AWASH2-2	18	0	10.5	-6.2	20	0.00	0.16	0.00	0.16	0.16	0.16	0.00	0.16	0.00	0.16
KOKA2	12.8	0	9.5	-5.6	18	0.01	0.24	0.00	0.24	0.24	0.24	0.00	0.24	0.00	0.24
WAKNA2	38.25	0	23.7	-14.1	45	0.00	0.17	0.00	0.17	0.17	0.17	0.00	0.17	0.00	0.17
WAKNA3	38.25	0	23.7	-14.1	45	0.00	0.17	0.00	0.17	0.17	0.17	0.00	0.17	0.00	0.17
WAKNA4	38.25	0	23.7	-14.1	45	0.00	0.17	0.00	0.17	0.17	0.17	0.00	0.17	0.00	0.17
ADAMA II	153	0	100.7	-59.7	191.25	0.02	0.23	0.00	0.23	0.23	0.23	0.00	0.23	0.00	0.23
ADAMA I	51	0	5	-5	54	0.00	0.20	0.00	0.20	0.20	0.20	0.00	0.20	0.00	0.20
G-GIB2-1	107	0	65.8	-39	125	0.00	0.22	0.00	0.22	0.22	0.22	0.00	0.22	0.00	0.22
G-GIBE1-1	70	0	39.5	-23.4	75	0.00	0.16	0.00	0.16	0.16	0.16	0.00	0.16	0.00	0.16
G-GIB2-2	107	0	65.8	-39	125	0.00	0.22	0.00	0.22	0.22	0.22	0.00	0.22	0.00	0.22
G-GIBE1-2	70	0	39.5	-23.4	75	0.00	0.16	0.00	0.16	0.16	0.16	0.00	0.16	0.00	0.16

G-GIB2-3	107	0	65.8	-39	125	0.00	0.22	0.00	0.22	0.22	0.22	0.00	0.22	0.00	0.22
G-GIB1-3	70	0	39.5	-23.4	75	0.00	0.16	0.00	0.16	0.16	0.16	0.00	0.16	0.00	0.16
G-GIB2-4	107	0	65.8	-39	125	0.00	0.22	0.00	0.22	0.22	0.22	0.00	0.22	0.00	0.22
G-GIB 3_1	187	0	92.8	-55	176.25	0.00	0.22	0.00	0.22	0.22	0.22	0.00	0.22	0.00	0.22
G-GIB 3_1	187	0	92.8	-55	176.25	0.00	0.22	0.00	0.22	0.22	0.22	0.00	0.22	0.00	0.22
G-GIB3_2	187	0	92.8	-55	176.25	0.00	0.22	0.00	0.22	0.22	0.22	0.00	0.22	0.00	0.22
G-GIB3_2	187	0	92.8	-55	176.25	0.00	0.22	0.00	0.22	0.22	0.22	0.00	0.22	0.00	0.22
G-GIB3_3	187	0	92.8	-55	176.25	0.00	0.22	0.00	0.22	0.22	0.22	0.00	0.22	0.00	0.22
G-GIB3_3	187	0	92.8	-55	176.25	0.00	0.22	0.00	0.22	0.22	0.22	0.00	0.22	0.00	0.22
G-GIB3_4	187	0	92.8	-55	176.25	0.00	0.22	0.00	0.22	0.22	0.22	0.00	0.22	0.00	0.22
G-GIB3_4	187	0	92.8	-55	176.25	0.00	0.22	0.00	0.22	0.22	0.22	0.00	0.22	0.00	0.22
G-GIB3_5	187	0	92.8	-55	176.25	0.00	0.22	0.00	0.22	0.22	0.22	0.00	0.22	0.00	0.22
G-GIB3_5	187	0	92.8	-55	176.25	0.00	0.22	0.00	0.22	0.22	0.22	0.00	0.22	0.00	0.22

Table E. 3: Generator dynamic parameters for model Type CSVGN1 (SVC)

