

IMPACT OF LARGE SCALE WIND POWER INTEGRATION ON ETHIOPIAN POWER SYSTEM TRANSIENT STABILITY

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**A thesis submitted to the school of electrical engineering and computing of Adama
Science and Technology university in partial fulfillment of the requirements for the
degree of Masters of Science in electrical power engineering**



**ADAMA SCIENCE AND TECHNOLOGY UNIVERSITY
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March 22, 2017

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 universities, and all sources of materials used for the thesis work have been fully acknowledged.

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Abstract

Ethiopian power system is a hydro dominant system where 84.19% of the electricity generation is hydro based. But in recent year Ethiopia electric power corporation is using wind power to solve electric power shortage. Currently 14.07% (153MW from Adama II wind farm, 120MW from Ashegoda wind farm and 51MW from Adama I wind farm) of the country's power is generated from wind.

Integration of large scale wind farm in to a power system presents some challenges that must be addressed, such as system operation and control, stability and power quality. Therefore, currently several wind impact studies have been carried out in different countries. From these studies it was understood that the level of wind power penetration and intermittent nature of wind have major impact on a power system.

This study focuses on the impact of wind power integration on the transient stability performance of a power system and different scenarios have been investigated. The analysis and modeling has been done using DIgSILENT simulation software based on data obtained from EEP and Adama II wind farm.

A very large wind power plant may contain hundreds of Megawatt-size wind turbines. These turbines are interconnected by an intricate collector system. While the impact of individual turbines on the the larger power system network is minimal, collectively, wind turbines can have a significant impact on a power system during a sever disturbance such as nearby fault. since it is not practical to represent all individual wind turbines to conduct simulations, a simplified equivalent representation is required . In this study, Adama II wind farm is aggregated from 102 wind turbines to single turbine representation and the model developed has been verified for its accuracy. The simulation has given 0.066% (0.1 MW)of active power flow and 0.081% (0.04 MVAR) of reactive power flow difference between full turbine representation and single turbine representation of Adama II wind farm.

The transient stability impact has been analyzed for different aspects like location of fault and generator technology. As per the result of this study, wind power integration has a positive impact on the the critical fault clearing time (CCT) of the power system for example, for a fault near to Ashegoda wind farm the CCT of Tekeze power plant has been improved by 226 ms and for a fault far from any of the wind farms the CCT has been improved by only 44 ms.

Key words: Transient stability, DIgSILENT, DFIG, PMSG, Wind turbine, Aggregation of wind farm, Critical fault clearing time

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Contents

Abstract	i
Acknowledgments	ii
List of figures	vii
List of tables	viii
Acronyms	ix
1 Introduction	1
1.1 Background	1
1.2 Statement of the Problem	1
1.3 Objective of the Study	2
1.3.1 General Objective	2
1.3.2 Specific Objective	2
1.4 Scope and Limitation of the Study	2
1.5 Thesis Outline	3
2 Theoretical Background and Literature Review	4
2.1 Theoretical Background	4
2.1.1 History of Wind Power Generation	4
2.1.2 Wind Power Generation in Ethiopia	4
2.2 Literature Review	5
2.2.1 Impact of Wind Power Integration on Power System Stability	6
3 Methodology	8
3.1 Introduction to Power System Stability	8
3.1.1 Transient Stability	9
3.2 Wind Turbine Modeling	11

3.2.1	Modeling of Type 3 Wind Turbine (DFIG)	13
3.2.2	Modeling of Type 4 Wind Turbine (PMSG)	17
3.3	Wind Farm Aggregation	22
3.3.1	Steps for Wind Farm Aggregations	24
4	Result Analysis and Discussion	28
4.1	Adama II Wind Farm Modeling	28
4.1.1	Adama II Cluster 1 Aggregation	29
4.2	Transient Stability of Ethiopian National Grid Without Wind Power Integration (Base Case Scenario)	42
4.2.1	Case One: Fault at 230 KV Koka to Kalitti Line	43
4.2.2	Case Two: Fault at 230KV Alamata to Kombolcha Line	47
4.2.3	Case Three: Fault at 230KV Fincha to Ghedo Line	50
4.3	Transient Stability of Ethiopian National Grid With Wind Power Integration (Present Case Scenario)	53
4.3.1	Case One: Fault at 230 KV Koka to Kaliti Line	53
4.3.2	Case Two: Fault at 230KV Alamata to Kombolcha Line	54
4.3.3	Case Three: Fault on 230KV Fincha to Ghedo Line	56
4.4	Transient Stability of Ethiopian National Grid if All the Wind Power Plants Use PMSG Technology (Third Case Scenario)	58
4.4.1	Case One: Fault on 230KV Koka to Kaliti Line	58
4.4.2	Case Two: Fault on 230KV Alamata to Kombolcha Line	60
4.4.3	Case Three: Fault on 230KV Fincha to Ghedo Line	61
5	Conclusion, Recommendation and Future Work	67
5.1	Conclusion	67
5.2	Recommendations	68
5.3	Future Work	69
	References	70

A	Micro Sitting of Adama II Wind Farm	72
B	Adama II Wind Farm All Clusters Parameters	73
C	Ethiopian High Voltage Grid Data	77

List of Figures

3.1	Classification of power system stability [1]	8
3.2	A single generator feeding an inductive load [1,7]	9
3.3	Single machine connected to an infinite bus [8]	10
3.4	Rotor angle response for different values of fault clearing time [1]	11
3.5	Typical power curve of single 1.5MW DFIG wind turbine	12
3.6	Components of doubly feed induction generator [9]	13
3.7	Equivalent electrical circuit of the DFIG [9]	16
3.8	Components of permanent magnet synchronous generator [12]	18
3.9	Equivalent electrical circuit of the PMSG [12]	20
3.10	Generic wind power plant topology [15,16]	23
3.11	Single turbine representation of a wind power plant (STR) [15]	23
3.12	a)Three turbine system and b) Single turbine representation [17]	24
3.13	Equivalent circuit of a transmission line [15]	25
3.14	Wind turbines connected in a daisy chained string and equivalent circuit [15]	26
4.1	Adama II wind power plant representation	29
4.2	Single turbine representation of cluster one of Adama II WPP	33
4.3	Full turbine representation of Adama II wind farm	36
4.4	8 turbine and single turbine representation of Adama II wind farm	37
4.5	Schematic representation of hydro power plants in Ethiopian power system	42
4.6	Ethiopian national grid	44
4.7	Rotor angle and speed of generators for case 1 without wind	45
4.8	Terminal voltage & reactive power of generators case 1 without wind . . .	46
4.9	Rotor angle for out of step condition for case 1 without wind	46
4.10	Active power for out of step condition for case 1 without wind	47
4.11	Rotor angle and speed of generators for case 2 without wind	48
4.12	Terminal voltage & reactive power of generators case 2 without wind . . .	48

4.13	Rotor angle for out of step condition for case 2 without wind	49
4.14	Active power for out of step condition for case 2 without wind	49
4.15	Rotor angle and speed of generators for case 3 without wind	50
4.16	Terminal voltage & reactive power of generators case 3 without wind . . .	51
4.17	Rotor angle for out of step condition for case 3 without wind	52
4.18	Active power for out of step condition for case 3 without wind	52
4.19	Rotor angle and speed of generators for case 1 with wind	54
4.20	Terminal voltage & reactive power of generators for case 1 with wind . .	54
4.21	Rotor angle and speed of generators for case 2 with wind	55
4.22	Terminal voltage & reactive power of generators case 2 with wind	56
4.23	Rotor angle and speed of generators for case 3 with wind	57
4.24	Terminal voltage & reactive power of generators case 3 with wind	57
4.25	Rotor angle and speed of generators with all PMSG case one	59
4.26	Terminal voltage and reactive power with all PMSG case one	59
4.27	Rotor angle and speed of generators with all PMSG case two	60
4.28	Terminal voltage and reactive power with all PMSG case two	61
4.29	Rotor angle and speed of generators with all PMSG case three	62
4.30	Terminal voltage and reactive power with all PMSG case three	62
4.31	Critical clearing time comparison for different scenarios	64
A.1	Micro sitting of Adama II wind farm	72

List of Tables

2.1	List of generating units in Ethiopia	5
4.1	Adama II wind power plant turbine generator specifications [19]	29
4.2	Summery of unit transformer equivalent impedance for all clusters	33
4.3	Summery of collector circuit impedance for all clusters	34
4.4	Power flow output from load flow calculation of full turbine representation	38
4.5	Power flow output from load flow calculation of aggregated 8 turbine representations	39
4.6	Power flow output from load flow calculation of single turbine representation	40
4.7	Power flow comparison for different wind farm representations	41
4.8	Transient stability response of the system for base case scenario	52
4.9	Transient stability response of the system for present case scenario	58
4.10	Transient stability response of the system for third scenario	63
4.11	Power system response comparison for different scenarios	63
B.1	GPS data and branch impedance of Adama II WP all clusters	73
C.1	Existing load data of the Ethiopian high voltage grid	77
C.2	Existing power plants in Ethiopia and generator specifications	82
C.3	Existing short circuit test values of two winding high voltage transformers	83
C.4	Existing short circuit test value of three winding high voltage transformer	90
C.5	Existing transmission line data of Ethiopian high voltage grid	95

Acronyms

AC	Alternating Current
CCT	Critical Clearing Time
CSG	Conventional Synchronous Generator
DC	Direct Current
DFIG	Doubly Feed Induction Generator
DPL	DIgSILENT Programming Language
EEP	Ethiopian Electric Power
FCT	Fault Clearing Time
FRT	Fault Ride Through
FSR	Full System Representation
GSC	Grid Side Converter
IGBT	Insulated Gate Bipolar Transistor
PI	Proportional Integrator
PMSG	Permanent Magnet Synchronous Generator
POI	Point Of Interconnection
PU	Per Unit
RSC	Rotor Side Converter
SCIG	Squirrel Cage Induction Generator
STR	Single Turbine Representation
VSC	Voltage Source Converter
WECC	Western Electric Coordinating Council
WGMG	Wind Generator Modeling Group
WPP	Wind Power Plant

Chapter 1

Introduction

1.1 Background

In recent years, the electrical generation from wind has received a lot of attention and has been developing rapidly worldwide, due to the exhaustion of fossil fuel sources and the policy of green house gas mitigation from power generation. However many issues are raised when power system is integrated with large amount of wind generation system, in terms of power system operation, control and protection. The issue of transient stability is becoming more and more important, since the wind power penetration is increased rapidly. But the financial and regulatory conditions have caused electric utility to build power system with less redundancy and operate them close to transient stability limits [1]. Hence there are more and more challenges for the control and protection to maintain the security and stability of power system with large wind penetration.

Currently Ethiopia is generating its electric power from renewable energy sources. As of this study, Ethiopia has a total installed capacity of 2302.6 MW, from this 84.19% (1938.6 MW) is generated from hydro power, 14.07% (324 MW) is generated from wind power and the remaining 1.74% (40 MW) is generated from diesel [2]. Since Ethiopia has high wind resource potential EEP has a plan to increase the power generated from wind more than 600 MW. Thus the growing level of wind power penetration in to the power system requires detailed analysis for its impact on the steady state and dynamic behavior of the power system.

1.2 Statement of the Problem

EEP has a plan to use wind power plants to solve the shortage of electric power supply. But besides the intermittent nature of wind, using different wind turbine technologies such as DFIG and PMSG, the location where the power plants going to be connected and its increased penetration in to the grid has its own impact on the stability of the power system. Thus, this impact has to be analyzed for its stability issues. In this study, transient stability issues will be considered.

1.3 Objective of the Study

1.3.1 General Objective

The main objective of this study is to investigate the impact of wind power integration on transient stability of Ethiopian power system.

1.3.2 Specific Objective

- To collect and analyze the wind power generation data of the currently existing wind power plants
- To develop a model for Wind farm aggregation for dynamic studies and validating the developed model. As a case study Adama II wind power plant.
- To make simulations on the system to study the impact of wind power integration on the national grid.
- To make conclusions and recommendations on how the transient stability of the grid is affected.

1.4 Scope and Limitation of the Study

All studies for each of the above stated objectives will be modeled and simulated in DIgSILENT power factory version 15.1.7 simulation software. The wind turbine models will be created to be generic in nature but are practical in that in their expansion may form part of a large network grid. All elements data type exist in DIgSILENT and all equipment specification are from data obtained from EEP and industry standards. Each model will be controlled by DIgSILENT programming language (DPL) scripts.

The main scope of this study is to investigate the impact of the added wind power on transient stability when transporting electric power between different parts of Ethiopia.

1.5 Thesis Outline

The thesis is structured as follows:

Chapter one is an introduction, this chapter explains the background and problem statement of the study and it also explains the objective of the study and limitation and scope of the study.

Chapter two is literature review; the chapter starts by introducing about wind power and follows with discussing the wind power plant in Ethiopia. Finally some studies regarding impact of wind power integration on a power system will be reviewed.

Chapter three is methodology, in this chapter the theories used in this thesis will be laid out. First power system stability is introduced and from the different stability types rotor angle stability which the main focus of this study especially transient stability is explained. Secondly model of a DFIG wind turbine for transient stability study is explained in detail. Finally wind farm aggregation technique will be described.

Chapter four is result analysis and discussion, in this chapter Adama II wind farm aggregation will be performed and the full turbine system and the aggregated representation will be analyzed using DIgSILENT simulation software, the transient stability in Ethiopian power system with and without wind integration will be investigated. Simulation will be done with a full system in DIgSILENT and the dynamic response of the system will be observed when subjected to various fault cases.

Chapter five presents conclusion, recommendation and future works

Chapter 2

Theoretical Background and Literature Review

2.1 Theoretical Background

This section tries to give a brief description on how Electric generation from wind is started and it also tries to express the wind power generation in Ethiopia.

2.1.1 History of Wind Power Generation

The power of wind have been utilized for at least 3000 years until the early twenty century wind energy was used to provide mechanical power to pump water or to grind grain. At the beginning of modern industrialization the use of the fluctuating wind energy was substituted by fossil fuel fired engines or the electric grid, which provided a more consistent power source. In 1891, the dane paul lacour was the first to build a wind turbine that generated electricity. Denish engineers improved the technology during World War I and II and used the technology to overcome energy shortage [3]. Currently three blade wind turbines dominated the market for grid connected horizontal axis wind turbines. Three bladed wind turbines have the advantage that the rotor moment of inertia is easier to understand and therefore often better to handle than the rotor moment of inertia of two bladed turbines [3].

The impact of wind power on a power system depends on level of penetration to the system. If energy produced by wind power (annually) as a percentage of the gross electricity consumption is less than 5% of the gross demand, it is categorized under low level penetration and if it is greater than 10% it is categorized under high level penetration [3].

2.1.2 Wind Power Generation in Ethiopia

Ethiopia generates most of its electricity from renewable energy sources, mainly hydro power. In 2003 E.C, over 96% of Ethiopia's electricity was from hydro power. The country began a large program to expand electricity in 2010 E.C from 2000 MW to 10,000 MW. This was to be done mainly with renewable resources wind and geothermal were included to offset seasonal difference in water levels. Most of the energy needs of Ethiopia are currently filled by bio-fuels for cooking, heating and off grid lighting. Now a day solar photovoltaic panels are being promoted to replace fuel based lighting and off grid electrical supply with a solar panel assembly plant opening in Addis Abeba in early 2013. The first

wind installation in the country was the 51 MW Adama I wind farm built in 2011. The 120 MW Ashegoda wind farm opened in October 2013 and was the largest wind farm in Africa at that time. The larger 153 MW Adama II wind farm went online in May 2015; bringing Ethiopia's installed wind capacity to 324 MW total [2].

Table 2.1: List of generating units in Ethiopia

No.	Power plant name	Region	Voltage level (KV)	Size (MW)	No. of units	Capacity* (MW)
1	Adama I WPP	Central	132	1.5	34	51
2	Awash II PP	Central	132	20	3	32
3	Awash III PP	Central	132	20	2	32
4	Koka PP	Central	132	20	3	43.2
5	Ashegoda WPP	North	230	1	120	120
6	Tekeze PP	North	230	86	4	300
7	Beles PP	North W.	400	133	4	460
8	Tis Abay I PP	North W.	132	36	2	11.4
9	Tis Abay II PP	North W.	132	36	2	72
10	MelkaWakena PP	South	230	45	4	153
11	Gilgel Gibe II PP	South W.	400	105	4	420
12	Gilgel Gibe I PP	South W.	230	73	3	184
13	AmertiNeshe PP	West	230	49	2	97
14	Fincha PP	West	230	40	4	134
15	Adama II WPP	Central	230	1.5	102	153
16	Dire-Dawa Diesel PP	East	132	4	10	40
Total capacity						2302.6

* The total capacity of the power plants is the product of no. of units, size of each unit and plant factor.

2.2 Literature Review

In this section, different studies that have been done on the impact of wind power integration will be reviewed and for those studies that have been done on Ethiopian power system, their short comings and the contribution of this study has been discussed.

2.2.1 Impact of Wind Power Integration on Power System Stability

Ch. Eping, J. Stenzel, M. Pöller, H. Müller [4] conducted a study on the impact of large scale wind power on power system stability, the objective of the study was to explain and understand, not to calculate actual numbers and figures. The phenomena that is subjected to investigation in the paper was the effect of wind power integration on transient stability limit of long tie-line. The study used DIgSILENT as a simulation tool. After a number of simulations it concluded that the location of wind generation can have a very large impact on transient stability, especially when high wind resources are located in one particular area leading to highly modified power flow includes tie line flow. The actual generator technology also has a considerable impact on transient stability. DFIG technology was able to improve the transient stability margin, when being equipped with low voltage ride through capability, reactive current boosting and ideally with fast voltage control. The integration of wind generation into sub transmission and distribution system has negative impact on transient stability due to reactive contribution is highly limited. As can be seen the objective of the study didn't include calculation of actual numbers and figures but in this study, actual numbers and figures will be calculated. It also tries to investigate the impact of wind power for faults occurring in different locations of the power system.

Considerable numbers of studies also been conducted on the impact of wind power integration on Ethiopian power system stability. G.Bekele and A.abdel [5] investigated a specific scenario on Adama I wind farm interaction with Ethiopian electric power corporation's grid. It only concerned with fault ride-through (FRT) capability, which includes voltage recovery at the wind terminal. In the study only PMSG wind turbine was considered and using DIgSILENT simulation software it tried to model Adama I wind farm by representing the 34 wind turbines with a single turbine. After modeling a three phase fault of 150 ms duration was introduced on the high voltage terminal of the wind farm and concluded that PMSG wind turbines provided to be promising in which it can ride from voltage deep with a short period of time and the active and reactive power performance is good, with respect to the three phase short circuit fault showing its immunity. But in this study only PMSG wind turbines were analyzed and their impact on the transient stability of the power system was not studied and also only a single location of fault which is near to the wind farm was considered. In this study the impact of both PMSG and DFIG wind turbine technologies on power system transient stability will be investigated and also the impact of wind power plant with different fault locations will be analyzed.

F.Shewarega and I.Erlich [6] tried to deal with the impact of large scale wind power integration on transient stability performance of a power system. The study uses a test system to investigate this impact with a fault location 50KM from the wind farm. In this

study DFIG wind turbine technology was considered for analyzing the impact. It made a complete modeling of DFIG wind turbine and simulated using DIgSILENT software. After a number of simulation and analysis it concluded that the electro-mechanical power oscillations, which typically occur following a grid fault in conventional synchronous generators are not prevalent in wind generation plants. The overall impact of wind on the transient stability performance of the network, as it increases the fault clearing time and can be characterized as adverse. But the critical clearing time decreases as the share of wind in relation to the overall installed capacity increases. In this study only DFIG type of wind turbines were considered and the impact of having distributed wind power plant was not deeply investigated and also it doesn't consider the effect when there are a number of power plants distributed in wide areas.

Chapter 3

Methodology

In this chapter, the theories used in this thesis has been laid out. First, power system stability is introduced and from the different stability types rotor angle transient stability is explained. Secondly, model of a DFIG wind turbine for transient stability study is explained in detail. Finally, wind farm aggregation technique will be described.

3.1 Introduction to Power System Stability

Power system stability may be broadly defined as the property of power system that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance [1, 7]. Sub categories of power system stability can be seen in Figure 3.1.

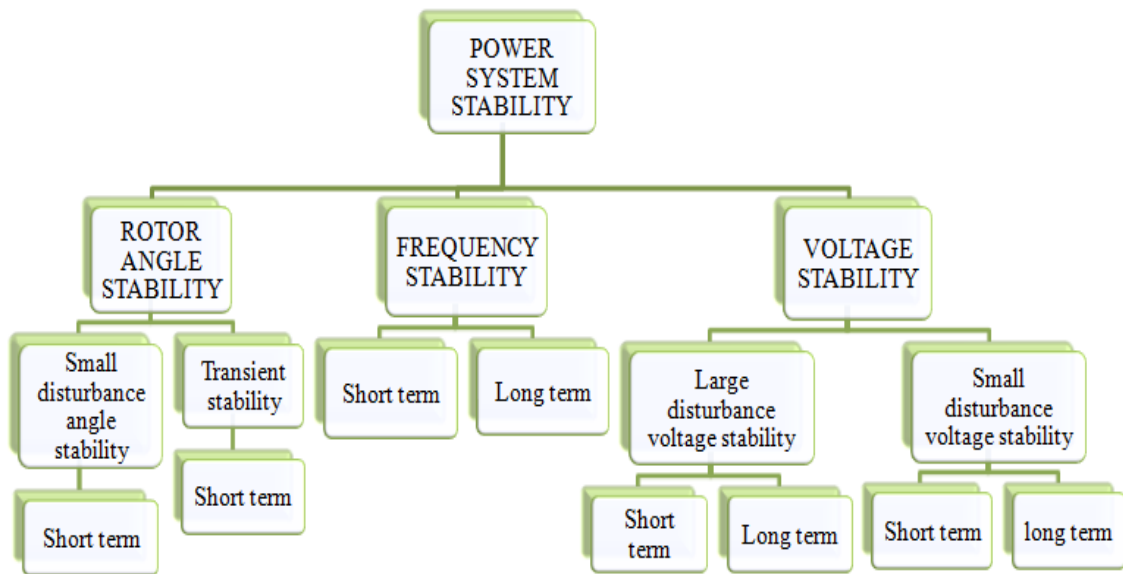


Figure 3.1: Classification of power system stability [1]

In case of Ethiopian power system both voltage stability and rotor angle stability are main stability problems. Rotor angle stability can be sub categorized into small disturbance angle stability and transient stability. Small disturbances can be, when changing the operation point of a generators or small voltage dips. Transient stability may be an issue in case of large disturbances such as disconnection of a line or faults where the voltage drops close to zero at the fault location.

3.1.1 Transient Stability

Rotor angle stability is the ability of interconnected synchronous machine of a power system to remain in synchronism. And one of the rotor angle stability is transient stability which will have great impact on the system stability. Transient stability is the ability of power system to maintain synchronism when subjected to sever transient disturbance. Transient stability is a fast phenomena usually occurring within one second for a generator close to the cause of disturbance. Transient stability limit is the maximum power transfer of the system without loss of equilibrium. Transient stability limit is always lower than steady state stability limit and hence much important. Transient stability limit depends on the type of disturbance and location and magnitude of disturbance. The power system stability can be observed from a power angle curve. The power angle can be obtained as follows considering a single generator feeding a load [1, 8].

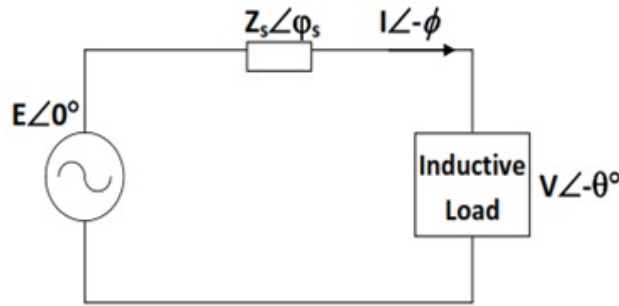


Figure 3.2: A single generator feeding an inductive load [1, 7]

Thus, from Figure 3.2, we have

$$\bar{E} = \bar{V} + I\bar{Z}_s \quad (3.1)$$

$$E\angle 0 = V\angle -\delta + I\angle -\phi * Z_s\angle \phi_s \quad (3.2)$$

$$I\angle -\phi = \frac{E\angle -\phi_s}{Z_s} - \frac{V\angle -(\delta + \phi_s)}{Z_s} \quad (3.3)$$

The apparent power transferred can be given as;

$$S = P + jQ = EI^* \quad (3.4)$$

Then substituting (3.3) into (3.4) we have

$$EI^* = \frac{E^2\angle -\phi_s}{Z_s} - \frac{EV\angle (\delta + \phi_s)}{Z_s} \quad (3.5)$$

From (3.5) taking the real part we have

$$P = \frac{E^2}{Z_s} \cos(\phi_s) - \frac{EV}{Z_s} \cos(\delta + \phi_s) \quad (3.6)$$

Where E is generator terminal voltage, V is load terminal voltage, Z_s is line impedance between generator and load and δ is load angle.

If a lossless line is assumed ϕ_s becomes 90° then substituting this value into (3.6), the power transferred becomes

$$P = \frac{EV}{X_s} \sin(\delta) \quad (3.7)$$

$$P_{max} = \frac{EV}{X_s}$$

Here P_{max} is the steady state stability limit of a power system it depends on the terminal voltages and the total reactance between the sending end and receiving ends of the system.

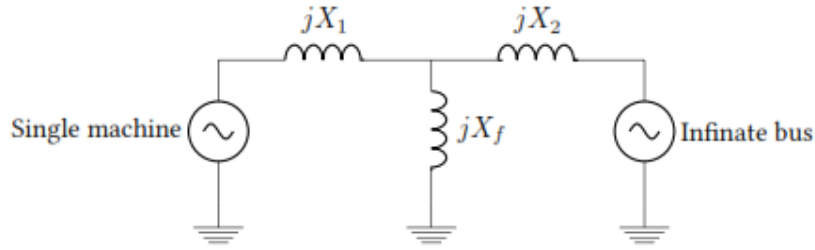


Figure 3.3: Single machine connected to an infinite bus [8]

Now let's consider a single machine connected to an infinite bus (SMIB) as shown in Figure 3.3 is subjected to a fault. Where X_f is the fault reactance and X_1 and X_2 are the reactances that connect the single machine to the infinite bus. Before fault ($X_f = \infty$) the impedance between the machine and the infinite bus is $X_1 + X_2$. But during fault X_f is introduced and using star to delta conversion the impedance between the machine and the infinite bus becomes

$$X_{during} = \frac{X_1 X_2}{X_f} + X_1 + X_2$$

For a three phase fault where $X_f = 0$, the power transfer from the single machine to the infinite bus is completely blocked as seen in the above equation $X_{during} = \infty$ thus during the fault the power transferred is zero. After the fault (post fault) the impedance is equal to the pre-fault impedance. For the maximum power transferred transient stability limit $P_{max} = \frac{EV}{X_s}$ is less than the steady state limit because Z_s for transient is greater than Z_s in steady state due to the fault impedance.

How much the angle increases during a disturbance depends on the time that the fault is sustained. If the swing equation given in (3.8) is integrated twice and damping is neglected, the angle increase with respect to time can be obtained.

$$\frac{Md^2\delta}{dt^2} = P_m - P_e - D\frac{d\delta}{dt} \quad (3.8)$$

Where M is angular moment of synchronous speed, P_m is mechanical power applied to the rotor of a generator, P_e electrical power produced in the air gap, D is damping coefficient at synchronous speed and δ is the angle of the rotor relative to the voltage stiff system.

$$\delta(t) = \frac{P_m - P_e}{M} t^2 + \delta_{init} \quad (3.9)$$

Rearranging terms the time can be calculated as:

$$t = \sqrt{\frac{M}{P_m - P_e} (\delta(t) - \delta_{init})} \quad (3.10)$$

The time at which the critical fault clearing angle obtained is called critical clearing time (CCT) can be obtained by substituting the value of critical angle in (3.10)

$$t_{crit} = \sqrt{\frac{M}{P_m - P_e} (\delta_{crit} - \delta_{init})} \quad (3.11)$$

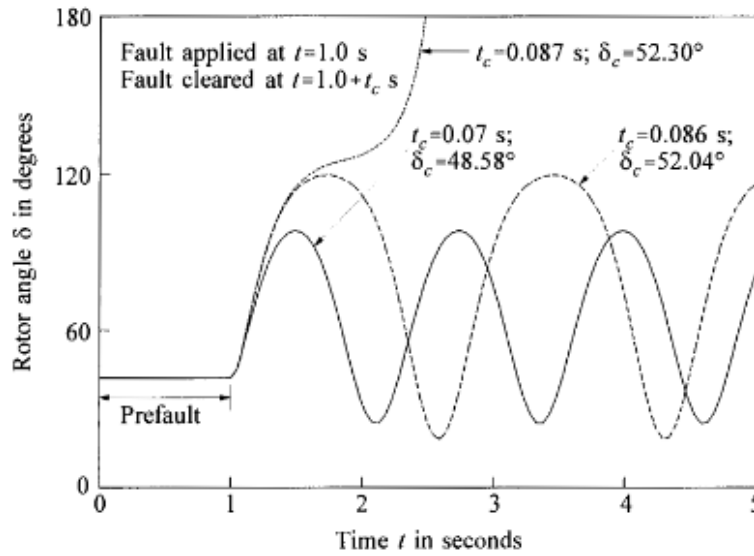


Figure 3.4: Rotor angle response for different values of fault clearing time [1]

3.2 Wind Turbine Modeling

The wind generation literatures focus mainly on four different types of wind generation topology [9, 10].

- Type 1: Fixed speed wind turbines
- Type 2: Limited variable speed

- Type 3: Variable speed with partial scale frequency converter
- Type 4: Variable speed with full-scale frequency converter

Type 1 refers to asynchronous squirrel cage induction generator (SCIG) connected to the grid via a transformer. Since the SCIG always draws reactive power this configuration uses a capacitor bank for reactive compensation. Type 2 uses wound rotor induction with a variable generator rotor resistance and capacitor bank for reactive power compensation. By utilizing the variable additional rotor resistance the speed of the generator can be varied by $\pm 10\%$. Type 3 is commonly known as doubly fed induction generator (DFIG). It consists of a wound rotor induction generator and a partial scale frequency converter on the rotor circuit. The speed range comprises 60% to 130% of synchronous speed. The main drawbacks are the use of slip rings and protection against grid faults. For the Type 4 configuration the wind generator is connected to the grid through a full-scale frequency converter. The frequency converter provides a reactive compensation and smoother grid connection. This topology usually uses wound rotor synchronous generator or a permanent magnet synchronous generator [9].

Types 3-4 all have fault ride through capabilities. However the main advantage of Type 4 compared to the other topology is smooth grid connection and any grid code can be applied as the generator is decoupled from the grid [8]. The fault ride through capabilities and grid code compliance of variable speed wind generators with full converter is more superior. The power curve of a wind turbine follows relationship between cut in wind speed and the rated capacity, approximately. As a case study for Adama II wind power generation 1.5MW SANY DFIG wind turbines are used and its power curve is given in Figure 3.5 and this curve is used in DIgSILENT software for modeling and simulation purpose.

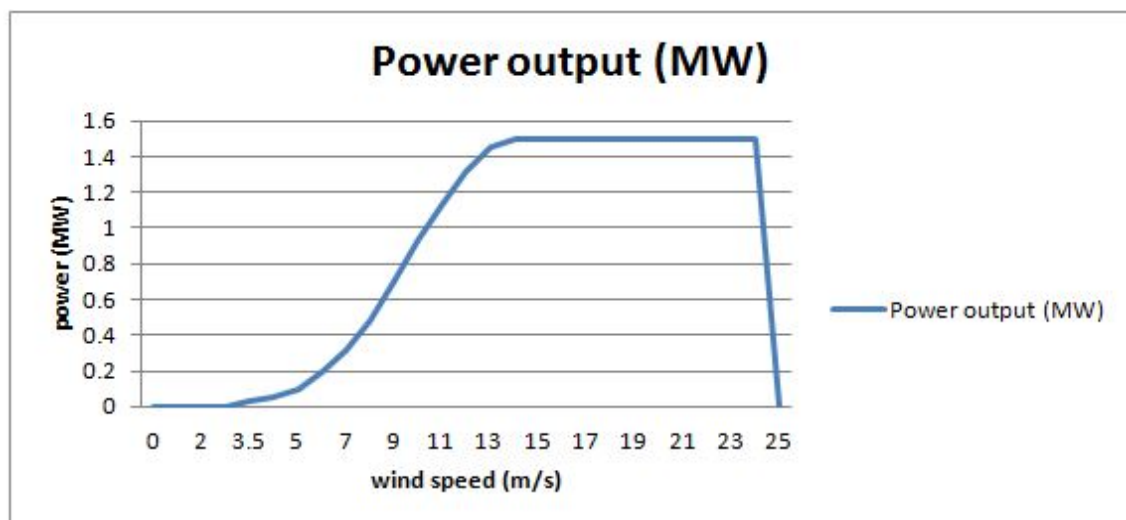


Figure 3.5: Typical power curve of single 1.5MW DFIG wind turbine

3.2.1 Modeling of Type 3 Wind Turbine (DFIG)

The DFIG is an attractive and popular option for large wind turbines (multi MW) due to its flexibility in variable speed range and lower cost of the power converters. Figure 3.6 illustrates the major components of the DFIG to be analyzed. In DFIG configuration, the generator rotor operates at a variable speed in order to optimize the tip speed ratio λ . The generator rotor speed is controlled to operate within a variable speed range centered on the generator synchronous speed. Therefore, the generator system operates in both a sub-synchronous and super-synchronous mode, typically between $\pm 30\%$ of synchronous speed. The rotor is controlled by a 3-phase converter connected to the wound rotor winding via slip rings. The stator is connected directly to the grid. A back to back VSC are included in rotor circuit. The converter must only handle the rotor power (only fraction of the total generator power), which is typically around 30% of rated power [9, 11].

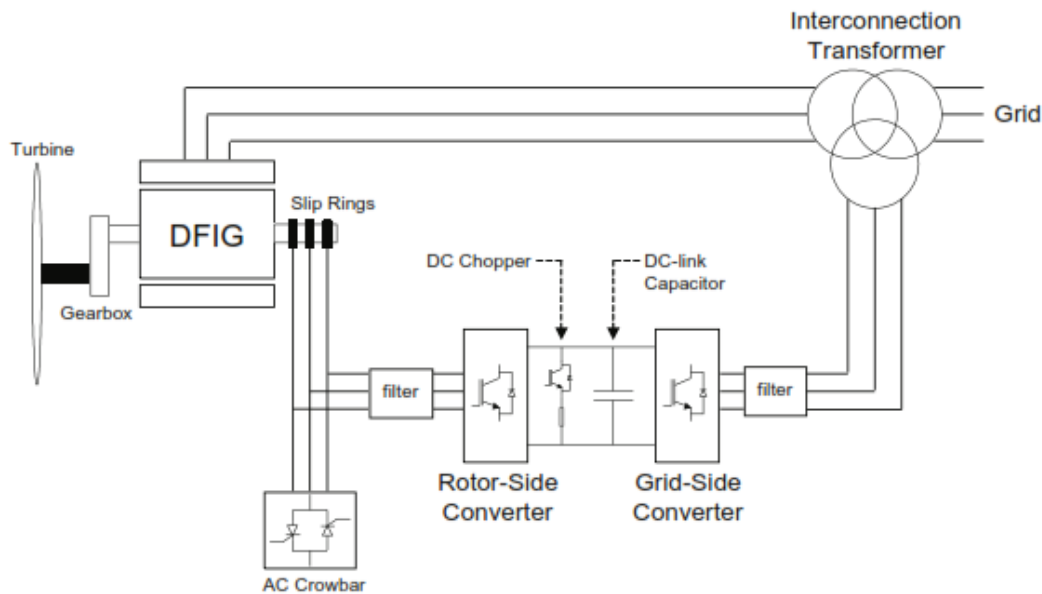


Figure 3.6: Components of doubly feed induction generator [9]

Torque Production in the DFIG

The DFIG consists of stator winding connected directly to the grid and wound rotor windings connected to power converters. The stator windings are energized by the grid to create the stator magnetic field. The rotor winding is energized by the converter to establish the rotor magnetic field. Torque is created by the interaction of the rotor magnetic field with stator magnetic field. The magnitude of the generated torque is dependent on both the strength of the two magnetic field and the angular displacement between the two. As

the stator is connected directly to the grid, the stator field is a function of the grid voltage, with a rotation based on the grid frequency and coinciding with the synchronous speed. Grid voltage is assumed constant during steady state operation therefore, stator flux can be considered constant. The rotor flux is dependent on the rotor current, which is controlled directly by the power converters. The torque production in DFIG can be directly controlled by control of the rotor current magnitude and angular position relative to the stator flux [9].

Rotor Side Converter (RSC)

The rotor side converter is used to control the torque production of the DFIG through direct control of the rotor currents. The RSC does this by applying a voltage to the rotor winding that corresponds to the desired current. The RSC will operate a varying frequency corresponding to the variable rotor speed requirements based on the wind speed. The RSC can use either a torque controller, speed controller or active power controller to regulate the output power of the DFIG. This output power is controlled to follow the wind turbines power speed characteristics curve. Typically a PI controller is used to control the torque, speed or power to its reference value. Whichever controller is used, the output of the controller is the reference rotor current required to generate the desired torque or power or to obtain the desired speed. An inner PI controller loop is then used to control the rotor current error to its reference value, with the rotor voltage reference as the controller output [9].

