

Impact Assessment of Large-Scale Integration of Wind Power to the National Grid: The case Adama wind-farm-II

Esayas Meshesha Sisayu



A Thesis submitted to Department of Electrical Engineering
School of Electrical Engineering and computing

Presented In partial fulfillment of the requirement for the
degree of MASTERS OF SCIENCE IN ELECTRICAL ENGINEERING
(ELECTRICAL POWER ENGINEERING)

Office of Graduate Studies
Adama Science and Technology University

Adama
June, 2018

Impact Assessment of Large-Scale Integration of Wind Power to the National Grid: The case Adama wind-farm-II

Esayas Meshesha Sisayu

Advisor: Dr. Santosh K. Hampannavar (Assistant Professor)

Co-advisor: Tefera T. Yetayew (PhD, Pursuing at AU, India)



A Thesis submitted to Department of Electrical Engineering
School of Electrical Engineering and computing

Presented In partial fulfillment of the requirement for the degree of
MASTERS OF SCIENCE IN ELECTRICAL ENGINEERING
(ELECTRICAL POWER ENGINEERING)

Office of Graduate Studies
Adama Science and Technology University

Adama
June, 2018

Approval of Board of Examiners

We, the undersigned, members of the Board of Examiners of the final open defense by _____ have read and evaluated his/her thesis entitled **“Impact Assessment of Large-Scale Integration of Wind Power to the National Grid: The case Adama wind-farm-II”** and examined the candidate. This is, therefore, to certify that the thesis has been accepted in partial Fulfillment of the requirement of the Degree MASTERS OF SCIENCE IN ELECTRICAL ENGINEERING (ELECTRICAL POWER ENGINEERING)

External Examiner

Signature

Date

Internal Examiner

Signature

Date

Chairperson

Signature

Date

Department Head

Signature

Date

School Dean

Signature

Date

Post Graduate Dean

Signature

Date

Declaration

I hereby declare that this MSc Thesis is my original work and has not been presented for a degree in any other university, and all sources of material used for this thesis/ dissertation have been duly acknowledged.

Name of candidate: Esayas Meshesha

Signature and date: _____

This MSc Thesis has been submitted for examination with my approval as thesis advisor/ dissertation Supervisor.

Name advisor: _____

Signature and date: _____

Date of submission.

Advisor's approval sheet

To: Electrical Engineering department

Subject: Thesis Submission

This is to certify that the thesis entitled “**Impact Assessment of Large-Scale Integration of Wind Power to the National Grid: The case Adama wind-farm-II**”, submitted in partial fulfillment of the requirements for the degree of Master's in Electrical Engineering (Electrical Power Engineering), the Graduate program of the department of Electrical Engineering, and has been carried out by Esayas Meshesha. Id. No GSR/02924/07, under my supervision. Therefore, I recommend that the student has fulfilled the requirements and hence hereby he can submit the thesis to the department.

Name of major Advisor

Signature

Date

Acknowledgement

I express my sincere gratitude towards my supervisors Dr. Santosh K. Hampannavar and Ato Tefera T. Yetayew (PhD, Pursuing at AU, India) for their continual support and enthusiasm for preparing this thesis work.

I would like to thank my colleagues who are working in Adama wind Farm-II for their support.

Abstract

The research in this thesis assess the impact of large-scale integration of wind power to the Ethiopian national grid, the case Adama wind farm II. The power grid with a number of stations integrated is a complex system and vulnerable to disturbances usually caused by transient short circuit faults that may result in oscillation of power flow in the network. In the existing or conventional power systems, such faults are damped by plants with synchronous generators equipped with stabilizers. High penetration of wind farms integrated to the grid may take large share of power generating plants and this will be a serious concern for the operator about the reliability and stability of the power system that needs revised grid connection code for wind farms.

The types of generator used in wind farms also have its own impact due to technical arrangement of the generators to the grid. Wind farms using permanent magnet synchronous generators (PMSG) are less exposed to grid faults whereas wind farms using double feed induction generators (DFIG) are highly exposed to grid faults since directly connected to the grid. In this regard, Ashegoda, Aysha and Adama I wind farms use permanent magnet synchronous generators (PMSG) and Adama wind farm II is using DFIG that is highly exposed to grid faults that may cause increase amplitude of oscillation whenever the system is excited may result in disconnection of the wind turbine. The sudden disconnection of wind turbine due to grid faults may have impact on transient stability of the national grid.

Out of the many problems arise due to grid integration of wind farms to the national grid, the research in this thesis mainly focus on impact assessment of large-scale grid integration of the wind farms that used DFIG, the case Adama wind farm II to the national grid. The problems to be assessed are transient fault-ride-through and power system stability caused by short circuit faults. Besides, the thesis studies the characteristics, operation, control and grid connection requirements as a basis on impact assessment. The investigation of the dynamic response of wind farms integrated to the grid (the case Adama wind farm II) will done using the aggregated model of grid-connected wind farm using MATLAB/Simulink tool and ETAP software's. The simulation of the realistic operation, that to carry out the grid fault impact on both DFIG wind turbines and the power system itself show the behavior and property of the system fault-ride-through capability. This dynamic behavior of the system during grid faults is simulated and assessed using a transmission power system connected with the wind farm generic model developed and delivered by System Operator.

Keywords: Large-Scale, DFIG, Aggregation, Grid- Connected, Fault-Ride-Through, System stability.

Table of Contents

Acknowledgement	i
Abstract	ii
List of Figures	v
List of Tables	vi
Abbreviations	vii
CHAPTER-1 Introduction	1
1.1 Background	1
1.2 Wind Energy conversion system	2
1.3 Impact integration of large scale wind Farm to Grid	4
1.4 Low voltage ride through impact on the power system	5
1.5 Motivation	7
1.6 Statement of the Problem	8
1.7 Objectives	9
1.8 Organization of the thesis	10
CHAPTER-2 Literature Review	11
2.1 Literatures	11
2.2 Fault Ride-through (FRT) Requirements	12
2.3 Other Requirements	14
2.4 International Experience	14
CHAPTER-3 Large-Scale-Wind Farm Aggregation	15
3.1 Large wind farm definition	15
3.2 Equivalent Circuit of Grid connected wind farm	18
3.3 Aggregated model for Grid connected Wind Farm	20
3.4 Assumption of An Aggregated Model	22
3.5 Assessment Criteria	23

3.6 Systematic Computation for fault ride through	26
3.6.1 LVRT with Fault outside the Collector System	26
3.6.2 LVRT with Fault within the Collector System	29
CHAPTER-4 Dynamic Modeling of DFIG	32
4.1 Modeling of DFIG	33
4.2 Rotor Side Converter	36
4.3 Grid Side Converter	38
4.4 DFIG Normal Operation	39
CHAPTER-5 Analysis and Results	42
5.1 Description	42
5.2 Short circuit Analysis	44
5.2.1 Double Fed Induction Generator during Fault	44
5.2.2 Two-Phase Shorted	46
5.2.3 Summary of Results	48
5.3 Transient stability Analysis	48
5.3.1 Simulation Result	50
5.4 Power flow Analysis	51
CHAPTER-6 Conclusion and Future Work	53
6.1 Conclusions	53
6.2 Future Work	54
References	55
Appendix	58
Appendix-A	58
Appendix-B	60
Appendix-C	61
Appendix-D	62

List of Figures

Figure 1-1 The power coefficient, C_p as a function of the tip speed ratio, λ	3
Figure 1-2 Typical low ride- through voltage characteristics	6
Figure 3-1 General Layout of Adama wind farm II	16
Figure 3-2 An aggregated Modeling of Adama wind farm-II (Using ETAP Software)	17
Figure 3-3 Simulations results for a solid symmetrical fault at bus 3	29
Figure 3-4 Low voltage ride-through study with fault at bus 4.....	29
Figure 3-5 Low voltage ride-through study with fault at bus 4.....	30
Figure 3-6 LVRT with an increased feeder impedance during short-circuit	30
Figure 4-1 General operating model of DFIG with converters	32
Figure 4-2 Power Flow Diagram of DFIG	33
Figure 4-3 Equivalent circuit of Doubly Fed Induction Generator	34
Figure 4-4 Rotor speed and active power control	37
Figure 4-5 Doubly fed induction generator with converters connected to a grid. [24].....	37
Figure 4-6 Reactive power and voltage control diagram.	38
Figure 4-7 DFIG during normal operation	41
Figure 5-1 DFIG during a voltage sag at three phase faults.....	45
Figure 5-2 DFIG under unbalanced 2-phase fault.....	47
Figure 5-3 Transient stability Analysis for Adama Wind Farm Aggregated one line diagram	49
Figure 5-4 the simulation output of transient stability	50

List of Tables

Table 2-1 Fault rid through criteria in practice [27].....	12
Table 3-1 Adama II wind power plant turbine generator specifications	18
Table 3-2 Parameters of Detailed and Simple aggregated model	24
Table 3-3 transformer equivalent impedance for all aggregated group	25
Table 3-4 Summery of collector circuit impedance for all aggregated group.....	25
Table 4-1 YSK15-04A generator Technical Specifications.....	40
Table 4-2 DFIG System and model parameters	40

Abbreviations

AC	Alternating Current
CCT	Critical Clearing Time
DC	Direct Current
DFIG	Doubly Feed Induction Generator
DTC	modified direct torque control
EEP	Ethiopian Electric Power
EEPCO	Ethiopian Electric Power Corporation
FCT	Fault Clearing Time
FRT	Fault Ride Through
FSR	Full System Representation
GSC	Grid Side Converter
HVRT	High Voltage Ride-through
LVRT	Low Voltage Ride Through
IGBT	Insulated Gate Bipolar Transistor
PCC	Point of Common Coupling
PI	Proportional Integrator
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
WECC	Wind Energy Conversion System
WF	Wind Farm
WPP	Wind Power Plant
WTGs	Wind Turbine Generators

CHAPTER ONE

1. Introduction

1.1 Background

Today wind energy conversion system is one of the most interesting energy source in terms of environmental energy security system, concern among the rest of renewable energy source, due to its technological maturity, cost competitive and good infra structure.

Ever increasing energy demand of the world, the country Ethiopia is producing electricity from hydro dominantly and also the government shows interest and investing to utilize renewable energy source of wind, solar and geothermal mainly to meet energy demand of the nation and contribute the global environmental issues. In the last decade, utilization of wind as a source of energy is growing in different place of the country. wind farm of Ashegoda (located Tigray region), Ayisha (located in Somali region) and Adama I & II (located in Oromia region) have been installed and integrated to the national grid.

In most cases the integration of higher levels of wind energy into an existing grid interfacing system does not require a major redesign, provided a thorough analysis before the integration is conducted to check the viability of wind energy conversion system integration(WECS). In some cases, the analysis indicates the necessity of additional high-performance control and compensating equipment to enable the system to recover from severe system disturbances.

The grid connected wind energy conversion system can affected by different problems from the grid side or energy conversion side, this problem affects the power system negatively. Some of these problems come from scholastic nature of the wind farm and the fault on the grid. This problem introduces a new factor of uncertainty or disturbances on the grid and the wind farm. These factors are the power quality, system security and system stability.

Using the control of the nodal voltage, maintaining system stability, ensuring load following and contributing of fault current, wind power penetration is still low (20% to 35%) of the total generating capability. To increase this level of penetration level, researches has their own impact on the grid integrity. Therefore, to imply the need for certain technology to enable smooth and proper integrity of the wind farm to the power system, this research set out to assess the addressed problems and discuss the various challenge of Adama wind farm II that directly integrated to the grid and set out to define the parameters and variables necessary for the smooth integration that the operator have to take measure for the addressed mitigating strategies.