Bus Number	Bus Name	Id	Mbase (MVA)	K	T1	T2	T3 (>0)	T4	T5	RMIN (reactor minimum Mvar)	VMAX	VMIN	CBASE (capacitor Mvar)
507003	HOLETA-500 500.0	1	900	100.00	0.00	0.00	0.63	0.00	0.03	0.00	1.00	0.00	450.00

Table E. 4: Control parameters for generators with exciter Type EXST1

Bus Number	Bus Name	Id	TR	VIMAX	VIMIN	TC	TB	KA	TA	VRMAX	VRMIN	KC	KF	TF (> 0)
907001	BELES-1 15.0	1	0.01	0.20	-0.30	0.04	0.04	60.00	0.02	5.00	-5.00	0.00	0.03	1.00
907002	T-ABA2-1 10.5	1	0.01	99.00	-99.00	0.01	0.01	400.00	0.02	5.00	-5.00	0.00	0.03	1.00
907003	TS-ABAY1-1 6.0	1	0.01	99.00	-99.00	0.01	0.01	400.00	0.02	5.00	-5.00	0.00	0.03	1.00
907004	BELES-2 15.0	1	0.01	0.20	-0.30	0.04	0.04	60.00	0.02	5.00	-5.00	0.00	0.03	1.00
907005	T-ABA2-2 10.50	1	0.01	99.00	-99.00	0.01	0.01	400.00	0.02	5.00	-5.00	0.00	0.03	1.00
907006	TS-ABAY1-2 6.00	1	0.01	99.00	-99.00	0.01	0.01	400.00	0.02	5.00	-5.00	0.00	0.03	1.00
907007	BELES-3 15.0	1	0.01	0.20	-0.30	0.04	0.04	60.00	0.02	5.00	-5.00	0.00	0.03	1.00

907008	TS-ABAY1-3	6.0	1	0.01	99.00	-99.00	0.01	0.01	400.00	0.02	5.00	-5.00	0.00	0.03	1.00
907009	BELES-4	15.0	1	0.01	0.20	-0.30	0.04	0.04	60.00	0.02	5.00	-5.00	0.00	0.03	1.00
908005	FINCHA3	13.8	1	0.01	0.20	-0.30	0.06	1.80	400.00	0.02	5.00	-5.00	0.00	0.03	1.00
908006	FINCHA4	13.8	1	0.01	0.20	-0.30	0.06	1.80	400.00	0.02	5.00	-5.00	0.00	0.03	1.00
909001	TEKEZE1	13.8	1	0.01	0.20	-0.30	0.04	0.40	60.00	0.02	5.00	-5.00	0.00	0.03	1.00
909002	TEKEZE4	13.8	1	0.01	0.20	-0.30	0.04	0.40	60.00	0.02	5.00	-5.00	0.00	0.03	1.00
909004	TEKEZE2	13.8	1	0.01	0.20	-0.30	0.04	0.40	60.00	0.02	5.00	-5.00	0.00	0.03	1.00
909005	TEKEZE3	13.8	1	0.01	0.20	-0.30	0.04	0.40	60.00	0.02	5.00	-5.00	0.00	0.03	1.00
915002	G-GIB2-1	15.0	1	0.01	0.20	-0.30	0.04	0.40	60.00	0.02	5.00	-5.00	0.00	0.03	1.00
915004	G-GIB2-2	15.0	1	0.01	0.20	-0.30	0.04	0.40	60.00	0.02	5.00	-5.00	0.00	0.03	1.00
915006	G-GIB2-3	15.0	1	0.01	0.20	-0.30	0.04	0.40	60.00	0.02	5.00	-5.00	0.00	0.03	1.00
915008	G-GIB2-4	15.0	1	0.01	0.20	-0.30	0.04	0.40	60.00	0.02	5.00	-5.00	0.00	0.03	1.00
915009	G-GIB 3_1	15.0	1	0.01	0.20	-0.30	0.04	0.40	60.00	0.02	5.00	-5.00	0.00	0.03	1.00
915009	G-GIB 3_1	15.0	2	0.01	0.20	-0.30	0.04	0.40	60.00	0.02	5.00	-5.00	0.00	0.03	1.00
915010	G-GIB3_2	15.0	1	0.01	0.20	-0.30	0.04	0.40	60.00	0.02	5.00	-5.00	0.00	0.03	1.00
915010	G-GIB3_2	15.0	2	0.01	0.20	-0.30	0.04	0.40	60.00	0.02	5.00	-5.00	0.00	0.03	1.00
915011	G-GIB3_3	15.0	1	0.01	0.20	-0.30	0.04	0.40	60.00	0.02	5.00	-5.00	0.00	0.03	1.00
915011	G-GIB3_3	15.0	2	0.01	0.20	-0.30	0.04	0.40	60.00	0.02	5.00	-5.00	0.00	0.03	1.00
915012	G-GIB3_4	15.0	1	0.01	0.20	-0.30	0.04	0.40	60.00	0.02	5.00	-5.00	0.00	0.03	1.00
915012	G-GIB3_4	15.0	2	0.01	0.20	-0.30	0.04	0.40	60.00	0.02	5.00	-5.00	0.00	0.03	1.00
915013	G-GIB3_5	15.0	1	0.01	0.20	-0.30	0.04	0.40	60.00	0.02	5.00	-5.00	0.00	0.03	1.00
915013	G-GIB3_5	15.0	2	0.01	0.20	-0.30	0.04	0.40	60.00	0.02	5.00	-5.00	0.00	0.03	1.00