Grid Side Converter (GSC)

The GSC is used to regulate the voltage of the DC link between the two converters. The GSC contains an outer loop that controls the DC link voltage attempting to control it to nominal value. An inner PI control loop controls the GSC current. Commonly GSC acts to set $Q_{gc} = 0$ and minimize active power output. As the GSC is directly connected to the grid, it must output power at a fixed frequency corresponding to the grid frequency [9].

Power Flow in DFIG

In the rotor circuit active power flows in one direction either to the rotor or from the rotor, thereby either absorbing or injecting active power to the grid. In either case the active power flows in only one direction through both converters. The converter arrangement allows for a variable frequency to maximize active power extraction. As the two converters are decoupled via the DC-link, the connection to the grid can be maintained at the grid

frequency and the voltage controlled to synchronize with the grid. The basis for injecting or absorbing active power is the varying operation of the DFIG when it goes from sub-synchronous speed to super-synchronous speed. Active power flows as a function of slip. At synchronous speed ω_s the magnetic field of the rotor rotates at the same speed as the stator magnetic field. The DFIG then essentially operates as a synchronous machine with DC current in the rotor windings, meaning no active power will be generated in the rotor windings and therefore all active power from the DFIG machine flows from the stator to the grid. When the wind speed increases, the speed of the rotor must change in order to optimize the efficiency of the aerodynamics system. Therefore rotor speed increases above the synchronous speed, resulting in a negative slip and super-synchronous operation. In this operation power flows from both the stator windings and rotor windings, as the wind speed decreases, rotor speed decreases and machine operates in sub-synchronous mode with a positive slip. Under this circumstance the rotor must absorb active power from the grid, essentially borrowing power for the rotor winding excitation [9].

DC-Link Chopper (DC Crowbar)

A braking resistor is provided in the DC link bus as a form of protection to dissipate excess energy during a grid fault. The resistor is connected to the DC-link bus in series with an IGBT and is referred to as either as the DC-link chopper or DC crowbar. The IGBT can control the amount of energy burned in the resistor, the resistor sized to handle a specific amount of energy during a grid fault [9].

AC Crowbar

An AC crowbar is implemented on the rotor side of the RSC, which acts to bypass the RSC by applying a short circuit to the rotor terminals. This acts to protect the RSC from over currents as well as to protect the DC link from over voltages. The crowbar is an important aspect in not only the protection of the converter component, rather in understanding the behavior of the DFIG machine during grid faults [9].

5th Order Machine Model

The 5th order model is derived in the synchronous coordinate system (d – q coordinate system). The q-axis or rotating coordinate system is aligned with the grid voltage and rotates at the nominal grid frequency of 50 HZ. Since stator is directly connected with the grid, the q- component of the stator voltage will appear to stand still as it is aligned with

the q-axis and rotating at the same speed for balanced 3-phase system, $u_{sd} = 0$. Figure 3.7 represents the T – equivalent circuit of DFIG, with the stator represented on the left and the rotor on the right. The interface between the two is represented by magnetizing inductance L_m , which also represents the air gap in the machine and is commonly referred to as the air gap flux [9, 11].

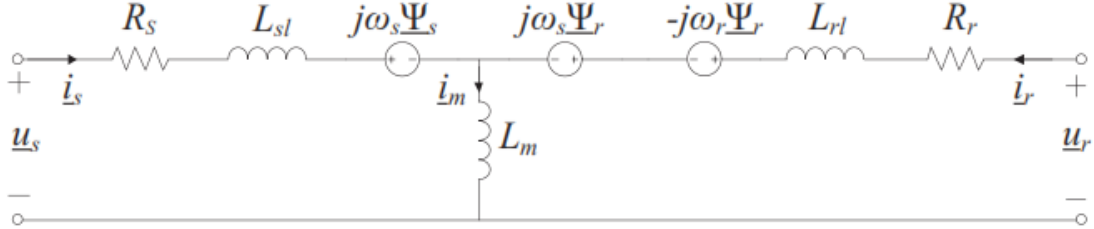


Figure 3.7: Equivalent electrical circuit of the DFIG [9]

Therefore, from Figure 3.7

$$u_s = R_s i_s + \frac{d\Psi_s}{dt} + j\omega_s \Psi_s \quad (3.12)$$

$$u_r = R_r i_r + \frac{d\Psi_r}{dt} + j(\omega_s - \omega_r) \Psi_r \quad (3.13)$$

$$\Psi_s = L_s i_s + L_m i_r \quad (3.14)$$

$$\Psi_r = L_m i_s + L_r i_r \quad (3.15)$$

Where u_s is stator voltage (also grid voltage), u_r is rotor voltage, Ψ_s is stator flux linkage, Ψ_r is rotor flux linkage, i_s is stator current, i_r is rotor current, R_s is stator resistance, R_r is rotor resistance, L_s is stator inductance, L_r is rotor inductance, L_m is magnetizing inductance, ω_s is grid frequency and ω_r is rotor frequency.

Then substituting value of Ψ_s and Ψ_r in to 3.12 and 3.13 we have;

$$u_s = \left(\frac{R_s}{L'_s} + j\omega_s \right) \Psi_s + \frac{d\Psi_s}{dt} - K_r \frac{R_s}{L'_s} \Psi_r \quad (3.16)$$

$$u_r = \left(\frac{R_r}{L'_r} + j(\omega_s - \omega_r) \right) \Psi_r + \frac{d\Psi_r}{dt} - K_s \frac{R_r}{L'_r} \Psi_s \quad (3.17)$$

Where

$$K_s = \frac{L_m}{L'_s} \quad K_r = \frac{L_m}{L'_r}$$

$$L'_s = L_s(1 - K_s K_r) \quad L'_r = L_r(1 - K_s K_r)$$

Then, the electromagnetic torque can be defined as

$$T_e = \frac{3}{2} P \frac{K_r}{L'_s} (\Psi_{rd} \Psi_{sq} - \Psi_{rq} \Psi_{sd}) \quad (3.18)$$

And from swing equation of a machine we have

$$\frac{J}{P} \frac{d\omega_r}{dt} = T_e - T_l - b \frac{\omega_r}{P} \quad (3.19)$$

Where P is poles of the machine, b is the speed dependent damping and J is inertia of the machine and turbine.

The swing equation is fundamental in describing and understanding the behavior of the DFIG during transient stability. To simplify the detailed DFIG model the stator flux dynamics or ($\frac{d\Psi_s}{dt} = 0$). Then, eliminating the time dependent portion of stator flux, two states are eliminated (Ψ_{sd}, Ψ_{sq}). Thus, the model is reduced from 5th order to 3rd order [9].

$$u_s = R_s i_s + j\omega_s \Psi_s \quad (3.20)$$

$$u_r = \frac{R_r}{L_r} \Psi_r - R_r \frac{L_m}{L_r} i_s + \frac{d\Psi_r}{dt} + j(\omega_s - \omega_r) \Psi_r \quad (3.21)$$

$$\frac{d\Psi_r}{dt} = -\frac{R_r}{L_r} \Psi_r + R_r K_r i_s + j(\omega_s - \omega_r) \Psi_r + u_r \quad (3.22)$$

Thus, the direct (d) and quadrature (q) values become

$$\frac{d\Psi_{rd}}{dt} = -\frac{R_r}{L_r} \Psi_{rd} + R_r K_r i_{sd} + j(\omega_s - \omega_r) \Psi_{rq} + u_{rd} \quad (3.23)$$

$$\frac{d\Psi_{rq}}{dt} = -\frac{R_r}{L_r} \Psi_{rq} + R_r K_r i_{sq} + j(\omega_s - \omega_r) \Psi_{rd} + u_{rq} \quad (3.24)$$

3.2.2 Modeling of Type 4 Wind Turbine (PMSG)

Till now, the most commonly used electrical system for a variable speed multi-pole synchronous generator wind turbine has consisted of a synchronous generator connected to the grid over a diode rectifier, an intermediary DC circuit and a thyristor inverter. However, due to the fast development in the last years of rapid switching valves with high power ratings, the use of self commutated converters (IGBT) is increasing in wind power applications. This is especially common for permanent magnet synchronous generators (PMSG), where both generator-side converter and grid-side converter are realized by IGBT converters (i.e. back-to-back converter). A diode rectifier is usually chosen for its low price and low losses, while an IGBT converter is used because it produces high quality power to the grid, i.e. current harmonics from the inverter are decreased and any desired power factor can be obtained and the energy can flow in both directions. An advantage of IGBT converter is that contrarily a diode rectifier solution is that it can produce a constant DC-voltage regardless of generator speed. It has the potential of utilizing the generator best. However, it is more expensive and has higher rectifier losses.

A typical configuration of variable speed multi-pole PMSG wind turbine is depicted in Figure 3.8. It consists of:

- Wind turbine mechanical level:
 - Aerodynamics
 - Gearless drive train
 - Pitch angle control
- Wind turbine electrical level:
 - Multi-pole permanent magnet synchronous generator (PMSG)
 - Frequency converter and its control

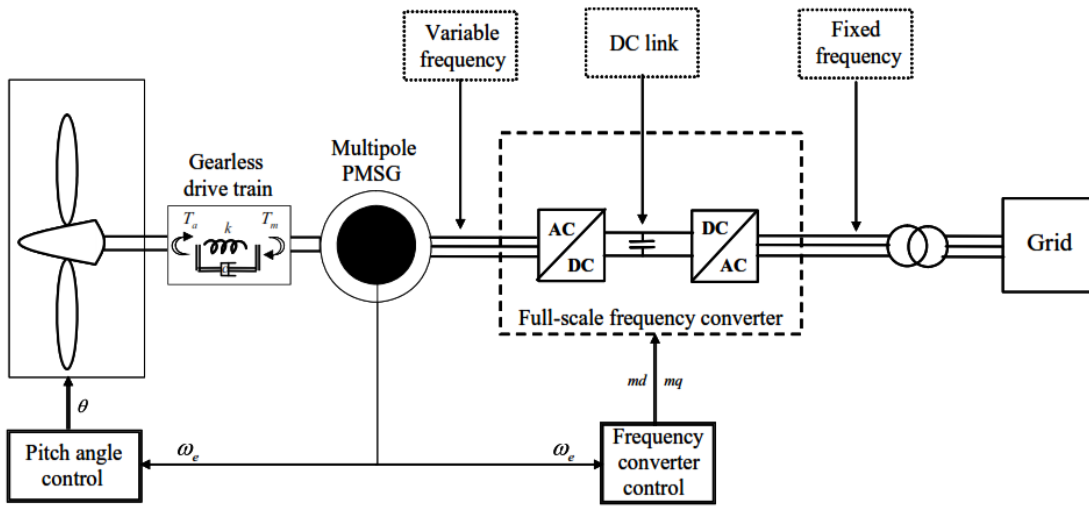


Figure 3.8: Components of permanent magnet synchronous generator [12]

In this configuration, the synchronous generator is connected to the power network through a frequency converter system that controls the speed of the generator and the power flow to the grid. The full-scale frequency converter system consists of two back-to-back voltage source converters (generator-side converter and the grid-side converter), controlled by IGBT switches and connected via a DC link, which behaves as an energy storage device. The use of such converter enables the PMSG to define its terminal voltage and its electric frequency according to the desirable optimal rotational speed of the wind turbine, independently of the fixed electric frequency and the voltage of the AC grid [12].

The aerodynamic rotor of the wind turbine is directly coupled to the generator without any gearbox, i.e. through a gearless drive train. The permanent magnets are mounted on the generator rotor shaft, while the stator consists of several windings and feeds into a full-scale frequency converter. As the converter system decouples the generator from the power network, the electrical frequency of the generator may vary as the wind speed changes, while the network frequency remains unchanged. Contrarily fixed speed wind turbines

where the power flow to the grid is dependent on the mechanical power that drives the wind turbine, in variable speed wind the power flow is set by the power converter. The rating of the converter system in this topology corresponds to the rated power of the generator plus losses [12].

The whole system is equipped with the wind turbine itself controller, i.e. pitch angle controller, and the frequency converter controller. Both controllers are using information about the generator speed. The converter's controller controls the generator speed by controlling the grid power according to a speed versus power control characteristic of the wind turbine. The pitch controller Controls the rotor speed as well, but it is operational only at high wind speeds when the power is reduced by pitching the blades in order to avoid the overloading of the converter and generators [12].

The total turbine power goes through the converter that converts the varying generator frequency to the constant grid frequency. Since the PMSG is connected to the grid through the back-to-back converter, only the active power of the PMSG is transferred to the grid. The reactive power cannot be exchanged through the DC link in the converter system. However, the grid-side converter, whose electric frequency and voltage are fixed to the grid, can be set to control the reactive power/voltage on the grid. Like the variable speed wind turbine with doubly-fed induction generator, this concept enables full active and reactive power control [12].

The electric frequency at the PMSG terminals, f_e , is the product of the mechanical frequency of the wind turbine rotor, f_m , and the number of generator pole-pairs p :

$$f_e = f_m p \quad (3.25)$$

Whereas the mechanical frequency of the generator rotor is related to the turbine rotor speed ω_m

$$\omega_m = 60 f_m \quad [rpm] \quad (3.26)$$

The common target of the control is to adjust the electrical frequency of the generator to the optimized mechanical frequency of the aerodynamic rotor and to keep the voltage at the PMSG terminals on a desired level [12].

The equivalent circuit for one phase of synchronous generator is shown in Figure 3.9. The equations describing a synchronous generator can be found in [1]. It is beyond the scope of this study to present a detailed treatment of the synchronous generator. A brief overview is however provided, in order to present the most important features of the permanent magnet synchronous generator (PMSG) used in wind turbines.

Synchronous machine models for power system analysis are usually based on the assumption that the magnetic flux distribution in the rotor is sinusoidal. With this assumption the

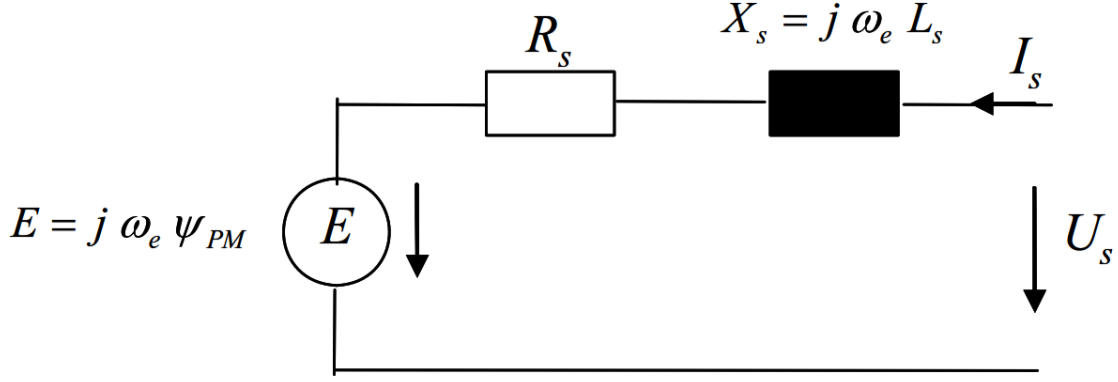


Figure 3.9: Equivalent electrical circuit of the PMSG [12]

flux can entirely be described by a vector and in the case of PMSG, the magnetic fields from the permanent magnets induces a voltage E in the stator winding, expressed as:

$$|E| = \omega_e \psi_{PM} = 2\pi f_e \psi_{PM} \quad (3.27)$$

Where ω_e is the electrical speed, ψ_{PM} is the magnitude of the flux induced in the stator by the permanent magnets of the rotor, and f_e is the electrical frequency. A current I_s in the stator winding causes losses and voltage drop, both phenomena are represented in the model by the resistance R_s . Apart from causing resistive voltage drop, the stator current also produces a magnetic field of its own, which is added to the field generated by the permanent magnets. Thus, the voltage U_s at the stator terminal of PMSG corresponds to the voltage induced by the total magnetic field. Depending on the phase delay of the stator current, the total magnetic field in the generator either increases or decreases as the current increases. The effect is represented by the synchronous reactance X_s in the model. The resistance R_s is normally much smaller than X_s , and therefore, it is normally neglected except in efficiency calculations.

The expressions of the active and reactive power of the generator in terms of E , U and the load angle δ can be derived:

$$P_{gen} = \frac{|E||U_s|}{X_s} \sin \delta \quad (3.28)$$

$$Q_{gen} = \frac{|E||U_s|}{X_s} \cos \delta - \frac{|U_s|^2}{X_s} \quad (3.29)$$

If the mechanical power input increases, i.e. the load angle (the phase shift between U and E) increases, the electrical power output increases also, reaching a maximum $\delta = 90^\circ$. The converter is able to generate or absorb active and reactive power, if both the load angle and voltage magnitude are controllable.

The equations of a PMSG can be expressed directly from the equations of a DC excited synchronous generator SG, with the simplification that PMSG does not have damper

winding [1]. The steady state voltage equations of the generator, expressed in the rotor-oriented dq-reference frame can be expressed as follows:

$$U_{sd} = R_s i_{sd} - \omega_e \psi_{sq} + \dot{\psi}_{sd} \quad (3.30)$$

$$U_{sq} = R_s i_{sq} + \omega_e \psi_{sd} + \dot{\psi}_{sq} \quad (3.31)$$

With the stator flux components:

$$\psi_{sd} = L_d i_{sd} + \psi_{PM} \quad (3.32)$$

$$\psi_{sq} = L_q i_{sq} \quad (3.33)$$

Where U_{sd} and U_{sq} are the terminal stator voltages, i_{sd} and i_{sq} are the stator currents, L_d and L_q are the stator inductances in the dq reference frame. In stability studies, where the stator transients can be neglected, the stator voltage equations can be reduced to:

$$U_{sd} = R_s i_{sd} - \omega_e \psi_{sq} \quad (3.34)$$

$$U_{sq} = R_s i_{sq} + \omega_e \psi_{sd} \quad (3.35)$$

The electrical torque of the generator is:

$$T_e = \frac{3}{2} p \text{Im}[\bar{\psi}_s^* \bar{i}_s] = \frac{3}{2} p [\psi_{sd} i_{sq} - \psi_{sq} i_{sd}] \quad (3.36)$$

If the generator is a round rotor machine, where $L_d = L_q$ the equation for the electrical torque results only from the permanent magnet flux and the q-component of the stator current:

$$T_e = \frac{3}{2} p \psi_{PM} i_{sq} \quad (3.37)$$

The active and reactive power of the synchronous generator can be then expressed as:

$$P_{gen} = T_e * \omega_m = \frac{3}{2} [U_{sd} i_{sd} + U_{sq} i_{sq}] \quad (3.38)$$

$$Q_{gen} = \frac{3}{2} [U_{sq} i_{sd} - U_{sd} i_{sq}] \quad (3.39)$$

In the case of variable speed wind turbines, the active and reactive powers of the generator are controlled by the converter, which acts on the generator stator voltage and current. As the generator is fully decoupled from the grid by the converter, the reactive power expressed previously is exchanged with the generator-side converter and not with the grid.

The PMSG has no damper windings. As a PMSG is connected to the grid through a converter, which provides a variable stator frequency according to the actual rotor speed, there is never any relative movement between stator and rotor field, which could induce a voltage in the damper winding [13]. Furthermore, due to the permanent excitation, a PMSG has no field windings, in which transient currents could be induced or damped,

respectively. Hence, in Case of transients the field windings do not contribute to damping either. The PMSG connected to a converter is thus a system without inherent damping. Nevertheless, an external damping of the system must then be applied by means of the converter control.

3.3 Wind Farm Aggregation

Avery large wind power plant may contain hundreds of megawatt size wind turbines. These turbines are interconnected by an intricate collector system. While the impact of individual turbines on the larger power system network is minimal, collectively wind turbines can have significant impact on the power system during a sever disturbance such as nearby fault. Although it is important to model a wind power plant to be as close as to the actual implementation but representing hundreds of turbines and the corresponding branches are not practical. So, a simplified equivalent representation is used [14].

Within a wind power plant, there are a lot of diversities in the line feeder and the wind speed at each turbine. Line impedance in the line feeder connecting each wind turbine to the point of interconnection differs from each other. The wind speed experienced by one turbine can be significantly different from another turbine located at another part of the wind power plant. In new wind power plants, the wind turbines used is generally of the same type and supplied by the same manufacturer. Generally a full system representation (FSR, where all turbines are represented) of a wind power plant shows the same behavior at the point of interconnection (POI) as wind power plant with a single turbine representation (STR) [15].

The collective behavior of a wind farm can be represented by single turbine representation (STR). Most frequently, the collector system is connected to a medium voltage of 12KV-34.3KV voltage level, where the wind turbines are connected to each other in a string (cluster) using underground cables. Each cluster may contain one or more groups of wind turbines. Each wind turbine is electrically attached to a unit transformer that steps up the generated terminal voltage to a medium voltage collector system. Then, the collector system is connected to a central substation transformer which in turn steps up the medium voltage to the transmission voltage level [15].

General Overview and Assumptions

In the following derivations we based our equivalent circuit on the apparent power loss (i.e. real power loss and reactive power loss). During deriving equivalent circuit for the

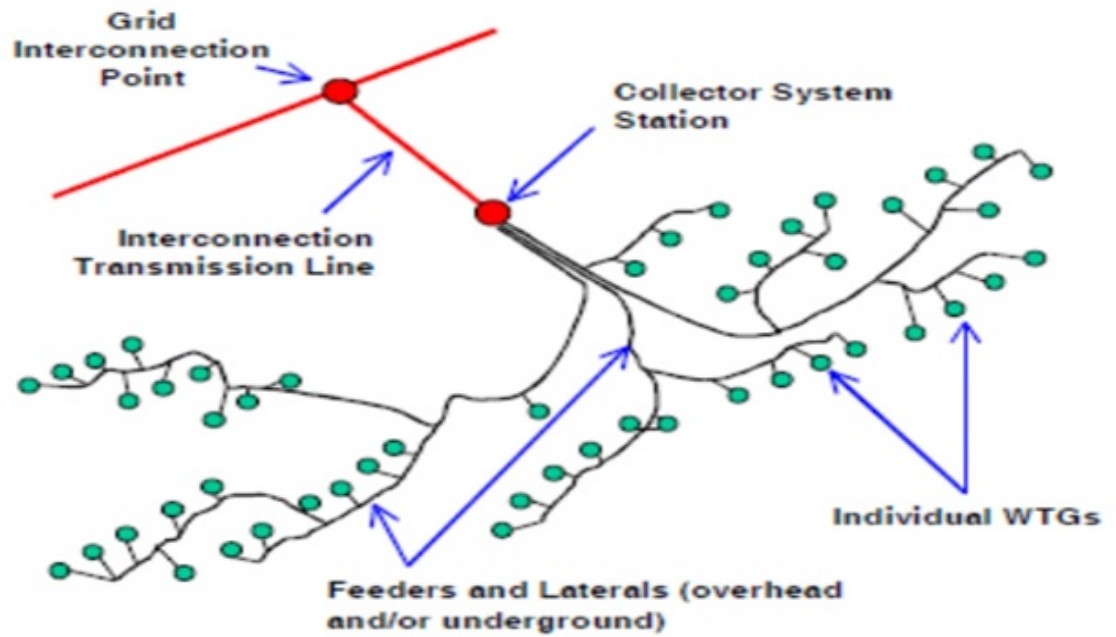


Figure 3.10: Generic wind power plant topology [15, 16]

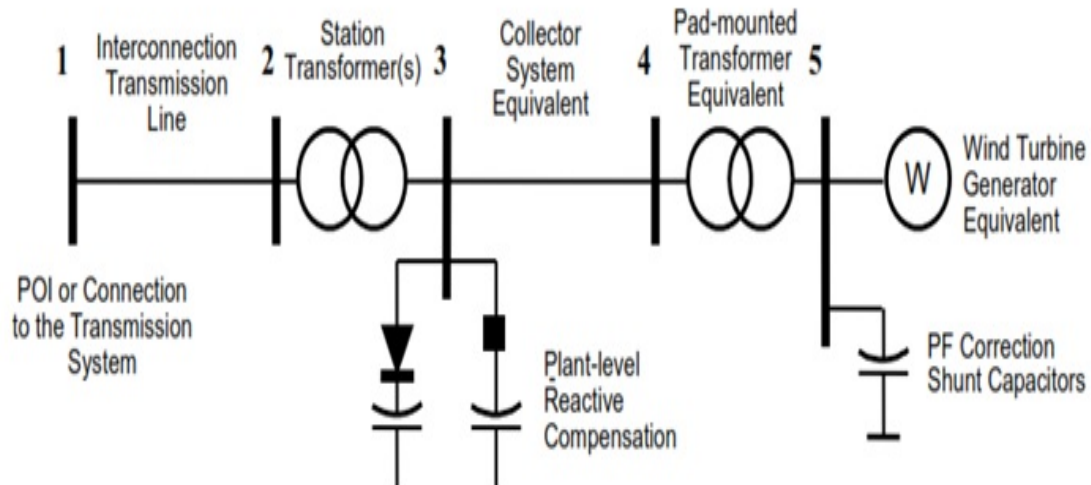


Figure 3.11: Single turbine representation of a wind power plant (STR) [15]

collector system the following assumptions are going to be considered [15].

1. The current injection from all wind turbines is assumed to be identical in magnitude and angle.
2. Reactive power generated by the line capacitive shunt is based on the assumption that the voltage at the buses is one per unit ($1pu$).

3.3.1 Steps for Wind Farm Aggregations

Step 1: Equivalent Wind Turbine

Reducing n number of wind turbines to a single wind turbine, the parameters from the equivalent machine are active power P_{eq} in MW, the reactive power Q_{eq} in MVar and the apparent power S_{eq} in MVA [16].

The parameters are given by:

$$P_{eq} = n * P_{MW} \quad (3.40)$$

$$Q_{eq} = n * Q_{MVar} \quad (3.41)$$

$$S_{eq} = n * S_{MVA} \quad (3.42)$$

Where n is the total number of wind turbines in the wind farm.

Step 2: Equivalent Unit Transformers

The equivalence of unit transformer connected to a turbine is made using loss formula [17]. To derive the equivalent impedance of a unit transformer, consider the system given in Figure 3.12 (a) which have three turbines and three unit transformers.

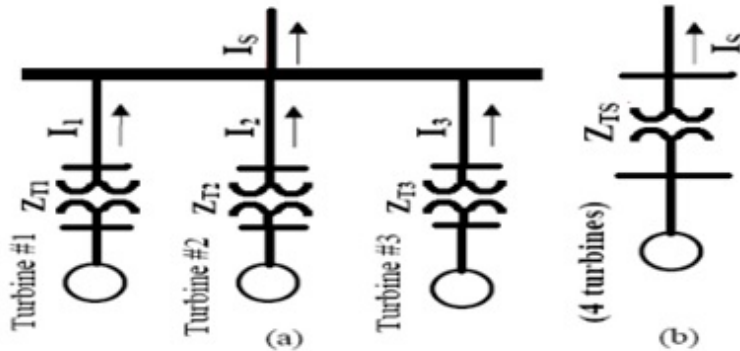


Figure 3.12: a) Three turbine system and b) Single turbine representation [17]

Thus, from Figure 3.12 (a) the voltage drop in each unit transformer becomes;

$$\Delta V_{ZT1} = I_1 Z_{T1} = \frac{S_1}{V} Z_{T1} = \frac{P_1}{V} Z_{T1} \quad (3.43)$$

$$\Delta V_{ZT2} = I_2 Z_{T2} = \frac{S_2}{V} Z_{T2} = \frac{P_2}{V} Z_{T2} \quad (3.44)$$

$$\Delta V_{ZT3} = I_3 Z_{T3} = \frac{S_3}{V} Z_{T3} = \frac{P_3}{V} Z_{T3} \quad (3.45)$$

Using (3.43) to (3.45) the power losses in the individual unit transformer becomes;

$$S_{ZT1} = \Delta V_{ZT1} I_1^* = \left(\frac{P_1 Z_{T1}}{V} \right) \left(\frac{P_1}{V} \right)^* = \frac{P_1^2}{V^2} Z_{T1} \quad (3.46)$$

$$S_{ZT2} = \Delta V_{ZT2} I_2^* = \left(\frac{P_2 Z_{T2}}{V} \right) \left(\frac{P_2}{V} \right)^* = \frac{P_2^2}{V^2} Z_{T2} \quad (3.47)$$

$$S_{ZT3} = \Delta V_{ZT3} I_3^* = \left(\frac{P_3 Z_{T3}}{V} \right) \left(\frac{P_3}{V} \right)^* = \frac{P_3^2}{V^2} Z_{T3} \quad (3.48)$$

Thus, the total power loss becomes;

$$S_{ZTS} = S_{ZT1} + S_{ZT2} + S_{ZT3} \quad (3.49)$$

Substituting values from (3.46) to (3.48) into (3.49) and rearranging terms

$$\frac{P_{Total}^2 Z_{TS}}{V^2} = \frac{P_1^2 Z_{T1}}{V^2} + \frac{P_2^2 Z_{T2}}{V^2} + \frac{P_3^2 Z_{T3}}{V^2} \quad (3.50)$$

$$Z_{TS} = \frac{\sum_{m=1}^n P_m^2 Z_{Tm}}{(\sum_{m=1}^n P_m)^2} \quad (3.51)$$

Where Z_{TS} is equivalent impedance of the unit transformers in a group.

Step 3: Shunt Parameter Representation

Considering the equivalent circuit of a transmission line given in Figure 3.13, due to the nature of a capacitor generating reactive power that is proportional to the square of the voltage across them, and considering that the bus voltage is close to unity under normal conditions, the representations of the shunt parameter can be considered as the sum of all the shunts in the power system network [15]. With the above assumptions presented, the total shunt capacitance within a WPP can be computed as;

$$B_{total} = \sum_{i=1}^n B_i \quad (3.52)$$

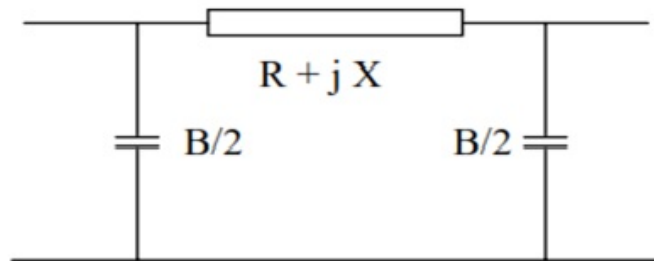


Figure 3.13: Equivalent circuit of a transmission line [15]

Step 4: Equivalent Collector System

The equivalent collector system should capture the behavior of the large wind farm in terms of power losses and voltage drop [15]. For the daisy chained string and its equivalent circuit shown in Figure 3.14, (note that the unit transformers are considered to be part of the generator itself). The current injection from each turbine is assumed to be identical (assumption no. 1). Therefore,

$$I_1 = I_2 = I_3 = I_4 = I_5 = I_6 = I$$

Then, the total current in the equivalent representation is given by

$$I_s = n * I$$

From Figure 3.14 the voltage drop across each impedance can be easily derived as

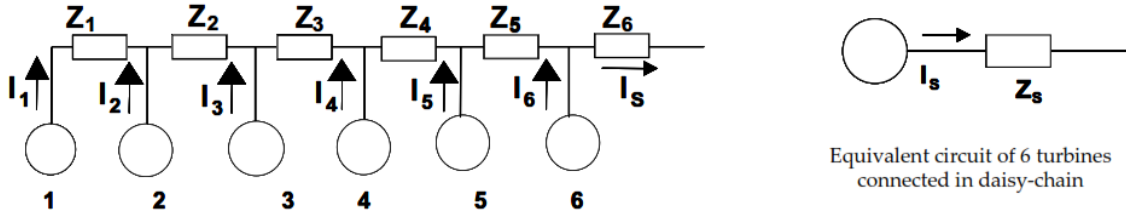


Figure 3.14: Wind turbines connected in a daisy chained string and equivalent circuit [15]

$$\Delta V_{Z1} = I_1 Z_1 = \left(\frac{S_1}{V} \right) Z_1 = \left(\frac{P_1}{V} \right) Z_1$$

$$\Delta V_{Z2} = (I_1 + I_2) Z_2 = \left(\frac{S_1}{V} + \frac{S_2}{V} \right) Z_2 = \left(\frac{P_1}{V} + \frac{P_2}{V} \right) Z_2$$

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$$\Delta V_{Z6} = (I_1 + I_2 + I_3 + I_4 + I_5 + I_6) Z_6 = \left(\frac{S_1}{V} + \frac{S_2}{V} + \frac{S_3}{V} + \frac{S_4}{V} + \frac{S_5}{V} + \frac{S_6}{V} \right) Z_6$$

Then, the apparent power loss in the line segment can be computed as:

$$S_{LossZ1} = \Delta V_{Z1} I_1^* = \left(\frac{P_1}{V} \right) \left(\frac{P_1}{V} \right) Z_1 = \left(\frac{P_{Z1}^2}{V^2} \right) Z_1$$

$$S_{LossZ2} = \Delta V_{Z2} I_2^* = \left(\frac{P_1}{V} + \frac{P_2}{V} \right) \left(\frac{P_1}{V} + \frac{P_2}{V} \right) Z_2 = \left(\frac{P_{Z2}^2}{V^2} \right) Z_2$$

.
.
.

$$S_{LossZ6} = \Delta V_{Z6} I_6^* = \left(\frac{P_{Z6}^2}{V^2} \right) Z_6$$

Therefore, the total loss becomes

$$S_{Tot_{loss}} = \left(\frac{P_{Z1}^2}{V^2}\right)Z_1 + \left(\frac{P_{Z2}^2}{V^2}\right)Z_2 + \left(\frac{P_{Z3}^2}{V^2}\right)Z_3 + \left(\frac{P_{Z4}^2}{V^2}\right)Z_4 \\ + \left(\frac{P_{Z5}^2}{V^2}\right)Z_5 + \left(\frac{P_{Z6}^2}{V^2}\right)Z_6 \quad (3.53)$$

$$\left(\frac{P_{Z6}^2}{V^2}\right)Z_S = \left(\frac{P_{Z1}^2}{V^2}\right)Z_1 + \left(\frac{P_{Z2}^2}{V^2}\right)Z_2 + \left(\frac{P_{Z3}^2}{V^2}\right)Z_3 + \left(\frac{P_{Z4}^2}{V^2}\right)Z_4 \\ + \left(\frac{P_{Z5}^2}{V^2}\right)Z_5 + \left(\frac{P_{Z6}^2}{V^2}\right)Z_6 \quad (3.54)$$

Then, rearranging terms the general expression for the impedance of the collector circuit can be calculated from (3.54)

$$Z_S = \frac{\sum_{m=1}^n P_{Zm}^2 Z_m}{(\sum_{m=1}^n P_{Zm}^2)^2} \quad (3.55)$$

Where Z_S represents the equivalent collector impedance and Z_m represents the individual series impedance

Step 5: Model Validation

After the aggregation process is completed, load flow analysis has been done using simulation software, so that the aggregated system will have the same output as that of the complete system output. Therefore, for this study, The full system representation and the aggregated system representation are simulated with DIgSILENT simulation software [18].

Chapter 4

Result Analysis and Discussion

In this chapter, first, the model of Adama II wind farm (Adama II WPP has been selected as a case study due to the fact that it has the highest number wind turbines in the country) aggregation is developed then the full turbine system and the aggregated representation has been analyzed using DIgSILENT simulation software. Secondly, the transient stability of Ethiopian power system with and without wind integration will be investigated. Finally, simulation of the model has been done with a full system in DIgSILENT and when subjected to various fault cases, the dynamic response of the system has been observed.

4.1 Adama II Wind Farm Modeling

Adama II Wind Park is situated on high plateau in eastern Ethiopia at an altitude of 2200m above sea level. The project site is approximately 90km east of capital city Addis Abeba and 3km North West of Adama city. The average wind speed in the area is 8 - 9m/s. The aggregate installed capacity of the wind farm is 153MW, each wind turbine generate a rated voltage of 690V. Each wind turbine is attached to a unit transformer that steps up the generator terminal voltage (690V) in to a medium voltage level of 33KV. All 102 turbines are grouped into eight clusters; one of the clusters have eleven turbines, while the remaining seven clusters have thirteen turbines each, grouped together and a 33KV overhead line connect each clusters to the central substation. The central substation has two 90MVA 33/230KV transformers and it is connected to Koka power plant as shown in Figure 4.1. The plants turbine and generator specification are shown in Table 4.1 [19].

Adama II wind power plant was commissioned in 2015 and the micro-sitting for each wind turbines is finalized. Thus, the actual distance between each wind turbines is taken to determine the cable length of the collector system. The procedure followed to model the wind farm is demonstrated using cluster 1 and the final values for the rest of the clusters have been summarized in tabular form.