1.2 Wind Energy conversion system

Wind Energy Conversion Systems (WECS) convert the energy in moving air (the wind) to electrical energy. The basic idea is quite simple and has been around for centuries: the wind strikes some sort of set of blades mounted on a shaft that is free to rotate. The wind hitting the blades generates a force that turns the shaft, and this rotational kinetic energy may then be used for any of a number of purposes (historically, things like pumping water, moving a saw, or turning grain-grinding stones, to name a few). In a WECS, the rotating shaft turns an electric generator that converts the rotational kinetic energy to electric energy.

The major components of a typical wind energy conversion system include a wind turbine, generator, interconnection apparatus and control systems. Wind turbines can be classified into the vertical axis type and the horizontal axis type. Most modern wind turbines use a horizontal axis configuration with two or three blades, operating either down-wind or up-wind. A wind turbine can be designed for a constant speed or variable speed operation. Variable speed wind turbines can produce 8% to 15% more energy output as compared to their constant speed counterparts, however, they necessitate power electronic converters to provide a fixed frequency and fixed voltage power to their loads. Power developed by the wind machine is mainly affected by wind speed, area swept by the rotor, density of air, rotational speed of the machine, radius of the rotor, number of blades, and total blade area. It is also affected by lift and drag characteristics of the blade profile. Some of the available power in the wind is converted by the rotor blades to mechanical power acting on the rotor shaft of the wind turbine. For steady-state calculations of the mechanical power from a wind turbine, the so called $C_p(\lambda, \beta)$ -curve can be used. The mechanical power P_{mech} can be determined as follows:

$$P_{mech} = 0.5 * \rho * A_r * C_p * (\lambda, \beta) * \omega^3 \quad (1.1)$$

$$\lambda = \frac{\Omega_r r_r}{\omega} \quad (1.2)$$

Where C_p is the power coefficient, β is the pitch angle, λ is the tip speed ratio, ω is the wind speed, Ω_r is the rotor speed (on the low-speed side of the gearbox), r_r is the rotor-plane radius, ρ is the air density and A_r is the area swept by the rotor. In Fig. 1.1, an example of a $C_p(\lambda, \beta)$ curve and the shaft power as a function of the wind speed for rated rotor speed, i.e., a fixed-speed wind turbine, can be seen.

The turbine power, the tip speed ratio λ and the C_p values are displayed in Figure 1.1 as function of wind speed. For a wind speed of 15m/s, the turbine output power is 1 pu of

its rated power, the pitch angle is 8.7° and the generator speed is 1.2 pu. The speed of the wind is variable in nature; at high speed it's necessary to limit the input power to the wind turbines, i.e., aerodynamic power control.

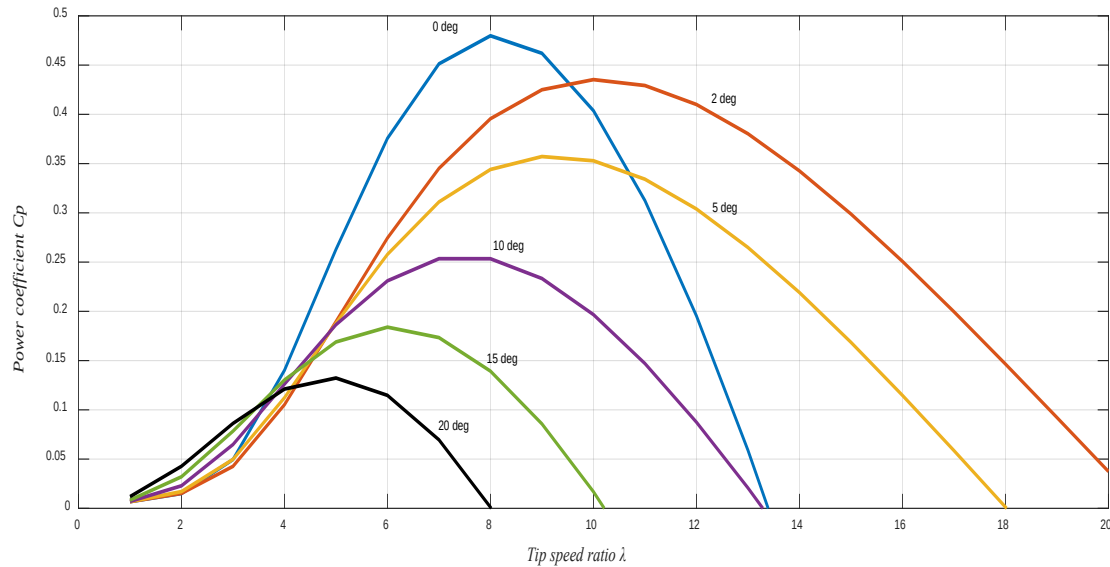


Figure 1-1 The power coefficient, C_p as a function of the tip speed ratio, λ .

There are three major ways of performing the aerodynamic power control, stall, pitch, or active stall control. In stall control the blades are designed to stall in high speeds and no pitch mechanism is required. However, pitch control is the most common controlling method of aerodynamic power generated by a turbine rotor of modern and large wind turbines. Almost all variable-speed wind turbines use pitch control. Below the rated wind speed, the turbine should produce as much power as possible using a pitch angle that maximizes the energy capture. Above the rated wind speed, the pitch angle is controlled in such a way that the aerodynamic power is at its rated. In order to limit the aerodynamic power, at high wind speeds, the pitch angle is controlled to decrease the angle of attack. The angle of attack is the angle between the chord line of the blade and the relative wind direction. It's also possible to increase the angle of attack towards stall in order to limit the aerodynamic power [2].

As the number of wind installations has grown worldwide at unprecedented rates in recent years; as well, the average size of the installations has increased due to the advent of larger capacity machine, variable speed technology, and an increasing number of large-scale sites. This raises the concern that widespread tripping of wind generators following disturbances that could lead to propagation of transient instabilities and could potentially cause local or system wide blackouts.

This has provoked many utilities to adopt low voltage ride-through (LVRT) for wind turbines. The requirement places an added interconnection cost on the manufacturer and will influence the overall financing of the project.

1.3 Impact integration of large scale wind Farm to Grid

Incorporation of great amount of distributed resources, such as wind energy, has a significant impact on power network, which are mainly related to environmental, economic and reliability aspects. Large-scale wind penetration levels are usually accommodated in power networks considering that the network is passively controlled and operated. Although there are several available tools to be used for wind power integration system [3], wind energy is still considered as a non-dispatchable and not centrally planned technology.

Impact of wind energy on power systems is thus focused on several issues related to security, stability, power quality and operation of power systems.

- Wind energy has several impacts on power flow that could lead to reverse power flow and, as a result, power systems operation will become more complex [7]. Moreover, power injection by wind farms may cause power losses in the distribution systems.
- All the utilities have to keep stable and reliable the voltage supply to the customers within specific limits of frequency and magnitude. Connection of wind farms may result in voltage changes, consequently, some countries have defined a higher short circuit level at the connection point, normally between 20 and 25 times the wind farm capacity. There are already some examples of successful operation of power networks with a lower short circuit level [8].
- Power quality is related to voltage variation and harmonic distortion in the network. However, the incorporation of wind energy in power networks could affect the quality of the supplied voltage to the customers. To reduce this impact, nowadays, variable speed wind turbines equipped with power electronics are widely used in wind energy conversion. Power electronics increase power quality because they raise the harmonic distortion [5].
- Protection system is also affected by wind farms since the incorporation of wind power injection alters power flows; so that conventional protection systems might fail under fault situations.
- In the past, power network was passive operated and kept up stable under most circumstances. However, this statement is no longer valid if considering an increase of

wind energy penetration. Recently, new requirements for wind units have been designed in order to keep power networks stable under several disturbances, such as low voltage ride through capability.

1.4 Low voltage ride through impact on the power system

Historically, wind turbines were connected to distribution systems. In the event of a large disturbance resulting in a significant dip in voltage close to the wind turbine it was accepted practice to trip the wind turbine. This action was based on the reasoning that distribution systems being supplied by radial systems could result in the wind farm being connected to the system following the disturbance and result in an islanded operation, which could cause unacceptable over voltage conditions [14]. With the evolution of wind turbine technology and the development of large wind farms connected to the bulk transmission network, the issue of voltage ride through sometimes also referred to as low voltage ride through or fault ride through, it became an important operating issue. This led to the development of voltage ride through requirements in various parts of the world. According to the new grid codes, instead of disconnection, the wind generators have to support the network during the power disturbances in the network. Therefore, it is necessary to carry out accurate transient simulations in order to understand the impact of the power system disturbances on a wind turbine operation. In the recent years, the ride-through analysis of the DFIG wind turbine under network disturbance has become an intensively studied problem. Due to the random nature, faults imposed on the grid can occur anywhere within the connected system. Also, due to transmission line impedance the voltages dip could be seen at the stator windings. The voltage dip can cause excessive currents on the rotor windings by the magnetic coupling. As a fail-safe mechanism, the DFIG automatically disconnects from the grid protecting the internal power electronic converter from over currents as well as over voltage on the converter dc link [7]. Most of the DFIG wind generators transient studies have been focused on the voltage dip analyses due to symmetrical three phase network faults. These kinds of faults, however, are very seldom. Single and two-phase earth faults are more common. Moreover, two-phase faults are more demanding for a DFIG than symmetrical three-phase faults. Thus, more research about unsymmetrical fault ride-through performance is required. Most DFIG wind turbine models that are used in transient analyses represent the generator by means of a two-axis model with constant lumped parameters. A model of DFIG that takes into account the equivalent circuit parameter variation presented. A significant part of the wind turbine model is the model of a frequency converter that supplies the rotor

of the DFIG. The converter is found to be the most sensitive part of the wind turbine when subjected to a short-circuit fault in the grid. The control of a frequency converter is usually based on field oriented control but also, the modified direct torque control (DTC) could be used. The frequency converters are usually equipped with a rotor over current protection circuit that is commonly called crowbar. The crowbar protects the rotor side frequency converter against the high rotor current transient that DFIG generates during the disturbance. A Typical LVRT characteristic is more or less defined by a minimum voltage throughout the duration of the fault followed by a ramping up to nominal level as the voltage recovers. The width of this minimum is dictated by the length of time to normally clear a transmission level fault (10 to 20 cycles) which then ramps up to the normal operating range with a given slope [7, 8]. Although the width and magnitude of the minimum are dictated by protection technologies and the location and type of fault, the slope of the recovery likely depends on the strength of the interconnection and reactive power support, whereby stronger systems could afford a much steeper increase and thus minimize the ride-through requirements of the generators. The functional operation of LVRT is based on the comparison of the characteristic with that of the terminal voltage. Essentially, once the voltage dips outside of the normal operating range the control system then compares the recovery of the fault with that of the minimum voltage level as given by the LVRT characteristic. As shown in Fig. 1-2, in the case in which the voltage falls below that of the LVRT characteristic, the generator may trip, however, anywhere above the minimum, the generator must remain connected and support the grid

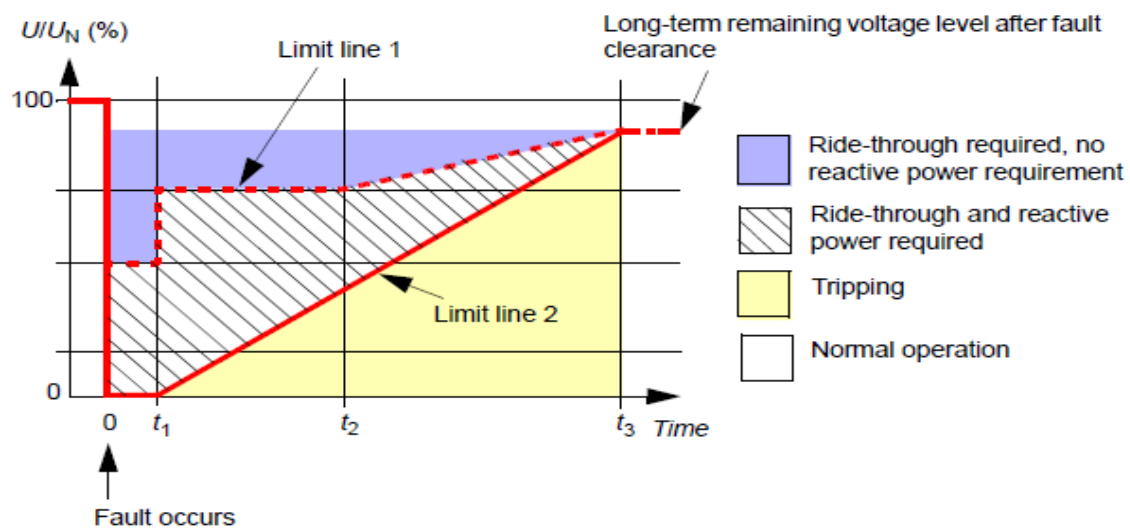


Figure 1-2 Typical low ride-through voltage characteristics

Under fault conditions, there are two major problems for existing DFIG based wind energy system:

1. Over current for rotor side converter and over voltage on dc link
2. Reconnection to recovered grid may cause stability issue.