Table E. 5: Control parameters for generators with exciter Type EXDC2

Bus Number	Bus Name	Id	TR (sec)	KA	TA (sec)	TB (sec)	TC (sec)	VR MAX or Zero	VR MIN	KE or Zero	TE (>0) (sec)	KF	TF1 (>1) (sec)	Switch Value =0	E1	SE (E1)	E2	SE (E2)
908002	NESHE-1 13.8	1	0.01	50.0	0.06	0.00	0.00	3.50	-2.50	-0.10	0.40	0.13	1.40	0.00	4.5	0.15	6.0	0.50
908004	NESHE-2 13.8	1	0.01	50.0	0.06	0.00	0.00	3.50	-2.50	-0.10	0.40	0.13	1.40	0.00	4.5	0.15	6.0	0.50

Table E. 6: Control parameters for generators with exciter Type IEEEEX1

Bus Number	Bus Name	Id	TR	KA	TA	TB	TC	VR MAX or Zero	VR MIN	KE or Zero	TE (>0)	KF	TF1 (>1)	0. Switch	E1	SE (E1)	E2	SE (E2)
911005	KOKA1 10.5	1	0.01	37.0	0.12	0.01	0.01	2.40	-2.4	0.00	0.8	0.06	0.30	0.00	1.73	0.33	2.80	0.69
911006	KOKA3 10.5	1	0.01	37.0	0.12	0.01	0.01	2.40	-2.4	0.00	0.8	0.06	0.30	0.00	1.73	0.33	2.80	0.69
911009	AWASH3-2 10.5	1	0.01	37.0	0.12	0.01	0.01	2.40	-2.4	0.14	0.8	0.06	0.30	0.00	1.73	0.33	2.80	0.69
911010	KOKA2 10.5	1	0.01	37.0	0.12	0.01	0.01	2.40	-2.4	0.00	0.8	0.06	0.30	0.00	1.73	0.33	2.80	0.69