Table 4.1: Adama II wind power plant turbine generator specifications [19]

Blade length	37m
Drive	Direct drive
Rated power	1.5 MW
Start up wind speed	3.5 m/s
Cut in wind speed	3.5 m/s
Rated wind speed	14.5 m/s
Cut out wind speed	25 m/s
Generator	DFIG
Rated output voltage	690 V
Converter	Full power IGBT converter

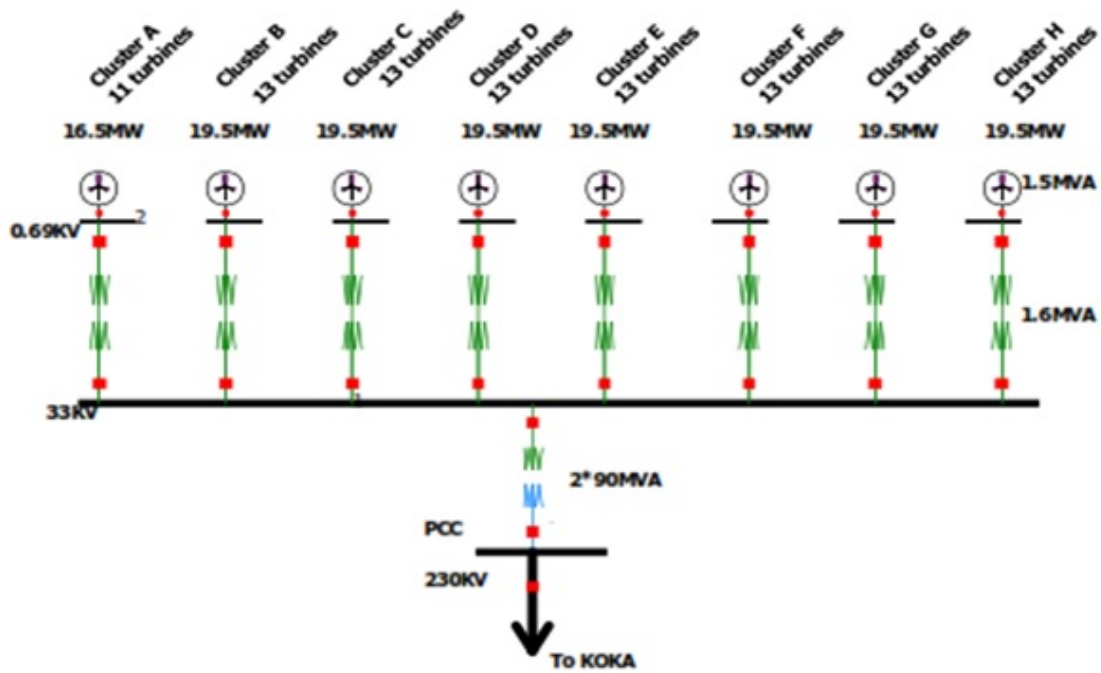


Figure 4.1: Adama II wind power plant representation

4.1.1 Adama II Cluster 1 Aggregation

Cluster 1 has two groups each with four and seven wind turbines connected in parallel. Detailed modeling of the cluster is shown below. All the data used in this analysis are give in Appendix B.

Step 1: Equivalent Wind Turbine Modeling

The large wind farm is composed of 102 SANY DFIGs, each delivering 1.5 MW of active power. Thus, according to equation (3.40):

$$P_{eq} = 102 * 1.5MW = 153MW$$

Step 2: Equivalent Unit Transformers Modeling

The resistive and reactive component of a single transformer can be given as

$$Z_{TS} = R_{TS} + jX_{TS}$$

But

$$R_{TS} = \frac{U_{Rr} * U_{rt}^2}{100S_{rt}} \quad (4.1)$$

$$X_{TS} = \frac{U_{Xr} * U_{rt}^2}{100S_{rt}} \quad (4.2)$$

Where

U_{Rr} is rated resistive voltage drop (%) = 1.3%

U_{Xr} is rated reactive voltage drop (%) = $\sqrt{U_{kr}^2 - U_{Rr}^2}$

U_{rt} is transformer primary voltage (0.69KV)

S_{rT} is transformer apparent power (1.6MVA)

U_{kr}^2 is transformer short circuit impedance (%)=6.5%

Therefore,

$$U_{Xr} = \sqrt{U_{kr}^2 - U_{Rr}^2}$$

$$U_{Xr} = \sqrt{6.5^2 - 1.3^2}$$

$$= 6.37\%$$

Then, substituting the values into (4.1) and (4.2):

$$R_{TS} = 0.00387\Omega$$

$$X_{TS} = 0.0187\Omega$$

$$Z_{TS1} = (0.00387 + j0.0187)\Omega$$

Group 1 Unit Transformer Modeling

Group one has four unit transformers connected in parallel as shown in the micro setting of the wind farm. Thus applying equation (3.51) we have

$$Z_{TS} = \frac{P_{01}^2 Z_{TS1} + P_{02}^2 Z_{TS2} + P_{03}^2 Z_{TS3} + P_{04}^2 Z_{TS4}}{(P_{01} + P_{02} + P_{03} + P_{04})^2}$$

But

$$\begin{aligned} Z_{TS1} &= Z_{TS2} = Z_{TS3} = Z_{TS4} \text{ are transformer leakage reactance and} \\ P_{01} &= P_{02} = P_{03} = P_{04} \text{ are rated power from each wind turbine} \end{aligned}$$

Thus, taking this consideration in to account equation (3.51) can be reduced to;

$$Z_{TS} = \frac{Z_{TS1}}{n} \quad (4.3)$$

Where n is the total number of turbines in the group. Since group one has four wind turbines and substituting value for transformer leakage reactance in equation (4.3)

$$Z_{TS} = \frac{(0.00387 + j0.0187)}{4} = 0.000968 + j0.00468 \Omega$$

In per units

$$Z_{TS} = \frac{1.6}{0.69^2} (0.000968 + j0.00468) = 0.00325 + j0.0157 \text{ PU}$$

Group 2 Unit Transformer Modeling

Group two have seven unit transformers connected in parallel. Similarly the equivalent impedance can be calculated using equation (4.3)

$$Z_{TS} = \frac{(0.00387 + j0.0187)}{7} = 0.0005529 + j0.00267 \Omega$$

In per units

$$Z_{TS} = \frac{1.6}{0.69^2} (0.0005529 + j0.00267) = 0.001858 + j0.008978 \text{ PU}$$

Step 3: Equivalent Shunt Parameter Modeling

The equivalency of shunt admittance is calculated using equation (3.52)

1. Group one shunt impedance

$$B_{G1} = 4 * 8.84 \mu s = 35.36 \mu s$$

2. Group two shunt impedance

$$B_{G2} = 7 * 8.84 \mu s = 61.88 \mu s$$

Step 4: Equivalent Collector System Modeling

Group One Collector Circuit Modeling

Group one has four wind turbines thus the equivalence can be calculated using equation (3.55)

$$Z_{CCG1} = \frac{P_{01}^2 Z_{01} + P_{02}^2 Z_{02} + P_{03}^2 Z_{03} + P_{04}^2 Z_{04}}{(P_{01} + P_{02} + P_{03} + P_{04})^2}$$

Where $Z_{01}, Z_{02}, Z_{03}, Z_{04}$ are the branch impedance between wind turbine $W_{TG14} - W_{TG15}, W_{TG15} - W_{TG16}, W_{TG16} - W_{TG17}, W_{TG17} - W_{TGCCG1}$ respectively as shown in the micro sitting of the wind farm $P_{01}, P_{02}, P_{03}, P_{04}$ are branch flows. Thus, substituting the values of branch impedance and power flow given in Appendix B.

$$Re(Z_{CCG1}) = \frac{1.5^2 * 0.0102 + 3^2 * 0.0066 + 4.5^2 * 0.0076 + 6^2 * 0.0739}{(1.5 + 3 + 4.5 + 6)^2} = 0.0129 \text{ PU}$$

$$Im(Z_{CCG1}) = \frac{1.5^2 * 0.005 + 3^2 * 0.0033 + 4.5^2 * 0.0037 + 6^2 * 0.0537}{(1.5 + 3 + 4.5 + 6)^2} = 0.00911 \text{ PU}$$

$$Z_{CCG1} = 0.0129 + j0.00911 \text{ pu}$$

Group Two Collector Circuit Modeling

Since group 2 has seven wind turbines using equation (3.55) and taking values from Appendix B:

$$Z_{CCG2} = \frac{P_{01}^2 Z_{01} + P_{02}^2 Z_{02} + P_{03}^2 Z_{03} + P_{04}^2 Z_{04} + P_{05}^2 Z_{05} + P_{06}^2 Z_{06} + P_{07}^2 Z_{07}}{(P_{01} + P_{02} + P_{03} + P_{04} + P_{05} + P_{06} + P_{07})^2}$$

$$Z_{CCG2} = 0.00287 + j0.00142 \text{ pu}$$

Thus, cluster 1 is reduced in to two turbine systems. Now to represent the cluster with a single turbine system group one and two impedances has to be reduced.

Thus, the unit transformer can be reduced as:

$$Z_{TS} = \frac{P_{G1}^2 Z_{TSG1} + P_{G2}^2 Z_{TSG2}}{(P_{G1} + P_{G2})^2}$$

Where P_{G1}^2 and P_{G2}^2 are the total power transferred in group 1 and group 2 respectively.

$$Z_{TS} = \frac{6^2 * (0.00325 + j0.0157) + 10.5^2 * (0.001858 + j0.00898)}{(6 + 10.5)^2}$$

$$Z_{TS} = 0.001182 + j0.005712 \text{ PU}$$

Then, the collector circuit can be reduced as

$$Z_{S1} = \frac{6^2 * (0.01288 + j0.00911) + 10.5^2 * (0.00287 + j0.00142)}{(6 + 10.5)^2}$$

$$Z_{S1} = 0.00287 + j0.00178 \text{ PU}$$

Thus, cluster 1 can becomes

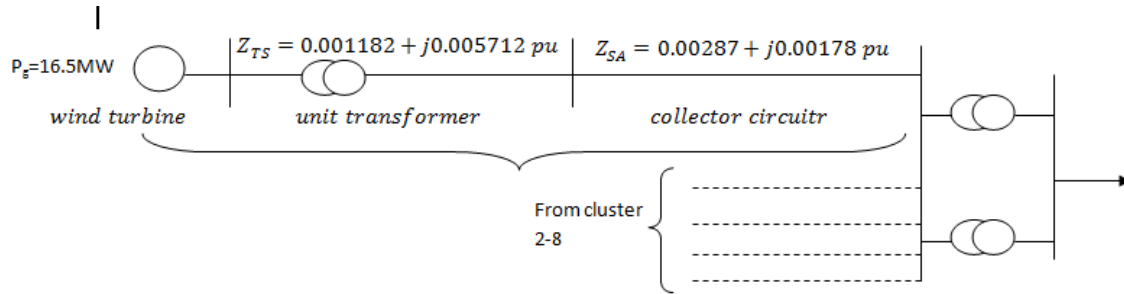


Figure 4.2: Single turbine representation of cluster one of Adama II WPP

Similarly, the rest of the clusters are modeled with single turbine system and their respective equivalent unit transformer and collector circuit impedance are shown in Tables 4.2 and 4.3.

Table 4.2: Summery of unit transformer equivalent impedance for all clusters

Cluster	No. of Xmer	Total power (MW)	$R_{eq}(PU)$	$X_{eq}(PU)$
1	11	16.5	0.00118	0.00571
2	13	19.5	0.00100	0.00483
3	13	19.5	0.00100	0.00483
4	13	19.5	0.00100	0.00483
5	13	19.5	0.00100	0.00483
6	13	19.5	0.00100	0.00483
7	13	19.5	0.00100	0.00483
8	13	19.5	0.00100	0.00483

Finally, single turbine representation parameters of Adama II wind farm has been determined with a base apparent power of $S_B = 100MVA$ and base voltage of $V_B = 33KV$. Thus, the unit transformer equivalent impedance has been calculated using equation(3.51) and substituting values from Table 4.2.

$$Z_{TSp} = 0.000128 + j0.000616 \text{ PU}$$

Table 4.3: Summary of collector circuit impedance for all clusters

Cluster	Length (Km)	Total power (MW)	$R_{eq}(PU)$	$X_{eq}(PU)$
1	1.436	16.5	0.002398	0.00162
2	3.568	19.5	0.00156	0.00102
3	0.15	19.5	0.00145	0.00090
4	5	19.5	0.00166	0.00112
5	5.612	19.5	0.00167	0.00111
6	0.09	19.5	0.00210	0.00132
7	5.451	19.5	0.00495	0.00325
8	5	19.5	0.00160	0.00106

Then, the collector circuit equivalent impedance has been calculated using equation (3.55) and substituting values from Table 4.3.

$$Z_{SP} = 0.0002714 + j0.000178 \text{ PU}$$

Step 5: Model Verification

As it can be seen from the above analysis, all 102 turbines of the plant has been reduced in to a single turbine. This has been done in two steps, first, the full turbine was aggregated into eight turbine representation and secondly, the eight turbines were aggregated to single turbine representation. The full turbine representation and its aggregate representations of the wind farm developed has been simulated with DIgSILENT and a load flow analysis has been performed.

Load Flow Analysis

A load flow study for the different case of the wind farm representation was performed and its outputs were summarized in Table 4.7.

- Case 1: The large wind farm is composed of 102 SANY DFIGs, each delivering 1.5 MW of active power. The turbine voltage is 690V. 102 unit transformers increase the terminal wind generator voltage from 690 V to medium voltage of 33KV. The wind farm has 8 main 33KV feeders, each of the seven feeders are connected with 13 wind turbines and the remaining one feeder is connected with 11 wind turbines as shown on Figure 4.3.
- Case 2: The large wind farm 102*1.5 MW is aggregated to 8 SANY DFIGs, seven

of them delivering 19.5 MW of active power and the remaining one aggregated generator deliver an active power of 16.5MW as shown on Figure 4.4.

- Case 3: The 8 DFIG were further aggregated to a single wind turbine delivering an active power of 153MW with an equivalent medium voltage collector system as in Figure 4.4.

From Tables 4.4, 4.5 and 4.6, the flow of active and reactive power at the common coupling were, 151.45 MW and 49.47MVAR for case 1, 151.32MW and 49.42 MVAR for case 2 and 151.35MW and 49.43MVAR for case 3. From this, it can be seen that there is 0.1MW active power flow (which is 0.066% of total active power transferred) and 0.04MVAR reactive power flow (which is 0.081% of the total reactive power transferred) difference between full turbine representation and single turbine representation of the power plant.

Practically any system can't be 100% efficient, thus, Adama II wind power plant has a capacity of generating 153 MW of power (rated capacity) but in each of the models developed there is an active power loss. The FSR has a total active power loss of 1.55 MW, which is 1.01% of the rated capacity of the wind farm (153 MW). In the second case there is a total of 1.68 MW of active power loss which is 1.098% of the rated capacity of the farm. And the STR has a total active power loss of 1.65 MW which is 1.078% of the rated capacity of the wind farm. Therefore, comparing the results obtained, the model developed is acceptable.

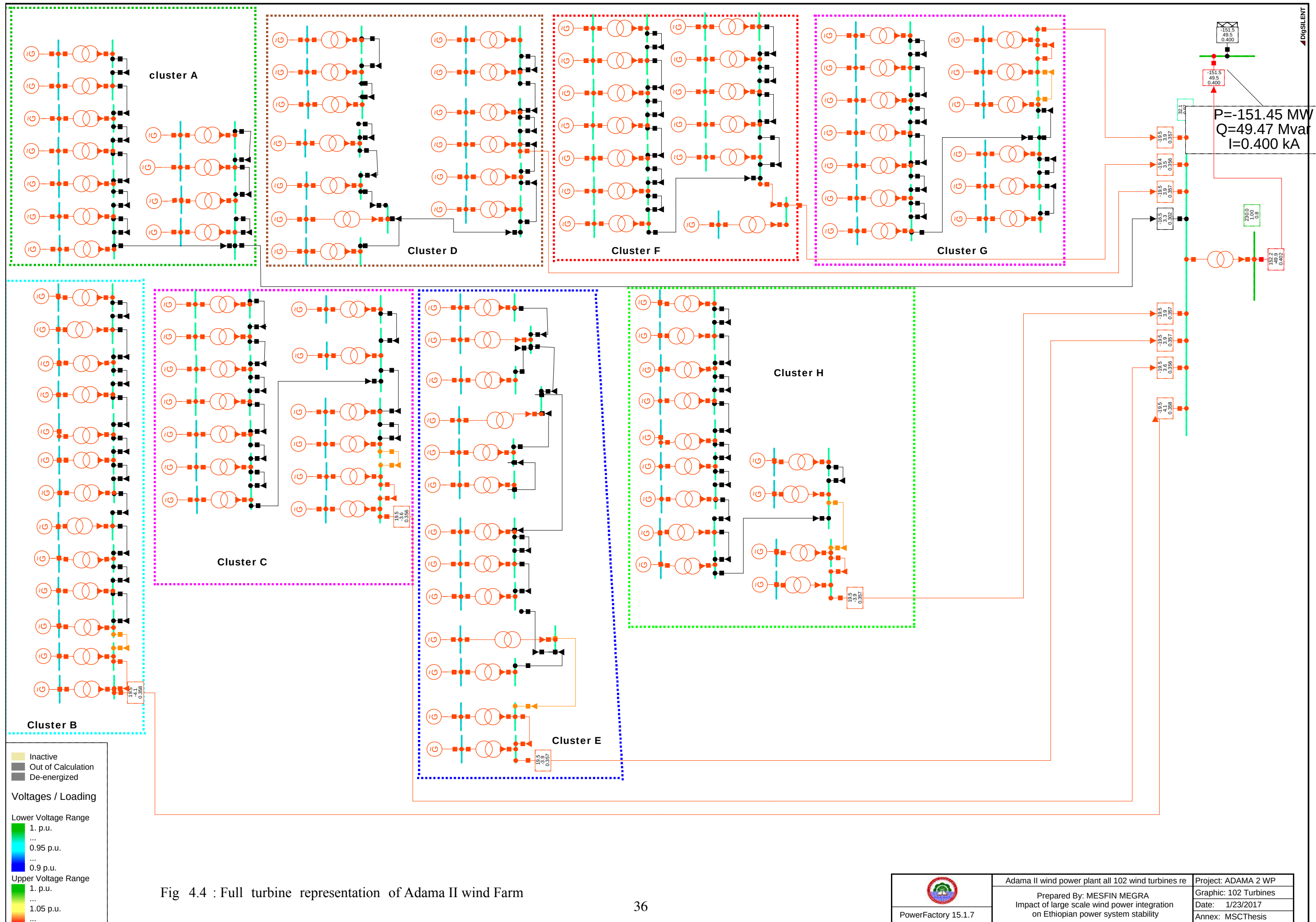


Fig 4.4 : Full turbine representation of Adama II wind Farm

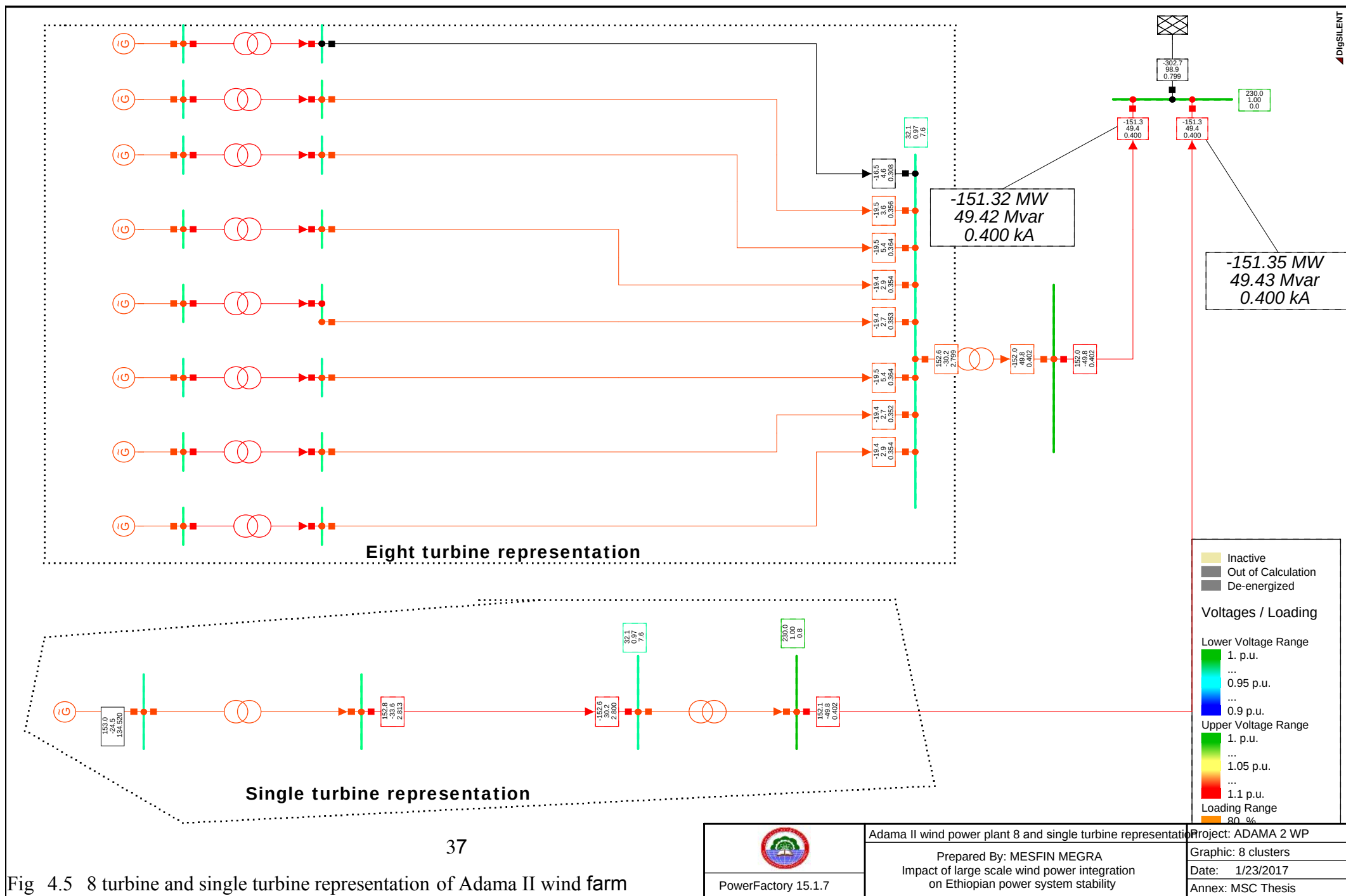


Fig 4.5 8 turbine and single turbine representation of Adama II wind farm

Table 4.4: Power flow output from load flow calculation of full turbine representations

						DigSILENT PowerFactory 15.1.7		Project:		
								Date: 1/23/2017		
Load Flow Calculation						Complete System Report: Grid Interchange				
AC Load Flow, balanced, positive sequence Automatic Tap Adjust of Transformers Consider Reactive Power Limits					Yes Yes	Automatic Model Adaptation for Convergence Max. Acceptable Load Flow Error for Nodes Model Equations			No 1.00 kVA 0.10 %	
Grid: 102 Turbines			System Stage: 102 Turbines			Study Case: Study Case			Annex: / 1	
Volt. Level [kV]	Generation [MW]/ [Mvar]	Motor Load [MW]/ [Mvar]	Load [MW]/ [Mvar]	Compen- sation [MW]/ [Mvar]	External Infeed [MW]/ [Mvar]	Interchange to	Power Interchange [MW]/ [Mvar]	Total Losses [MW]/ [Mvar]	Load Losses [MW]/ [Mvar]	NoLoad Losses [MW]/ [Mvar]
0.69	153.00 -25.03	0.00 0.00	0.00 0.00	0.00 0.00	0.00 0.00	33.00 kV	153.00 -25.03	0.00 0.00 0.15 9.13	0.00 0.00 0.15 9.13	0.00 0.00 0.00 0.00
33.00	0.00 0.00	0.00 0.00	0.00 0.00	0.00 0.00	0.00 0.00	0.69 kV 230.00 kV	-152.85 34.16 152.73 -30.20	0.12 -3.96 0.15 9.13 0.56 19.67	0.12 0.33 0.15 9.13 0.46 19.23	-0.00 -4.29 0.00 0.00 0.11 0.44
230.00	0.00 0.00	0.00 0.00	0.00 0.00	0.00 0.00	-151.45 49.47	33.00 kV	-152.17 49.88	0.72 -0.41 0.56 19.67	0.72 2.20 0.46 19.23	0.00 -2.61 0.11 0.44
Total:	153.00 -25.03	0.00 0.00	0.00 0.00	0.00 0.00	-151.45 49.47		0.00 0.00	1.55 24.44	1.44 30.90	0.11 -6.46

Table 4.5: Power flow output from load flow calculation of aggregated 8 turbine representations

						DigSILENT PowerFactory 15.1.7		Project:															
								Date: 1/23/2017															
Load Flow Calculation											Complete System Report: Grid Interchange												
AC Load Flow, balanced, positive sequence						Automatic Model Adaptation for Convergence		No															
Automatic Tap Adjust of Transformers						Max. Acceptable Load Flow Error for		1.00 kVA															
Consider Reactive Power Limits						Nodes		0.10 %															
Model Equations																							
Grid: 8 clusters						System Stage: 8 clusters						Study Case: Study Case						Annex: / 1					
Volt. Level		Generation		Motor Load		Load		Compen- sation		External Infeed		Interchange to		Power Interchange		Total Losses		Load Losses		Noload Losses			
[kV]		[MW]/ [Mvar]		[MW]/ [Mvar]		[MW]/ [Mvar]		[MW]/ [Mvar]		[MW]/ [Mvar]				[MW]/ [Mvar]		[MW]/ [Mvar]		[MW]/ [Mvar]		[MW]/ [Mvar]			
0.69		153.00		0.00		0.00		0.00		0.00						0.00		0.00		0.00			
		-41.90		0.00		0.00		0.00		0.00						0.00		0.00		0.00			
												33.00 kV		153.00		0.16		0.16		0.00			
														-41.90		0.75		0.75		0.00			
33.00		0.00		0.00		0.00		0.00		0.00						0.25		0.25		-0.00			
		0.00		0.00		0.00		0.00		0.00						-12.46		0.16		-12.62			
												0.69 kV		-152.84		0.16		0.16		0.00			
														42.65		0.75		0.75		0.00			
												230.00 kV		152.60		0.56		0.46		0.11			
														-30.20		19.64		19.20		0.44			
230.00		0.00		0.00		0.00		0.00		-151.32						0.72		0.72		0.00			
		0.00		0.00		0.00		0.00		49.42						-0.41		2.20		-2.61			
												33.00 kV		-152.04		0.56		0.46		0.11			
														49.83		19.64		19.20		0.44			
Total:		153.00		0.00		0.00		0.00		-151.32				0.00		1.68		1.58		0.11			
		-41.90		0.00		0.00		0.00		49.42				0.00		7.53		22.31		-14.79			

Table 4.6: Power flow output from load flow calculation of single turbine representations

						DigSILENT PowerFactory 15.1.7		Project:			
								Date: 1/23/2017			
Load Flow Calculation						Complete System Report: Grid Interchange					
AC Load Flow, balanced, positive sequence Automatic Tap Adjust of Transformers Consider Reactive Power Limits						Yes Yes	Automatic Model Adaptation for Convergence Max. Acceptable Load Flow Error for Nodes Model Equations			No 1.00 kVA 0.10 %	
Grid: single turbine		System Stage: single turbine				Study Case: Study Case			Annex: / 1		
Volt. Level [kV]	Generation [MW]/ [Mvar]	Motor Load [MW]/ [Mvar]	Load [MW]/ [Mvar]	Compen- sation [MW]/ [Mvar]	External Infeed [MW]/ [Mvar]	Interchange to	Power Interchange [MW]/ [Mvar]	Total Losses [MW]/ [Mvar]	Load Losses [MW]/ [Mvar]	NoLoad Losses [MW]/ [Mvar]	
0.69	153.00 -24.51	0.00 0.00	0.00 0.00	0.00 0.00	0.00 0.00	33.00 kV	153.00 -24.51	0.00 0.00 0.15 9.10	0.00 0.00 0.15 9.10	0.00 0.00 0.00 0.00	
33.00	0.00 0.00	0.00 0.00	0.00 0.00	0.00 0.00	0.00 0.00	0.69 kV 230.00 kV	-152.85 33.61 152.63 -30.20	0.22 -3.42 0.15 9.10 0.56 19.65	0.22 0.14 0.15 9.10 0.46 19.21	0.00 -3.56 0.00 0.00 0.11 0.44	
230.00	0.00 0.00	0.00 0.00	0.00 0.00	0.00 0.00	-151.35 49.43	33.00 kV	-152.07 49.84	0.72 -0.41 0.56 19.65	0.72 2.20 0.46 19.21	0.00 -2.61 0.11 0.44	
Total:	153.00 -24.51	0.00 0.00	0.00 0.00	0.00 0.00	-151.35 49.43		0.00 0.00	1.65 24.92	1.54 30.65	0.11 -5.73	

Table 4.7: Power flow comparison for different wind farm representations

Case 1 Full turbine representation with 102 wind turbines			
Feeder name	Total current flow [KA]	Total Active power flow [MW]	Total reactive power flow [MVar]
Cluster 1	0.302	16.48	3.31
Cluster 2	0.358	19.47	4.12
Cluster 3	0.356	19.46	3.63
Cluster 4	0.357	19.48	3.90
Cluster 5	0.357	19.47	3.87
Cluster 6	0.356	19.45	3.55
Cluster 7	0.357	19.47	3.89
Cluster 8	0.357	19.47	3.93
Substation	0.400	152.17	49.88
Case 2: Aggregation to 8 turbines			
Feeder name	Total current flow [KA]	Total Active power flow [MW]	Total reactive power flow [MVar]
Cluster 1	0.308	16.48	4.60
Cluster 2	0.356	19.48	5.44
Cluster 3	0.364	19.48	5.44
Cluster 4	0.354	19.48	5.44
Cluster 5	0.352	19.48	5.44
Cluster 6	0.364	19.48	5.44
Cluster 7	0.353	19.48	5.44
Cluster 8	0.354	19.48	5.44
Substation	0.400	152.04	49.83
Case 3: Single turbines representation			
Feeder name	Total current flow [KA]	Total Active power flow [MW]	Total reactive power flow [MVar]
Substation	0.400	152.07	49.84

4.2 Transient Stability of Ethiopian National Grid Without Wind Power Integration (Base Case Scenario)

The transient simulation of full system has been done using the DIgSILENT software. The power system is modeled based on the 2016 data obtained from EEP. The whole Power Grid data of the country is given in Appendix C.

To analyze the transient stability of the power system, three fault cases are simulated in DIgSILENT. Even though every synchronous machines in the power system will respond to any fault in the power system, the locations of the fault have its own effect. Therefore, for this study, the power plants are divided into three areas depending on their location as shown in Figure 4.5. Thus, area 1 contains Awash II & III, Koka and Melka Wakena power plants, area 2 contains Belese, Tekeze and Tis abay I & II and area 3 contains Fincha and Gilgel Gibe I & II. All of the generators are equipped with typical voltage controllers and power system stabilizers so that all local modes are damped. In this scenario, all the power plants use conventional synchronous generator (even the wind power plants are replaced with their equivalent conventional synchronous generators). The total power produced is 2302.6 MW while the peak load is 1372.3 MW.

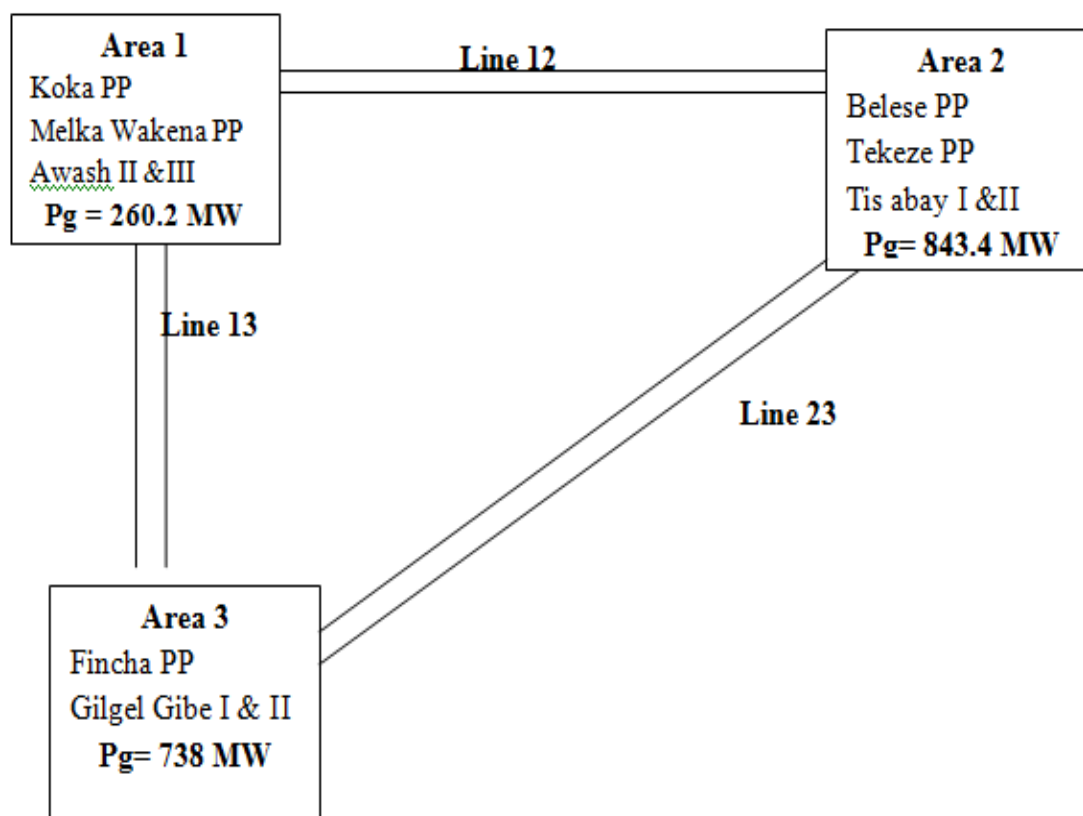


Figure 4.5: Schematic representation of hydro power plants in Ethiopian power system

The fault cases applied in this study are the following.

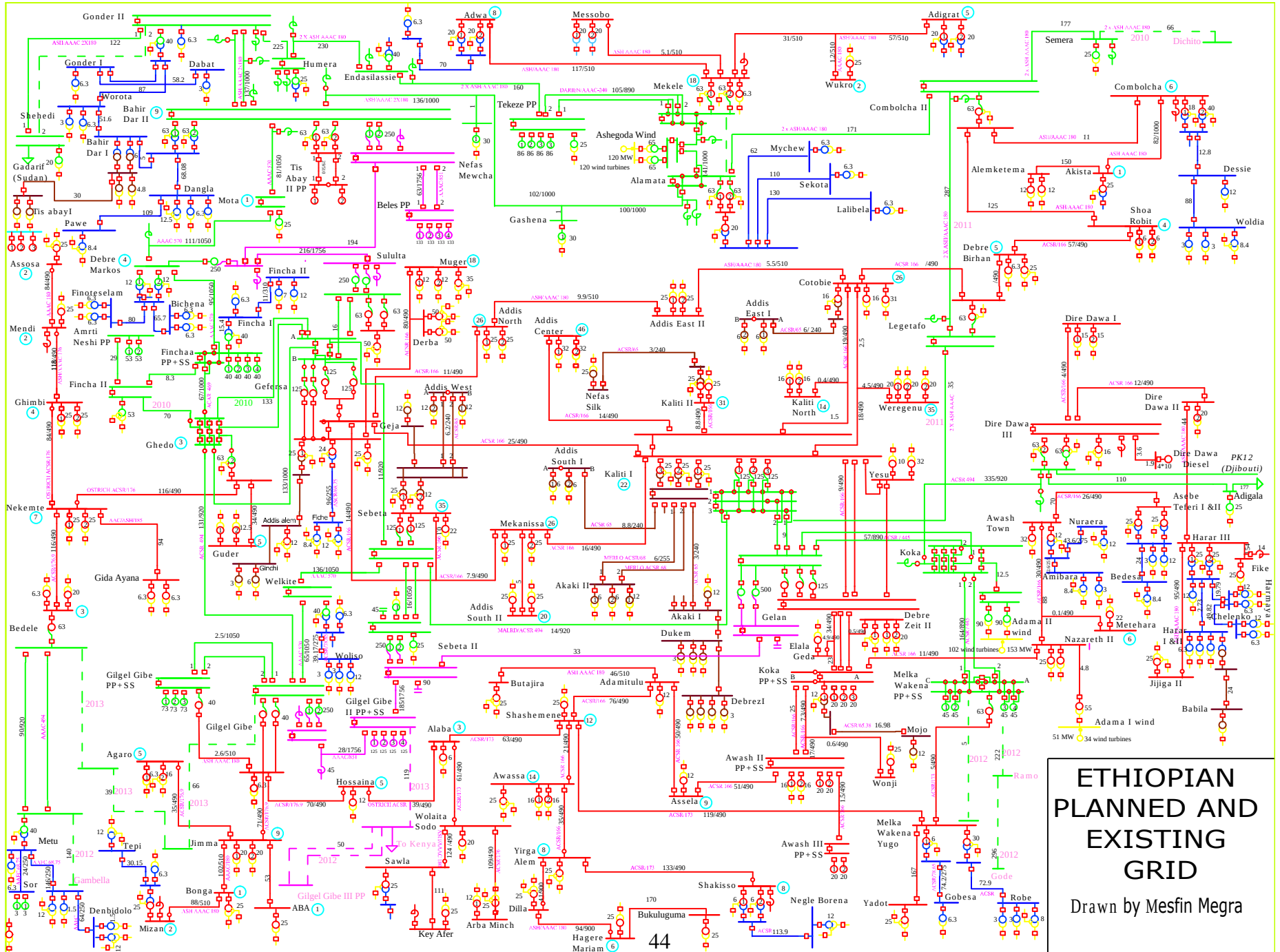
1. **Case 1:** Three phase fault on 230 KV Koka to Kalitti line which is located near area 1 and the fault is cleared by opening the circuit breaker on both side of the line.
2. **Case 2:** Three phase fault on 230 KV Alamata to Kombolcha line which is located near area 2 and the fault is cleared by opening the circuit breaker on both side of the line.
3. **Case 3:** Three phase fault on 230 KV Fincha to Ghedo line which is located near area 3 and the fault is cleared by opening the circuit breaker on both side of the line.