Without proper control scheme, DFIG induces large currents on the rotor side as the excitation current is low during faults. The generator flux is not maintained when the stator voltage drops or negative rotating flux may appear if the system is severely unbalanced. It's desirable to regulate the terminal voltage (or reactive power) in order to achieve voltage stability and maintain a smooth voltage profile at the point of interconnection [11]. Following fault recovery, the grid voltage increases to approximately 95% of the rated value, however, the grid is still considered to be very weak. An attempt to reconnect the WECS under this condition can make the system unstable as the WECS being reconnected it pulls the grid voltage low due to reactive power.

1.5 Motivation

The main motivation to pursue this research has been the rapid advancements in Wind farm technology, resulting in the quest for economic ways of generating large amounts of power and its integration into the grid along with existing conventional generation stations. The more wind energy gets integrated into grid, the higher the concerns due to the intermittent nature of its generation and non-uniform behavior from its generator technology especially during severe grid disturbances. All these impacts raise questions about system protection schemes [1]. Introduction of new smart Ideas in Power Systems; integration of renewable energy into grid on larger scales; emerging electricity in new services; and, new technologies and resources are all driving factors for this research. The final goal is to help contribute towards improvement of reliability of power to grid system from wind farms both economically and safely.

Investigation into Fault Ride Through (FRT) criteria development provides a pathway for transmission companies to develop their own FRT criteria while taking into account their network and existing generation characteristics but Ethiopia has no still grid code requirements criteria.

Low Voltage Ride-through (LVRT), one of the grid code requirements that are directly impacted by protection settings of the wind farm, has been investigated as one of the research objectives. The thesis initially carries out a comprehensive review of the existing literature

related to large scale wind integration, pertaining to grid or the power system. The treatment in this thesis for case studies revolves around Adama wind farm II Power System and large-scale wind integration into its transmission grid.

With higher level of penetration, it is possible that (Wind Turbine Generators) WTGs are the dominant generation units providing fault currents, used for sensing by protective relaying scheme, due to faults in specific geographical regions. Unreliable protection performance in such a critical grid situation is highly undesirable from overall power system security viewpoint. There are well-established practices to evaluate symmetrical components for fault currents and voltages. The outcomes of this research will also lead towards understanding better operation strategies for wind farm power integration on grid transmission operators [18].

1.6 Statement of the problem

Wind power generation in Ethiopia growing rapidly and this has to lead a higher growth in the supply of electricity with a sustainable manner. However, the growing number of wind projects have been under-taken. This need to have enhancement to facilitate the performance of the wind power integration, including like the development of wind power studies to analyzing the operation of electricity with high wind penetrations to the grid with a maximum output.

In order to keep the system operating securely, operation assessment must be take place on power transfers. Therefore, high power penetration studies are necessary to assess the technical feasibility between the grid and the wind farm integration, to investigate wind power from wind turbine generators to the network. This Power penetration studies comprise of Power flow, short circuit and transient stability studies under the Fault Ride through capability of the wind farm. The operation and control of WTG integrated to grid power systems poses a variety of challenging problems. The solution of which requires extensive analysis of power system with Wind Turbine Generators (WTGs).

1.7 Objectives

The main objective of the research is to Assess and investigate the impact of Large- scale Integration of Wind Power to the National Grid, the case Adama wind farm II. The successful achievement of the main objective will be realized achieving the following specific objectives:

- A review of wind farms impact on power networks and on Grid codes requirements are analyzed.
- Study and investigate the modeling of wind generators for power flow studies using power system generic model.
- Verify the basic characteristics using the model of Adama wind farm II by perform simulation result.
- Perform simulations, analyze the results and further tune the models to verify that the overall model meets the grid integration requirements.
- Study and evaluate the performance of the system to grid on short circuit faults.
- Analyze the performance of the overall system to transient fault-ride-through faults and asses the power system stability issues.
- Evaluate the impact of Adama wind farm II grid integration for transient fault-ride-through and power system stability in general, and give conclusion and recommendation.

1.8 Organization of the thesis

In Chapter 1, the background of the wind energy system, wind energy conversion system and motivation of this project is presented. This chapter also introduces the low voltage ride through capability of DFIG and grid connection codes. The report is organized to provide in depth information about the research done on the DFIG wind energy system, active crowbar and fault detection methods in the subsequent chapters.

Chapter 2 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 3 present the aggregation of the wind farm model of a DFIG wind turbine for transient stability study is explained in detail. Finally, wind farm aggregation technique will be described.

Chapter 4 gives the theoretical explanation of the DFIG from the stator reference frame using the mathematical model and equivalent circuit analysis. The rotor side control scheme is discussed with vector control method.

Chapter 5 provides the DFIG response to different types of fault in the grid during disturbances. The behavior of the DFIG is analyzed under variable wind conditions and when faults are introduced in to the network.

Chapter 6 presents the implementation and strategy of fault detection method and recommended protection scheme. Active crowbar protection is integrated to DFIG using MATLAB Simulink. System recovery is explained and simulation results verify the theory and the proposed protection technique. The last chapter provides an overview of the research undertaking, briefly and summarizes the development of the active crow bar and **DFIG** generators for WECS. Finally, further research recommendation is discussed.

CHAPTER TWO

Literature Review

2.1 Literatures

There are numbers of studies have been conducted on the impact of wind power integration on Ethiopian power system stability. On Adama I wind farm interaction with Ethiopian electric power corporation's grid [3]. 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 the study the impact of both PMSG wind turbine technologies on power system stability will be investigated and also the impact of wind power plant will be analyzed.

Also, the impact of large scale wind power integration on transient stability performance of a power system [1]. 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. 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.

Impact of large scale wind power integration on Ethiopian power system transient stability [4], this study concerned on power system transient stability that 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. The transient stability impact has been analyzed for different aspects like location of fault and generator technology.

2.2 Fault Ride-through (FRT) Requirements

FRT requirements are one of the essential elements of most of the existing grid codes. Because of the large capacity of wind connected to a transmission system requires wind farms to remain in operation during any network disturbance or fault. FRT means that generator or wind farms should be able to stay connected to the grid during a fault or disturbance across a specified voltage envelope. These requirements are specified in terms of voltage versus time characteristics of the connection point. Different countries have different specified envelopes depending on network voltages or characteristics of the network as shown in Table 2.1 below.

Table 2-1 Fault ride through criteria in practice [27]

S.N.	Grid code	Fault duration (ms)	Fault duration (cycles)	Min voltage level (% of Vnom)	Voltage restoration (s)
1	Germany (Eon)	150	7.5	0	1.5
2	UK	140	7	0	1.2
3	Ireland	625	31.25	15	3
4	Nordel	250	12.5	0	0.75
5	Denmark (<100 kV)	140	7	25	0.75
6	Denmark (<100 kV)	100	5	0	10
7	Belgium (large voltage dips)	200	10	0	0.7
8	Belgium (small voltage dips)	1500	75	70	1.5
9	Canada (AESO)	625	37.5	15	3
10	Canada (Hydro-Quebec)	150	9	0	1
11	USA	625	37.5	15	3
12	Spain	500	25	20	1
13	Italy	500	25	20	0.8
14	Sweden (<100 MW)	250	12.5	25	0.25
15	Sweden (>100 MW)	250	12.5	0	0.8

FRT or Low Voltage Ride-through not only require the wind turbines to remain in operation during a fault or disturbance but also needs swift restoration of active and reactive power after the fault. Certain existing codes, wind farms are required to support the system voltage

through reactive power support during the fault. With several available wind generation technologies, grid inter-connection and having concerns over their capability to support grid as effectively as conventional generation, transmission system dictates the development of stricter grid code requirements. New wind generation technologies claim to support transmission networks but existing large wind generation connected to a transmission system raises many concerns for not being able to fully support the system during system level disturbances. The response of a large wind farm during a voltage disturbance could possibly affect system stability [28-30]. With the increasing capacity of wind farms and the possibility of participation in the electricity market towards real-time frequency keeping and reserve management, wind farms cannot afford to go off-grid.

To ensure security of supply, increased penetration and emerging requirements in the form of grid codes different parts of the world including, USA, UK, Germany, Denmark, France, Netherland, etc., oblige wind farms to ensure certain specified capabilities and frequency response [27]. These codes also demand existing and newly installed wind farms to stay connected during various voltage and frequency events.

To avoid disconnection of wind generators from the grid, the performance of protection schemes and the ability of available generator technologies are to be tested for compliance with the internationally available fault ride-through criteria. This is strictly monitored for adherence by the grid operators under situations where generators are disconnected during grid faults. The protection performance of wind farms, short-circuit strengths, fault responses and ability to ride through the faults, needs to be well understood as part of this research. Literature on FRT criteria is available but does not cover their development of criteria detailing the role of protection and wind technology types.

Some grid operators require participation towards voltage stabilization and system recovery during both a fault and the post fault period [31]. FRT not only requires the wind turbines to remain in operation during a fault or disturbance but also needs fast restoration of active and reactive power after the fault. In certain codes, it is required to support the system voltage through positive reactive power during the fault. FRT is subdivided into Low Voltage Ride-through (LVRT) and High Voltage Ride-through (HVRT). FRT capability implies that generators must be able to remain connected during any fault event for defined voltage profile. In some countries, grid codes require all newly installed wind turbines to have FRT or LVRT capability [32,33], enough to satisfy voltage duration curves. These

curves require wind farms to achieve certain voltage support, protection co-ordination and considerations with the system to ensure that they could ride through any fault event [34].

2.3 Other Requirements

There are several other requirements from grid codes for wind farms or generators in general that are not included in this literature review. Requirements such as FRT, active power and frequency control, and reactive power control and voltage regulation may sometimes relate to protection and coordination issues of large wind farms.

2.4 International Experience

China and India have recently progressed well into wind generation. Now a day, China and the US had a share of beyond 27% and 21 % respectively in total global wind generation. Europe has historically been the largest regional market for wind generation in terms of total installed capacity (beyond 77GW, or 33% of the world total). [25].

European countries contribute the most to the world's wind generation compared to the rest of the world. Denmark produces 19% of total power generation through wind, while Spain and Germany are at 14% and 8% respectively [25]. The precedence of wind integration at a larger scale in these countries raises questions of standardized methodology for ride-through studies for other countries and also raises the question as to how much wind or renewable integration remains economical while fulfilling other expectations [26].