Table E. 7: Control parameters for generators with exciter Type SCRX

Bus Number	Bus Name	Id	TA/ TB	TB (>0)	K	TE	EMIN	EMAX	CSWITCH (0=bus fed, 1=solid fed)	rc/rfd
908001	FINCHA1 13.8	1	0.1	10.0	100.0	0.1	0.0	5.0	0.0	0.0
908003	FINCHA2 13.8	1	0.1	10.0	100.0	0.1	0.0	5.0	0.0	0.0
911003	AWASH2-1 10.5	1	0.1	10.0	100.0	0.1	0.0	5.0	0.0	0.0
911004	AWASH3-1 0.5	1	0.1	10.0	100.0	0.1	0.0	5.0	0.0	0.0
911007	M-WAKNA1 13.8	1	0.1	10.0	100.0	0.1	0.0	5.0	0.0	0.0
911008	AWASH2-2 10.5	1	0.1	10.0	100.0	0.1	0.0	5.0	0.0	0.0
911011	M-WAKNA2 3.8	1	0.1	10.0	100.0	0.1	0.0	5.0	0.0	0.0
911012	M-WAKNA3 3.8	1	0.1	10.0	100.0	0.1	0.0	5.0	0.0	0.0
911013	M-WAKNA4 13.8	1	0.1	10.0	100.0	0.1	0.0	5.0	0.0	0.0
915003	G-GIBE1-1 13.8	1	0.1	10.0	100.0	0.1	0.0	5.0	0.0	0.0
915005	G-GIBE1-2 13.8	1	0.1	10.0	100.0	0.1	0.0	5.0	0.0	0.0
915007	G-GIBE1-3 13.8	1	0.1	10.0	100.0	0.1	0.0	5.0	0.0	0.0

Table E. 8: Control parameters for generators with governor Type HYGOV

Bus Number	Bus Name	Id	R, Permanent Droop	r, Temporary Droop	Tr (> 0) Governor Time Constant	Tf (> 0) Filter Time Constant	Tg (> 0) Servo Time Constant	VELM, Gate Velocity Limit	GMAX/GMIN Maximum/ Minimum Gate Limit	TW (> 0) Water Time Constant	At, Turbine Gain	Dturb, Turbine Damping	qNL, No Load Flow
907001	BELES-1 15.0	1	0.05	0.4	5	0.05	0.5	0.2	1 / 0	1.75	1.15	0.4	0.08
907002	T-ABA2-1 10.5	1	0.04	0.5	6	0.05	0.5	0.167	1.2 / 0	2	1.2	0.5	0.1
907003	TS-ABAY1-1 6.0	1	0.04	0.5	6	0.05	0.5	0.167	1.2 / 0	2	1.2	0.5	0.1
907004	BELES-2 15.0	1	0.05	0.4	5	0.05	0.5	0.2	1 / 0	1.75	1.15	0.4	0.08
907005	T-ABA2-2 10.5	1	0.04	0.5	6	0.05	0.5	0.167	1.2 / 0	2	1.2	0.5	0.1
907006	TS-ABAY1-2 6.0	1	0.04	0.5	6	0.05	0.5	0.167	1.2 / 0	2	1.2	0.5	0.1