For evaluating transient stability the critical fault clearing time (CCT) is evaluated for all cases. The CCT represents a useful measure for characterizing the transient performance of a given dispatch scenario. In this study, only a single plant which is mostly affected by the fault cases created is taken from each area.

4.2.1 Case One: Fault at 230 KV Koka to Kalitti Line

In this case a 3 phase fault is applied on the 230 KV line from Koka to Kaliti which is close to power plants in area one. The critical fault clearing time (CCT) is determined by repetitive transient simulation, and for the fault occurred at 230 KV Koka to Kaliti line, the CCT of Melka Wakena generator becomes $T_{CCT} = 246\text{ms}$. Thus, for a fault at 230 KV Koka to Kaliti line, the protective device has to act in a time below the CCT. Figures 4.7 and 4.8 shows the rotor angle with respect to reference machine, speed in pu and terminal voltage & reactive power of different generators from each area. If the protective devices operate after the CCT, Melka Wakena power plant will become unstable (out of step) as shown in Figure 4.9. Thus, for a fault at 230 KV Koka to Kaliti line the critical power plant is Melka Wakena power plant.

Figure 4.7, The red curve show values for Melka Wakena generator which is located in area one, the blue curve shows the values for Fincha power plant which is located in area three and the green curve shows the values for Tekeza power plant.



As can be seen from Figure 4.7, for the fault at the 230 KV Koka to Kaliti line, the rotor angle of Melka Wakena generator increases to 128.763° . When the fault is cleared, the rotor angle of Melka Wakena generator oscillates for 0.754 s until it reaches a steady state value of -22.178° from the initial rotor angle of -24.647° .

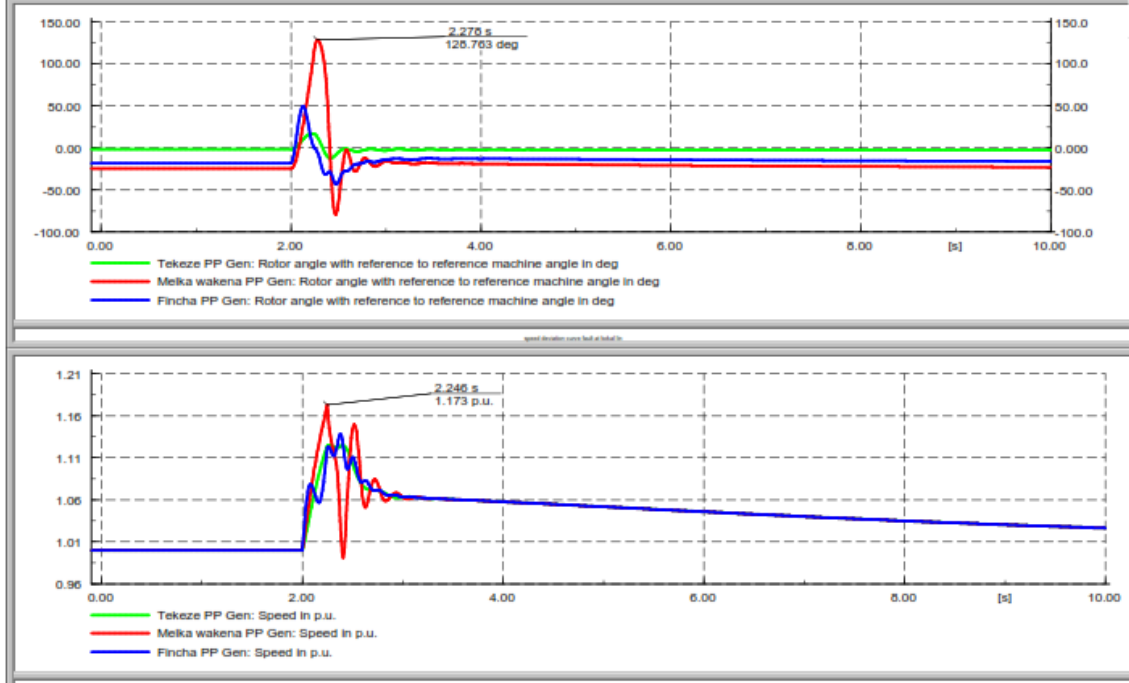


Figure 4.7: Rotor angle and speed of generators for case 1 without wind

One can observe from Figure 4.8, with the occurrence of fault on 230 KV Koka to Kaliti line, the terminal voltage of Melka Wakena power plant decrease to 0.3 pu. On the other hand, in order to support the voltage drop caused by the occurrence of fault, the generator of Melka Wakena supply 124.269 MVar of reactive power.

With the occurrence of fault at 230 KV Koka to Kaliti line, when the fault clearing time is made to exceeds the CCT, the rotor angle of Melka Wakena generator spreads out fast and loses the synchronism. This is due to the fact that, with a delayed fault clearing time, the acceleration area is greater than deceleration area (according to the equal area criteria). Thus, the kinetic energy gained during the acceleration period can't be completely expended; consequently, the speed remains greater than ω_o and δ continues to increase leading to loss of synchronism of Melka Wakena generator. Figures 4.9 and 4.10 shows, for a delayed fault clearing time for a the occurrence of fault at 230 KV Koka to Kaliti line, the rotor angle and active power of Melka Wakena generator oscillates continually between negative and positive regions.

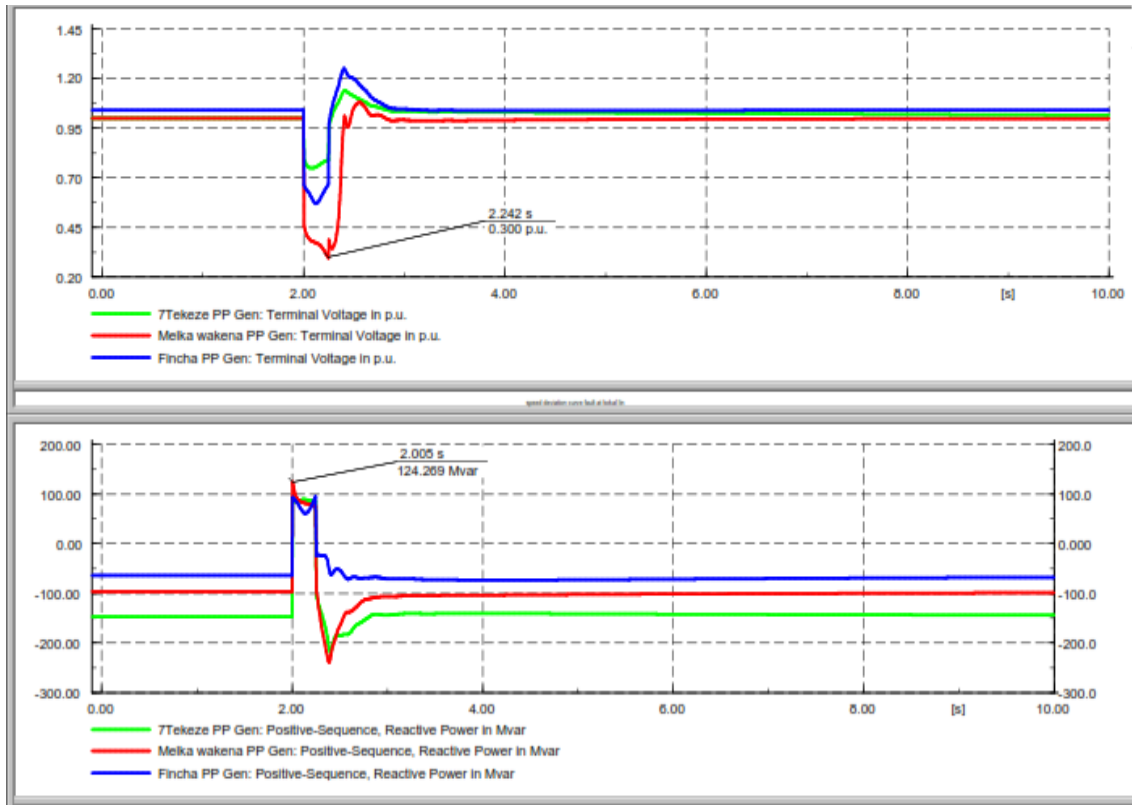


Figure 4.8: Terminal voltage & reactive power of generators case 1 without wind

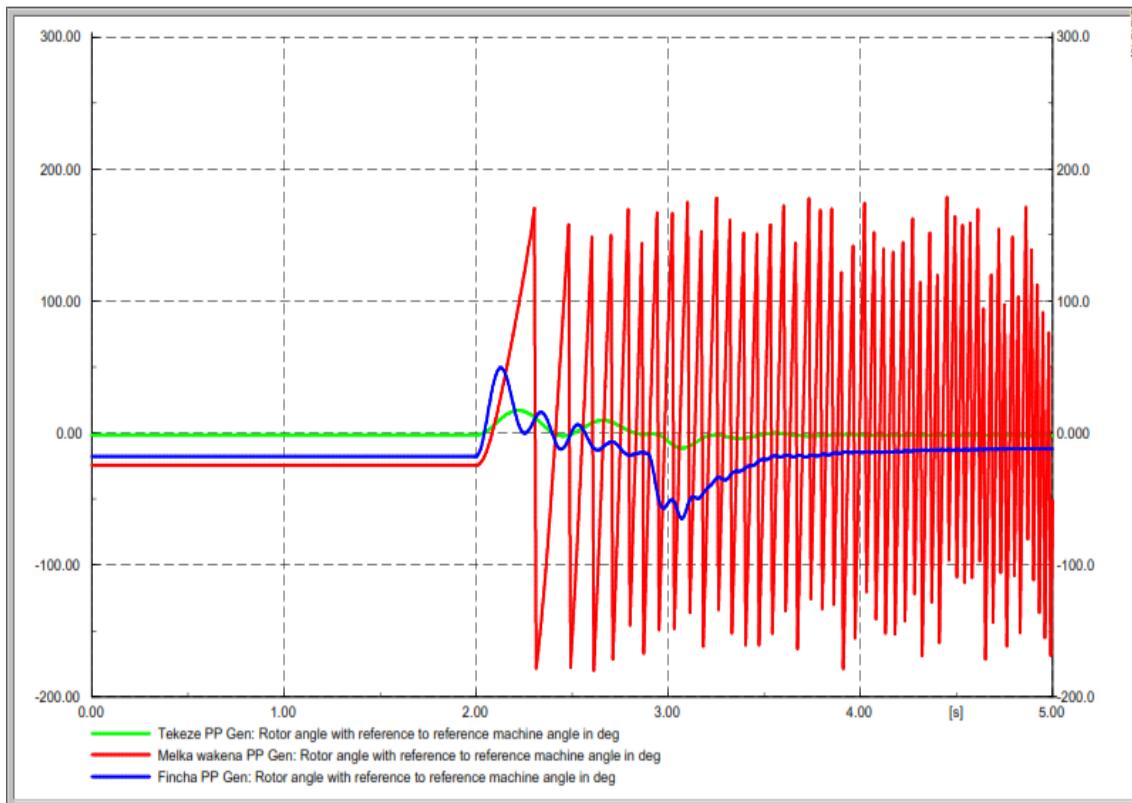


Figure 4.9: Rotor angle for out of step condition for case 1 without wind

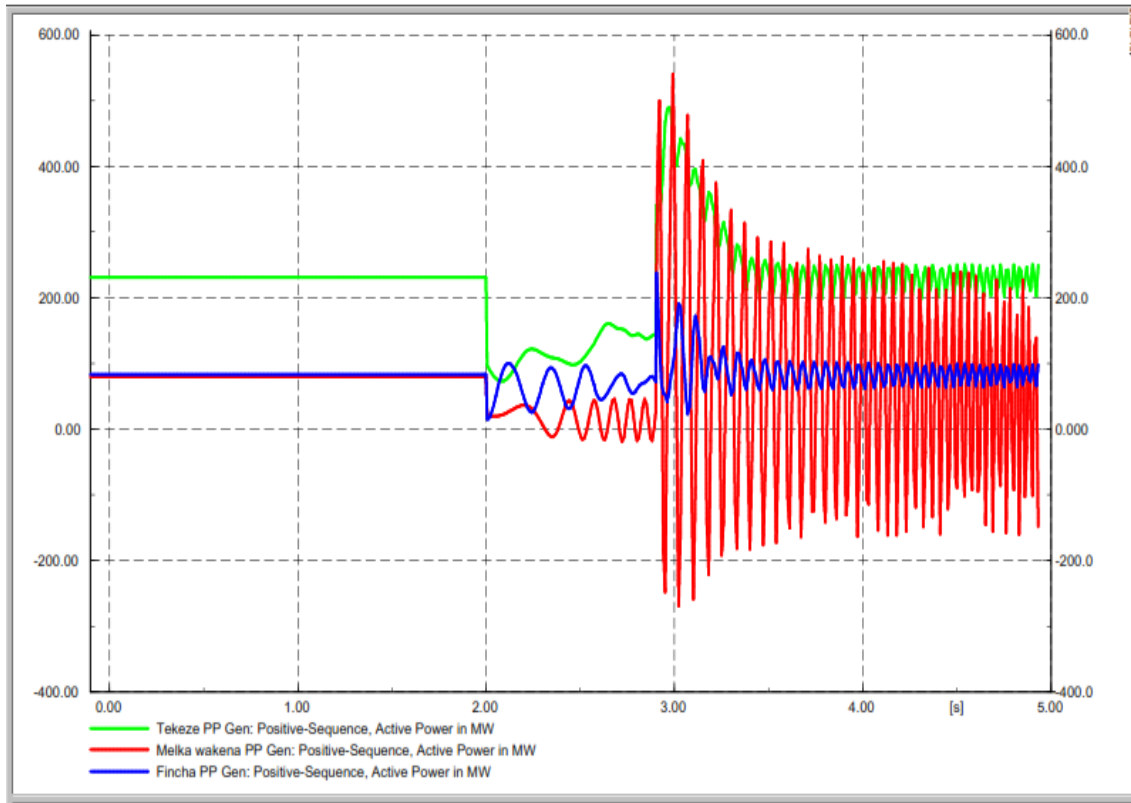


Figure 4.10: Active power for out of step condition for case 1 without wind

4.2.2 Case Two: Fault at 230KV Alamata to Kombolcha Line

In this case a 3 phase fault is applied at the 230 KV line from Alamata to Kombolcha which is close to power plants in area Two. The critical fault clearing time (CCT) has been determined by repetitive transient simulation, and for the occurrence of fault at 230 KV Alamata to Kombolcha line, the CCT of Tekeze generator becomes $T_{CCT} = 331\text{ms}$. Thus, for a fault at 230 KV Alamata to Kombolcha line, the protective devices has to act in a time below 331 ms. Figures 4.11 and 4.12 shows the rotor angle with respect to reference machine, speed in pu and terminal voltage & reactive power of different generators from each area. If the protective devices operate after the CCT, Tekeze power plant will become unstable (out of step) as shown in figure 4.13. Thus, for a fault occurrence at 230 KV Alamata to Kombolcha line, Tekeze is the critical power plant.

As can be seen from Figure 4.11, for the fault at the 230 KV Alamata to Kombolcha line, the rotor angle of Tekeze generator increases to 119.17° . When the fault is cleared by opening the circuit breaker of 230 KV Alamata to Kombolcha line, the rotor angle of Tekeze generator oscillates for 1.669 s until it reaches steady state value of 0.601° from the initial rotor angle of -1.571° . Whereas, the speed also oscillates for some period and settles to a new steady state value of 1.05 pu from initial value of 1.0 pu.

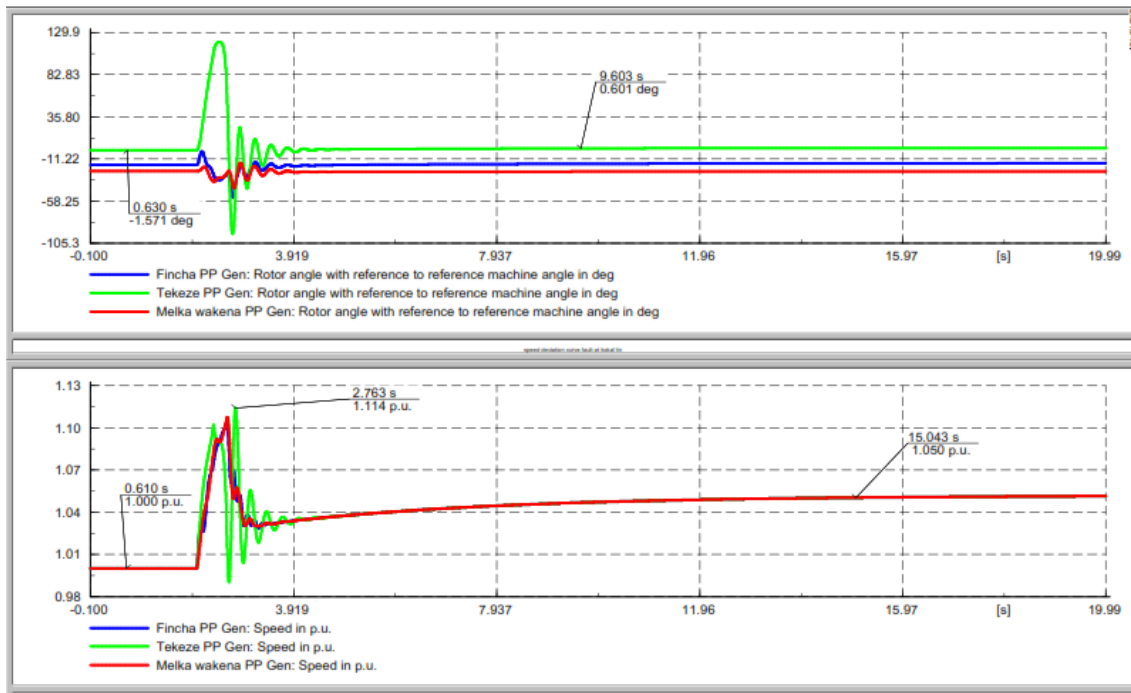


Figure 4.11: Rotor angle and speed of generators for case 2 without wind

One can observe from Figure 4.12, with the occurrence of fault at 230 KV Alamata to Kombolcha line, the terminal voltage of Tekeze power plant decreases to 0.396 pu. On the other hand, in order to support the voltage drop caused by the occurrence of fault at 230 KV Alamata to Kombolcha line the generator of Tekeze power plant will supply 244.306 MVar of reactive power.

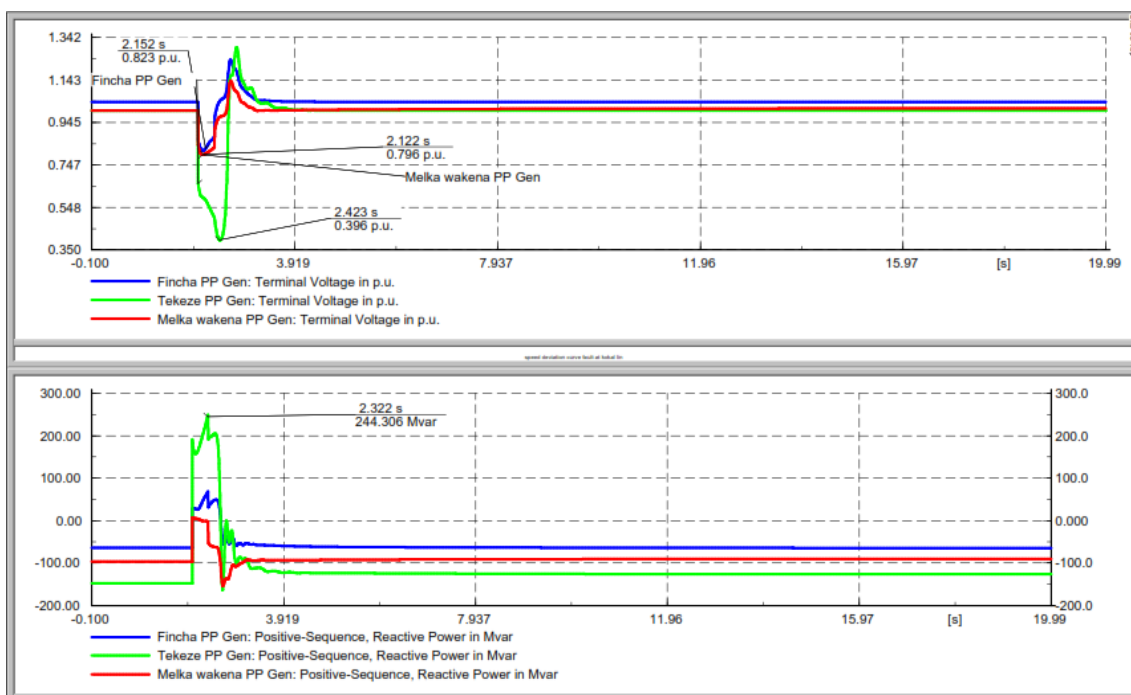


Figure 4.12: Terminal voltage & reactive power of generators case 2 without wind

For a delayed fault clearing with occurrence of fault at 230 KV Alamata to Kombolcha line, the rotor angle of Tekeze generator spreads out fast and loses the synchronism. This is due to the fact that, with a delayed fault clearing time, the acceleration area is grater than deceleration area (equal area criteria). Thus, the kinetic energy gained during the acceleration period can't be completely expended; consequently, the speed remains greater than ω_o and δ continues to increase leading to loss of synchronism of Tekeze generator. Figures 4.13 and 4.14 shows, for a delayed fault clearing time for the fault occurred at 230 KV Alamata to Kombolcha line, the rotor angle and active power of Tekeze generator oscillation continually between negative and positive regions.

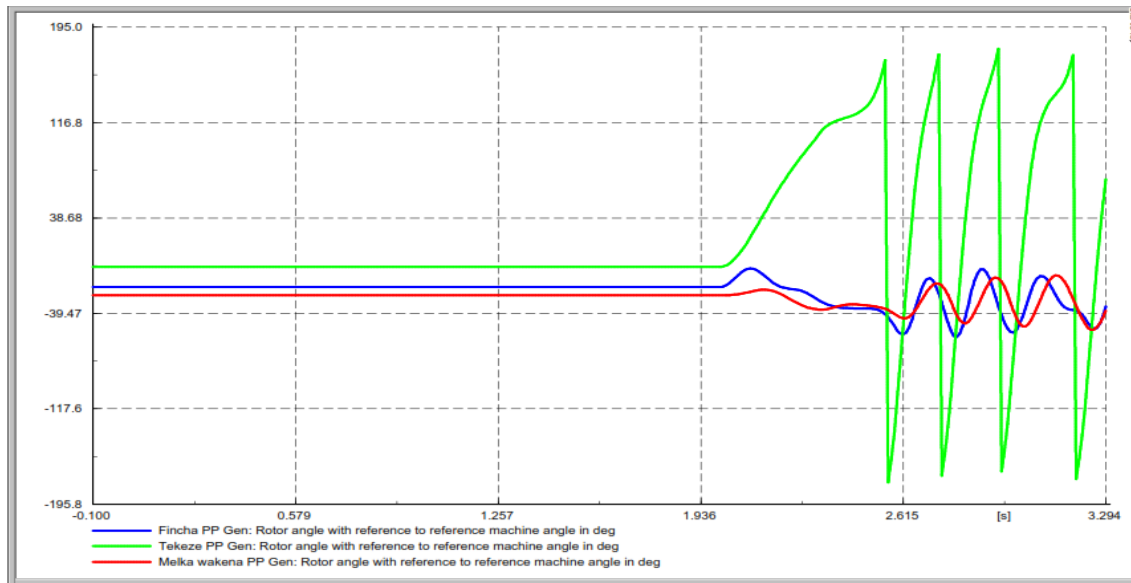


Figure 4.13: Rotor angle for out of step condition for case 2 without wind

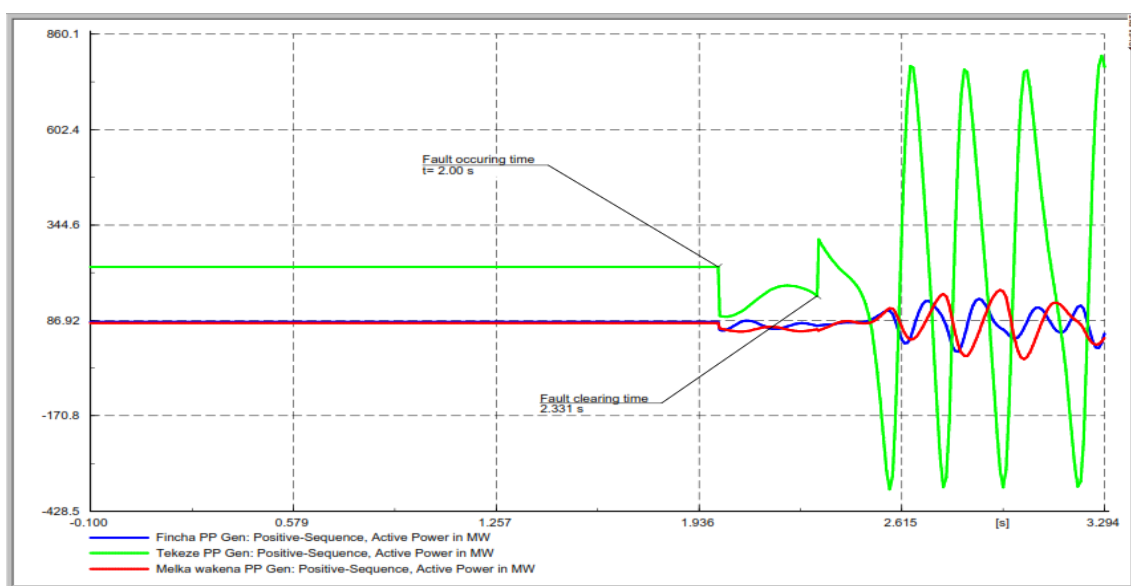


Figure 4.14: Active power for out of step condition for case 2 without wind

4.2.3 Case Three: Fault at 230KV Fincha to Ghedo Line

In this case a 3 phase fault is applied on a 230 KV line from Fincha to Ghedo which is close to power plants in area three. The critical fault clearing time (CCT) has been determined by repetitive transient simulation. Thus, for the occurrence of fault at 23 KV Fincha to Ghedo line, the CCT of Fincha generator becomes $T_{CCT} = 119\text{ms}$. For a fault at 230 KV Fincha to Ghedo line, the protective devices has to act in a time below 119 ms. Figures 4.15 and 4.16 shows the rotor angle with respect to reference machine, speed in pu and terminal voltage & reactive power of different generators from each area. If the protective devices operate after the CCT, Fincha power plant will become unstable (out of step) as shown in figure 4.17. Therefore, for a fault at 230 KV Fincha to Ghedo line, Fincha is the critical power plant.

As can be seen from Figure 4.15, for the fault occurrence at Fincha to Ghedo line, the rotor angle of Fincha generator increases to 127.564° . When the fault is cleared by opening the circuit breaker of 230 KV Fincha to Ghedo line, the rotor angle of Fincha generator oscillates for 0.871 s until it reaches steady state value of -17.542° from the initial rotor angle of -17.931° . Like the rotor angle of Fincha generator, the speed of fincha generator also oscillates for some period and settles to a new steady state value of 1.024 pu from initial value of 1.0 pu.

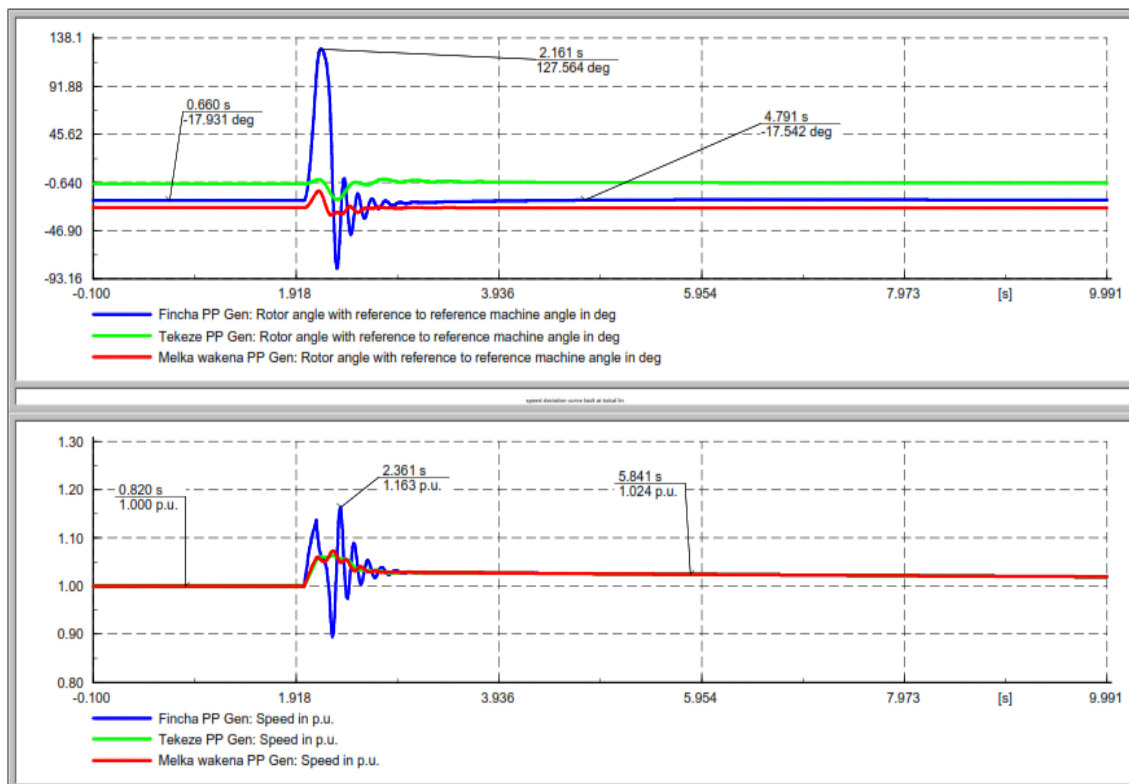


Figure 4.15: Rotor angle and speed of generators for case 3 without wind

One observe from Figure 4.16, with the occurrence of fault at 230 KV fincha to Ghedo line, the terminal voltage of Fincha power plant decreases to 0.228 pu. On the other hand, in order to support the voltage drop caused due to the fault occurred at 230 KV Fincha to Ghedo line the generator of Fincha power plant supply a reactive power of 113.908 MVar.

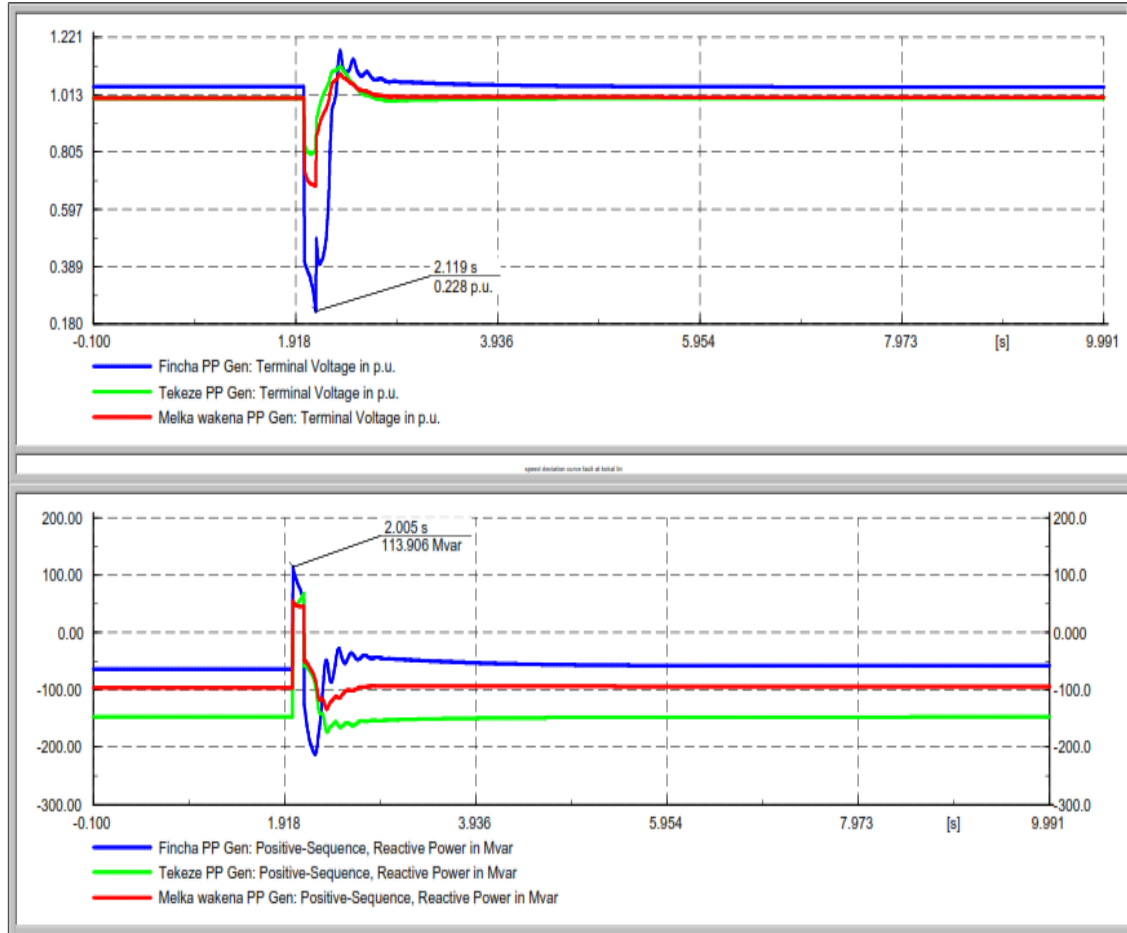


Figure 4.16: Terminal voltage & reactive power of generators case 3 without wind

When the fault clearing time for a fault occurred at 230 KV Fincha to Ghedo line extends beyond the CCT, the rotor angle of Fincha generator spreads out fast and loses the synchronism. This is due to the fact that, with a delayed fault clearing time, the acceleration area is grater than deceleration area (equal area criteria). Thus, the kinetic energy gained during the acceleration period can't be completly expended; consequently, the speed remains greater than ω_0 and δ continues to increase leading to loss of synchronism of Fincha generator. Figures 4.17 and 4.18 shows, for a delayed fault clearing time of the fault occurred at 230 KV Fincha to Ghedo line, the rotor angle and active power of Fincha generator oscillation continually between negative and posetive regions.