In our country Ethiopia, Large scale wind farms connected to the EEPSCO grid have to comply with the grid requirements for the EEPSCO power system to be stable, reliable and serve its customers with quality power. Even though most countries' power system operators have grid connection requirements for wind farms, EEPSCO has not yet developed one for wind farms [3]. The findings of the literatures are important inputs for EEPSCO to make further studies on wind farm interaction with grid as well as to develop wind farm grid connection requirements. Moreover, it is also very important to use reliable and quality wind turbine concepts. In the study [3], Adama wind farm with PMSG WT is proved to be promising. Comparison of the simulation result with the previous requirements shows that Adama wind farm can ride from voltage deep within a short time. The active and reactive power performance of the wind farm is also good with respect to three phase short circuit fault showing its immunity [3].

CHAPTER THREE

Large-Scale-Wind Farm Aggregation

3.1 Large wind farm definition

Large scale wind (also often called 'utility scale') refers to wind energy projects greater than 1 megawatt (MW). This category can include large arrays of 100 or more turbines owned by large corporations or a single locally-owned wind turbine greater than 1 MW in size.

A large-Scale layout diagram of Adama wind farm-II, illustrated in Figure 3.1, is a set of several individual turbines connected together in a large area of land. Having many turbines on a large site also helps smooth the irregularity of wind due to the wind diversity.

A pad mount transformer is installed at the foot of each turbine. It increases the voltage level through an underground collector. The collector system is a set of feeders connecting all pad mount transformers both together and to the substation. The layout of a wind farm stays the same throughout its life unless an upgrade is considered.

A large wind farm is connected to a grid as shown in Figure 3.1. It is a good approach to reduce its size by equivalencing all the wind turbines to an aggregated wind farm for Power flow and stability study as shown in Figure 3.2.

A wind farm will typically include several wind turbine generators. For conducting transient stability studies in which the primary purpose is to examine the impact of the wind farm on system dynamic performance of the system, it is not necessary to represent each wind turbine in the wind farm separately. Typically, the wind farm is represented by a single suitably-sized equivalent interconnected to the grid at the appropriate point of interconnection. All the wind turbine generators are the SANY 1.5 MW DFIG machines. The wind farm shown in Fig-3.2 consists of eight wind turbine generators and each represents 13 turbines merged as a single turbine, i.e., thus turbine are 102 turbines aggregated as eight turbines. The figure above for the various feeders connecting the wind turbine generators, the pad mount transformers at each wind turbine, and the interconnection to the grid are provided. Adama wind farm-II, as shown in Figure 3.1, consists of one hundred two turbines of the same types. A WTG is usually rated at low three phase voltage output (690 V). A pad mounted transformer at each turbine generator steps up the voltage to the medium voltage

Adama wind Farm-II General Layout

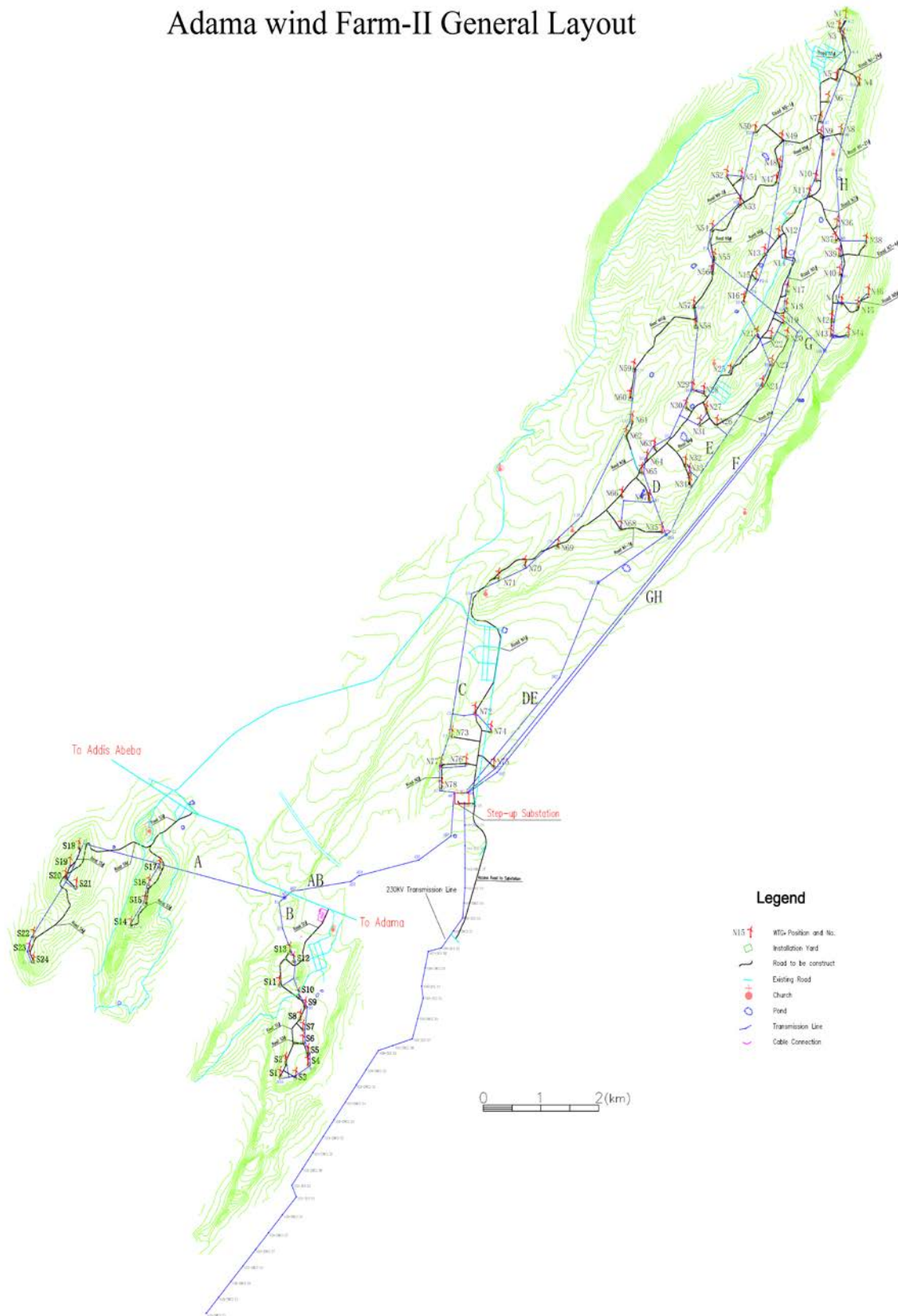


Figure 3-1 General Layout of Adama wind farm II

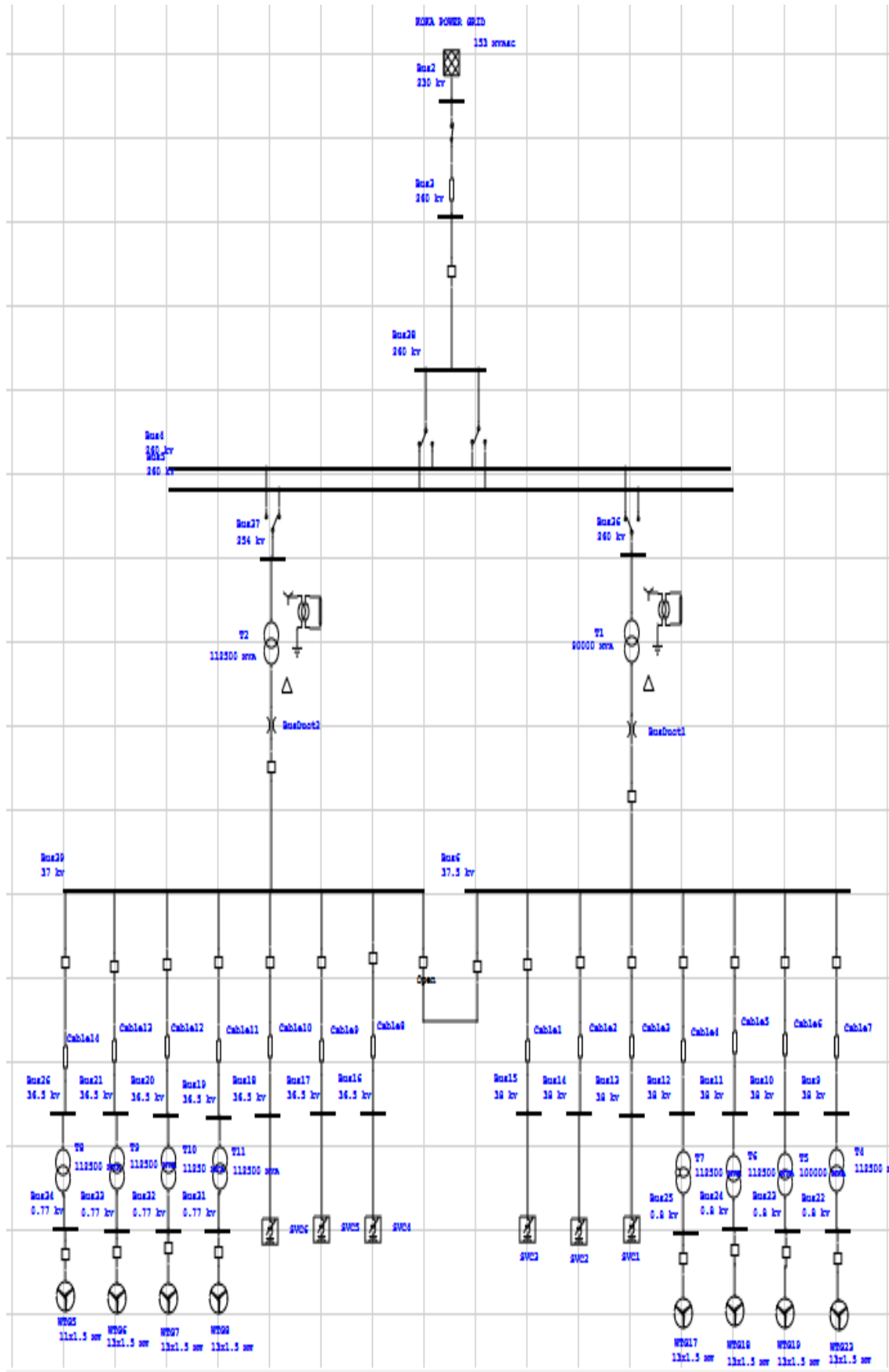


Figure 3-2 An aggregated Modeling of Adama wind farm-II (Using ETAP Software)

collector system (0.69 kV $\rightarrow$ 33kV). Several turbines that are physically close together are connected to laterally to form a group. Several of these groups are connected to a larger main feeder. Several of these feeders are connected to the substation where the substation transformer steps up the voltage to a desired transmission level (i.e., 33kv to 230 kV). On the substation the WF can have Two substation transformers. An example of a WPP layout can be seen in Figure 3.2.

Within a WPP, different turbines operate under appreciably the same conditions. Line impedance connecting each wind turbine to the Point of Interconnection (POI) the same to each other. At a particular instant in time, the wind speed experienced by one turbine can be significantly the same from another turbine located at another part of the wind farm (WF). The diversity of a WF is a good attribute in many ways. For example, the output variability of the entire WF is attenuated with respect to the variability observed on a single wind turbine. The interaction between a WF and the grid is determined by the collective behavior of the WF. In contrast, a conventional powerplant interacts with the grid as a single large generator.

Table 3-1Adama II wind power plant turbine generator specifications

Parameters	Values
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

3.2 Equivalent Circuit of Grid connected wind farm

Wind farm equivalencing, describes methods of equivalencing collector system in a large WF. We simplified a WF with many wind turbines into a simplified turbine representation, as shown in Figure 3.1. The full system representation (FSR) is a representation of WF where every turbine is represented along with the interconnecting collector system connecting each turbine with another, and connecting group of turbines to the point of inter

connection (POI). A Single Turbine Representation (STR) is a representation of WF where a single turbine is used to represent the entire Wind Power Plant WPP.