907007	BELES-3 15.0	1	0.05	0.4	5	0.05	0.5	0.2	1 / 0	1.75	1.15	0.4	0.08
907008	TS-ABAY1-3 6.0	1	0.04	0.5	6	0.05	0.5	0.167	1.2 / 0	2	1.2	0.5	0.1
907009	BELES-4 15.0	1	0.05	0.4	5	0.05	0.5	0.2	1 / 0	1.75	1.15	0.4	0.08
908001	FINCHA1 13.8	1	0.04	0.5	6	0.05	0.5	0.167	1 / 0	2	1.2	0.3	0.1
908002	NESHE-1 13.8	1	0.04	0.5	6	0.05	0.5	0.167	1 / 0	2	1.2	0.3	0.1
908003	FINCHA2 13.8	1	0.04	0.5	6	0.05	0.5	0.167	1 / 0	2	1.2	0.3	0.1
908004	NESHE-2 13.8	1	0.04	0.5	6	0.05	0.5	0.167	1 / 0	2	1.2	0.3	0.1
908005	FINCHA3 13.8	1	0.04	0.5	6	0.05	0.5	0.167	1 / 0	2	1.2	0.3	0.1
908006	FINCHA4 13.8	1	0.04	0.5	6	0.05	0.5	0.167	1 / 0	2	1.2	0.3	0.1
909001	TEKEZE1 13.8	1	0.04	0.5	6	0.05	0.5	0.167	1 / 0	2	1.2	0.4	0.1
909002	TEKEZE4 13.8	1	0.04	0.5	6	0.05	0.5	0.167	1 / 0	2	1.2	0.4	0.1
909004	TEKEZE2 13.8	1	0.04	0.5	6	0.05	0.5	0.167	1 / 0	2	1.2	0.4	0.1
909005	TEKEZE3 13.8	1	0.04	0.5	6	0.05	0.5	0.167	1 / 0	2	1.2	0.4	0.1
911003	AWASH2-1 10.5	1	0.04	0.5	6	0.05	0.5	0.167	1 / 0	2	1.2	0.3	0.1
911004	AWASH3-1 10.5	1	0.04	0.5	6	0.05	0.5	0.167	1 / 0	2	1.2	0.3	0.1
911005	KOKA1 10.5	1	0.04	0.5	6	0.05	0.5	0.167	1 / 0	2	1.2	0.3	0.1
911006	KOKA3 10.5	1	0.04	0.5	6	0.05	0.5	0.167	1 / 0	2	1.2	0.3	0.1
911007	WAKNA1 13.8	1	0.04	0.5	6	0.05	0.5	0.167	1 / 0	2	1.2	0.4	0.1
911008	AWASH2-2 10.5	1	0.04	0.5	6	0.05	0.5	0.167	1 / 0	2	1.2	0.4	0.1
911009	AWASH3-2 10.5	1	0.04	0.5	6	0.05	0.5	0.167	1 / 0	2	1.2	0.4	0.1
911010	KOKA2 10.5	1	0.04	0.5	6	0.05	0.5	0.167	1 / 0	2	1.2	0.4	0.1
911011	WAKNA2 13.8	1	0.04	0.5	6	0.05	0.5	0.167	1 / 0	2	1.2	0.4	0.1
911012	WAKNA3 13.8	1	0.04	0.5	6	0.05	0.5	0.167	1 / 0	2	1.2	0.4	0.1
911013	WAKNA4 13.8	1	0.04	0.5	6	0.05	0.5	0.167	1 / 0	2	1.2	0.4	0.1
915002	G-GIB2-1 15.0	1	0.04	0.5	6	0.05	0.5	0.167	1 / 0	2	1.2	0.4	0.1
915003	G-GIBE1-1 13.8	1	0.04	0.5	6	0.05	0.5	0.167	1 / 0	2	1.2	0.4	0.1
915004	G-GIB2-2 15.0	1	0.04	0.5	6	0.05	0.5	0.167	1 / 0	2	1.2	0.4	0.1

915005	G-GIBE1-2 13.8	1	0.04	0.5	6	0.05	0.5	0.167	1 / 0	2	1.2	0.4	0.1
915006	G-GIB2-3 15.0	1	0.04	0.5	6	0.05	0.5	0.167	1 / 0	2	1.2	0.4	0.1
915007	G-GIBE1-3 13.8	1	0.04	0.5	6	0.05	0.5	0.167	1 / 0	2	1.2	0.4	0.1
915008	G-GIB2-4 15.0	1	0.04	0.5	6	0.05	0.5	0.167	1 / 0	2	1.2	0.4	0.1
915009	G-GIB 3_1 15.0	1	0.04	0.5	6	0.05	0.5	0.167	1 / 0	2	1.2	0.4	0.1
915009	G-GIB 3_1 15.0	2	0.04	0.5	6	0.05	0.5	0.167	1 / 0	2	1.2	0.4	0.1
915010	G-GIB3_2 15.0	1	0.04	0.5	6	0.05	0.5	0.167	1 / 0	2	1.2	0.4	0.1
915010	G-GIB3_2 15.0	2	0.05	0.4	5	0.05	0.5	0.2	1 / 0	1.75	1.15	0.4	0.08
915011	G-GIB3_3 15.0	1	0.05	0.4	5	0.05	0.5	0.2	1 / 0	1.75	1.15	0.4	0.08
915011	G-GIB3_3 15.0	2	0.05	0.4	5	0.05	0.5	0.2	1 / 0	1.75	1.15	0.4	0.08
915012	G-GIB3_4 15.0	1	0.05	0.4	5	0.05	0.5	0.2	1 / 0	1.75	1.15	0.4	0.08
915012	G-GIB3_4 15.0	2	0.05	0.4	5	0.05	0.5	0.2	1 / 0	1.75	1.15	0.4	0.08
915013	G-GIB3_5 15.0	1	0.05	0.4	5	0.05	0.5	0.2	1 / 0	1.75	1.15	0.4	0.08
915013	G-GIB3_5 15.0	2	0.05	0.4	5	0.05	0.5	0.2	1 / 0	1.75	1.15	0.4	0.08