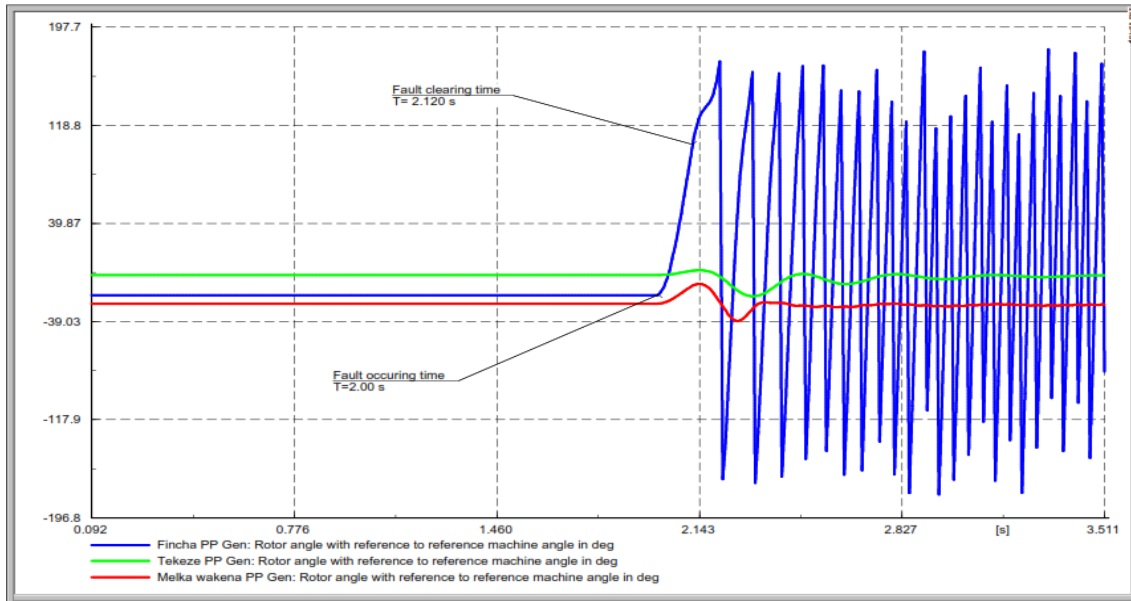


Figure 4.17: Rotor angle for out of step condition for case 3 without wind

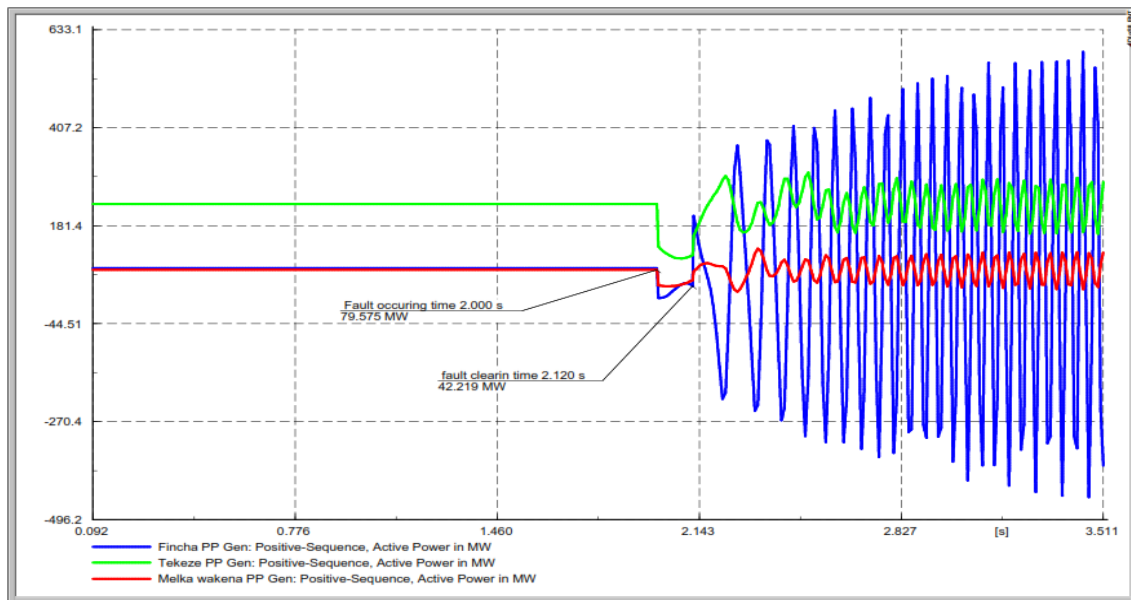


Figure 4.18: Active power for out of step condition for case 3 without wind

Thus, summarizing the above analysis the CCT and Settling time of each fault case is given in Table 4.8.

Table 4.8: Transient stability response of the system for base case scenario

No.	Fault location	Critical power plant	CCT	Settling time
1	Koka to kaliti line	Meka Wakena	246 ms	0.754 s
2	Alamata to Kombolcha line	Tekeze	331 ms	1.669 s
3	Fincha to Ghedo line	Fincha	119 ms	0.871 s

4.3 Transient Stability of Ethiopian National Grid With Wind Power Integration (Present Case Scenario)

In this scenario, the existing wind farms are integrated to the power system in accordance with the present technology used. Like the base case scenario the same three fault cases will be analyzed. Here again the total power produced is 2302.6 MW and the peak load also remains the same as the base case which is 1372.3 MW.

4.3.1 Case One: Fault at 230 KV Koka to Kaliti Line

In this case a 3 phase fault is applied on the 230 KV line from Koka to Kaliti which is close to power plants in area one. The critical fault clearing time (CCT) of Melka Wakena generator is taken from base case scenario of fault on 230 KV Koka to Kaliti line which is 246ms and after conducting a simulation the generator remain stable at this CCT. However, it is found that the generator continues to remain stable for subsequent simulation at a fault clearing time of 247ms, where theoretically it should be out of step condition according to the base case scenario. As a result, repetitive simulations are conducted to identify the actual CCT. The fault time is increased by 0.01 s in each simulation until the generator experiences out of step condition. By conduction this simulation, it was found that the generator of Melka Wakena power plant starts experiencing out of step condition at a fault clearing time (FCT) of 0.432 s. This means the actual CCT is 0.431 s. For a fault occurred at 230 KV Koka to Kaliti line, after 431 ms Melka Wakena power plant become unstable (out of step). Thus, for a fault occurred at 230 KV Koka to Kaliti line Melka Wakena is the critical power plant.

As can be seen from Figure 4.19, for the fault occurred at Koka to Kaliti line, the rotor angle of Melka Wakena generator increases to 131.374° . When the fault is cleared by the circuit of the 230 KV Koka to Kaliti line, the rotor angle of Melka Wakena generator oscillates for 0.896 s until it reaches steady state value of -19.104° from the initial rotor angle value of -21.018° . Whereas, the speed also oscillates for some period and settles to a new steady state value of 0.989 pu from initial value 1.0 pu.

One can observe from Figure 4.20, with the occurrence of fault at 230 KV Koka to Kaliti line, the terminal voltage of Melka Wakena power plant decreases to 0.275 pu. On the other hand, in order to support the voltage drop caused by the fault occurred at 230 KV Koka to Kaliti line, the generator of Melka Wakena supply a reactive power of 128.840 MVar.

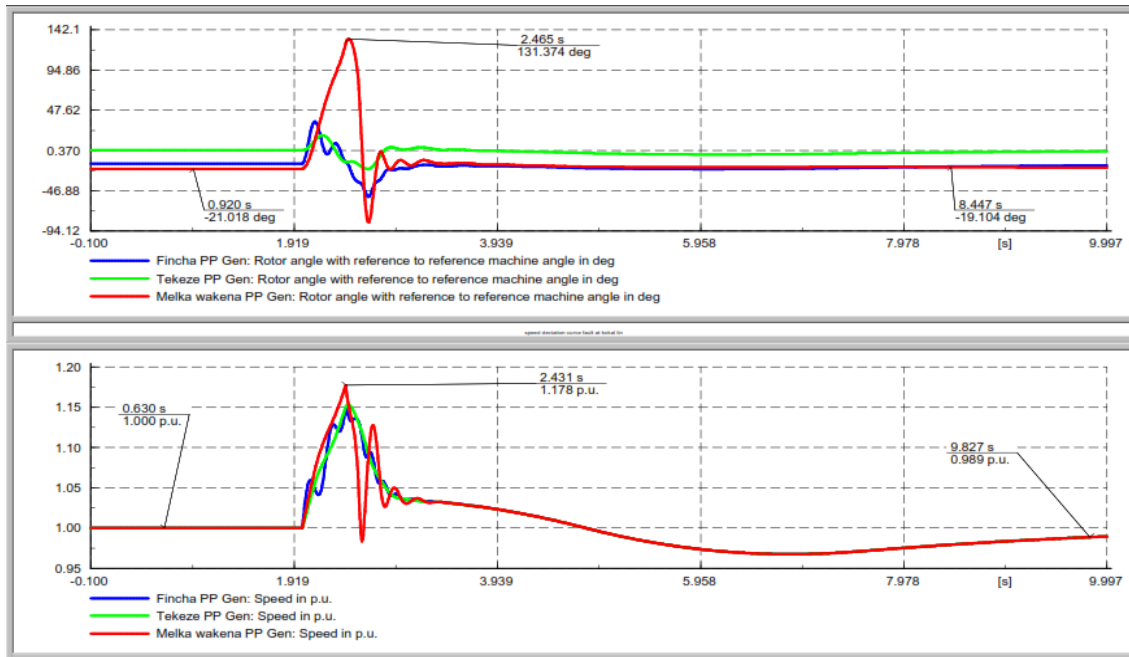


Figure 4.19: Rotor angle and speed of generators for case 1 with wind

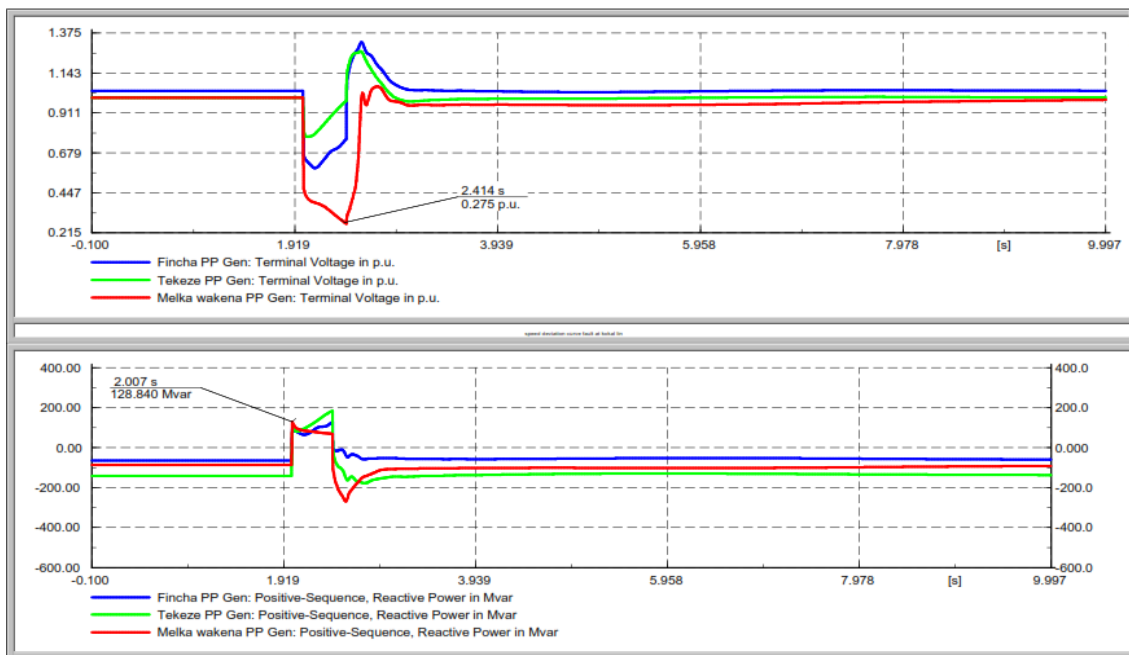


Figure 4.20: Terminal voltage & reactive power of generators for case 1 with wind

4.3.2 Case Two: Fault at 230KV Alamata to Kombolcha Line

In this case a 3 phase fault is applied at the 230 KV line from Alamata to Kombolcha which is close to power plants in area two. The critical fault clearing time (CCT) of Tekeze generator is taken from the base case scenario to be 331ms and after conducting a simulation the generator remain stable at this CCT. However, it is found that the generator

continues to remain stable for subsequent simulation at a fault clearing time of 332ms, where theoretically it should be out of step condition as in the base case. Thus, after a repetitive simulation the actual value of CCT is found to be 557ms. For a fault occurred at Alamata to Kombolcha line, after 557 ms generator of Tekeze power plant become unstable (out of step). Thus, for a fault at 230 KV Alamata to Kombolcha line Tekeze is critical power plant.

As can be seen from Figure 4.21, for a fault occurred at 230 KV Alamata to Kombolcha line, the rotor angle of Tekeze generator increases to 121.097° . When the fault is cleared by opening of the circuit breaker of the 230 KV Alamata to Kombolcha line, the rotor angle of Tekeze power plant oscillates for 2.181 s until it reaches steady state value of 0.982° from the initial rotor angle value of 6.825° . Whereas the speed also oscillates for some period and settles to a new steady state value of 1.015 pu from initial value of 1.0 pu.

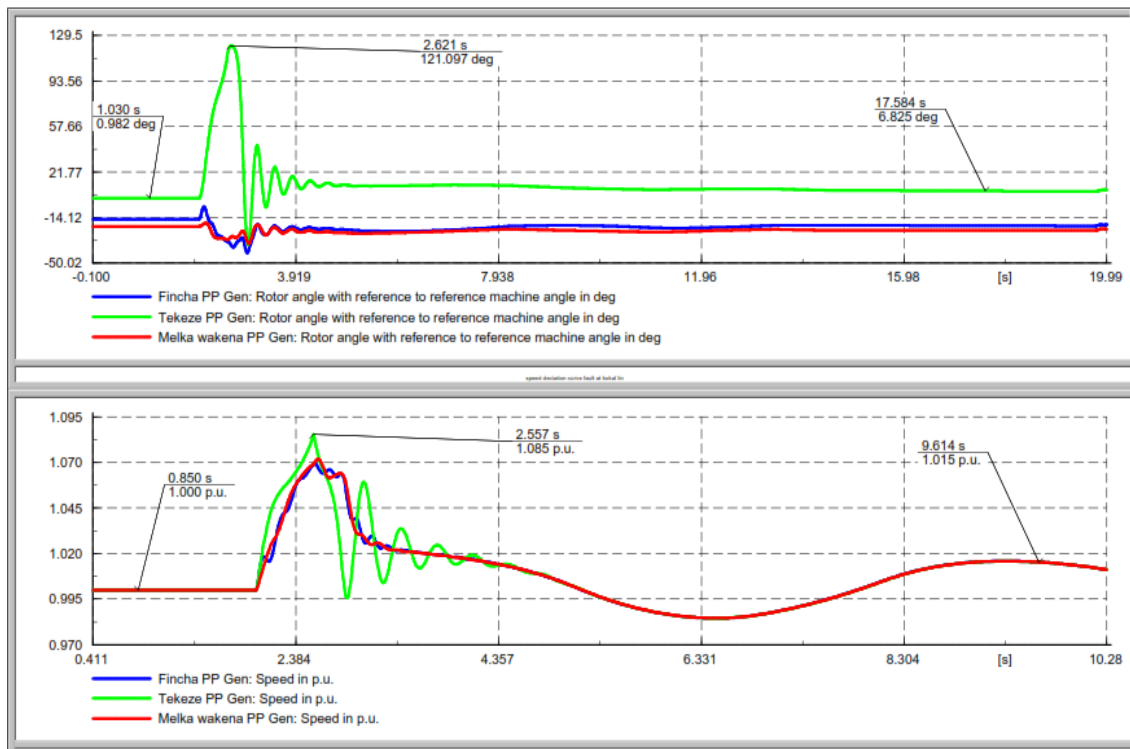


Figure 4.21: Rotor angle and speed of generators for case 2 with wind

One can observe from Figure 4.22, with the occurrence of fault at 230 KV Alamata to Kombolcha line, the terminal voltage of Tekeze power plant decreases to 0.304 pu. On the other hand, to support the voltage drop caused due to the fault at 230 KV Alamata to Kombolcha line, the generator of Tekeze power plant supply a reactive power of 181.581 MVar.

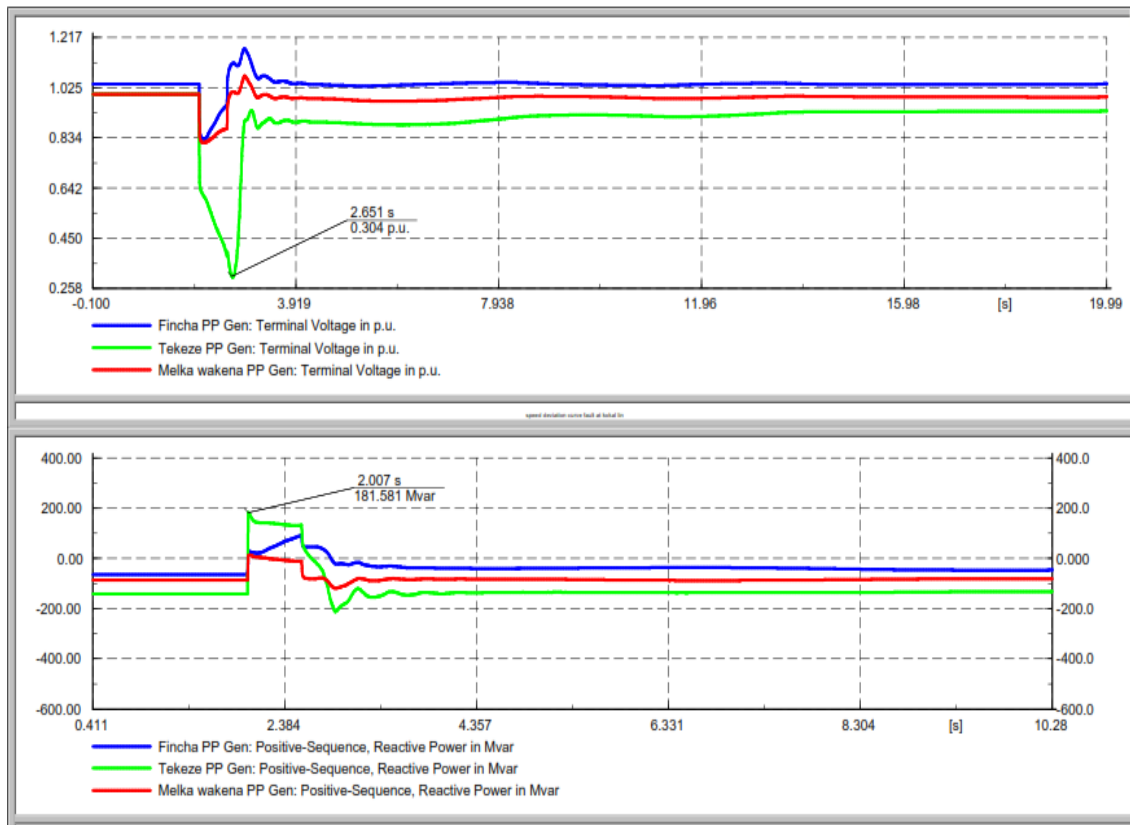


Figure 4.22: Terminal voltage & reactive power of generators case 2 with wind

4.3.3 Case Three: Fault on 230KV Fincha to Ghedo Line

In this case a 3 phase fault is applied at the 230 KV line from Fincha to Ghedo which is close to power plants in area three. The critical fault clearing time (CCT) of Fincha power plant is taken from the base case scenario to be 119ms and after conducting a simulation the generator remain stable at this CCT. However, it is found that the generator continues to remain stable for subsequent simulation at a fault clearing time of 120ms, where theoretically it should be out of step condition as in the base case scenario. Thus, after a repetitive simulation, the actual value of CCT is found to be 163 ms. For a fault occurred at Fincha to ghedo line, after 163 ms generator of Fincha power plant become unstable (out of step). thus, for a fault at 230 KV Fincha to Ghedo line Fincha is the critical power plant.

As can be seen from Figure 4.23, for a fault occurred at 230 KV Fincha to Ghedo line, the rotor angle of Fincha power plant increases to 136.627° . When the fault is cleared by opening the circuit breaker of the 230 KV Fincha to Ghedo line, the rotor angle of Fincha power plant oscillates for 0.977 s until it reaches steady state value of -16.181° from the initial rotor angle value of -15.28° . Whereas the speed also oscillates for some period and settles to a steady state value equals to the initial value 1.0 pu.

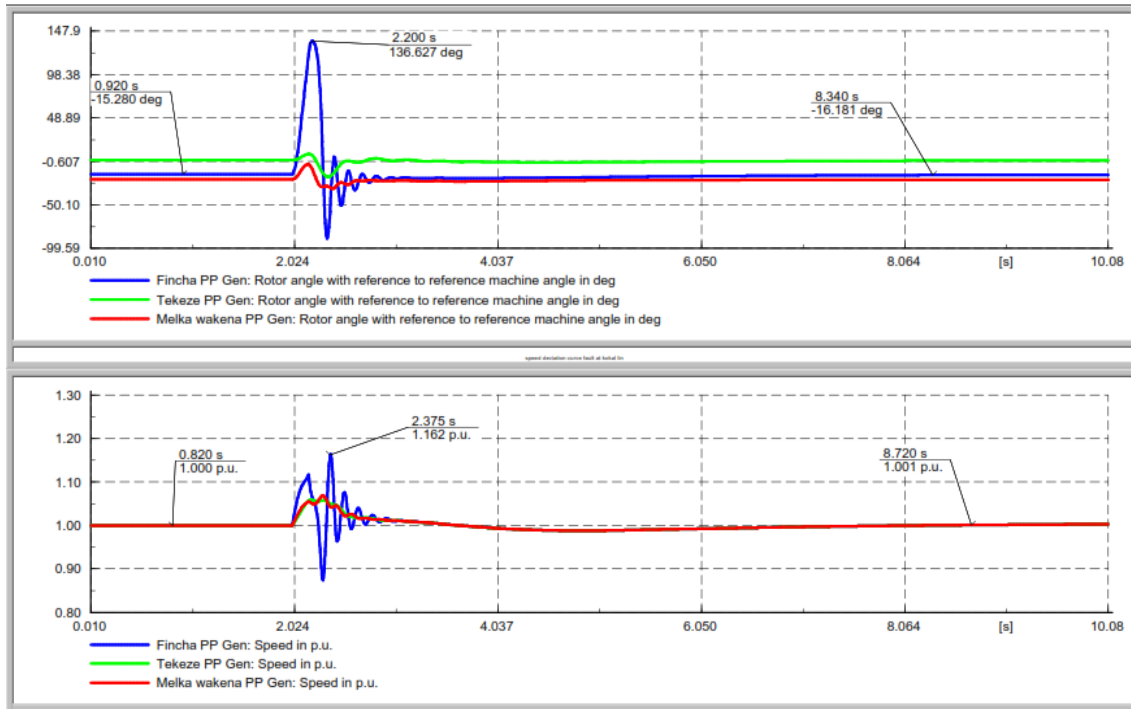


Figure 4.23: Rotor angle and speed of generators for case 3 with wind

One can observe from Figure 4.24, with the occurrence of fault at 230 KV Fincha to Ghedo line, the terminal voltage decreases to 0.212 pu. then in order to support the voltage drop caused due to the fault occurred at 230 KV Fincha to Ghedo line, the generator of Fincha power plant supply reactive power of 112.533 MVar.

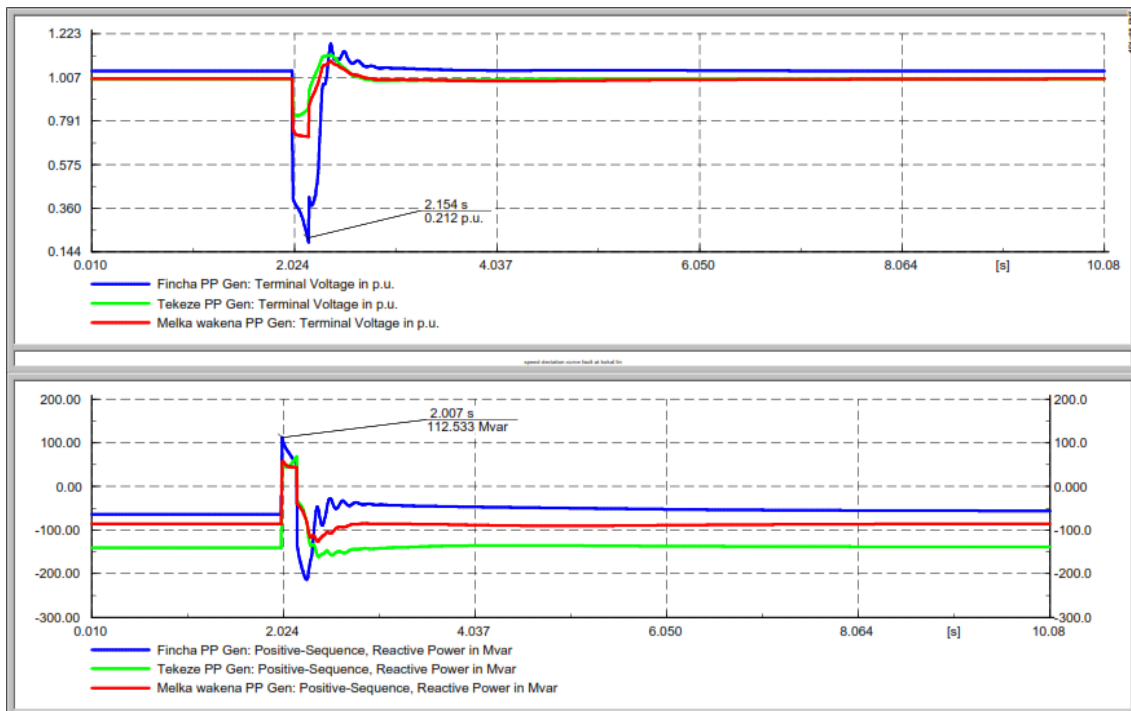


Figure 4.24: Terminal voltage & reactive power of generators case 3 with wind

Thus, summarizing the above analysis the CCT and Settling time of each fault case is given in Table 4.9.

Table 4.9: Transient stability response of the system for present case scenario

No.	Fault location	Critical power plant	CCT	Settling time
1	Koka to kaliti line	Meka Wakena	431 ms	0.896 s
2	Alamata to Kombolcha line	Tekeze	557 ms	2.181 s
3	Fincha to Ghedo line	Fincha	163 ms	0.977 s

4.4 Transient Stability of Ethiopian National Grid if All the Wind Power Plants Use PMSG Technology (Third Case Scenario)

In the present case scenarios DFIG wind turbine technology was dominant, but recently PMSG technology is dominating the market. Thus, in this scenario the transient stability of different power plants will be analyzed if all the wind power plants integrated use a PMSG generator technology.

4.4.1 Case One: Fault on 230KV Koka to Kaliti Line

In this case also a 3 phase fault is applied at the 230 KV line from Koka to Kalitti which is close to power plants in area one. The critical fault clearing time (CCT) of Melka Wakena power plant is taken from the present case scenario to be CCT= 431ms and after conducting a simulation the generator remain stable at this CCT. However, it is found that the generator continues to remain stable for subsequent simulation at a fault clearing time of 432ms, where theoretically it should be out of step condition as in the Present case scenario. As a result, repetitive simulations are conducted to identify the actual CCT. By conducting this simulation, it was found that the generator of Melka Wakena power plant starts experiencing out of step condition at a fault clearing time (FCT) of 0.466 s, that means, the actual CCT of Melka Wakena power plant for this specific scenario is 0.465 s.

As can be observed from Figure 4.25, for a fault occurred at 230 KV of Koka to Kaliti line, the rotor angle of Melka Wakena power plant increases to 132.698° . When the fault is cleared, the rotor angle of Melka Wakena power plant oscillates for 912 ms until it reaches a steady state value of -10.810° from the initial rotor angle value of -20.391° . Whereas

the speed also oscillates for some period and settles to a steady state value of 1.0 pu from initial value of 1.0 pu.

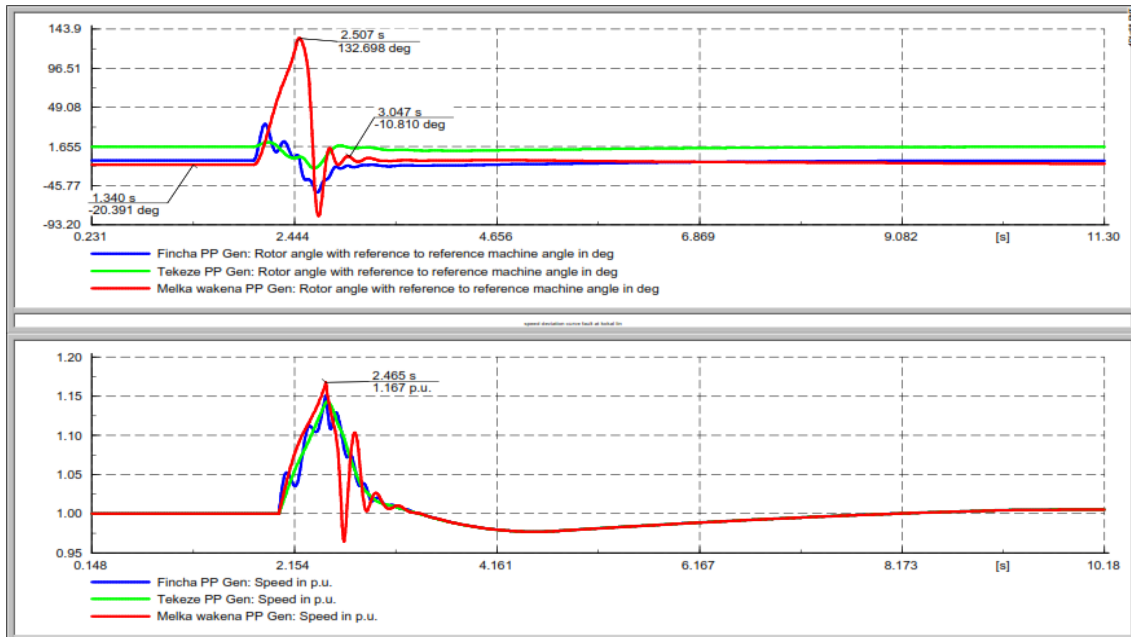


Figure 4.25: Rotor angle and speed of generators with all PMSG case one

One can observe from Figure 4.26, the terminal voltage of Melka Wakena power plant decreases to 0.253 pu. Then in order to support the voltage drop caused due to the fault occurred at 230 KV Koka to Kaliti line, the generator of Melka Wakena power plant supply a reactive power of 129.998 MVar.

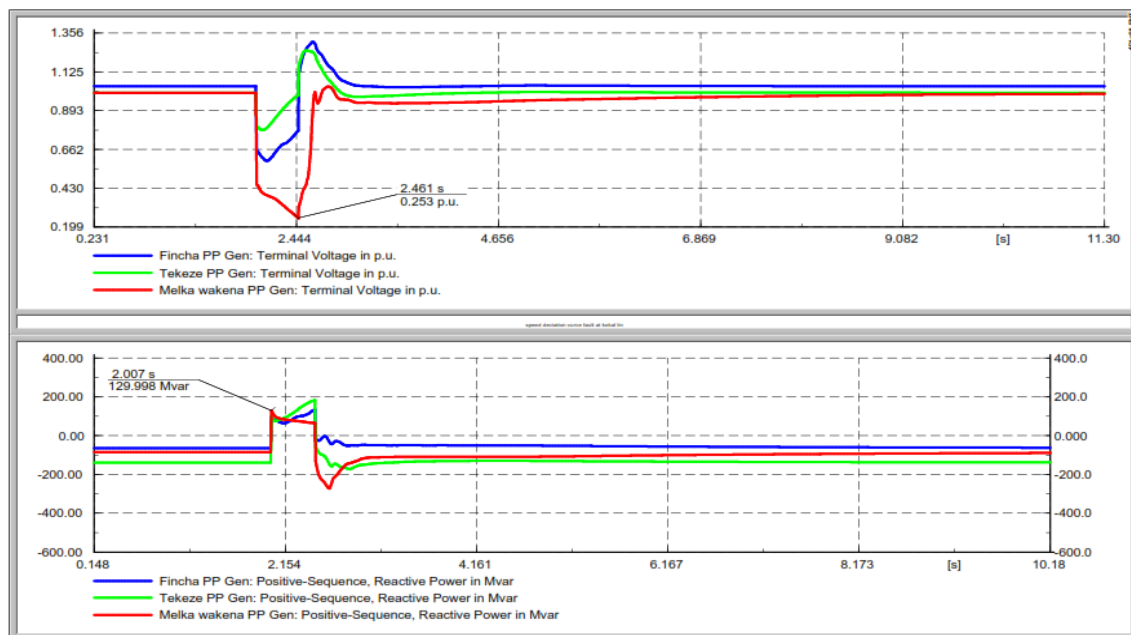


Figure 4.26: Terminal voltage and reactive power with all PMSG case one

4.4.2 Case Two: Fault on 230KV Alamata to Kombolcha Line

Similarly, in this case the critical fault clearing time (CCT) of Tekeze power has been determined by repetitive transient simulation. For the fault occurred at 230 KV Alamata to Kombolcha line, CCT of Tekeze has been determined to be 577ms. Thus, for a fault at 230 KV Alamata to Kombolcha line, the protective devices has to act in a time below 557 ms.

As can be observed from Figure 4.27, for a fault occurred at 230 KV Alamata to Kombolcha line, the rotor angle of Tekeze power plant increases to 118.877° . When the fault is cleared, the rotor angle of Tekeze power plant oscillates for 1.682 s until it reaches a steady state value of 10.657° from the initial rotor angle value of 2.052° . Whereas the speed of Tekeze power plant also oscillates for some period and settles to a steady state value of 0.968 pu from initial value of 1.0 pu.

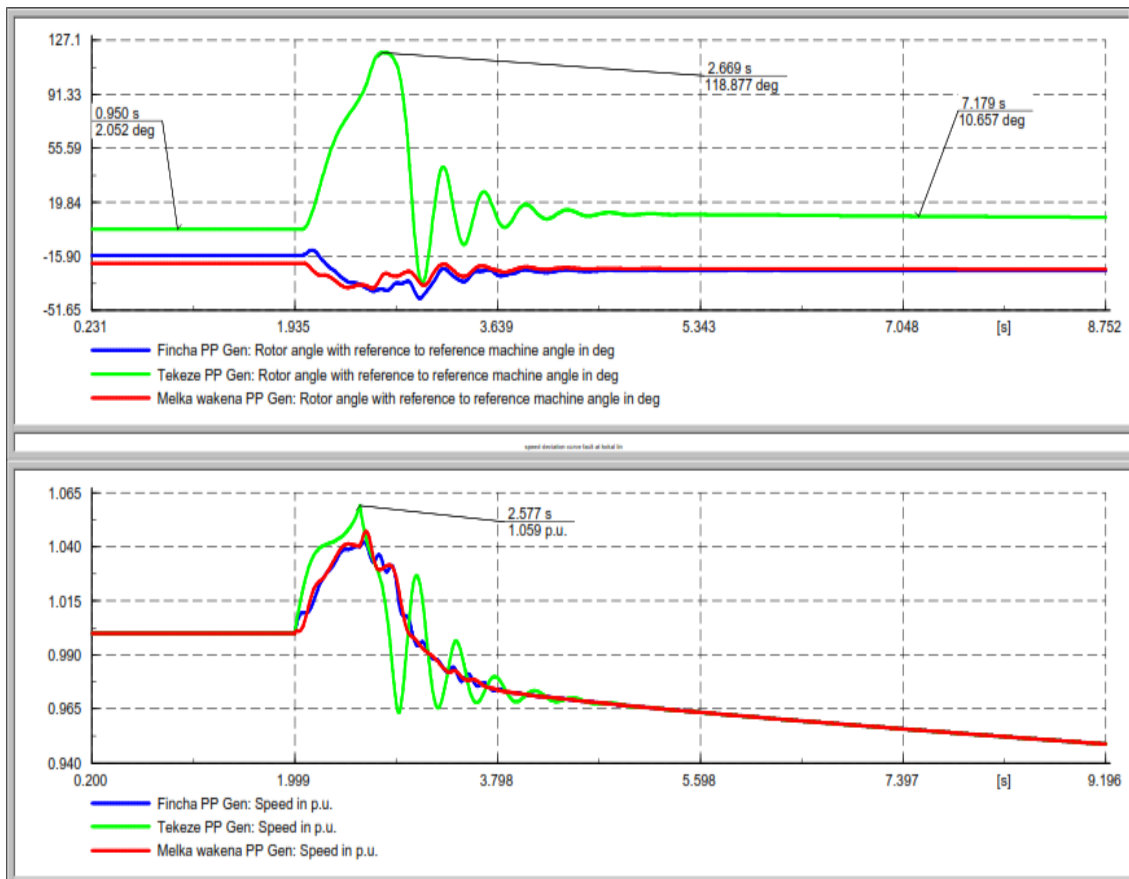


Figure 4.27: Rotor angle and speed of generators with all PMSG case two

One can observe from Figure 4.28, the terminal voltage of Tekeze power plant decreases to 0.296 pu. Then in order to support the voltage drop caused due to the fault occurred at 230 KV Alamata to Kombolcha line, the generator of Tekeze power plant will supply a reactive power of 190.146 MVar.