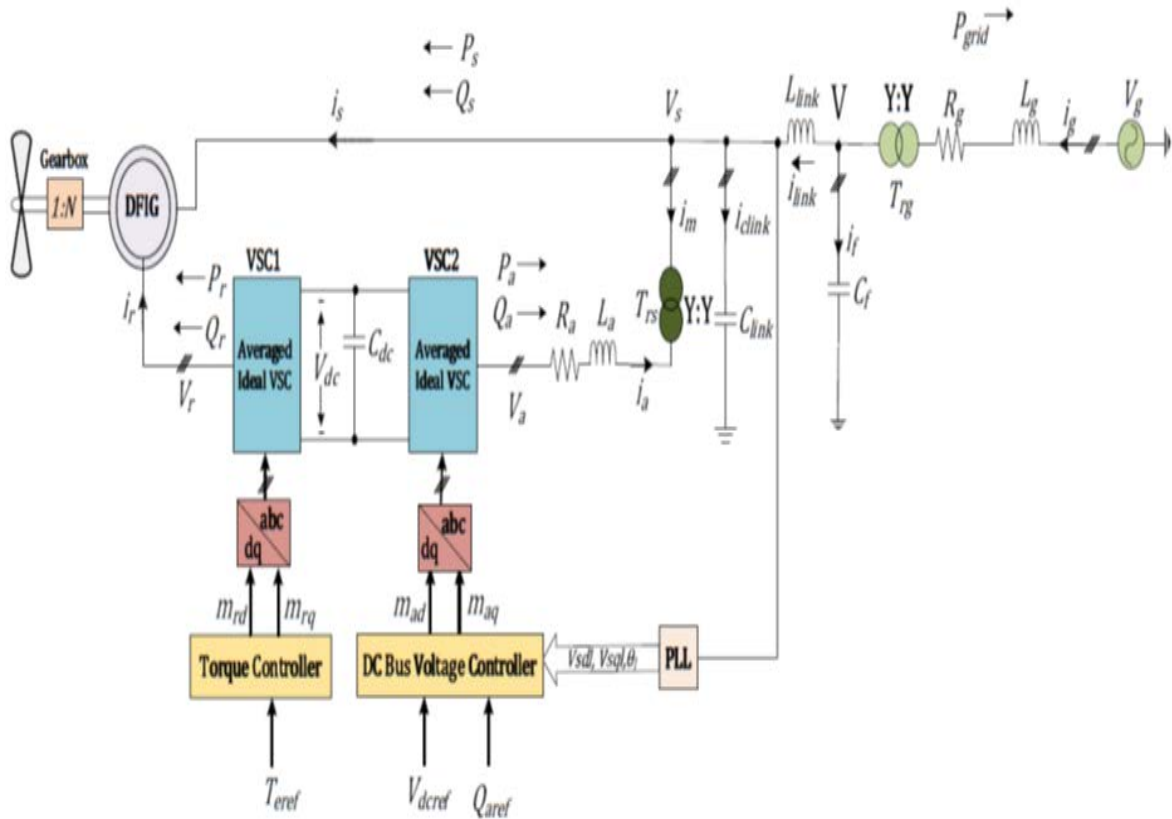


Table 3-3 A schematic diagram of a grid-connected single DFIG-based wind turbine with its control system. [24]

This representation is more practical for bulk system simulations. A later section of the report will provide technical justification for the use of the STR in power flow and dynamic stability simulations. For the case of Adama wind farm-II, the WF contain the same types of wind turbines. So, The Adama-II WF could have clusters that are the same electrical connection point of view. The plant connected through a long overhead feeder, while another portion of the plant is connected through short underground feeders. This same diversity of significant to be represented with a model similar to the STR by defining distinct WTG groups, each of which can be modeled as an STR. Several methods of grouping considerations are also possible, resulting in a multiple turbine representation (MTR) that can more accurately represent the unique characteristics of a significantly non-diverse WPP.

The turbine is interfaced with the grid through a linking inductance, L_{link} , a transformer, T_{rg} , and a transmission line where an ideal voltage source, V_g , is the grid as mentioned in Figure 3.3. The high voltage side of the T_{rg} , is connected with V_g . The stator of the DFIG is directly

connected to L_{link} , while the rotor is connected through the ac-dc-ac back-to-back Voltage Source Convertors (VSCs) to L_{link} . Figure 3.3 shows the two back-to-back converters, rotor side and grid side converters that are referred to as VSC1 and VSC2, respectively.

Thus capacitors, C_{link} and C_f , provide a low-impedance path for switching harmonics, which are generated by VSCs. The voltage at PCC is V , where L_{link} and T_{rg} , are connected. The transmission line consists of resistance, R_g , and inductance, L_g , connected in series. The mechanical dynamics of Figure 3.1 is described by

$$J \frac{d\omega_r}{dt} = T_{tur} - T_e \quad (3.1)$$

where J is the moment of inertia, ω_r is the machine rotor speed, T_{tur} is considered to be turbine torque and T_e is the electrical torque [5,6,7]. Equation (3.1) is significant in analyzing the stability of the wind power system as it helps to describe the effect of any mismatch between the electrical and the mechanical torques generated by the turbine. A detailed description and a non-linear mathematical model of each block of the overall system as shown in Figure 3.3 is synchronously developed [24].

3.3 Aggregated model for Grid connected Wind Farm

In order to make the aggregation model, it is necessary to develop an equivalent representation of the wind power plant considering the power losses and the voltage drop. Every different layout has a different impact on the line impedances to the grid interconnection bus. The idea is to calculate the equivalent characteristics of the lines according to the initial conditions and the configuration of the lines.

Equivalent Wind Turbine:

Reducing n wind turbines to a single wind turbine, the parameters for the equivalent machine are the active power in megawatts, the reactive power in megavolt amps reactive and the apparent power in megavolt amps. The parameters are given by:

$$P_{eq} = N * P_{MWp.u} \quad (3.2)$$

$$Q_{eq} = N * Q_{MVar p.u} \quad (3.3)$$

$$S_{eq} = N * S_{MVA p.u} \quad (3.4)$$

Where P_{eq} the equivalent Real Power, N is the number of wind turbine, Q_{eq} the equivalent Reactive power, S_{eq} the equivalent Apparent power.

Two assumptions can be taken. Firstly, the current injections from all the wind turbines have the same magnitude and angle and, secondly, the reactive power generated by the line capacitive shunts is based on the assumption that the voltage is 1 p.u.

Two types of layouts are examined. The first one, corresponding to just one row, shows a daisy chain configuration and the second one, corresponding to the aggregation of a different number of rows, shows different branches connected to the same node. The derivation of all the formulas shown here, is explained in detail in [21].

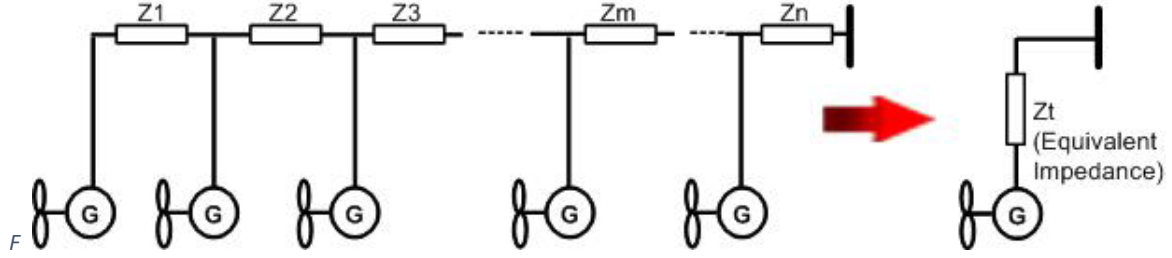


Figure 3-4 Distribution network aggregation Case 1

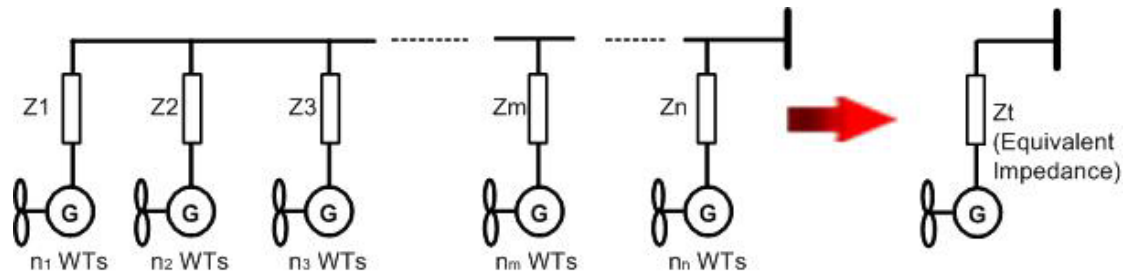


Figure 3-5 Distribution network aggregation Case 2

When the distribution looks like the distribution in figure 3.1, the equivalent impedance is:

$$Z_t = \frac{\sum_{m=1}^n (m^2 Z_m)}{n^2} \quad (3.4)$$

where Z_m is the impedance in branch m and n is the number of branches.

For the shunt representation the equivalent susceptance is:

$$\sum_{i=1}^n B_i \quad (3.5)$$

When the lines are in parallel, such as in figure 3.2, the formula for the equivalent resultant line of the aggregated model considering the same amount of losses of the lines of the detail model, is:

$$Z_t = \frac{\sum_{m=1}^n ((n_m)^2 * Z_m)}{(\sum_{m=1}^n (n_m))^2} \quad (3.6)$$

where Z_m is impedance in branch m and n_m is the number of wind turbines at branch m .

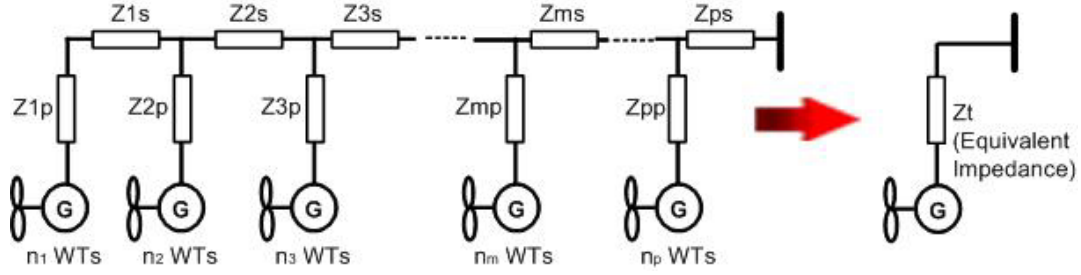


Figure 3-6 wind turbine network aggregation Case 3

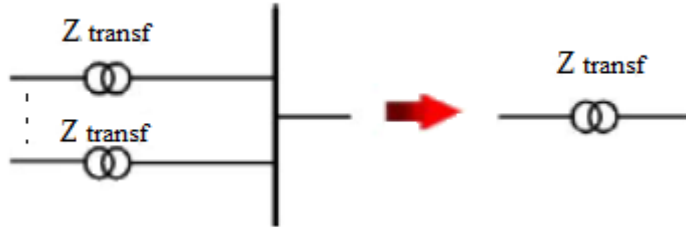


Figure 3-7 Transformer Aggregation

Other kinds of configuration such as the one in figure 3.6 can be found. Then the equivalent impedance is

$$Z_t = \frac{\sum_{m=1}^p n_m^2 Z_{mp} + \sum_{m=1}^s (\sum_{m=1}^p n_m)^2 Z_{ms}}{(\sum_{m=1}^p n_m)^2} \quad (3.7)$$

where Z_{mp} is the impedance in each branch m , Z_{ms} is the impedance in between branch m and branch $m+1$ and n_m is the number of wind turbines in branch m .