Appendix F: Parameters of Wind Machines

The parameters of wind generators of model Type WT4G1 and the electrical control parameters of model Type WT4E1 are given in Table F.1 and F.2.

Table F. 1: Generator parameters for wind machines of model Type WT4G1

Bus Number	Bus Name	Id	Mbase (MVA)	TIQCmd, Converter time constant for Iqcmd, second	TIpCmd, Converter time constant for Ipcmd, second	VLVPL1-Low Voltage power Logic (LVPL), voltage 1 (pu)	VLVPL2, LVPL voltage 2 (pu)	GLVPL-LVPL gain	High Voltage reactive Current (HVRC) logic, voltage (pu)	CURHVRCR, HVRC logic, current (pu)	Rip_LVPL, Rate of active current change	T_LVPL, Voltage sensor for LVPL, second
909006	ASHEGODA-WF 33	1	90	0.02	0.02	4	0.9	1.11	1.2	2	2	0.02
909006	ASHEGODA-WF 33	2	37.5	0.02	0.02	4	0.9	1.11	1.2	2	2	0.02
911015	ADAMA WF-II 33	1	191.25	0.02	0.02	4	0.9	1.11	1.2	2	2	0.02
911016	ADAMA I WF 3	1	54	0.02	0.02	4	0.9	1.11	1.2	2	2	0.02

Table F. 2: Control parameters for wind machines of model Type WT4E1

Bus Number	Bus Name	Id	Tfv-V-regulator filter	Kpv-V-regulator proportional gain	Kiv-V-regulator integrator gain	Kpp-T-regulator proportional gain	Kip-T-regulator integrator gain	Kf-Rate feedback gain	Tf-Rate feedback time constant	QMX-V-regulator max limit	QMN-V-regulator min limit	IPMAX-Max active current limit
909006	ASHEGODA-WF 33.0	1	0.15	18	5	0.05	0.1	0	0.08	0.47	-0.47	1.1
909006	ASHEGODA-WF 33.0	2	0.15	18	5	0.05	0.1	0	0.08	0.47	-0.47	1.1
911015	ADAMA WF-II 33.0	1	0.15	18	5	0.05	0.1	0	0.08	0.47	-0.47	1.1
911016	ADAMA I WF 33.0	1	0.15	18	5	0.05	0.1	0	0.08	0.47	-0.47	1.1

TRV-V-sensor	dPMX, Max limit in power PI controller (pu)	dPMN, Min limit in power PI controller (pu)	T_Power, Power filter time constant	KQi, MVAR/Voltage gain	VMINCL, Min. voltage limit	VMAXCL, Max. voltage limit	KVi, Voltage/MVAR Gain	Tv-Lag time constant in Wind Var controller	Tp-Pelec filter in fast PF controller	ImaxTD-Converter current limit	Iphl-Hard active current limit	Iqhl-Hard reactive current limit
0	0.5	-0.5	0.05	0.1	0.9	1.1	120	0.05	0.05	1.7	1.11	1.11
0	0.5	-0.5	0.05	0.1	0.9	1.1	120	0.05	0.05	1.7	1.11	1.11
0	0.5	-0.5	0.05	0.1	0.9	1.1	120	0.05	0.05	1.7	1.11	1.11
0	0.5	-0.5	0.05	0.1	0.9	1.1	120	0.05	0.05	1.7	1.11	1.11