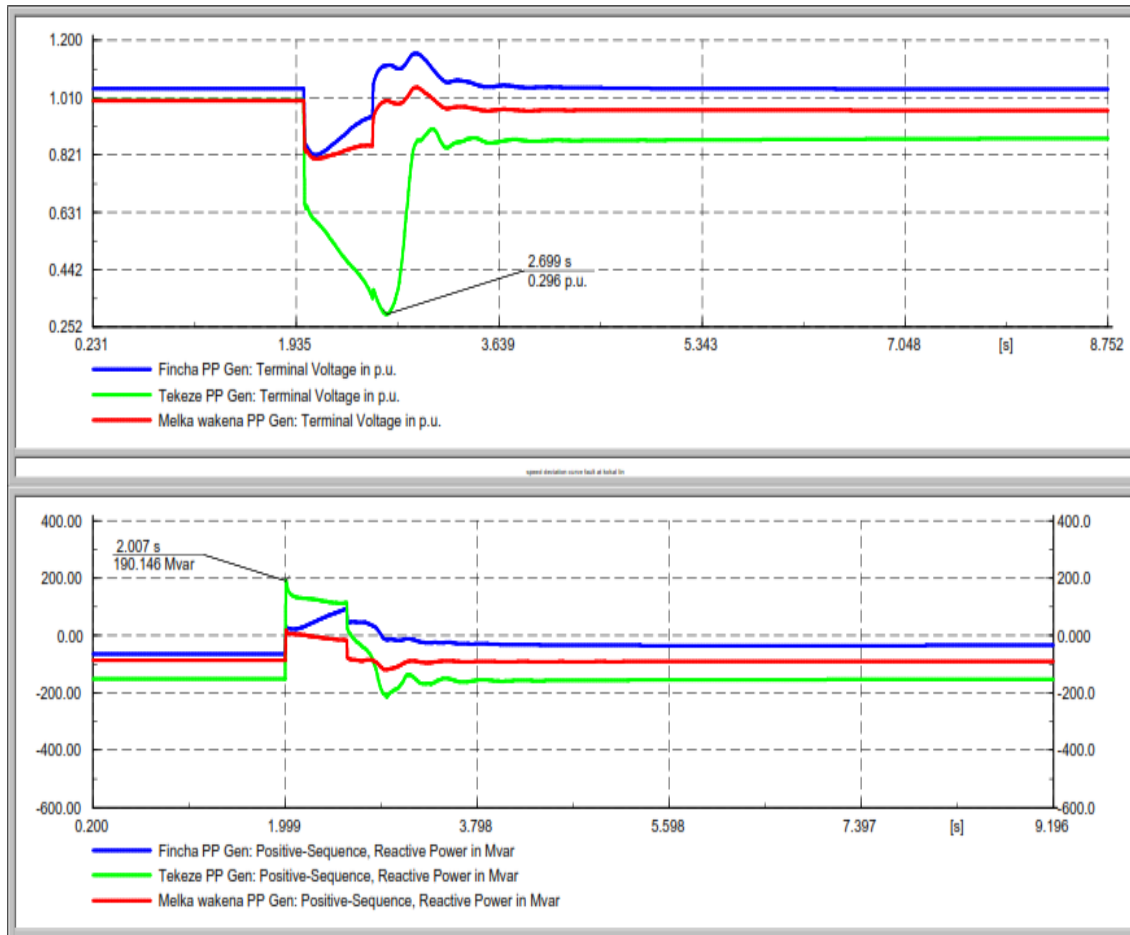


Figure 4.28: Terminal voltage and reactive power with all PMSG case two

4.4.3 Case Three: Fault on 230KV Fincha to Ghedo Line

Similarly, for a fault occurred at 230 KV Fincha to Ghedo line the critical fault clearing time (CCT) has been determined by repetitive transient simulation. For the fault occurred at 230 Fincha to Ghedo line, CCT of Fincha power plant has been determined to be 161ms. Thus, for a fault at 230 KV Fincha to Ghedo line, the protective device has to act in a time below 161 ms.

As can be observed from Figure 4.29, the rotor angle of Fincha power plant increases to 129.596° . When the fault is cleared, the rotor angle of Fincha power plant oscillates for 965 ms until it reaches a steady state value of -19.664° from the initial rotor angle value of -14.954° . On the other hand the speed of Fincha power plant also oscillates for some period and settles to a steady state value of 0.98 pu from initial value 1.0 pu.

One can observe from Figure 4.30, the terminal voltage decreases to 0.207 pu. Then in order to support the voltage drop caused due to the fault occurred at 230 KV Fincha to Ghedo line, the generator of Fincha power plant supply a reactive power of 112.631 MVar.

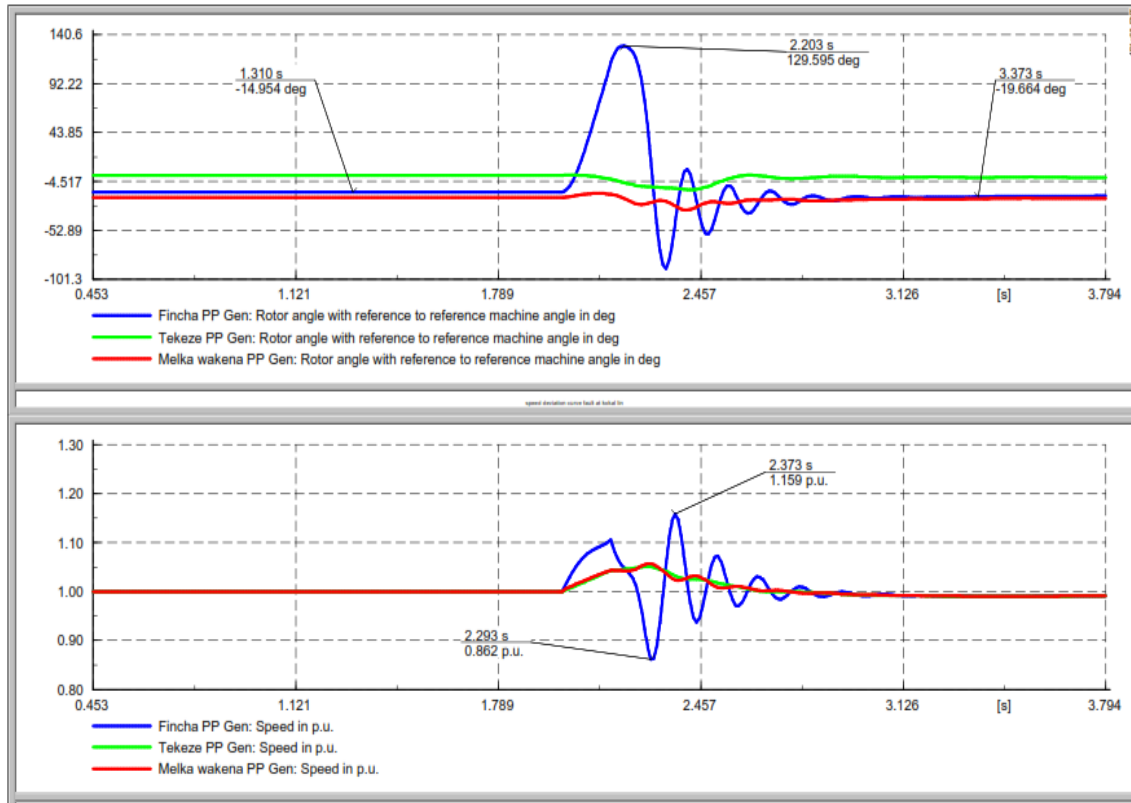


Figure 4.29: Rotor angle and speed of generators with all PMSG case three

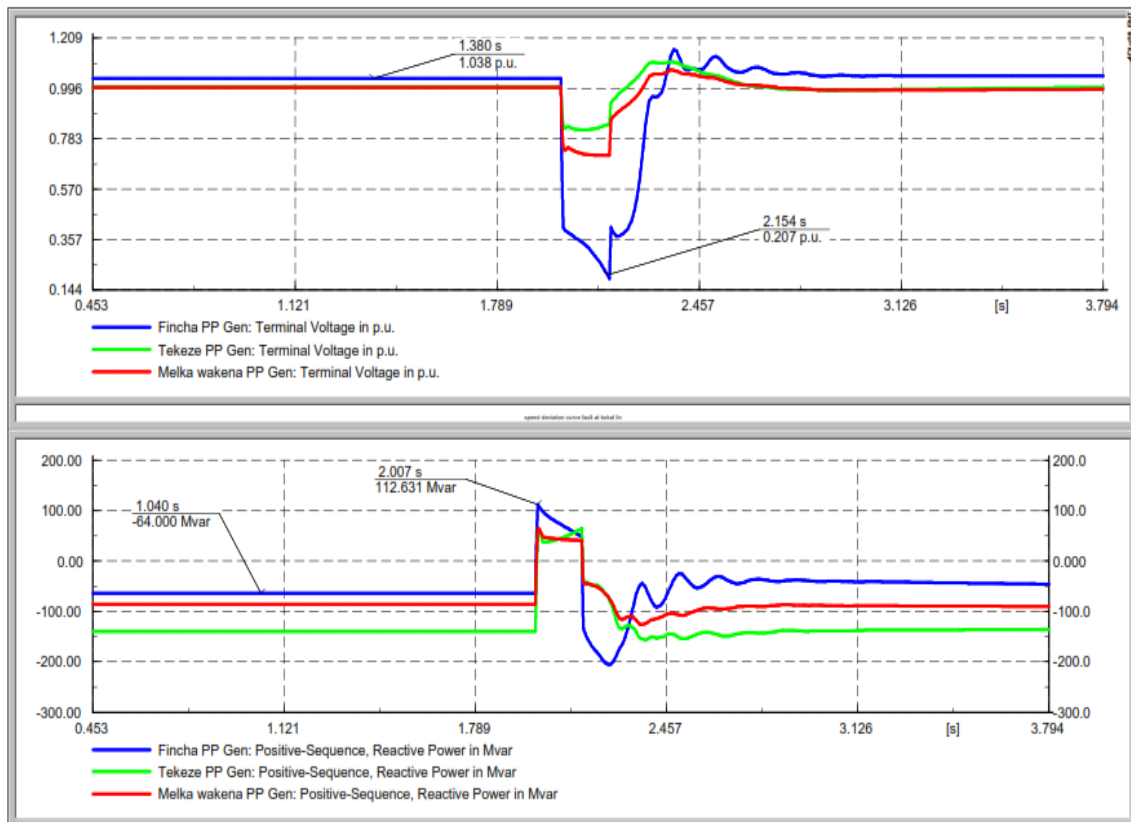


Figure 4.30: Terminal voltage and reactive power with all PMSG case three

Then, summarizing the above analysis the CCT and Settling time of each fault case is given in Table 4.10.

Table 4.10: Transient stability response of the system for third scenario

No.	Fault location	Critical power plant	CCT	Settling time
1	Koka to kaliti line	Meka Wakena	465 ms	0.912 s
2	Alamata to Kombolcha line	Tekeze	577 ms	1.682 s
3	Fincha to Ghedo line	Fincha	161 ms	0.965 s

Therefore, according to the above three scenarios analyzed we can observe that the critical fault clearing time of the power system increases with the integration of a wind power plant. Table 4.11 shows the responses of the power system for the different scenarios discussed above.

Table 4.11: Power system response comparison for different scenarios

Scenario	Critical power plant	CCT [ms]	Max. voltage drop [pu]	Max. rotor angle swing [deg]	Max.reactive power injected [MVar]
Base case scenario	Melka Wakena	246	0.3	128.763	124.269
	Tekeze	331	0.396	119.17	244.306
	Fincha	119	0.228	127.564	113.908
Present case scenario	Melka Wakena	431	0.275	131.374	128.84
	Tekeze	557	0.304	121.097	181.581
	Fincha	163	0.212	136.627	112.533
Third case Scenario	Melka Wakena	465	0.253	132.698	129.998
	Tekeze	577	0.296	118.877	190.146
	Fincha	161	0.207	129.596	112.631

From Table 4.11 it can be observed that the voltage drop during the fault is deeper with wind power integration than with synchronous generators (Base case). This is due to the reactive current support during a fault being limited to around rated current in wind power plants. Conventional synchronous generators have a considerable thermal overloading capability and can supply reactive current up to three or four times rated current to the system.

With regard to voltage recovery after the fault has been cleared, the results of the the three scenarios show that wind integration have a negative impact on voltage recovery. Slower voltage recovery increases the risk of other units to disconnect on under voltage.

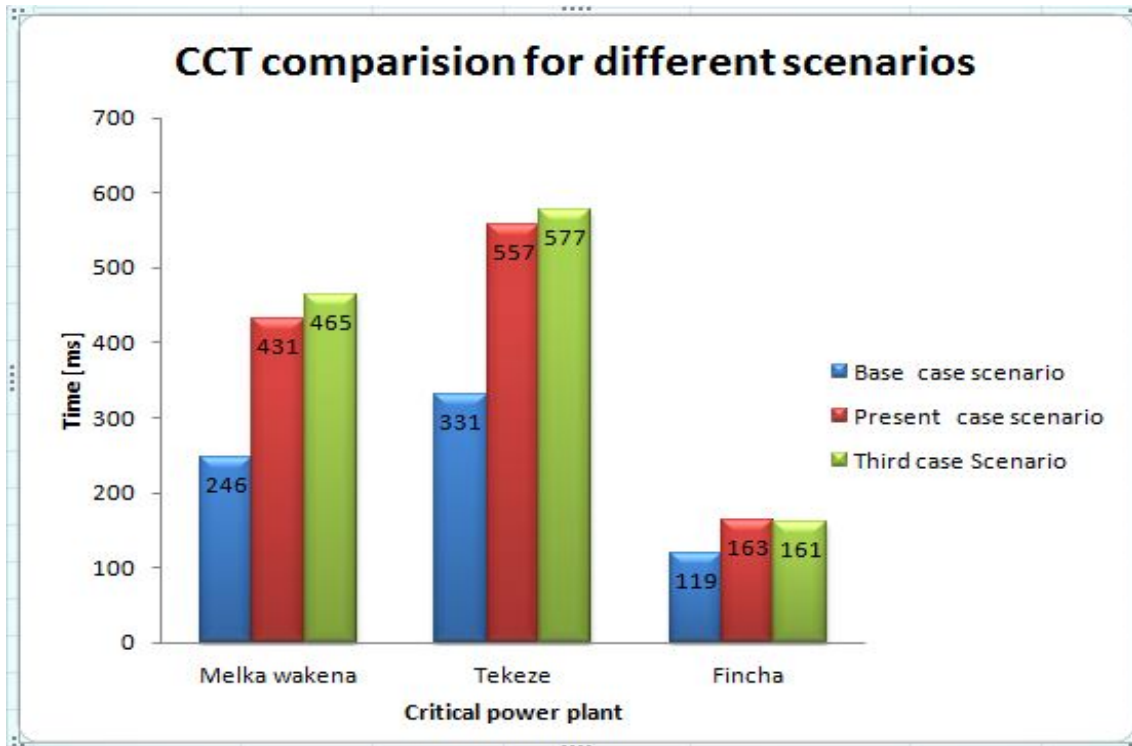


Figure 4.31: Critical clearing time comparison for different scenarios

From Table 4.11 and Figure 4.31 one can observe the following points about the critical fault clearing time of the system.

From the present case scenario it can be observed that:

1. With the integration of the wind power plant, the critical clearing time of Melka Wakena power plant which is located in area one and near to Adama I and II wind farm is increased by 42.92% (185ms) from the base case.
2. Similarly, with wind power integration, the CCT of Tekeze power plant which is located in area two and near to Ashegoda wind farm is increased by 40.57% (226ms) from the base case.
3. Finally with the integration of wind power, the CCT of Fincha power plant which is located in area three and far from any of the wind farms is increased by 26.99% (44ms) from the base case.

From the third case scenario it can be observed that:

1. With the integration of wind power equipped with a PMSG technology, the critical clearing time of Melka Wakena power plant which is located in area one and near to Adama I and II wind farm is increased by 47.097% (219ms) from the base case, and 7.31% (34ms) from the present case.

2. Similarly, with the integration of wind power equipped with a PMSG technology, the CCT of Tekeze power plant which is located in area two and near to Ashegoda wind farm is increased by 42.63% (246ms) from the base case, and 3.47% (20ms) from the present case
3. Finally, With the integration of wind power equipped with a PMSG technology, the CCT of Fincha power plant which is located in area three and far from any of the wind farms is increased by 26.09% (42ms) from the base case and decreased by 1.22% (2ms) from the present case.

From the above observations it can be concluded that, Melka Wakena and Tekeze power plants which are located near to a wind farm shows a great improvement in the critical fault clearing time for faults occurring near to the wind farms. Whereas, Fincha power plant shows some improvement in its fault clearing time but the effect is less than that of those plants near to the wind farm. The CCT is improved due to the fact that the wind power plants are reducing their output during the fault period therefore, they are not contributing to the acceleration of the inertia in each area. After the fault is cleared the active power control of the wind generator is acting very fast helping the system to recover quickly.

From Table 4.11, one can observe the maximum rotor angle swing increase with wind power integration. The max rotor angle swing for a fault occurring at 230 KV Koka to kaliti line, with the present case scenario, the maximum rotor angle swing for the generator of Melka Wakena power plant increased by 1.99% from the base case. Similarly, for a fault occurring at 230 KV Alamata to Kombolcha line, with the present case scenario, the maximum rotor angle swing for the generator of Tekeze power plant increased by 1.59% from the base case. Finally, with the present case scenario, the maximum rotor angle swing for the generator of Fincha power plant increased by 6.63%. this increase in maximum swing angle is due to the fact that the reactive power support by the wind turbines at PCC is limited.

The reactive power capability of DFIG presents similarities to the conventional synchronous generator (CSG) capability. It depends on the active power generated, the slip and the limitations due to stator and rotor maximum currents as well as the maximum rotor voltage. The asynchronous active power flows can aid in maintaining the rotor angle stability of the system. However, the manner in which wind generation injects reactive power into the system can be critical in maintaining angular stability of the synchronous units. Utilizing wind generation to control voltage and reactive power in the system can ease the reactive power burden on synchronous generators, and minimize angular separation in the system following a contingency event and can provide a significant level of support.

With full decoupling capability between the converters of PMSG, in case of grid disturbance, the GSC is controlled so that it can support the voltage recovery by supplying necessary reactive power to maintain the transient stability. The transient stability can be enhanced further by temporarily increasing the voltage above the regulation reference for the duration of the first acceleration period of the machine. The voltage increased above its nominal value will increase the electric power transmitted and this will also increase the deceleration of the machine.

It has been shown, that PMSG wind turbines with full-scale frequency converter have a better grid support capability than DFIG wind turbines with partial-scale frequency converter. Due to the full converter system PMSG wind turbines can provide a higher amount of reactive power to the grid. This yields that the voltage level is supported to a higher level and recovers faster. The PMSG wind turbine itself is furthermore fully decoupled from the grid by the converter and is thus less subjected to the impact of a grid fault.

In contrast to this, DFIG wind turbines are direct grid connected generators. A disadvantage of direct grid connected generators is that the generator is demagnetized in case of a grid fault and high transient short circuit currents arise in the generator. This can on the one hand lead to a tripping of relay settings followed by disconnection of necessary supply units. On the other hand additional protective equipment, as e.g. a crowbar, has to be installed in the turbine to prevent disconnection of the turbine itself. Due to this direct grid connection, generator, converter and turbine system are directly exposed to the grid fault impact. As a consequence of a grid fault, generator speed and torque oscillations occur in the doubly fed induction generators.

The reactive power supply capability of DFIG wind turbines is smaller compared to full converter connected wind turbines. Because of the smaller size of the partial scale frequency converter the rotor current, which can be supplied to the DFIG, is limited. This in turn limits the amount of reactive power, which can be provided to the grid. A second disadvantage is that during severe grid faults the rotor side converter is possibly blocked by the crowbar, which temporarily reduces the reactive power supply even further. However, if the financial advantage using a cheaper partial-scale converter prevails, those disadvantages must be accepted.

Chapter 5

Conclusion, Recommendation and Future Work

5.1 Conclusion

In this study, the impact of wind generation on transient stability of Ethiopian power system have been investigated. For this purpose, a detailed model of Ethiopian power system was set up and the impact of wind power on this system was studied. Before integrating the wind farm an aggregation method was used to reduce the wind farm from multi number of turbine representation in to single turbine representation for transient stability analysis.

According to the simulation results of Adama II wind farm aggregation model, the total active and reactive power flowing to the point of common coupling is 151.45 MW & 49.47 MVAR for FSR and 151.35 MW & 49.43 MVAR for STR. The difference in the active and reactive power for FSR and STR is 0.1 MW (0.066%) and 0.04 MVAR (0.081%) respectively. this indicates that the model developed have the same load flow result and it is acceptable.

Different scenarios have been set up for analyzing the impact of wind power on transient stability of Ethiopian power system with respect to fault location and generator technology aspects were studied. Stability in this paper is measured by the critical clearing time.

- For a fault on 230 KV koka to Kaliti line Melka Wakena power plant is the critical power plant. During this fault case, Melka Wakena has different response in the CCT. For the base case scenario the CCT found to be 246 ms, for the present case scenario the CCT is improved to 431 ms and for the third case scenario the CCT is further improved to 465 ms. Thus from the base case scenario the CCT was improved by 47.097 % when PMSG is used.
- For a fault on 230 KV Alamata to Kombolcha line Tekeze is the critical power plant. During this fault case, Tekeze has different values of CCT. For the base case scenario the CCT found to be 331 ms, for the present case scenario the CCT is improved to 557 ms and for the third case scenario the CCT is further improved to 577 ms. Thus from the base case scenario the CCT was improved by 42.63 % when PMSG is used.
- For a fault on 230 KV Fincha to Ghedo line Fincha is the critical power plant. During this fault case, Fincha has different values of CCT. For the base case scenario the CCT found to be 119 ms, for the present case scenario the CCT is improved to 163

ms and for the third case scenario the CCT is improved to 161 ms. Thus from the base case scenario the CCT was improved by 26.09 % when PMSG is used.

In general, wind power integration has a positive impact on the critical fault clearing time. For a fault near to the wind farm the CCT is improved with great amount, on the other hand wind integration has a minimal impact on the critical fault clearing time for a fault occurring far from the wind farm, like for the fault in area three in this study which is far from any of the wind farms integrated.

The actual generator technology also has its own impact on the transient stability of the power system. According to this study, the PMSGs with proper controllers performed better than DFIGs with respect to increase of the CCT, produce real and reactive power, decrease rotor angle deviation of all generator buses during fault condition and thus leads to improvement in transient stability.

Finally, from the analysis, it can be concluded that the integration of wind tends to increase the maximum rotor angle swing of the generators in the power system. This is due to the fact that reactive power injected by the WPP at the PCC is limited.

5.2 Recommendations

According to this study, the CCT of different power plants which are using conventional synchronous generator was improved. Thus, EEP has to continue constructing wind power plants in different parts of the country. According to this study in the next projects EEP have to focus on using PMSG technology. Besides the wind generator technology, as much as possible EEP have to consider distributing the wind farms so that it can improve the transient stability of the power system independent of the position of fault.

5.3 Future Work

In this study only impact of wind power generation on transient stability of the power system was analyzed. In the future stability effects like voltage stability and frequency stability, which are as important as the transient stability has to be analyzed. Also the cost of using different wind turbine technology has to be studied with respect to its advantage in improving the transient stability of a power system. Wind is an intermittent source therefore, this intermittent nature has to be analyzed for its impact on the transient stability of the power system. Finally, as it is indicated in this study, the maximum rotor angle swing of the generators increase with wind power integration. Since this swing will affect the transient stability, in the future the ways of reducing this swing has to be studied in detail.

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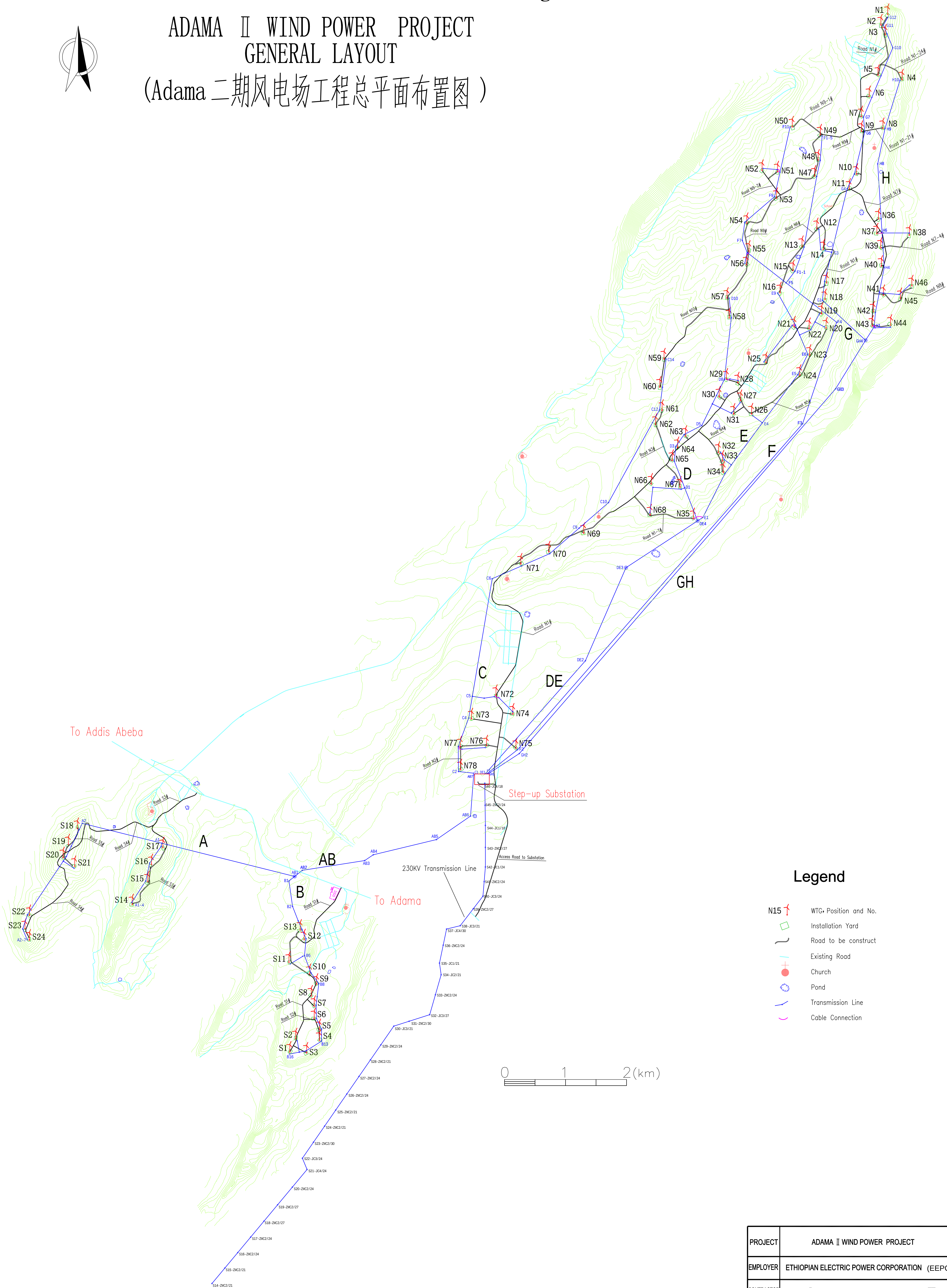
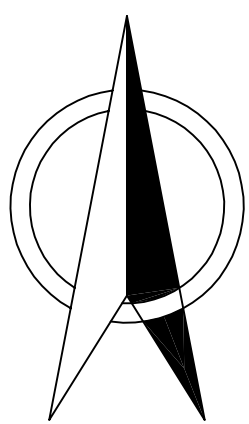
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Micrositting of Adama II wind farm

ADAMA II WIND POWER PROJECT
GENERAL LAYOUT

(Adama 二期风电场工程总平面布置图)



Legend

- N15 WTG Position and No.
- Installation Yard
- Road to be construct
- Existing Road
- Church
- Pond
- Transmission Line
- Cable Connection

PROJECT	ADAMA II WIND POWER PROJECT		
EMPLOYER	ETHIOPIAN ELECTRIC POWER CORPORATION (EEPCo)		
CONTRACTOR	HYDROCHINA-CGCOC JV		
DESIGNER	中国水电顾问集团北京勘测设计研究院 HYDROCHINA BEIJING ENGINEERING CORPORATION		PAGE
DESIGNED			SHEET
CHECKED			SCALE
AUDITED			VER.
APPROVED			00
REV.	DATE	DESCRIPTION	DWG. NO.

Appendix B

Adama II Wind Farm All Clusters Parameters

Table B.1: GPS data and branch impedance of Adama II WP all clusters

Cluster A								
ID	Y(N)	X(E)	Branch		Distance (km)	C (μ F/km)	R (PU)	X (PU)
			From	To				
S 24	944001.82	516018.5	S 24	S 23	0.2	0.27	0.005	0.002
S 23	944186.97	515947.12	S 23	S 22	0.2	0.27	0.005	0.003
S 22	944405.88	516021.49	S 22	S 21	0.8	0.27	0.018	0.009
S 21	945211.07	516761.78	S 21	S 20	0.2	0.27	0.005	0.003
S 20	945353.43	516572.13	S 20	S 19	0.2	0.27	0.005	0.003
S 19	945564.36	516657.81	S 19	S 18	0.3	0.27	0.007	0.003
S 18	945829.49	516805.56	S 18	CCG1	1.4	0.44	0.033	0.016
S 14	944583.05	517705.6	S 14	S 15	0.5	0.27	0.010	0.005
S 15	944955.24	517959.13	S 15	S 16	0.3	0.27	0.007	0.003
S 16	945238.76	518020.91	S 16	S 17	0.3	0.27	0.008	0.004
S 17	945516.38	518207.05	S 17	CCG1	0.1	0.44	0.002	0.001
Cluster B								
S1	942168.06	520288.05	S1	S2	0.24	0.27	0.005	0.003
S2	942385.6	520384.92	S2	S3	0.29	0.27	0.007	0.003
S3	942152.07	520563.57	S3	S4	0.30	0.27	0.007	0.003
S4	942358.71	520774.3	S4	S5	0.18	0.27	0.004	0.002
S5	942535.96	520774	S5	S6	0.20	0.27	0.004	0.002
S6	942713.6	520687.93	S6	S7	0.20	0.27	0.005	0.002
S7	942917.44	520687.93	S7	S8	0.18	0.27	0.004	0.002
S8	943086.19	520639.44	S8	S9	0.21	0.27	0.005	0.002
S9	943279.64	520727.92	S9	S10	0.20	0.27	0.004	0.002
S10	943440.99	520614.75	S10	S11	0.39	0.27	0.009	0.004
S11	943638.43	520273.85	S11	S12	0.45	0.27	0.010	0.005
S12	944008.32	520522.88	S12	S13	0.17	0.27	0.004	0.002
S13	944164.78	520458.7	S13	CC	3.57	0.44	0.053	0.038

GPS data and branch impedance of all clusters (continued)

ID	Y(N)	X(E)	Branch		Distance	C	R	X
			From	To	(km)	(μF/km)	(PU)	(PU)
Cluster C								
N59	953525.34	526422.13	N59	N60	0.47	0.27	0.011	0.005
N60	953063.79	526352.65	N60	N61	0.38	0.27	0.009	0.004
N61	952683.99	526390.55	N61	N62	0.25	0.27	0.006	0.003
N62	952452.56	526283.88	N62	N69	2.14	0.27	0.048	0.024
N69	950671.58	525106.43	N69	N70	0.65	0.27	0.015	0.007
N70	950364.77	524534.2	N70	N71	0.50	0.27	0.011	0.006
N71	950165.12	524074.33	N71	N72	2.19	0.44	0.032	0.024
N74	947705.84	523943.87	N74	N72	0.41	0.27	0.009	0.005
N72	948012.05	523667.55	N72	N73	0.56	0.44	0.013	0.006
N73	947627.17	523266.97	N73	N77	0.49	0.27	0.007	0.005
N76	947185.9	523511.1	N76	N77	0.43	0.27	0.006	0.005
N77	947169.4	523083.22	N77	N78	0.37	0.44	0.006	0.004
N78	946794.71	523087.22	N78	CC	0.15	0.44	0.002	0.002
Cluster D								
N57	954520.85	527455.04	N57	N58	0.33	0.27	0.007	0.004
N58	954196.85	527490.33	N58	N29	1.00	0.27	0.023	0.011
N28	953134.66	527633.19	N28	N29	0.20	0.27	0.004	0.002
N29	953195.34	527445.94	N29	N30	0.31	0.27	0.007	0.004
N30	952904.52	527325.98	N30	CCG2	0.85	0.27	0.013	0.009
N27	952843.84	527678.27	N27	N31	0.36	0.27	0.008	0.004
N31	952620.81	527564.51	N31	N30	0.37	0.44	0.008	0.004
N63	952258.81	526775.14	N63	N64	0.23	0.27	0.003	0.002
N64	952072.97	526645.48	N64	N65	0.23	0.27	0.003	0.002
N65	951862.43	526556.8	N65	CCG3	0.46	0.27	0.007	0.005
N68	950968.19	526196.41	N68	N66	0.51	0.27	0.012	0.006
N66	951475.54	526213.4	N66	N67	0.47	0.27	0.011	0.005
N67	951424.16	526684.66	N67	CCG4	5.00	0.44	0.074	0.054
Cluster E								
N16	954609.93	528324.08	N16	N21	0.61	0.27	0.014	0.007

GPS data and branch impedance of all clusters (continued)

ID	Y(N)	X(E)	Branch		Distance (km)	C (μ F/km)	R (PU)	X (PU)
			From	To				
N25	953467.66	528093.25	N25	N21	0.74	0.27	0.017	0.008
N21	954050.19	528555.01	N21	CCG1	0.53	0.27	0.012	0.006
N22	954023.4	528800.74	N22	N21	0.25	0.44	0.006	0.003
N19	954265.03	529004.48	N19	N20	0.25	0.27	0.006	0.003
N20	954030.9	529078.96	N20	CCG2	0.28	0.27	0.006	0.003
N23	953586.03	528809.94	N23	N24	0.37	0.27	0.005	0.004
N24	953257.02	528647.59	N24	N26	1.01	0.27	0.015	0.011
N26	952623.91	527858.42	N26	CCG3	1.06	0.27	0.016	0.011
N32	951994.69	527314.18	N32	N33	0.16	0.27	0.004	0.002
N33	951851.83	527381.36	N33	CCG4	0.18	0.27	0.004	0.002
N34	951667.59	527394.26	N34	N35	0.90	0.27	0.013	0.010
N35	950908.81	526903.7	N35	CCG5	5.61	0.44	0.083	0.060
Cluster F								
N52	956614.14	528029.77	N52	N51	0.25	0.27	0.006	0.003
N51	956591.55	528281.29	N51	N53	0.44	0.27	0.010	0.005
N50	957327.43	528524.12	N50	N51	0.77	0.27	0.018	0.009
N53	956156.47	528265.3	N53	N54	0.64	0.27	0.014	0.007
N54	955745.79	527779.44	N54	N55	0.46	0.27	0.010	0.005
N56	955066.39	527772.94	N56	N55	0.23	0.27	0.005	0.003
N55	955289.33	527813.83	N55	CCG1	0.79	0.44	0.018	0.009
N49	957195.57	528984.09	N49	N48	0.42	0.27	0.009	0.005
N48	956781.99	528948.1	N48	N47	0.27	0.27	0.006	0.003
N47	956520.57	528890.91	N47	N13	0.80	0.27	0.018	0.009
N13	955368.5	528684.38	N13	N15	0.42	0.27	0.010	0.005
N15	954972.72	528536.92	N15	CCG2	5.00	0.44	0.074	0.054
N78	947143.91	523995.56	N78	CCG3	0.09	0.44	0.001	0.001
Cluster G								
N1	959170.01	530089.67	N1	N2	0.21	0.27	0.005	0.002
N2	958996.37	529977.21	N2	N3	0.18	0.27	0.004	0.002
N3	958835.29	530046.56	N3	N5	0.67	0.27	0.015	0.008
N5	958172.38	529930.31	N5	N6	0.38	0.27	0.009	0.004

GPS data and branch impedance of all clusters (continued)

ID	Y(N)	X(E)	Branch		Distance (km)	C (μ F/km)	R (PU)	X (PU)
			From	To				
N6	957824.69	529785.25	N6	N7	0.35	0.27	0.008	0.004
N7	957496.28	529658.69	N7	N9	0.24	0.27	0.006	0.003
N9	957253.65	529659.69	N9	N10	0.71	0.27	0.016	0.008
N10	956550.36	529577.41	N10	N11	0.27	0.27	0.006	0.003
N11	956307.83	529458.55	N11	CCG1	1.08	0.44	0.025	0.012
N14	955314.12	529034.87	N14	N12	0.36	0.27	0.008	0.004
N12	955660.72	528927.7	N14	CCG2	0.55	0.44	0.012	0.006
N17	954770.38	529087.06	N17	N18	0.27	0.27	0.004	0.003
N18	954498.06	529062.57	N18	CCG3	5.45	0.44	0.081	0.059
Cluster H								
N4	958099.13	530324.48	N4	N8	0.86	0.27	0.019	0.010
N8	957300.64	530010.08	N8	N36	1.48	0.27	0.034	0.017
N36	955818.27	529938.31	N36	N37	0.24	0.27	0.006	0.003
N37	955575.64	529910.82	N37	N39	0.24	0.27	0.005	0.003
N38	955551.38	530443.38	N38	N37	0.53	0.27	0.012	0.006
N39	955342.21	529975.3	N39	N40	0.30	0.27	0.007	0.003
N40	955044.3	529984.79	N40	CCG1	0.48	0.27	0.007	0.005
N46	954723.31	530485.25	N46	N45	0.28	0.27	0.006	0.003
N45	954514.86	530299.2	N45	N41	0.29	0.27	0.006	0.003
N41	954565.64	530018.49	N41	CCG2	0.32	0.44	0.007	0.004
N42	954296.82	529853.23	N42	N43	0.24	0.27	0.003	0.003
N44	954077.78	530136.05	N44	N43	0.30	0.27	0.004	0.003
N43	954061.69	529834.14	N43	CCG3	5.00	0.44	0.074	0.054