The expression of the transformer impedance shown in figure 3.7, is:

$$Z'_{transf} = \frac{Z_{transf}}{n_{turbines}} \quad (3.8)$$

where $n_{turbines}$ are the number of wind turbines aggregated in the model

3.4 Assumption of An Aggregated Model

It is important to consider the influence of power wind plants in power systems. In order to analyze their behavior and influence it is convenient to create aggregated models of wind farms that allow different analysis to carry out. A large-Scale wind farm like Adama wind Farm can have more than one hundred wind turbines, therefore not all the turbines can be represented in detail because the computation time would be too long and also because the increased possibility of making mistakes if every turbine is considered when modeling the entire wind farm.

The following assumptions are made to closely represent a real wind farm without simulating each wind turbine.

1. A large wind farm is divided into several groups of turbines, depending on their characteristics, the wind profile or the distribution of the layout.
2. For each group of wind turbines, the wind speed is considered uniform.
3. The groups are arranged in sequence according to the wind speed they encounter.
4. All the turbines are exposed to the same turbulence level.
5. It is not necessary that every group of wind turbines is composed of the same number of wind turbines, it depends on the number of turbines with the same characteristics, but finally the total amount of wind turbines in the wind farm representation should remain the same.
6. Not only the wind turbines, but also the distribution network in the wind farm should be aggregated. This means that the resulting line or lines should be equivalent to the original ones. In order to do this the power losses and voltage drop are considered.

On the whole, and in a simplified manner, in the equivalent aggregated model the idea is:

$$S_{eq} = \sum S_i \quad (3.9)$$

$$C_{eq} = \sum C_i \quad (3.10)$$

$$P_{m,eq} = \sum P_{m,i} \quad (3.11)$$

where the subscript i represents the single turbine in the aggregation.

3.5 Assessment Criteria

Wind farms with wind turbine generators can be simulated by a complete model including the modeling of all the wind turbines and the wind farm electrical network. To represent wind turbines in wind farms without increasing unnecessarily the model order, reduced models have been used. But this complete model presents a high order model if a wind farm with high number of wind turbines is modeled and therefore the simulation time is long. To reduce the complexity of the wind farm model and the simulation time when simulating wind farms with wind turbines in power systems, aggregated models of wind farms have been developed by the aggregation of wind turbines with identical wind into an equivalent wind turbine. The aggregation of wind turbine generators with identical wind speeds into an equivalent wind turbine generator experiencing that wind speed has been considered. This equivalent wind turbine presents the same per unit model and parameters of that of individual wind turbine generator. The two main assumptions made while reducing the wind park to a single equivalent are:

- All wind turbines have same operating point.
- If difference in operating point exists it is not too large.

When reducing the aggregate model of the large wind farm for the purpose of simulation studies the following criteria shall be fulfilled:

A simple aggregated model is considered in all the studies (Power flow analysis, Short circuit analysis and Transient stability analysis) for representing wind farms. Simple aggregation is explained by considering the Adama wind farm. By assuming the direction of the wind velocity as shown in Figure 3.2 and neglecting the wake effect, the wind farm is represented by its simple aggregated model as shown in Figure 3.8. The parameters of WTGs in simple aggregated model is explained in Table3.3

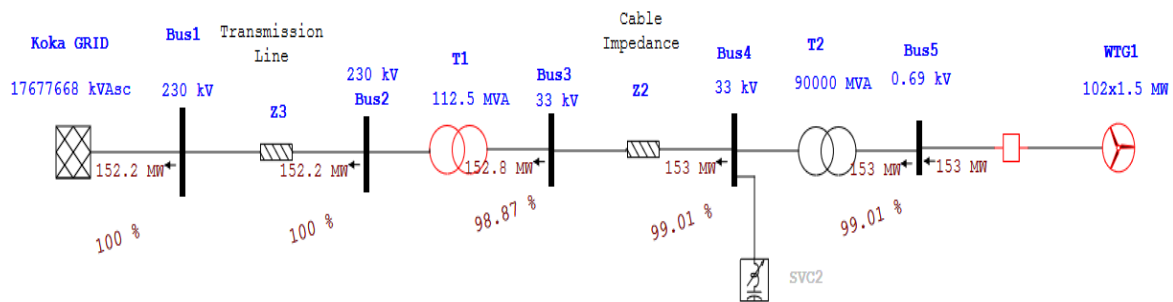


Figure 3-8 a simple single aggregated wind farm

Table 3-2 Parameters of Detailed and Simple aggregated model

N ₀	Nomenclature	Detailed model of wind farm	Simple aggregation model of wind farm
1.	Stator Resistance	R_s	R_s / N_t^*
2.	Stator Reactance	X_s	X_s / N_t
3.	Rotor Resistance	R_r	R_r / N_t
4.	Rotor Reactance	X_r	X_r / N_t
5.	Mutual Reactance	X_m	X_m / N_t
6.	Inertia of the turbine	H_t	$H_t * N_t$
7.	Inertia of the generator	H_g	$H_g * N_t$
* N_t -Number of wind turbine generators			

Table 3-3 transformer equivalent impedance for all aggregated group

Group	No. of Transformer	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

Table 3-4 Summary of collector circuit impedance for all aggregated group

Group	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

3.6 Systematic Computation for fault ride through

3.6.1 LVRT with Fault outside the Collector System

A symmetrical three-phase fault, through an impedance = $0 + j 0$ p.u., is simulated on bus 2 as shown in Figure 3.8 by the red arrow. The fault is located outside of the 33-kV wind farm collector system. If the fault appears at 0.2 sec and is removed at 0.8 sec, the low voltage ride-through shows that the wind farm is able to recover all the total generation power as shown in the first plot of Figure 3.9. The time to clear the fault has been extended to reach the critical time, or stability limit of 0.833 sec.

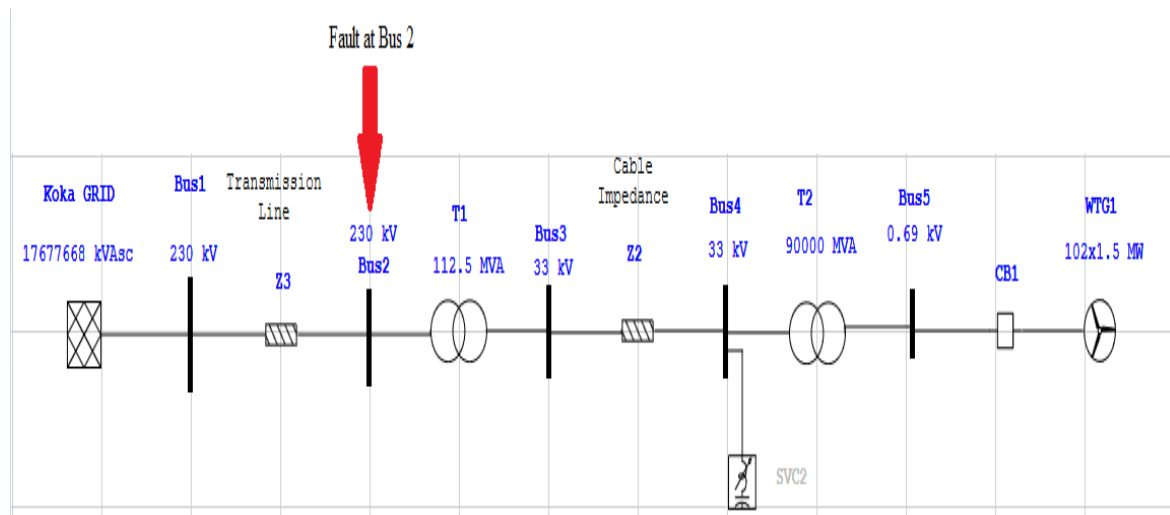


Figure 3-9 Low voltage ride-through study with fault at bus 2

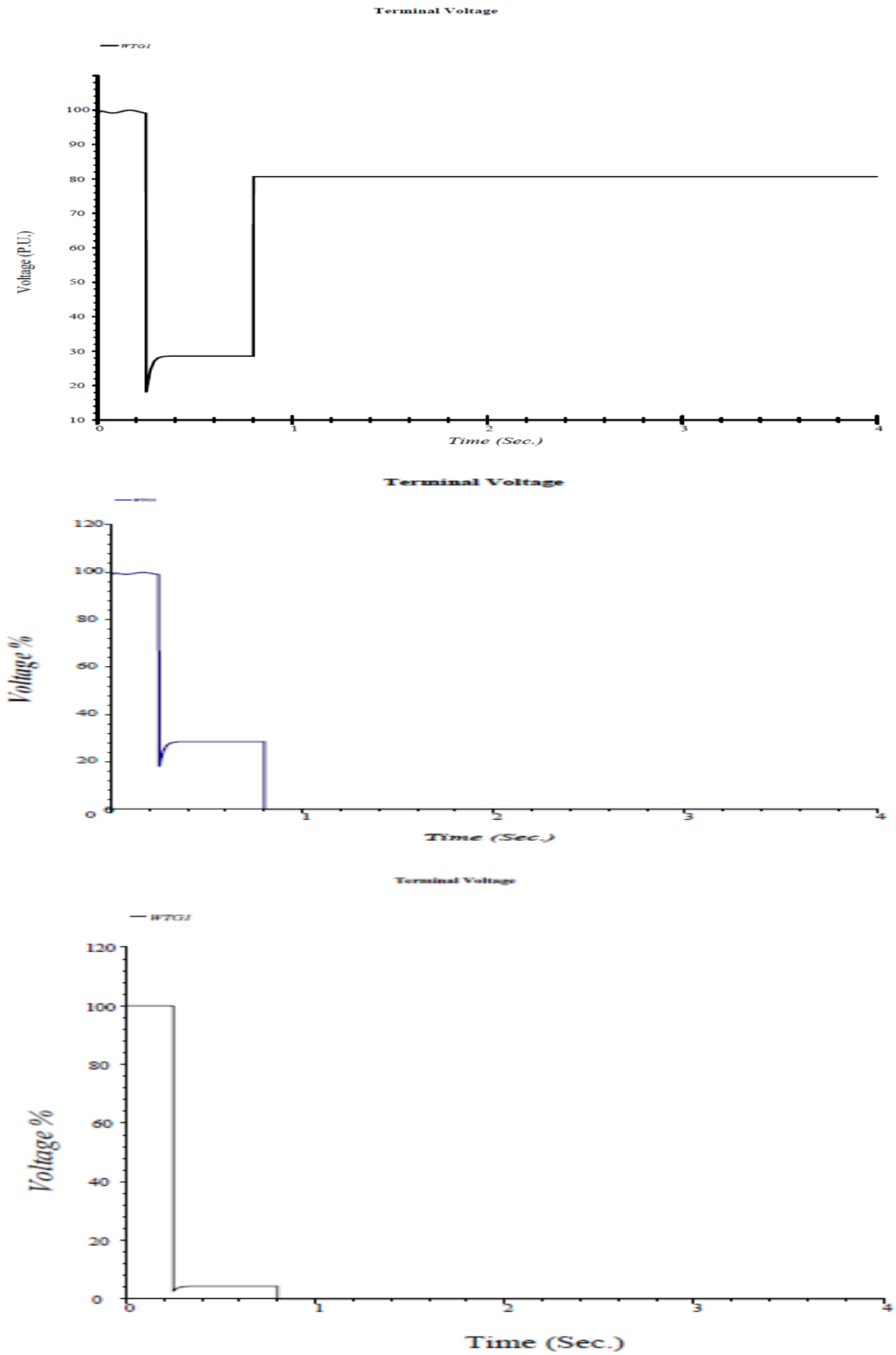


Figure 3-10 Simulation results for symmetrical three-phase solid fault at bus 2

If the fault lasts for 0.833 sec or more, all 102 wind turbines will disconnect from the grid, and there is a total generation loss as shown in the second plot of Figure 3.9. The analysis of terminal voltages on all wind turbines during the fault shows voltages within the lowest value of 0.198 p.u. and the highest value of 0.221 p.u. as shown on the last plot of Figure 3.9.

For the same fault conditions at bus 2, the Cases have the same stability limit time of 0.833 sec. A symmetrical fault has been simulated outside of the collector system on bus 3, as diagrammed in Figure 3.13. The bus is located between the collector system and the substation.

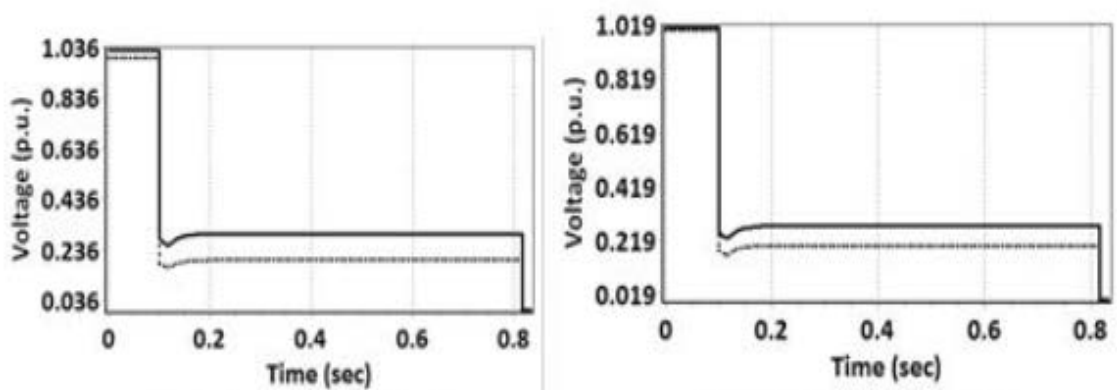


Figure 3-11 Stability time limits for fault at bus 3

For the fault at bus 3, the impedance of the substation does not contribute to the limitation of short circuit current from the large wind farm. The fault appears at 0.1 sec. During the short circuit, the voltages on all wind turbines drop from 1 p.u. to the lower range between 0.01 and 0.24 p.u.

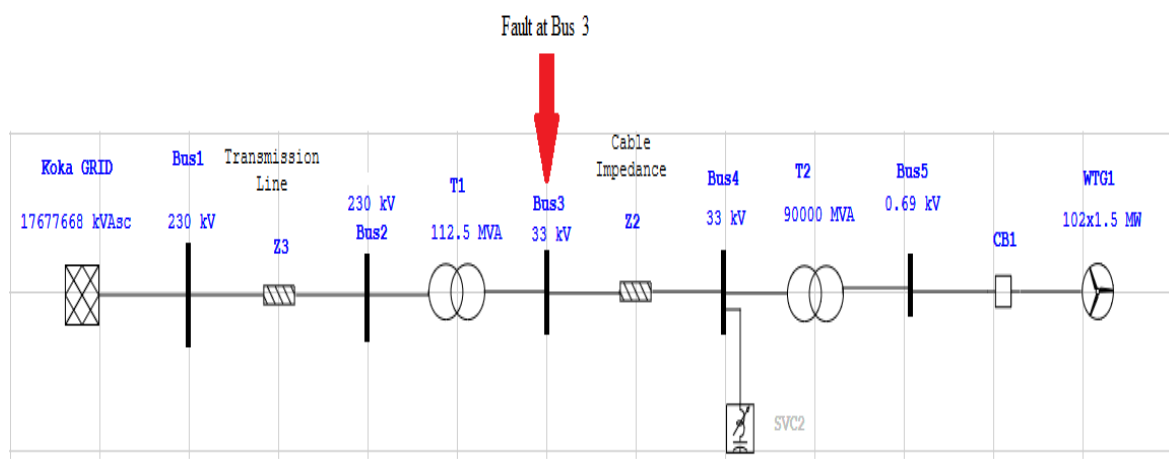


Figure 3-12 Low voltage ride-through study with fault at bus 3

All the wind turbines will disconnect from the grid at the same time of 0.33 sec as shown in Figure 3.12. The analysis of aggregated models of 102 wind turbines to a single wind turbine with and without the 33-kV equivalent collector system gives the same results, as shown respectively in the second and the last plots of Figure 3.13.

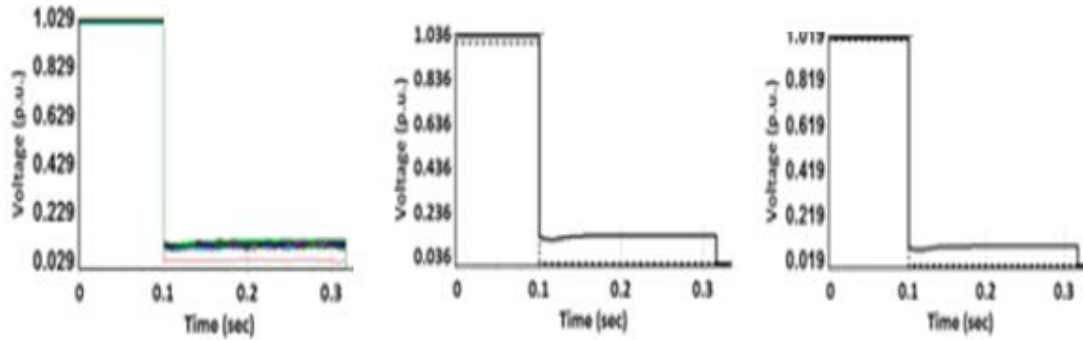


Figure 3-33 Simulations results for a solid symmetrical fault at bus 3

Bus 3 represents the line of symmetry as the wind turbines see the fault. For faults located between bus 3 and the point of interconnection to the grid, all wind turbines have the same behavior in terms of the time they will trip from the grid. They are likely to trip at the same time.

3.6.2 LVRT with Fault within the Collector System

A symmetrical fault, through an impedance = $0 + j 0$ p.u., has been simulated within the collector system between the eight groups of 102 wind turbines having an aggregated 13 turbines at bus 4 as shown by the red arrow in Figure 3-14.

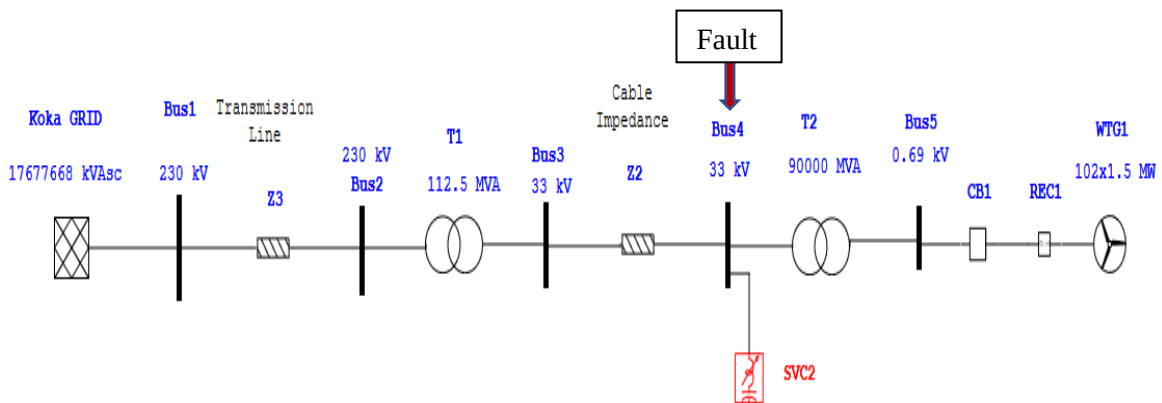


Figure 3-4 Low voltage ride-through study with fault at bus 4

A monitoring of voltages on wind turbines has been performed on all wind turbines through the wind farm as shown in Figure 6.15. The plot of voltages shows that all wind turbines do

not have the same terminal voltage during the short circuit. Wind turbines will trip at different times in accordance with the wind turbine LVRT curve.

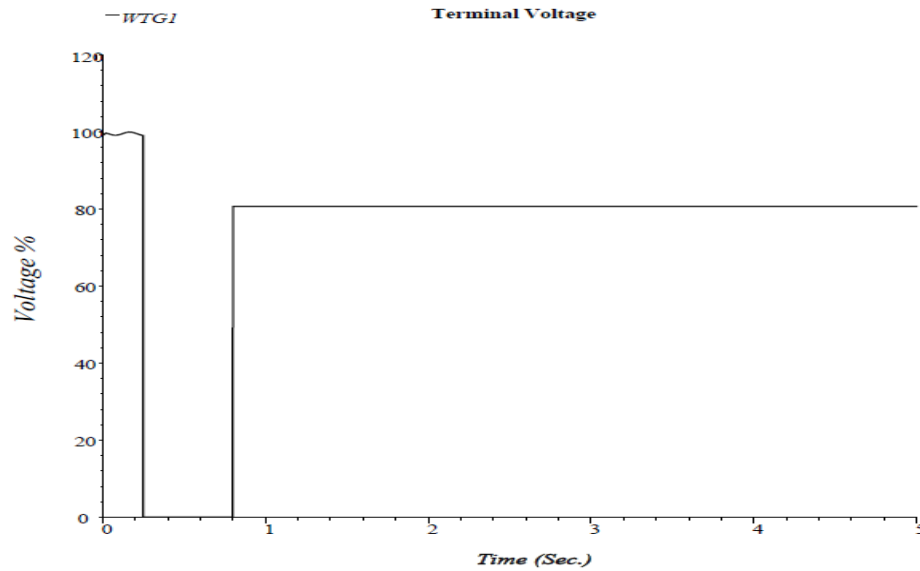


Figure 3-5 Low voltage ride-through study with fault at bus 4

The analysis of low voltage ride-through on each wind turbine on the faulted feeder shows that all the wind turbines from the last in the queue to the point of fault have a lower voltage of 0.008 p.u. They will trip at time 0.217 sec. The fault on the last daisy-chain is likely propagating through the entire wind farm. In order to stop the propagation, a high impedance value is inserted by increasing the impedance of the feeder between buses during the short circuit. The plots of voltage during short circuit are given in Figure 3.16.

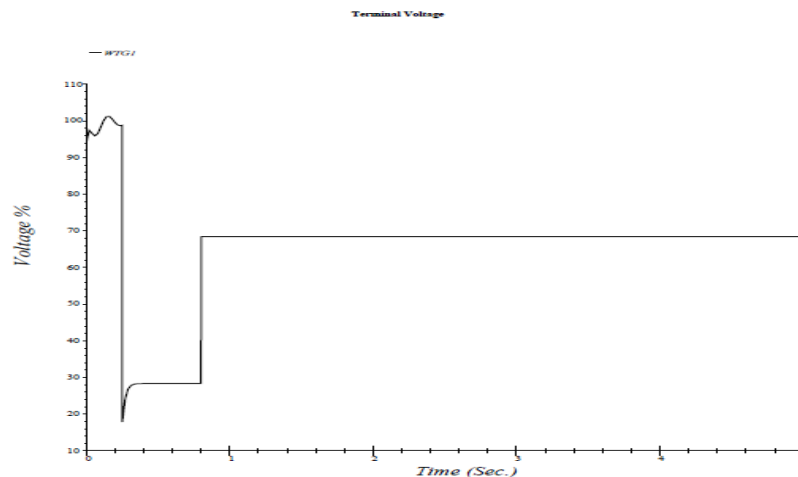


Figure 3-6 LVRT with an increased feeder impedance during short-circuit

Voltages on the wind turbines increase from 0.08 to 0.28 V. They will trip from the grid at 0.28 sec. We realize that in this case the wind farm is not going to trip as before at the time

1.33sec. The fault will ride through for 0.84 sec more. The wind farm is going to disconnect totally from the grid at time 1.81 sec.