Appendix C

Ethiopian High Voltage Grid Data

Table C.1: Existing load data of the Ethiopian high voltage grid

No.	Name of Bus	P [MW]	Q [Mvar]
1	A.Samuel	1.149	0.378
2	ABA	3.31	1.088
3	Adami Tulu	6.68	2.196
4	Addis center	80.778	26.551
5	Addis east I	14.277	4.693
6	Addis east II	30.826	10.132
7	Addis N	63.001	20.708
8	Addis S 1	13.823	4.543
9	Addis s II	47.439	15.592
10	Addis w I	18.8	6.2
11	Addis w II	13.723	4.511
12	Adigala	0.199	0.065
13	Adigrat	4.946	1.626
14	Adwa	9.71	3.192
15	Agaro	4.821	1.585
16	Akaki	6.079	1.998
17	Akaki SP	7.482	2.459
18	Akasita	6.619	2.176
19	Alaba	3.382	1.112
20	Alamata 2	1.872	0.615
21	Alem katema	2.206	0.725
22	alem ketema	4.51	1.482
23	Alemaya	4.413	1.451
24	Alemaya 33	2.206	0.725
25	Amibara	3.591	1.18
26	Ariba minch	9.269	3.047
27	Aseb Teferi	3.211	1.056
28	Asebe 33	0.026	0.008
29	Assela	9.815	3.226
30	Assosa	5.516	1.813

Existing load data of the Ethiopian high voltage grid (continued)

No.	Name of Bus	P [MW]	Q [Mvar]
31	Awash II	2.699	0.887
32	Awash 7	3.842	1.263
33	Awash II	2.989	0.983
34	Awassa	12.192	4.007
35	B/Dar 1	7.002	2.302
36	B/Dar 2 1	8.086	2.658
37	B/Dar 2 2	3.517	1.156
38	Babile	1.236	0.406
39	Bale robe	5.652	1.858
40	Bedeke	6.654	2.187
41	Bedessa	2.96	0.973
42	Bichena	2.569	0.844
43	Boculolguma	4.413	1.451
44	Bonga	4.601	1.512
45	Bonga	1.739	0.572
46	Butajira	3.423	1.125
47	Butajira 33	2.021	0.664
48	Chelenko	2.889	0.95
49	Combolcha I	13.228	4.348
50	cotobie 15	21.305	7.033
51	D/birhan	4.911	1.614
52	D/Ddewa I	10.808	3.552
53	D/Dewa 2	3.352	1.102
54	D/Dewa 3	2.303	0.757
55	D/marikos	2.529	0.831
56	D/Zeit I	2.566	0.844
57	D/Zeit II	59.499	19.6
58	D/Zeit II	29.749	9.778
59	D/Zeit II	0.996	0.327
60	Dabat	2.042	0.671
61	Dangla	5.552	1.825
62	Dembi Dolo	0.6	0
63	Derba 33	34.2	11.241

Existing load data of the Ethiopian high voltage grid (continued)

No.	Name of Bus	P [MW]	Q [Mvar]
64	Dessie	8.429	2.771
65	Dilla 1	2.206	0.725
66	Dilla 2	7.723	2.538
67	Dukem	1.267	0.416
68	Elala Geda	6.89	2.265
69	Fincha SG 1	4.292	1.411
70	Fincha SG 2	3.324	1.093
71	Finchaa	3.391	1.115
72	Finote selam	4.907	1.613
73	Fitche	10.59	-5.13
74	Fitche	4.192	1.378
75	fitche 15	8.274	-2.72
76	G.Gibe	2.514	0.826
77	Gambela I	1.1	0
78	Gashena	3.31	1.088
79	Gedja	1.662	0.546
80	Geferssa	5.3	2.56
81	Geferssa	15.157	4.982
82	Ghedo	2.84	0.934
83	Ghimbi	2.597	0.854
84	Gida ayana	6.941	2.281
85	Ginchi 15	4.413	1.451
86	Gobessa	1.725	0.567
87	Gonder	0.835	0.275
88	Gonder I	0.842	0.277
89	Gonder II	12.495	4.107
90	Guder	7.479	2.458
91	H.Mariam	2.825	0.928
92	Harar	4.263	1.401
93	Harar 3	5.254	1.727
94	Harar III	3.798	1.248
95	Hossaina	5.064	1.665
96	Humera	3.383	1.112

Existing load data of the Ethiopian high voltage grid (continued)

No.	Name of Bus	P [MW]	Q [Mvar]
97	Jijiga II	6.376	2.096
98	Jijiga II	5.046	1.659
99	Jimma	9.271	3.047
100	Kaliti n	12.311	4.047
101	Kalliti I	16.064	5.28
102	Kalliti II	19.412	6.381
103	Koka	2.903	0.954
104	Lalibela	1.101	0.362
105	Lgetafo	48	16
106	Maychew	1.993	0.655
107	Mekanissa	25.797	8.479
108	Mekelle	17.894	5.881
109	Mendi	2.206	0.725
110	Mesebo	37.966	12.479
111	Metehara	7.175	2.358
112	Metema	30	9.861
113	Metu	1.811	0.595
114	Mizan	1.319	0.434
115	Modjo	3.179	1.045
116	Mota	1.683	0.553
117	Muger	25.218	8.289
118	MWakena Yugo	4.812	1.582
119	N/mewucha	2.206	0.725
120	Nazret II	24.733	8.129
121	Neg. Borena	1.906	0.627
122	Neg. Borena	1.027	0.0338
123	Nekemte	5.638	1.853
124	Nifas silk	19.885	6.536
125	Pawie	2.324	0.764
126	Sabeta	9.414	3.094
127	Sabeta B	12.63	4.151
128	Sabeta I	16.096	5.29
129	Sekota	0.923	0.304

Existing load data of the Ethiopian high voltage grid (continued)

No.	Name of Bus	P [MW]	Q [Mvar]
130	Semera	6.619	2.176
131	shakisso	7.047	2.316
132	Shashmane	18.754	6.164
133	Shewa robit	2.252	0.74
134	Shire	2.297	0.755
135	Sululta 15	20.961	6.89
136	Sululta 33	2.206	0.725
137	Tepi	2.629	0.864
138	Tepi	1.801	0.592
139	Wergenu	54.65	17.963
140	Wo.Sodo	6.868	2.258
141	Woldia	3.794	1.247
142	Woliso	7.723	2.538
143	Woliso 33	1.103	0.363
144	Wolkita	1.659	0.545
145	Wolkite	2.548	0.838
146	Wonji pulp	11.989	3.941
147	woreta	4.044	1.329
148	wukro	3.353	1.102
149	Yesu	5.392	1.772
150	Yirgalem	8.826	2.901
151	Yirgalem	2.206	0.725

Table C.2: Existing power plants in Ethiopia and generator specifications

No.	Plant	No. of unit	Total Capacity	Voltage level	Nominal Apparent power	Nominal Voltage	Gen type	P_{max}	Q_{min}	Q_{max}	X'_d	X'_q	X''_d	X''_q	T''_q
1	Beles	4	460	400	133	15	Hydro	117	-1	1	0.3	0.3	0.25	0.25	0.05
2	Gilgel Gibe II	4	420	400	125	15	Hydro	107	-50	50	0.3	0.3	0.22	0.22	0.05
3	Tekeze	4	300	230	87.6	13.8	Hydro	78.03	-38	38	0.3	0.3	0.17	0.17	0.05
4	Gilgel Giba I	3	184	230	75	13.8	Hydro	70	-21	21	0.3	0.3	0.16	0.16	0.05
5	Melika Wakena	4	153	230	45	13.8	Hydro	38.25	-31.5	30.15	0.3	0.3	0.17	0.17	0.05
6	Finchaa	4	134	230	35	13.8	Hydro	33.3	-16	21	0.3	0.3	0.12	0.12	0.05
7	Tis Abay II	2	72	132	40	10.5	Hydro	36	-28	20	0.3	0.3	0.37	0.37	0.05
8	Tis Abay I	3	11.4	132	4.8	6	Hydro	3.8	-2.9	2.9	0.3	0.3	0.18	0.18	0.05
9	Koka	3	43.2	43.2	18	10.5	Hydro	12.8	-12	11.6	0.3	0.3	0.24	0.24	0.05
10	Awash II	3	32	132	20	10.5	Hydro	18	-15	13	0.3	0.3	0.16	0.16	0.05
11	Awash III	2	32	132	20	10.5	Hydro	18	-15	13	0.3	0.3	0.16	0.16	0.05
12	Ashegoda WP	120	120	230	60	15	Wind	50	-30	30	0.3	0.3	0.23	0.23	0.05
13	Adama II WP	102	153	230	180	33	Wind	151	-75	75	0.3	0.3	0.25	0.25	0.05
14	Adama I WP	34	51	132	60	33	Wind	51	-30	30	0.3	0.3	0.23	0.23	0.05
15	Dire Dewa Diesel	10	40	132	12.5	15	Diesel	10	-6	6	0.3	0.3	0.2	0.2	0.05

Table C.3: Existing short circuit test values of two winding high voltage transformers

No.	Node 1	Node 2	Vn1	Vn2	Sn	No load current [%]	No load losses [Kw]	Uk [%]	Ur [%]
1	Gimbi	Ghimbi	132	15	20	0.2883	19.18	8.007	0.340
2	Gimbi	Ghimbi	132	15	20	0.2594	19.125	8.007	0.340
3	Mendi	mendi	132	33	25	0	0	13.713	0.590
4	Mendi	mendi	132	33	25			13.713	0.590
5	Semera	Semera	230	33	20	0.19	17.79	12.407	0.410
6	Ditcheto	Ditcheto	230	33	20	0.19	17.79	12.407	0.410
7	Amibara	Amibara	66	16	3	1.3	5.5	6.962	0.930
8	Amibara	Amibara	66	16	3	1.3	5.5	6.962	0.930
9	Wonji pulp	Wonji Pulp	132	15	16	0.779	14.7	8.014	0.470
10	Awash 2	awash II	132	15	20	0.312	18.258	8.206	0.310
11	Metehara	Metehara	132	15	18	0	0	9.908	0.400
12	elala Geda	Elala Geda	132	15	16	0.1572	11.592	16.027	0.933
13	Nazret II	Nazret II	132	15	20	0.11	19.09	9.707	0.360
14	Nazret II	Nazret II	132	15	20	0.11	19.09	9.707	0.360
15	Adami tulu	Adami tulu	132	15	12	0.53	13	11.920	0.690
16	Assela	Assela	132	15	12	0.53	13	11.920	0.690
17	Adama - 1	Adama- 1 33	132	33	55	0.1527	26.21	3.054	1.329
18	MWK yugo	MWK Yugo	230	132	63	0.4	30	7.603	0.210
19	MWK yugo	MWK Yugo	230	132	63	0.4	30	7.603	0.210
20	Alut. Lang	Alu. Lang			10	0	0	8.611	0.430
21	Alut. Lang	Alu. Lang			10	0	0	8.611	0.430
22	M.Wakena	M.Wakena	230	132	63	0.4	30	11.904	0.320
23	M.Wakena	M.Wakena2	230	13.8	45	0.5	45	11.011	0.480
24	M.Wakena	M.Wakena3	230	13.8	45	0.5	45	11.011	0.480
25	M.Wakena	M.Wakena3	230	13.8	45	0.5	45	11.011	0.480
26	M.Wakena	M.Wakena1	230	13.8	45	0.5	45	11.011	0.480
27	Adama II	Adama II	230	33	90	0.26	54.5	13.504	0.320
28	Adama II	Adama II	230	33	90	0.26	54.5	13.504	0.320
29	Adama 1 33	Adama 1	33	10.5	55	0.1527	26.21	3.054	1.329
30	Modjo	Modjo	45	15	3	1.06	3.69	5.858	0.820
31	Adma II	Adama II	33	10.5	160	0.26	54.5	13.504	0.320
32	Bale robe	Bale robe	66	15	6	1.27	6.281	6.646	0.780

Existing short circuit test values of two winding high voltage transformers (cont...)

No.	Node 1	Node 2	Vn1	Vn2	Sn	No load current [%]	No load losses [Kw]	Uk [%]	Ur [%]
33	gobessa	Gobessa	66	33	6.3	0.7	6.5	7.519	0.540
34	D/Zeit 2	D/Zeit 2	132	15	16	0.68	17.8	10.608	0.400
35	D/Zeit 2	D/Zeit 2	132	15	16	0.68	17.8	10.608	0.400
36	Addis Center	Addis Center	132	15	25	0.2	21.3	10.310	0.460
37	Addis Center	Addis Center	132	15	25	0.27	21.7	10.310	0.460
38	Kaliti N	Kaliti N	132	15	16	0.3	18.27	7.807	0.340
39	Kaliti N	Kaliti N	132	15	16	0.3	18.27	7.807	0.340
40	Kaliti II	Kaliti II	132	15	20	0.312	18.258	8.106	0.310
41	Yesu	Yesu	132	15					
42	Mekanissa	Mekanissa	132	15	20	0.149	15.99	8.108	0.350
43	Mekanissa	Mekanissa	132	15	20	0.1366	16.0214	8.108	0.350
44	Addis s II	Addis S II	132	15	20	0.11	19.09	9.707	0.360
45	Addis s II	Addis S II	132	15	20	0.11	19.09	9.707	0.360
46	Kaliti I	Kaliti I	230	132	125	0.28	20	20.603	0.330
47	Kaliti I	Kaliti I	230	132	125	0.28	20	20.603	0.330
48	Kaliti I	Kaliti I	230	132	125	0.28	20	20.603	0.330
49	a.Samuel	A.Samuel	45	15	1.5	0	0	6.147	0.760
50	Addis S I	Addis S I	45	15	6	0.59	8.25	7.217	0.500
51	Addis S I	Addis S I	45	15	6	0.59	8.25	7.217	0.500
52	Akaki	akaki	45	15	9	0.49	9.87	6.018	0.460
53	Dukem	Dukem	45	15	3	1.06	3.69	6.056	0.820
54	Dukem	Dukem	45	15	3	1.06	3.69	6.056	0.820
55	D/Zeit 1	D/Zeit 1	45	15	1.5	0	0	5.845	0.720
56	D/Zeit 1	D/Zeit 1	45	15	1.5	0	0	5.744	0.710
57	Nifas silk	Nifas silk	45	15	20	0.565	13.575	8.310	0.400
58	Akaki Sp	Akaki SP	45	15	6	1	9	8.040	0.800
59	Akaki Sp	Akaki SP	45	15	6	1	9	8.040	0.800
60	Shahsmane	Shahsmane	132	15	20	0.134	15.46	8.108	0.350
61	Awasa	Awasa	132	15	12	0.3633	12.401	11.920	0.690
62	Awasa	Awasa	132	15	12	0.3633	12.401	11.920	0.690
63	Alaba	Alaba	132	15	6	0.54	9	7.426	0.620
64	W.Sodo	W.sodo	132	15	20	0.252	19.044	7.907	0.340

Existing short circuit test values of two winding high voltage transformers (cont...)

No.	Node 1	Node 2	Vn1	Vn2	Sn	No load current [%]	No load losses [Kw]	Uk [%]	Ur [%]
65	Ariba minch	Ariba minch	132	15	12.5	0.2456	9.6	8.226	0.650
66	Hossaina	Hossaina	132	15	6.3	0.2254	5.6	8.045	0.850
67	H.mariam	H.mariam	132	33	9.6	0.3958	20.38	5.043	0.163
68	Yadot	Yadot	132	33	20	0	0	10.910	0.470
69	Bucu luguma	Bucu luguma	132	33	9.6	0	0	5.205	0.230
70	Gelan	Gelan	230	132	100	0	0	0.010	0.000
71	Gelan	Gelan	230	132	100	0	0	0.010	0.000
72	Gelan	Gelan	230	132	100	0	0	0.010	0.000
73	Gelan	Gelan	400	230	266	0.0921	80	6.438	0.096
74	Gelan	Gelan	400	230	266	0.0921	80	6.438	0.096
75	Sebeta	Sebeta b	132	15	40	0.083	18.546	12.014	0.580
76	Sebeta - 1	Sebeta	230	132	125	0.28	20	20.603	0.330
77	Sebeta - 1	Sebeta	230	132	125	0.28	20	20.603	0.330
78	Sebeta - 1	Sebeta	230	132	125	0.28	20	20.603	0.330
79	Sebeta II	Sebeta II 33	230	33	20	0.11	20.7	9.928	0.750
80	Sebeta II	Sebeta II	400	230	133	0.0921	80	6.438	0.096
81	Sebeta II	Sebeta II	400	230	133	0.0921	80	6.438	0.096
82	Addis W2	Addis W 2	45	15	9	0.41	9.72	6.126	0.563
83	Addis W 1	Addis W 1	45	15	9	0.41	9.72	6.018	0.470
84	Gedja	Gedja	45	15	3	0	0	6.147	0.760
85	Wolkite	Wolkite	66	15	6.3	0.2	7.112	9.045	0.900
86	Sebeta 1	Sebeta 1	66	45	9	0.119	1.918	9.736	0.643
87	Woliso	Woliso	66	15	3	0.71	3.32	6.431	0.630
88	Woliso	Woliso	66	15	3	0.71	3.32	6.431	0.630
89	Woliso	Woliso 33	66	33	9.6	0	0	6.521	0.520
90	Gida Ayana	Gida Ayana	132	33	20	0	0	10.910	0.470
91	GG old	GG	132	15	6.3	0.2254	5.6	8.145	0.850
92	Jimma	Jimma	132	15	16	0.2	17.34	7.908	0.360
93	Agaro	Agaro	132	15	6.3	0	0	8.045	0.850
94	Bedele	Bedele	132	15	6.3	0.1587	5.7	8.244	0.850
95	Nekemte	Nekemte	132	15	20	0.237	18.913	8.008	0.350
96	Nekemte	Nekemte	132	15	20	0.2525	19.044	7.907	0.340

Existing short circuit test values of two winding high voltage transformers (cont...)

No.	Node 1	Node 2	Vn1	Vn2	Sn	No load current [%]	No load losses [Kw]	Uk [%]	Ur [%]
97	ABA	ABA	132	15	9.6	0	0	6.321	0.520
98	GG-1	GG-1	230	132	30	0.052	11.84	9.002	0.200
99	GG-1	GG-1	230	13.8	73	0.3493	33.88	12.600	0.300
100	GG-1	GG-1	230	13.8	73	0.3493	33.88	12.600	0.300
101	GG-1	GG-1	230	13.8	73	0.3493	33.88	12.600	0.300
102	Bedele	Bedele	230	132	65	0	0	12.420	0.980
103	GG-2	GG-2	400	15	125	0.08	65.352	14.402	0.230
104	GG-2	GG-2	400	15	125	0.08	65.352	14.402	0.230
105	GG-2	GG-2	400	15	125	0.08	65.352	14.402	0.230
106	GG-2	GG-2	400	15	125	0.08	65.352	14.402	0.230
107	GG old	GG old	400	230	133	0.0921	80	6.438	0.096
108	GG old	GG old	400	230	133	0.0921	80	6.438	0.096
109	Weregenu	Weregenu	132	15	16	0.44	11.909	8.108	0.360
110	Weregenu	Weregenu	132	15	16	0.44	11.84	7.908	0.350
111	Cotobie i	Cotobie I 15	132	15	12	0.2486	11.8	12.020	0.700
112	D/birehan	D/Birehan	132	15	6	0.4	6.7	7.127	0.620
113	Legetafo	Legetafo	132	15	31.5	0.28	20	20.603	0.330
114	Legetafo	Legetafo	132	15	31.5	0.28	20	20.603	0.330
115	Addis E II	Addis E II	132	15	20	0.226	15	8.107	0.330
116	Addis E II	Addis E II	132	15	20	0.226	15	8.107	0.330
117	Legetafo	Legetafo	230	132	125	0	0	12.009	0.470
118	Legetafo	Legetafo	230	132	125	0	0	12.009	0.470
119	Sululta	Suluilta 132	230	132	65	0.3876	30	7.844	0.217
120	Sululta	Suluilta 132	230	132	65	0.3876	30	7.844	0.217
121	Sululta	Sululta	400	230	133	0.0921	80	6.438	0.096
122	Sululta	Sululta	400	230	133	0.0921	80	6.438	0.096
123	Addis E i	Addis E I	45	15	6	0.673	8.45	7.218	0.510
124	Addis E I	Addis E I	45	15	6	0.662	8.9	7.318	0.510
125	D. Dawa I	D. Dawa I	132	15	12	0	0	8.525	0.650
126	D. Dawa I	D. Dawa I	132	15	12	0	0	8.525	0.650
127	D. Dawa I	D. Dawa I	132	15	6.3	0	0	6.331	0.630
128	D.Dawa II	D.Dawa II	132	15	16	0.483	12.132	7.808	0.350

Existing short circuit test values of two winding high voltage transformers (cont...)

No.	Node 1	Node 2	Vn1	Vn2	Sn	No load current [%]	No load losses [Kw]	Uk [%]	Ur [%]
129	D.Dawa II	D.Dawa II	132	15	16	0.4812	12.24	8.008	0.350
130	Fik	Fik	132	33	20	0	0	10.910	0.470
131	Adigala	Adigala	230	33	20	0.1369	22.474	7.808	0.350
132	Babile	Babile	45	15	1.5	5.9683	0.9	0.820	2.500
133	Harar I	Harar	45	15	6.3	0.16	5.12	7.124	0.590
134	Asb TFR	Asb TFR	66	33	9.6	0	0	6.491	0.384
135	Beddessa	Beddessa	66	15	3	1.15	6	6.645	0.770
136	Harar I	Harar	66	15	6.3	0.62	6.83	8.222	0.600
137	Harar I	Harar	66	15	6.3	0.62	6.83	8.222	0.600
138	Harar I	Harar	66	15	6.3	0.62	6.83	8.222	0.600
139	Alemaya 2	alemaya	66	15	6.3	0.18	5.38	7.124	0.590
140	Alemaya 2	Alemaya 33	66	33	9.6	0	0	6.521	0.520
141	Chelenko	Chelenko	66	15	6.3	0.16	5.12	7.124	0.590
142	Harer III	Harer III	66	15	9.6	0.13	8.3	7.223	0.580
143	Sor	sor	66	15	1.5	0	0	5.945	0.730
144	Sor	sor	66	15	1.5	0	0	5.945	0.730
145	Metu	Metu	66	15	3	0	0	6.752	0.840
146	Gambela I	Gambela I	66	15	1.5	0	0	5.744	0.710
147	Gambela I	Gambela I	66	15	1.5	0	0	5.744	0.710
148	Dembi Dolo	Dembi Dolo	66	15	1.5	0	0	5.644	0.700
149	Dembi Dolo	Dembi Dolo	66	15	1.5	0	0	5.644	0.700
150	Shewa Robit	Shewa Robit	132	15	6	0.4	6.7	7.127	0.620
151	Alem ketema	Alem ketema	132	33	9.6	0	0	8.026	0.640
152	Combolcha II	Combolcha II	230	132	63	0	0	12.009	0.470
153	Dessie	Dessie	66	15	12	0.4	3.6	7.009	0.350
154	Dessie	Dessie	66	15	12	0.4	3.6	7.009	0.350
155	Woldia	Woldia	66	15	3	0.73	3.287	6.334	0.660
156	Woldia	Woldia	66	15	3	0.73	3.287	6.334	0.660
157	Lalibela	Lalibela	66	15	6.3	0.18	5.38	6.817	0.480
158	Sekota	Sekota	66	15	6.3	0.18	5.38	6.817	0.480
159	Tis abay 2	Tis Abay 2	132	10.5	24	0.35	26.21	7.804	0.260
160	Tis abay 2	Tis Abay 2	132	10.5	24	0.35	26.21	7.804	0.260

Existing short circuit test values of two winding high voltage transformers (cont...)

No.	Node 1	Node 2	Vn1	Vn2	Sn	No load current [%]	No load losses [Kw]	Uk [%]	Ur [%]
161	Mota	Mota	230	33	20	0.306	20.96	8.405	0.300
162	Metema	Metema	230	33	12	0	0	11.936	0.920
163	D/markos	D/markos	400	230	125	0	0	6.083	0.630
164	Beles	Beles	400	15	133	0.08	80	13.502	0.220
165	Beles	Beles	400	15	133	0.08	80	13.502	0.220
166	Beles	Beles	400	15	133	0.08	80	13.502	0.220
167	Beles	Beles	400	15	133	0.08	80	13.502	0.220
168	B/dar II	B/Dar II	400	230	133	0.0921	80	6.438	0.096
169	B/dar II	B/Dar II	400	230	133	0.0921	80	6.438	0.096
170	B/Dar I	B/Dar I	45	15	4.8	0	0	7.029	0.640
171	B/Dar I	B/Dar I	45	15	4.8	0	0	7.029	0.640
172	B/Dar I	B/Dar I	66	45	9	0.2	4.077	3.411	0.270
173	Woreta	Woreta	66	15	6.3	0.76	6.214	7.430	0.670
174	Gonder I	Gonder	66	15	3	1.13	6	6.744	0.770
175	Gonder I	Gonder I	66	15	6.3	0.73	6.248	7.430	0.670
176	Dabat	Dabat	66	15	6.3	0.5476	6	13.954	1.617
177	Dangla	Dangla	66	15	6.3	0.62	6.83	8.222	0.600
178	Bichena	Bichena	66	15	6.3	0.62	6.83	8.222	0.600
179	Bichena	Bichena	66	15	6.3	0.62	6.83	8.222	0.600
180	Finote Selam	Finote Selam	66	15	6.3	0.62	6.83	8.222	0.600
181	Finote Selam	Finote Selam	66	15	6.3	0.62	6.83	8.222	0.600
182	Guder	Guder	132	15	12	0	0	7.924	0.610
183	Guder	Guder	132	15	12	0	0	7.924	0.610
184	Gaferssa	Gaferssa	132	15	25	0.081	18.354	9.707	0.360
185	Muger	Muger	132	15	12	0.53	13	11.920	0.690
186	Muger	Muger	132	15	12	0.53	13	11.920	0.690
187	Addis N	Addis N	132	15	25	0.16	17.9	12.387	0.550
188	Addis N	Addis N	132	15	25	0.16	17.9	12.262	0.538
189	Fincha	Fincha 2	230	13.8	40.3	0.4384	45.7	11.499	0.450
190	Fincha	Fincha 2	230	13.8	40.3	0.4384	45.7	11.499	0.450
191	Fincha	Fincha 2	230	13.8	40.3	0.4384	45.7	11.499	0.450
192	Fincha	Fincha 1	230	13.8	40.3	0.4384	45.7	11.499	0.450

Existing short circuit test values of two winding high voltage transformers (cont...)

No.	Node 1	Node 2	Vn1	Vn2	Sn	No load current [%]	No load losses [Kw]	Uk [%]	Ur [%]
193	Geferssa	Geferssa	230	132	125	0.28	20	20.603	0.330
194	Geferssa	Geferssa	230	132	125	0.28	20	20.603	0.330
195	Geferssa	Geferssa	230	132	125	0.28	20	20.603	0.330
196	Geferssa	Geferssa	230	132	125	0.28	20	20.603	0.330
197	Neshe	Neshe	230	13.8	60	0	0	12.416	0.620
198	Neshe	Neshe	230	13.8	60	0	0	12.416	0.620
199	Addis alem	Addis alem	45	15	3	0	0	6.147	0.760
200	Addis alem	Addis alem	45	15	3	0	0	6.147	0.760
201	Ginchi	Ginchi	45	15	12	0.7	11	7.021	0.540
202	FNCH SG 1	FNCH SG 1	66	15	7	0.1856	5.111	7.137	0.730
203	FNCH SG 2	FNCH SG 2	66	15	3	0.3204	3.567	5.941	0.700
204	Mesebo	Mesebo	132	15	16	0.25	13	8.009	0.380
205	Mesebo	Mesebo	132	15	16	0.25	13	8.009	0.380
206	Wukro	Wukro	132	15	20	0.312	18.258	8.106	0.310
207	ABA	ABA	132	15	40	0	0	16.016	0.720
208	Tekeze	Tekeze	230	13.8	90	0.26	54.5	13.504	0.320
209	Tekeze	Tekeze	230	13.8	90	0.26	54.5	13.504	0.320
210	Tekeze	Tekeze	230	13.8	90	0.26	54.5	13.504	0.320
211	Tekeze	Tekeze	230	13.8	90	0.26	54.5	13.504	0.320
212	Humera	Humera	230	33	20	0	0	13.022	0.760
213	Maychew	Maychew	66	15	6.3	0.23	5.38	6.916	0.470
214	Shire	Shire	66	15	6.3	0.23	5.38	6.916	0.470
215	Shire	Shire	66	33	6.3	0	0	8.018	0.540

Table C.4: Existing short circuit test value of three winding high voltage transformer

No.	Node 1	Node 2	Node 3	Vn1	Vn2	Vn2	Sn1	Sn2	Sn3	Uk1 [%]	Uk2 [%]	Uk3 [%]	Ur1 [%]	Ur2 [%]	Ur3 [%]
1	Assosa	Assosa	Assosa	132	33	15	20	9.6	9.6	1.93	2.54	6.89	0.19	0.42	0.41
2	Awash 7K	Awash 7k	Awash 7k	132	66	15	12	12	4	12.02	0.67	6.70	0.71	0.04	0.39
3	Koka	Koka	Koka 2	132	15	10.5	18	6	18	3.94	2.67	9.63	0.43	0.16	0.54
4	Koka	Koka	Koka 3	132	15	10.5	18	6	18	3.95	2.68	9.55	0.44	0.16	0.53
5	Koka	Koka	Koka 1	132	15	10.5	18	6	18	10.01	2.67	9.61	0.43	0.15	0.52
6	Koka	Koka	Koka 2 15	132	45	15	12	4	4	3.18	4.97	18.57	0.19	0.80	0.97
7	Awash 2	Awash 2	Awash 2	132	15	10.5	6	6	20	4.10	8.41	3.12	0.19	0.35	0.14
8	Awash 2	Awash 2	Awash 2 1	132	15	10.5	4.2	4.2	14	2.90	5.91	2.19	0.13	0.27	0.10
9	Awash 3	Awash 3	Awash 3-2	132	15	10.5	4.2	4.2	14	2.90	5.91	2.19	0.13	0.27	0.10
10	Awash 3	Awash 3	Awash 3-1	132	15	10.5	6	6	20	4.10	8.41	3.12	0.19	0.35	0.14
11	MWK Yugo	MEK Yugo	MWK Yugo	132	66	15	6	6	6	6.16	7.08	15.06	0.83	0.00	0.68
12	MWK Yugo	MEK Yugo	MWK Yugo	132	66	15	6	6	6	6.16	7.09	15.08	0.83	0.00	0.71
13	Nuraera	Nuraera	Nuraera	66	33	15	9.6	9.6	6.4	0.79	2.71	0.90	0.39	0.14	0.27
14	Nuraera	Nuraera 33	Nuraera	66	33	15	9.6	9.6	6.4	0.79	2.71	0.90	0.39	0.14	0.27
15	D/Zeit 2	D/Zeit 2	D/Zeit 2	132	33	15	16	16	8	8.41	1.09	6.82	0.39	0.12	0.19
16	Kaliti i	Kaliti I	Kaliti I	132	45	15	18	18	6	11.34	0.52	5.88	0.51	0.07	0.28
17	Kaliti i	Kaliti I	Kaliti I	132	45	15	18	18	6	11.34	0.52	5.88	0.51	0.07	0.28
18	Kaliti i	Kaliti I	Kaliti I	132	45	15	18	18	6	11.34	0.52	5.88	0.51	0.07	0.28

Existing short circuit test value of three winding high voltage transformer (continued...)

No.	Node 1	Node 2	Node 3	Vn1	Vn2	Vn2	Sn1	Sn2	Sn3	Uk1 [%]	Uk2 [%]	Uk3 [%]	Ur1 [%]	Ur2 [%]	Ur3 [%]
19	Kaliti II	Kaliti II	Kaliti II	132	45	15	20	20	8	10.98	0.70	6.81	0.52	0.11	0.28
20	Yirgalem	Yirgalem	Yirgalem	132	33	15	20	12	8	6.30	5.50	6.08	0.31	0.28	0.30
21	Yirgalem	Yirgalem	Yirgalem	132	45	15	12	12	4	12.20	4.03	7.30	0.00	0.00	0.00
22	shakiso	shakiso	shakiso	132	66	15	6	6	6	10.14	7.08	15.06	0.82	0.00	0.78
23	shakiso	shakiso	shakiso	132	66	15	6	6	6	10.09	7.08	15.06	0.82	0.00	0.78
24	W.sodo	W.sodo	W.sodo	132	66	15	6	6	6	10.06	7.06	14.98	0.77	0.00	0.68
25	Dilla	Dilla	Dilla	132	33	15	20	12	8	6.30	5.50	6.08	0.31	0.28	0.30
26	Sawla	Sawla	Sawla	132	66	33	100	100	100	53.42	35.56	106.66	2.67	1.78	5.33
27	Neg. Borena	Neg. Borena	Neg. Borena	66	33	15	100	100	100	105.00	302.50	182.50	5.25	15.13	9.13
28	Sabeta	Sabeta	Sabeta 1	132	45	15	20	8	8	4.40	1.79	6.78	0.13	0.16	0.22
29	Sabeta	sabeta 2	sabeta 1	132	45	15	12	4	4	4.16	4.78	18.45	0.19	0.80	0.97
30	Butajira	Butajira 33	Butajira	132	33	15	20	9.6	9.6	1.93	2.55	6.89	0.19	0.42	0.41
31	Wolkite	Wolkite	Wolkite	230	66	33	16	16	16	5.56	2.76	8.68	0.25	0.25	0.25
32	Bonga	Bonga	Bonga	132	33	15	20	9.6	9.6	1.93	2.54	6.89	0.19	0.42	0.41
33	Mizan	Mizan	Mizan	132	66	33	20	9.6	9.6	4.14	2.50	7.27	0.30	0.29	0.40
34	GG old	GG old	GG old	230	132	33	40	40	40	11.71	30.92	47.13	0.42	1.10	1.68
35	Tepi	Tepi	Tepi	66	33	15	9.6	5.04	5.04	3.85	4.07	12.57	0.20	0.21	0.27
36	Cotobie I	Cotobie	Cotobie 15	132	45	15	12	12	4	11.98	0.51	5.00	0.08	0.02	0.22

Existing short circuit test value of three winding high voltage transformer (continued...)

No.	Node 1	Node 2	Node 3	Vn1	Vn2	Vn2	Sn1	Sn2	Sn3	Uk1 [%]	Uk2 [%]	Uk3 [%]	Ur1 [%]	Ur2 [%]	Ur3 [%]
37	D/Birehan	D/Birehan	D/Birehan	132	33	15	20	16	16	13.61	6.51	10.43	0.62	0.30	0.47
38	Sululta 132	Sululta 33	Sululta 15	132	33	15	50	25	25	5.16	17.69	6.96	0.17	0.59	0.23
39	Fitche	Fitche	Fitche	66	33	15	12	12	8	8.79	0.07	8.02	0.55	0.00	0.50
40	Fitche	Fitche	Fitche	66	33	15	12	12	8	8.79	0.07	8.02	0.55	0.00	0.50
41	D.Dewa 1	D.Dewa 1	D.Dewa 1	132	66	15	20	20	20	7.88	5.70	14.76	0.45	0.36	0.46
42	Harer III	Harer III	Harer III	132	66	33	20	9.6	9.6	3.84	2.41	6.90	0.18	0.17	0.24
43	Harer III	Harer III	Harer III	132	66	33	20	9.6	9.6	3.84	2.41	6.90	0.18	0.17	0.24
44	ASB Teferi	ASB Teferi	ASB Teferi	132	66	15	9.6	6.4	6.4	4.36	22.60	6.91	0.21	0.21	0.24
45	ASB Teferi	ASB Teferi	ASB Teferi	132	66	15	9.6	6.4	6.4	4.36	22.60	6.91	0.21	0.21	0.24
46	Hurso	Hurso	Hurso	132	33	15	100	100	100	105.00	302.50	182.50	5.25	15.12	9.13
47	D.Dawa 3	D.Dawa 3	D.Dawa 3	230	132	15	63	18.9	18.9	2.29	3.73	6.34	0.08	0.12	0.21
48	D.Dawa 3	D.Dawa 3	D.Dawa 3	230	132	15	63	18.9	18.9	2.29	3.73	6.34	0.08	0.12	0.21
49	Gambela 2	Gambela 2	Gambela 2	230	66	33	40	20	20	11.26	8.21	13.81	0.40	0.29	0.49
50	Metu	Metu	Metu	230	66	33	40	20	20	11.26	8.21	13.81	0.40	0.29	0.49
51	JiJiga 2	JiJiga 2	JiJiga 2	132	33	15	20	9.6	9.6	4.03	2.16	6.82	0.19	0.19	0.24
52	Combolcha I	Combolcha I	Combolcha I	132	66	15	6	6	12	6.38	13.24	5.15	0.29	0.60	0.23
53	Combolcha I	Combolcha I	Combolcha I	132	66	15	6	6	12	6.38	13.24	5.15	0.29	0.60	0.23
54	Aksta	Aksta	Aksta	132	66	33	20	9	20	4.64	6.40	17.80	0.05	0.15	0.46

Existing short circuit test value of three winding high voltage transformer (continued...)

No.	Node 1	Node 2	Node 3	Vn1	Vn2	Vn2	Sn1	Sn2	Sn3	Uk1 [%]	Uk2 [%]	Uk3 [%]	Ur1 [%]	Ur2 [%]	Ur3 [%]
55	D/markos	D/markos	D/markos	230	66	15	6.3	2.7	2.7	2.75	0.94	3.85	0.38	0.00	0.00
56	D/markos	D/markos	D/markos	230	66	15	6.3	2.7	2.7	2.75	0.94	3.85	0.38	0.00	0.00
57	B/Dar II	B/Dar II	B/Dar II	230	132	15	50	16.7	16.7	3.12	4.69	8.29	0.13	0.47	0.42
58	B/Dar II	B/Dar II	B/Dar II	230	132	15	50	16.7	16.7	3.12	4.69	8.29	0.13	0.47	0.42
59	B/Dar II	B/Dar II	B/Dar I	230	66	15	63	63	23	10.01	5.12	8.00	0.50	0.26	0.04
60	B/Dar II	B/Dar II	B/Dar I	230	66	15	63	63	23	10.01	5.12	8.00	0.50	0.26	0.04
61	Gonder II	Gonder II	Gonder II	230	66	15	16	16	16	4.67	4.01	9.02	3286.00	0.32	0.29
62	N/Mewucha	N/Mewucha	N/Mewucha	230	33	15	30	20	10	2.60	0.97	0.62	0.10	0.02	0.02
63	Gashena	Gashena	Gashena	230	33	15	30	20	10	2.60	0.97	0.62	0.10	0.02	0.02
64	Woreta	Woreta	Woreta	66	33	15	12	12	12	8.79	0.10	8.02	0.55	0.01	0.50
65	Pawie	Pawie	Pawie	66	33	15	12	12	12	8.79	0.10	8.02	0.55	0.01	0.50
66	Gonder II	Gonder II	Gonder II	66	33	15	12	12	12	8.79	0.10	8.02	0.55	0.01	0.50
67	Geferssa	Geferssa	Geferssa	132	33	15	24	12	12	3.34	4.02	10.97	0.20	0.40	0.40
68	Geferssa	Geferssa	Geferssa	132	45	15	18	6	6	3.81	1.51	5.71	0.16	0.22	0.23
69	Geferssa	Geferssa	Geferssa	132	66	15	20	20	20	7.88	5.70	14.76	0.45	0.36	0.46
70	Muger	Muger	Muger	132	33	15	28	8	20	2.00	4.02	10.83	0.11	0.40	0.40
71	Derba	Derba	Derba	132	33	6.3	100	100	100	0.02	0.02	0.02	0.00	0.00	0.00
72	Derba	Derba	Derba	132	33	6.3	100	100	100	0.02	0.02	0.02	0.00	0.00	0.00

Existing short circuit test value of three winding high voltage transformer (continued...)

No.	Node 1	Node 2	Node 3	Vn1	Vn2	Vn2	Sn1	Sn2	Sn3	Uk1 [%]	Uk2 [%]	Uk3 [%]	Ur1 [%]	Ur2 [%]	Ur3 [%]
73	Fincha	Fincha	Fincha	230	66	15	12.02	12.02	8	4.70	0.86	6.94	0.00	0.00	0.87
74	Ghedo	Ghedo	Ghedo	230	132	15	16	4	4	1.84	3.94	1.88	0.09	0.15	0.10
75	Ghedo	Ghedo	Ghedo	230	132	15	38	11	11	1.31	2.24	3.80	0.04	0.17	0.15
76	Alamata	Alamata	Alamata	132	66	15	16	6.4	9.6	2.64	2.48	7.12	0.12	0.21	0.24
77	Adewa	Adewa	Adewa	132	66	15	9.6	6.4	6.4	4.42	2.35	6.99	0.21	0.21	0.24
78	Adewa	Adewa	Adewa	132	66	15	9.6	6.4	6.4	4.38	2.29	6.93	0.21	0.21	0.24
79	Adigrat	Adigrat	Adigrat	132	66	15	9.6	6.4	6.4	4.37	2.27	6.91	0.21	0.21	0.24
80	Adigrat	Adigrat	Adigrat	132	66	15	9.6	6.4	6.4	4.37	2.27	6.91	0.21	0.21	0.24
81	Alamata	Alamata	Alamata	230	132	15	40	23	23	2.30	7.50	9.01	0.08	0.25	0.30
82	Alamata	Alamata	Alamata	230	132	15	40	23	23	2.30	7.50	9.01	0.08	0.25	0.30
83	Mekele	Mekele	Mekele	230	132	15	40	23	23	2.30	7.50	9.01	0.08	0.25	0.30
84	Mekele	Mekele	Mekele	230	132	15	40	23	23	2.30	7.50	9.01	0.08	0.25	0.30
85	Tekeze	Tekeze 33	Tekeze	230	33	6	20	20	20	8.02	8.01	13.90	0.50	0.40	0.50
86	endsilasie	Shire	Shire	230	66	15	40	20	20	9.01	6.40	11.31	0.32	0.23	0.40

Table C.5: Existing transmission line data of Ethiopian high voltage grid

No.	Voltage (KV)	From Bus		To Bus		Conductor	Line Rating (MVA)	Length (km)	Positive Sequence				Zero Sequence			
		Name		Name		Type			R Ω/km	X Ω/km	B $\mu\text{S}/\text{km}$	R_0 Ω/km	X_0 Ω/km	B_0 $\mu\text{S}/\text{km}$		
1	45	BABILE		HARAR I		Merlo	17	24	0.6168	0.4122	2.7599	0.8079	1.4684	1.6329		
2	45	BABILE		JIJIGA		Merlo	17	93	0.6168	0.4122	2.7599	0.8079	1.4684	1.6329		
3	45	KOKA		MODJO		Raven	17	17.4	0.6	0.4209	2.7322	0.7911	1.477	1.6232		
4	45	KOKA		NAZRET1		Raven	17	11.8	0.6	0.4209	2.7322	0.7911	1.477	1.6232		
5	45	KALITI1		ADDIS-S1		Raven	17	8.8	0.6	0.4209	2.7322	0.7911	1.477	1.6232		
6	45	KALITI1		AKAKI		Raven	17	3	0.6	0.4209	2.7322	0.7911	1.477	1.6232		
7	45	KALITI1		AKAKI-SP		Merlo	17	6	0.6168	0.4194	2.7188	0.7613	1.4742	1.4846		
8	45	KALITI1		AKAKI-SP		Merlo	17	6	0.6168	0.4194	2.7188	0.7613	1.4742	1.4846		
9	45	A-SAMUEL		AKAKI		Raven	17	18	0.6	0.4209	2.7322	0.7911	1.477	1.6232		
10	45	AKAKI		DUKEM		Raven	17	15	0.6	0.4209	2.7322	0.7911	1.477	1.6232		
11	45	DUKEM		DB-ZEITI		Raven	17	8.4	0.6	0.4209	2.7322	0.7911	1.477	1.6232		
12	45	KALTWO		NEFASILK		Raven	17	3	0.6	0.4209	2.7322	0.7911	1.477	1.6232		
13	45	KALTWO		NEFASILK		Raven	17	3	0.6	0.4209	2.7322	0.7911	1.477	1.6232		
14	45	COTOBIE		ADDIS-E1		Raven	17	6	0.6	0.4209	2.7322	0.7911	1.477	1.6232		
15	45	SEBETA1		ADDIS-W 2		Raven	17	6.2	0.6	0.4209	2.7322	0.7911	1.477	1.6232		
16	45	SEBETA1		GEDJA		Merlo	17	23	0.6168	0.4122	2.7599	0.8079	1.4684	1.6329		
17	45	SEBETA2		ADDIS-W 1		Raven	17	6.8	0.6	0.4209	2.7322	0.7911	1.477	1.6232		

Existing transmission line data of Ethiopian high voltage grid (continued...)

No.	Voltage (KV)	From Bus		To Bus		Conductor	Line Rating (MVA)	Length (km)	Positive Sequence				Zero Sequence			
		Name		Name		Type			R Ω/km	X Ω/km	B $\mu\text{S}/\text{km}$	R_0 Ω/km	X_0 Ω/km	B_0 $\mu\text{S}/\text{km}$		
18	45	TS-ABAY1		B.DAR1		Pemice	25	30	0.311	0.3939	2.9041	0.5021	1.4501	1.6823		
19	45	GEFERSA		A.ALEM		Raven	17	29.6	0.6	0.4209	2.7322	0.7911	1.477	1.6232		
20	45	A.ALEM		GINCHI		Raven	17	35	0.6	0.4209	2.7322	0.7911	1.477	1.6232		
21	45	YIRGALEM		DILLA1		Merlo	17	39.7	0.6168	0.4122	2.7599	0.8079	1.4684	1.6329		
22	66	AW SH-7KL		AMIBARA		Merlo	24	42.6	0.6169	0.4175	2.7211	0.8078	1.4584	1.6149		
23	66	AW SH-7KL		NURAERA		Merlo	24	103	0.6169	0.4175	2.7211	0.8078	1.4584	1.6149		
24	66	ASB-TFR		BEDDESA		Merlo	24	24	0.6169	0.4175	2.7211	0.8078	1.4584	1.6149		
25	66	D.DAW A1		ALEMAYA2		Merlo	24	25.3	0.6169	0.4175	2.7211	0.8078	1.4584	1.6149		
26	66	HARAR1		HARAR3		Merlo	24	7	0.6169	0.4175	2.7211	0.8078	1.4584	1.6149		
27	66	WOLKITE		WOLISO		Quail	27	39.2	0.502	0.4189	2.7428	0.6929	1.4598	1.6224		
28	66	M.W K-YUG		BALEROBE		ACSR	28	72.9	0.4882	0.4137	2.7563	0.6791	1.4546	1.6272		
29	66	M.W K-YUG		GOBESSA		Quail	27	74.2	0.502	0.4189	2.7428	0.6929	1.4598	1.6224		
30	66	SHAKISO		NEG-BORE		Quail	27	113.9	0.502	0.4189	2.7428	0.6929	1.4598	1.6224		
31	66	GAMBELA2		GAMBELA1		Merlo	24	15	0.6169	0.4175	2.7211	0.8078	1.4584	1.6149		
32	66	SOR		METU		Merlo	24	24	0.6169	0.4175	2.7211	0.8078	1.4584	1.6149		
33	66	METU		GAMBELA1		Merlo	24	146	0.6169	0.4175	2.7211	0.8078	1.4584	1.6149		
34	66	GAMBELA1		DEMBI DO		Merlo	24	64	0.6169	0.4175	2.7211	0.8078	1.4584	1.6149		

Existing transmission line data of Ethiopian high voltage grid (continued...)

No.	Voltage (KV)	From Bus		To Bus		Conductor	Line Rating (MVA)	Length (km)	Positive Sequence				Zero Sequence			
		Name		Name					Type	R Ω/km	X Ω/km	B μS/km	R ₀ Ω/km	X ₀ Ω/km	B ₀ μS/km	
35	66	MIZAN		TEPI		Quail	27	30.2	0.502	0.4189	2.7428	0.6929	1.4598	1.6224		
36	66	B.DAR2		B.DAR1		Merlo	24	4.5	0.6169	0.4175	2.7211	0.8078	1.4584	1.6149		
37	66	B.DAR2		DANGLA		Merlo	24	68.6	0.6169	0.4175	2.7211	0.8078	1.4584	1.6149		
38	66	B.DAR1		WORETA		Merlo	24	51.6	0.6169	0.4175	2.7211	0.8078	1.4584	1.6149		
39	66	WORETA		GONDER1		Merlo	24	87	0.6169	0.4175	2.7211	0.8078	1.4584	1.6149		
40	66	GONDER1		DABAT		Merlo	24	58.4	0.6169	0.4175	2.7211	0.8078	1.4584	1.6149		
41	66	GONDER1		GONDAR2		Merlo	24	4.3	0.6169	0.4175	2.7211	0.8078	1.4584	1.6149		
42	66	DANGLA		PAW IE		Merlo	24	109	0.6169	0.4175	2.7211	0.8078	1.4584	1.6149		
43	66	DB.MARKS		BITCHENA		Merlo	24	65.7	0.6169	0.4175	2.7211	0.8078	1.4584	1.6149		
44	66	DB.MARKS		FNOT-SLM		Merlo	24	80	0.6169	0.4175	2.7211	0.8078	1.4584	1.6149		
45	66	FINCHAA		FNCH-SG1		Racoon	30	11	0.4282	0.4138	2.7782	0.6191	1.4547	1.6348		
46	66	FNCH-SG1		FNCH-SG2		Racoon	30	15.4	0.4282	0.4138	2.7782	0.6191	1.4547	1.6348		
47	66	GEFERSA		FITCHE		Merlo	24	96	0.6169	0.4175	2.7211	0.8078	1.4584	1.6149		
48	66	COMBO-1		DESIE		Merlo	24	12.7	0.6169	0.4175	2.7211	0.8078	1.4584	1.6149		
49	66	DESIE		WOLDIA		Merlo	24	88	0.6169	0.4175	2.7211	0.8078	1.4584	1.6149		
50	66	ALAMATA		LALIBELA		Quail	27	104.9	0.502	0.4189	2.7428	0.6929	1.4598	1.6224		
51	66	ALAMATA		MAYCHEW		Quail	27	48	0.502	0.4189	2.7428	0.6929	1.4598	1.6224		

Existing transmission line data of Ethiopian high voltage grid (continued...)

No.	Voltage (KV)	From Bus		To Bus		Conductor	Line Rating (MVA)	Length (km)	Positive Sequence				Zero Sequence			
		Name		Name		Type			R Ω/km	X Ω/km	B $\mu\text{S}/\text{km}$	R_0 Ω/km	X_0 Ω/km	B_0 $\mu\text{S}/\text{km}$		
52	66	ALAMATA		SEKOTA		Quail	27	80	0.502	0.4189	2.7428	0.6929	1.4598	1.6224		
53	66	ADWA		SHIRE		Penguin	36	66.4	0.3165	0.4043	2.8468	0.5074	1.4452	1.6583		
54	66	ALEMAYA2		CHELENKO		Quail	27	49.8	0.502	0.4189	2.7428	0.6929	1.4598	1.6224		
55	66	ALEMAYA2		HARAR3		Quail	27	19	0.502	0.4189	2.7428	0.6929	1.4598	1.6224		
56	132	KOKA		AW ASH2		Tiger	82	25.4	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
57	132	KOKA		DBZT2-TP		Tiger	82	38.6	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
58	132	KOKA		ELALA-TP		Tiger	82	23.8	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
59	132	KOKA		NAZRETH2		Tiger	82	11.5	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
60	132	KOKA		WONJI-TP		Tiger	82	7.4	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
61	132	KOKA		YESU		Tiger	82	58.7	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
62	132	WONJPULP		WONJI-TP		Tiger	82	0.6	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
63	132	AW ASH2		AW ASH-3		Tiger	82	1.5	0.2609	0.422	2.7311	0.5129	1.2123	1.74		
64	132	AW ASH2		AW ASH-3		Tiger	82	1.5	0.2609	0.422	2.7311	0.5129	1.2123	1.74		
65	132	AW ASH2		ASSELA		Tiger	82	51.2	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
66	132	AW ASH2		WONJI-TP		Tiger	82	18	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
67	132	METAHARA		METEHARA T		Tiger	82	0	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
68	132	AW SH-7KL		ASEBETEFIR		Tiger	82	99	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		

Existing transmission line data of Ethiopian high voltage grid (continued...)

No.	Voltage (KV)	From Bus		To Bus		Conductor	Line Rating (MVA)	Length (km)	Positive Sequence				Zero Sequence			
		Name		Name		Type			R Ω/km	X Ω/km	B $\mu\text{S}/\text{km}$	R_0 Ω/km	X_0 Ω/km	B_0 $\mu\text{S}/\text{km}$		
69	132	AW SH-7KL		DD.DS-TP		Tiger	82	205	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
70	132	AW SH-7KL		METEHARA T		Tiger	82	29.6	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
71	132	D.DAW A-3		D.DAW A-1		Tiger	82	3.7	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
72	132	D.DAW A-3		D.DAW A-2		Tiger	82	12.4	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
73	132	D.DAW A-3		DD.DS-TP		Tiger	82	3.6	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
74	132	D.DAW A-2		HARAR-3		Ash	91	43.8	0.2132	0.4265	2.7015	0.4777	1.1958	1.6615		
75	132	HARAR-3		JIJIGA2		Ash	91	95	0.2132	0.4265	2.7015	0.4777	1.1958	1.6615		
76	132	HARAR-3		FIK		Ash	91	153.9	0.2132	0.4265	2.7015	0.4777	1.1958	1.6615		
77	132	ELALA-TP		ELALA-GD		Tiger	82	4.9	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
78	132	ELALA-TP		KALITI1		Tiger	82	43.3	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
79	132	NAZRETH2		METEHARA T		Tiger	82	88.2	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
80	132	DB-ZEIT2		DBZT2-TP		Tiger	82	0.1	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
81	132	KALITI1		YESU		Ash	91	9	0.2132	0.4265	2.7015	0.4777	1.1958	1.6615		
82	132	KALITI1		A.CENTER		Tiger	82	14.4	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
83	132	KALITI1		B.W GN-TP		Tiger	82	17.5	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
84	132	KALITI1		DBZT2-TP		Tiger	82	28.5	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
85	132	KALITI1		GEFERSA		Tiger	82	24.8	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		

Existing transmission line data of Ethiopian high voltage grid (continued...)

No.	Voltage (KV)	From Bus		To Bus		Conductor	Line Rating (MVA)	Length (km)	Positive Sequence				Zero Sequence			
		Name		Name		Type			R Ω/km	X Ω/km	B $\mu\text{S}/\text{km}$	R_0 Ω/km	X_0 Ω/km	B_0 $\mu\text{S}/\text{km}$		
86	132	KALITI-I		KALTWO		Tiger	82	7	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
87	132	KALITI-I		KLT.N-TP		Tiger	82	1.5	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
88	132	KALITI-I		MEKANISA		Tiger	82	16.2	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
89	132	KLT.N-TP		COTOBI-I		Tiger	82	18.7	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
90	132	KLT.N-TP		KALTI-N		Tiger	82	0.4	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
91	132	B.W GN-TP		B.W RGENU		Tiger	82	4.5	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
92	132	B.W GN-TP		COTOBI-I		Tiger	82	2.5	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
93	132	COTOBI-I		ADE-II		Ash	91	5.5	0.2132	0.4265	2.7015	0.4777	1.1958	1.6615		
94	132	COTOBI-I		COTOBI-II		Tiger	82	8	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
95	132	COTOBI-I		D.BERHAN		Tiger	82	107.5	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
96	132	D.BERHAN		COTOBI-II		Tiger	82	100	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
97	132	D.BERHAN		SHW A-RBT		Tiger	82	57.5	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
98	132	SHW A-RBT		COMBOL-I		Tiger	82	68.8	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
99	132	COMBOL-I		AKSTA		Ash	91	106	0.2132	0.4265	2.7015	0.4777	1.1958	1.6615		
100	132	COMBOL-I		COMBOL-II		Ash	91	7	0.2132	0.4265	2.7015	0.4777	1.1958	1.6615		
101	132	M.W AKNA		YADOT		Ash	91	100	0.2132	0.4265	2.7015	0.4777	1.1958	1.6615		
102	132	M.W AKNA		M.W K-YUG		Ostrich	89	5	0.2247	0.4229	2.6986	0.4892	1.1921	1.6604		

Existing transmission line data of Ethiopian high voltage grid (continued...)

No.	Voltage (KV)	From Bus		To Bus		Conductor	Line Rating (MVA)	Length (km)	Positive Sequence				Zero Sequence			
		Name		Name		Type			R Ω/km	X Ω/km	B $\mu\text{S}/\text{km}$	R_0 Ω/km	X_0 Ω/km	B_0 $\mu\text{S}/\text{km}$		
103	132	M.W K-YUG		S.SHEMEN		Ostrich	89	119.2	0.2247	0.4229	2.6986	0.4892	1.1921	1.6604		
104	132	S.SHEMEN		ALABA		Ostrich	89	63.2	0.2247	0.4229	2.6986	0.4892	1.1921	1.6604		
105	132	S.SHEMEN		A.TULU		Tiger	82	76.8	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
106	132	S.SHEMEN		AW ASA		Tiger	82	21.6	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
107	132	A.TULU		BUTAJIRA		Ash	91	46.8	0.2132	0.4265	2.7015	0.4777	1.1958	1.6615		
108	132	A.TULU		ASSELA		Tiger	82	51	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
109	132	AW ASA		YIRGALEM		Tiger	82	35.1	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
110	132	YIRGALEM		DILLA		Ash	91	40	0.2132	0.4265	2.7015	0.4777	1.1958	1.6615		
111	132	YIRGALEM		SHAKISO		Tiger	82	133.2	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
112	132	GIDA- AYANA		NEKEMPTTE		Ash	91	93.6	0.2132	0.4265	2.7015	0.4777	1.1958	1.6615		
113	132	ALABA		HOSAINA		Ostrich	89	39.6	0.2247	0.4229	2.6986	0.4892	1.1921	1.6604		
114	132	ALABA		W.SODO		Ostrich	89	61.8	0.2247	0.4229	2.6986	0.4892	1.1921	1.6604		
115	132	W.SODO		SAW LA		Ash	91	124	0.2132	0.4265	2.7015	0.4777	1.1958	1.6615		
116	132	W.SODO		A.MINCH		Ostrich	89	109.1	0.2247	0.4229	2.6986	0.4892	1.1921	1.6604		
117	132	HOSAINA		G.G OLD		Ostrich	89	70.6	0.2247	0.4229	2.6986	0.4892	1.1921	1.6604		
118	132	G.G OLD		G-GIBE-1		Ostrich	89	2.6	0.2247	0.4229	2.6986	0.4892	1.1921	1.6604		
119	132	G.G OLD		JIMMA		Ostrich	89	71.3	0.2247	0.4229	2.6986	0.4892	1.1921	1.6604		

Existing transmission line data of Ethiopian high voltage grid (continued...)

No.	Voltage (KV)	From Bus		To Bus		Conductor	Line Rating (MVA)	Length (km)	Positive Sequence				Zero Sequence			
		Name		Name		Type			R Ω/km	X Ω/km	B $\mu\text{S}/\text{km}$	R_0 Ω/km	X_0 Ω/km	B_0 $\mu\text{S}/\text{km}$		
120	132	JIMMA		BONGA		Ash	91	102.3	0.2135	0.4242	2.7366	0.4655	1.2145	1.7676		
121	132	JIMMA		BONGA		Ash	91	102.3	0.2135	0.4242	2.7366	0.4655	1.2145	1.7676		
122	132	JIMMA		ABA		Ash	91	47	0.2132	0.4265	2.7015	0.4777	1.1958	1.6615		
123	132	JIMMA		AGARO		Ostrich	89	34.8	0.2247	0.4229	2.6986	0.4892	1.1921	1.6604		
124	132	AGARO		B.BEDELE		Ostrich	89	81.4	0.2247	0.4229	2.6986	0.4892	1.1921	1.6604		
125	132	B.BEDELE		NEKEMPTE		Ash	91	116	0.2132	0.4265	2.7015	0.4777	1.1958	1.6615		
126	132	BONGA		MIZAN		Ash	91	88.3	0.2132	0.4265	2.7015	0.4777	1.1958	1.6615		
127	132	GHEDO		GUDER		Ostrich	89	34	0.2247	0.4229	2.6986	0.4892	1.1921	1.6604		
128	132	GHEDO		NEKEMPTE		Ostrich	89	115.9	0.2247	0.4229	2.6986	0.4892	1.1921	1.6604		
129	132	NEKEMPTE		GHIMBI		Ostrich	89	84.3	0.2247	0.4229	2.6986	0.4892	1.1921	1.6604		
130	132	GHIMBI		MENDI		Ash	91	130	0.2132	0.4265	2.7015	0.4777	1.1958	1.6615		
131	132	WIND-P		MEKELE		Ash	91	15	0.2132	0.4265	2.7015	0.4777	1.1958	1.6615		
132	132	GEFERSA		DERBA-TAP		Ash	91	62	0.2132	0.4265	2.7015	0.4777	1.1958	1.6615		
133	132	GEFERSA		ADDIS-N		Tiger	82	11.1	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
134	132	GEFERSA		SEBTA-TP		Tiger	82	10.8	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
135	132	MUGER		DERBA-TAP		Ash	91	18	0.2132	0.4265	2.7015	0.4777	1.1958	1.6615		
136	132	ADDIS-N		ADE-II		Ash	91	9.9	0.2132	0.4265	2.7015	0.4777	1.1958	1.6615		

Existing transmission line data of Ethiopian high voltage grid (continued...)

No.	Voltage (KV)	From Bus		To Bus		Conductor	Line Rating (MVA)	Length (km)	Positive Sequence				Zero Sequence			
		Name		Name		Type			R Ω/km	X Ω/km	B $\mu\text{S}/\text{km}$	R_0 Ω/km	X_0 Ω/km	B_0 $\mu\text{S}/\text{km}$		
137	132	SEBATA		SEBTA-TP		Tiger	82	1	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
138	132	MEKANISA		ADS-II		Ash	91	2	0.2132	0.4265	2.7015	0.4777	1.1958	1.6615		
139	132	MEKANISA		SEBTA-TP		Tiger	82	7.8	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
140	132	MESOBO		MEKELE		Ostrich	89	5.1	0.2247	0.4229	2.6986	0.4892	1.1921	1.6604		
141	132	WUKRO		WUKRO-TP		Ostrich	89	1.2	0.2247	0.4229	2.6986	0.4892	1.1921	1.6604		
142	132	MEKELE		ADWA		Ostrich	89	116.7	0.2247	0.4229	2.6986	0.4892	1.1921	1.6604		
143	132	MEKELE		WUKRO-TP		Ostrich	89	31	0.2247	0.4229	2.6986	0.4892	1.1921	1.6604		
144	132	ADIGRAT		WUKRO-TP		Ostrich	89	56.6	0.2247	0.4229	2.6986	0.4892	1.1921	1.6604		
145	132	T-ABAY2		B.DAR2		Ash	91	29	0.2135	0.4242	2.7366	0.4655	1.2145	1.7676		
146	132	T-ABAY2		B.DAR2		Ash	91	29	0.2135	0.4242	2.7366	0.4655	1.2145	1.7676		
147	132	D.DAW -DS		DD.DS-TP		Tiger	82	1.9	0.2606	0.4243	2.6799	0.5262	1.1936	1.6534		
148	132	MENDI		ASSOSA		Ash	91	80	0.2132	0.4265	2.7015	0.4777	1.1958	1.6615		
149	132	DILLA		H.MARIAY		Ash	91	90	0.2132	0.4265	2.7015	0.4777	1.1958	1.6615		
150	132	H.MARIAY		B.LUGUMA		Ash	91	170	0.2132	0.4265	2.7015	0.4777	1.1958	1.6615		
151	132	AKSTA		A-KETEMA		Ash	91	150.2	0.2132	0.4265	2.7015	0.4777	1.1958	1.6615		
152	132	DERBA-TAP		DERBA CM		Ash	91	49.5	0.2132	0.4265	2.7015	0.4777	1.1958	1.6615		
153	230	FINCHA		GHEDO		ACAR	284	67.2	0.0791	0.424	2.7302	0.3193	1.1361	1.8292		

Existing transmission line data of Ethiopian high voltage grid (continued...)

No.	Voltage (KV)	From Bus		To Bus		Conductor	Line Rating (MVA)	Length (km)	Positive Sequence				Zero Sequence			
		Name		Name		Type			R Ω/km	X Ω/km	B $\mu\text{S}/\text{km}$	R_0 Ω/km	X_0 Ω/km	B_0 $\mu\text{S}/\text{km}$		
154	230	FINCHA		FINCHA-II		Twin Ash	318	8.3	0.1067	0.3261	3.5224	0.3469	1.0382	2.153		
155	230	FINCHA		DB-MRKOS		Yew	280	95.2	0.0815	0.4234	2.7343	0.3217	1.1355	1.831		
156	230	GHEDO		GEFERSA		Yew	284	133	0.0815	0.4234	2.7343	0.3217	1.1355	1.831		
157	230	GHEDO		G-GIBE-OLD		Mallard	274	130	0.0859	0.4179	2.7424	0.3261	1.13	1.8346		
158	230	GHEDO		FINCHA-II		Twin Ash	318	69.7	0.1067	0.3261	3.5224	0.3469	1.0382	2.153		
159	230	GEFERSA		SEBATA-1		Mallard	274	10.6	0.0859	0.4179	2.7424	0.3261	1.13	1.8346		
160	230	GEFERSA		SULULTA		Twin Ash	318	16.7	0.1069	0.3174	3.6425	0.3371	1.0672	2.208		
161	230	GEFERSA		SULULTA		Twin Ash	318	16.7	0.1069	0.3174	3.6425	0.3371	1.0672	2.208		
162	230	SEBATA-1		KALITI1		Mallard	274	14.3	0.0859	0.4179	2.7424	0.3261	1.13	1.8346		
163	230	SEBATA-1		SEBETA-2		Yew	280	15	0.0817	0.4147	2.8039	0.3119	1.1645	1.8456		
164	230	SEBATA-1		SEBETA-2		Yew	280	15	0.0817	0.4147	2.8039	0.3119	1.1645	1.8456		
165	230	SEBATA-1		WOLKITE		Yew	280	136.2	0.0815	0.4234	2.7343	0.3217	1.1355	1.831		
166	230	NESHE		FINCHA-II		Twin Ash	318	29.2	0.1067	0.3261	3.5224	0.3469	1.0382	2.153		
167	230	G-GIBE-1		G-GIBE-OLD		Mallard	274	5	0.0861	0.4092	2.8124	0.3163	1.159	1.8496		
168	230	G-GIBE-1		G-GIBE-OLD		Mallard	274	5	0.0861	0.4092	2.8124	0.3163	1.159	1.8496		
169	230	KALITI1		DUKEM TAP 1		Redwing	257	33	0.0958	0.4126	2.7879	0.326	1.1624	1.8382		
170	230	KALITI1		DUKEM TAP 2		Redwing	257	33	0.0958	0.4126	2.7879	0.326	1.1624	1.8382		

Existing transmission line data of Ethiopian high voltage grid (continued...)

No.	Voltage (KV)	From Bus		To Bus		Conductor	Line Rating (MVA)	Length (km)	Positive Sequence				Zero Sequence			
		Name		Name		Type			R Ω/km	X Ω/km	B $\mu\text{S}/\text{km}$	R_0 Ω/km	X_0 Ω/km	B_0 $\mu\text{S}/\text{km}$		
171	230	KALITI1		COTOBI-II		Twin Ash	318	34.9	0.1069	0.3174	3.6425	0.3371	1.0672	2.208		
172	230	KALITI1		COTOBI-II		Twin Ash	318	34.9	0.1069	0.3174	3.6425	0.3371	1.0672	2.208		
173	230	KOKA		D.DAW A3		Mallard	274	335.1	0.0861	0.4092	2.8124	0.3163	1.159	1.8496		
174	230	KOKA		D.DAW A3		Mallard	274	337	0.0861	0.4092	2.8124	0.3163	1.159	1.8496		
175	230	KOKA		DUKEM TAP 1		Mallard	274	33	0.0861	0.4092	2.8124	0.3163	1.159	1.8496		
176	230	KOKA		DUKEM TAP 2		Mallard	274	33	0.0861	0.4092	2.8124	0.3163	1.159	1.8496		
177	230	KOKA		AW SH-7KL		Mallard	274	129.3	0.0859	0.4179	2.7424	0.3261	1.13	1.8346		
178	230	KOKA		M-W AKNA		Redwing	257	163.9	0.0958	0.4126	2.7879	0.326	1.1624	1.8382		
179	230	KOKA		M-W AKNA		Redwing	257	163.9	0.0958	0.4126	2.7879	0.326	1.1624	1.8382		
180	230	AW SH-7KL		D.DAW A3		Mallard	274	205.1	0.0859	0.4179	2.7424	0.3261	1.13	1.8346		
181	230	D.DAW A3		ADIGALA		Twin Ash	318	120	0.1067	0.3261	3.5224	0.3469	1.0382	2.153		
182	230	D.DAW A3		DJIB-PK12		Twin Ash	318	277	0.1067	0.3261	3.5224	0.3469	1.0382	2.153		
183	230	DJIB-PK12		ADIGALA		Twin Ash	318	167	0.1067	0.3261	3.5224	0.3469	1.0382	2.153		
184	230	DB-MRKOS		MOTA		Yew	280	111.8	0.0815	0.4234	2.7343	0.3217	1.1355	1.831		
185	230	B.DAR2		GONDAR2		Twin Ash	318	137	0.1067	0.3261	3.5224	0.3469	1.0382	2.153		
186	230	B.DAR2		N.MEW TP		Twin Ash	318	136.4	0.1067	0.3261	3.5224	0.3469	1.0382	2.153		
187	230	B.DAR2		MOTA		Yew	280	83	0.0815	0.4234	2.7343	0.3217	1.1355	1.831		

Existing transmission line data of Ethiopian high voltage grid (continued...)

No.	Voltage (KV)	From Bus		To Bus		Conductor	Line Rating (MVA)	Length (km)	Positive Sequence			Zero Sequence		
		Name		Name					Type	R Ω/km	X Ω/km	B μS/km	R ₀ Ω/km	X ₀ Ω/km
188	230	N.MEW TP		GASHE-TA		Twin Ash	318	102.3	0.1067	0.3261	3.5224	0.3469	1.0382	2.153
189	230	N.MEW TP		N.MEW CHA		Twin Ash	318	1	0.1067	0.3261	3.5224	0.3469	1.0382	2.153
190	230	ALAMATA		COMBOL-II		Twin Ash	318	168.8	0.1069	0.3174	3.6425	0.3371	1.0672	2.208
191	230	ALAMATA		COMBOL-II		Twin Ash	318	168.8	0.1069	0.3174	3.6425	0.3371	1.0672	2.208
192	230	ALAMATA		MEKELE		Twin Ash	318	140.7	0.1069	0.3174	3.6425	0.3371	1.0672	2.208
193	230	ALAMATA		MEKELE		Twin Ash	318	141.1	0.1069	0.3174	3.6425	0.3371	1.0672	2.208
194	230	ALAMATA		GASHE-TA		Twin Ash	318	102.3	0.1067	0.3261	3.5224	0.3469	1.0382	2.153
195	230	MEKELE		TEKEZE		Twin Ash	318	105	0.1069	0.3174	3.6425	0.3371	1.0672	2.208
196	230	MEKELE		TEKEZE		Twin Ash	318	105	0.1069	0.3174	3.6425	0.3371	1.0672	2.208
197	230	TEKEZE		ENDASILA		Twin Ash	318	159.5	0.1069	0.3174	3.6425	0.3371	1.0672	2.208
198	230	TEKEZE		ENDASILA		Twin Ash	318	159.5	0.1069	0.3174	3.6425	0.3371	1.0672	2.208
199	230	COMBOL-II		COTOBII-II		Twin Ash	318	286.9	0.1067	0.3261	3.5224	0.3469	1.0382	2.153
200	230	COMBOL-II		COTOBII-II		Twin Ash	318	286.9	0.1067	0.3261	3.5224	0.3469	1.0382	2.153
201	230	COMBOL-II		SEMERA		Twin Ash	318	170	0.1067	0.3261	3.5224	0.3469	1.0382	2.153
202	230	GONDAR2		METEMA		Twin Ash	318	165	0.1069	0.3174	3.6425	0.3371	1.0672	2.208
203	230	GONDAR2		METEMA		Twin Ash	318	165	0.1069	0.3174	3.6425	0.3371	1.0672	2.208
204	230	WOLKITE		G-GIBE-OLD		Yew	280	70	0.0815	0.4234	2.7343	0.3217	1.1355	1.831

Existing transmission line data of Ethiopian high voltage grid (continued...)

No.	Voltage (KV)	From Bus		To Bus		Conductor	Line Rating (MVA)	Length (km)	Positive Sequence				Zero Sequence			
		Name		Name					Type	R Ω/km	X Ω/km	B μS/km	R ₀ Ω/km	X ₀ Ω/km	B ₀ μS/km	
205	230	GAMBELA2		METU		Twin Ash	318	150	0.1067	0.3261	3.5224	0.3469	1.0382	2.153		
206	230	BEDELLE		METU		Twin Ash	318	90.5	0.1067	0.3261	3.5224	0.3469	1.0382	2.153		
207	230	GASHE-TA		GASHENA		Twin Ash	318	1	0.1067	0.3261	3.5224	0.3469	1.0382	2.153		
208	230	SEMER A		DITCHETO		Twin Ash	318	55	0.1067	0.3261	3.5224	0.3469	1.0382	2.153		
209	230	HUMERA		ENDASILA		Twin Ash	318	229.7	0.1069	0.3174	3.6425	0.3371	1.0672	2.208		
210	230	HUMERA		ENDASILA		Twin Ash	318	229.7	0.1069	0.3174	3.6425	0.3371	1.0672	2.208		
211	400	G-GIBE-2		GIGIBE-OLD		Twin Aster	1341	27.9	0.0248	0.3292	3.7523	0.2932	0.8293	2.6758		
212	400	G-GIBE-2		SEBETA-2		Twin Aster	1341	183.5	0.0248	0.3292	3.7523	0.2932	0.8293	2.6758		
213	400	D-MARKOS		BAHIR DAR-II		Twin Aster	1341	193.7	0.0248	0.3292	3.7523	0.2932	0.8293	2.6758		
214	400	D-MARKOS		SULULTA		Twin Aster	1341	215.6	0.0248	0.3292	3.7523	0.2932	0.8293	2.6758		
215	400	BELES		BAHIR DAR-II		Twin Aster	1341	62.8	0.0244	0.3096	3.7509	0.2634	0.9123	2.3683		
216	400	BELES		BAHIR DAR-II		Twin Aster	1341	62.8	0.0244	0.3096	3.7509	0.2634	0.9123	2.3683		