During a short circuit within a large wind farm, the number of wind turbines tripping can be reduced by increasing the impedance of the feeder connecting the point of fault to the rest of the collector system. The insertion of impedance on the faulted feeder will also increase the stability limit time of the wind farm. An insertion of resistance will cause an increase of active power losses through the wind farm. An increase of 100 times has been done only on the reactive impedance component of feeder. The low voltage ride-through simulation gives better results, as summarized in Figure 3.16. There is a net increase of wind farm voltage during the short-circuit.

An aggregated model cannot be used to determine why some wind turbines trip and others do not in a large wind farm, nor can it determine the sequence in which they will disconnect from the grid. Faults within a large wind farm are likely to appear anywhere within the wind farm; a number of points can be identified at the sectionalizing post to buffer the propagation of the fault. A proposal for the wind farm under study will be to insert self-impedance at the sectionalizing post, between bus and the feeder. A smart system will locate the position of the short circuit, identify the faulted feeder and insert a self-impedance in series with the faulted feeder during the short circuit.

CHAPTER FOUR

Model and Operating Principle of DFIG

In order to investigate the impacts of these doubly fed induction generators installations on the operation and control of the power system, accurate models are required. The doubly fed induction generator can supply power at constant voltage and constant frequency while the rotor speed varies. This makes it suitable for variable speed wind energy applications. Additionally, when a back-to-back converter is used in the rotor circuit, the speed range can be extended above synchronous speed and power can be generated both from the stator and the rotor. An advantage of DFIG drive is that the rotor converter need only be rated for a fraction of the total output power, the fraction depending on the allowable sub- and super-synchronous speed range.

The rotor side converter (RSC) usually provides active and reactive power control of the machine while the grid-side converter (GSC) keeps the voltage of the DC-link constant. The additional freedom of reactive power generation by the GSC is not mostly used; the rotor side converters are used. However, within the available current capacity the GSC can be controlled to participate in reactive power generation in steady state as well as during low voltage periods. The GSC can supply the required reactive current very quickly while the RSC passes the current through the machine resulting in a delay. Both converters can be temporarily overloaded, so the DFIG is able to provide a considerable contribution to grid voltage support during short circuit periods. In this chapter the introduction of DFIG, AC-DC-AC converter control and finally the Simulink® MATLAB simulation for grid connected Doubly Fed Induction Generator is presented.

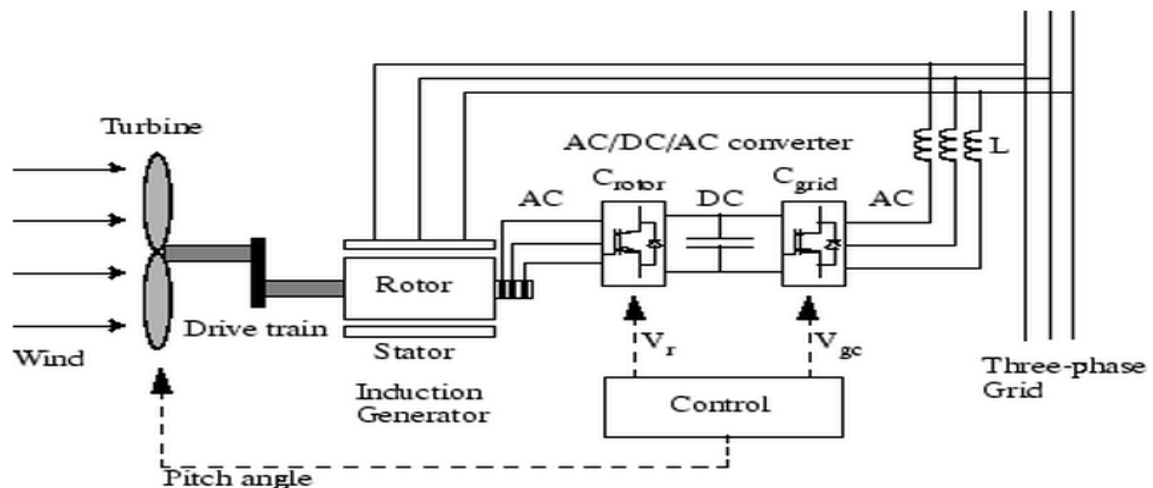


Figure 4-1 General operating model of DFIG with converters

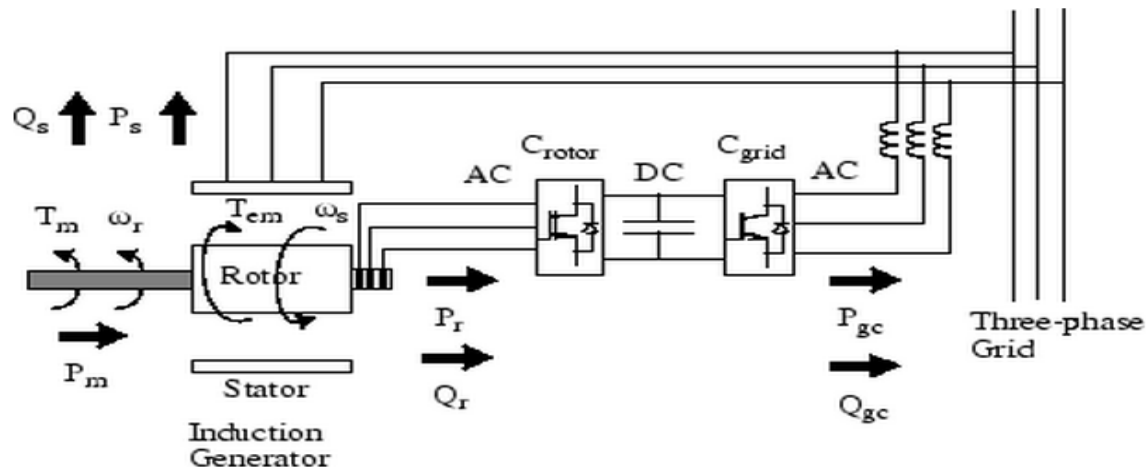


Figure 4-2 Power Flow Diagram of DFIG

The power flow parameters are:

P_m -Mechanical power captured by the wind turbine and transmitted to the rotor

P_s - Stator electrical power output

Q_r -Rotor reactive power output

P_r - Rotor electrical power output

Q_{gc} - C_{grid} reactive power output

P_{gc} - C_{grid} electrical power output

T_m - Mechanical torque applied to rotor

Q_s - Stator reactive power output

ω_r -Rotational speed of rotor

T_{em} - Electromagnetic torque applied to the rotor by the generator

J - Combined rotor and wind turbine inertia coefficient

ω_s -Rotational speed of the magnetic flux in the air-gap of the generator, this speed is named synchronous speed. It is proportional to the frequency of the grid voltage and to the number of generator poles.

4.1 Modeling of DFIG

A Large-Scale wind turbine were built today in most world countries, in which wind energy is transformed into electrical energy using a simple squirrel-cage induction machine directly connected to a three-phase power grid. The generator shaft and the rotor of the wind turbine are coupled with a fixed-ratio gearbox. In some cases, induction generators use pole-adjustable winding configurations to enable operation at different synchronous speeds. However, at any given operating point, this turbine has to operate at a constant speed. The construction and performance of fixed-speed wind turbines

mainly depends on the characteristics of mechanical sub circuits, such as, pitch control time constants, main breaker maximum switching rate and etc. The response time of the mechanical circuits is may be in the range of tens of milliseconds. As a result, each time a gust of wind hits the turbine, a fast and strong variation of electrical output power can be observed. Due to these load variations, it requires a stiff power grid to enable stable operation and a robust mechanical design to absorb high mechanical stresses. Overall, this construction strategy results in expensive mechanical construction, especially at high-rated power [10]. Key advantages of adjustable speed generator compared to fixed speed generators

- They are cost effective and provide simple pitch control; the controlling speed of the generator (frequency) allows the pitch control time constants to become longer, reducing pitch control complexity and peak power requirements. At lower wind speed, the pitch angle is usually fixed. Pitch angle control is performed only to limit maximum output power at high wind speed.
- They reduce mechanical stresses; gusts of wind can be absorbed, i.e., energy is stored in mechanical inertia of the turbine, creating an "elasticity" that reduces torque pulsations.
- They have ability to dynamically compensate for torque and power pulsations caused by back pressure of the tower. This back pressure causes noticeable torque pulsations at a rate equal to the turbine rotor speed times the number of rotor wings.
- They improve power quality; torque pulsations can be reduced due to the elasticity of the wind turbine system. This eliminates electrical power variations, i.e., fewer flickers.
- They improve the system frequency; turbine speed is adjusted as a function of wind speed to maximize output power. Operation at a maximum power point can be realized over a wide power range. As a result, energy efficiency can be improved by up to 10%.
- They reduce acoustic noise, because low speed operation is possible at lower conditions.

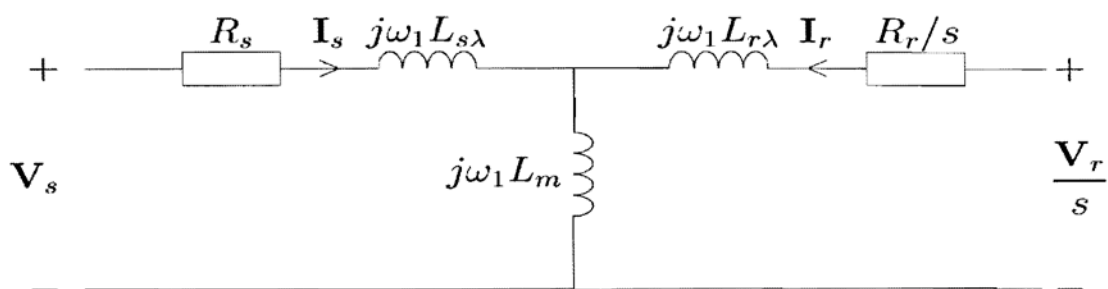


Figure 4-3 Equivalent circuit of Doubly Fed Induction Generator

The equivalent circuit of the doubly-fed induction generator, with inclusion of magnetizing losses can be seen in Fig. 4.3. The equivalent circuit is valid for one equivalent Y phase and for steady-state calculations.

In the case that the DFIG is delta connected the machine can still be represented by this equivalent Y representation. In this section the J_{ω} - method is adopted for calculations. Note, that if the rotor voltage, V_r in Fig. 4.3, is short circuited the equivalent circuit for the DFIG becomes the ordinary equivalent circuit for a cage-bar induction machine. Applying Kirchhoff's voltage law to the circuit in Fig. 4.3 yields [6, 10].

$$V_s = R_s i_s + J_{\omega 1} L_{s\lambda} I_s + J_{\omega 1} L_m (I_s + I_r). \quad (4.1)$$

$$\frac{V_r}{s} = \frac{R_r}{s} i_r + J_{\omega 1} L_{r\lambda} I_r + J_{\omega 1} L_m (I_s + I_r). \quad (4.2)$$

The following notations are used;

V_s -stator voltage;

V_r -rotor voltage;

I_s -stator current;

$L_{s\lambda}$ -stator leakage inductance

ω_1 -stator frequency;

L_m -magnetizing inductance;

S -slip.

R_s stator resistance;

R_r rotor resistance;

I_r rotor current;

L_r A rotor leakage inductance;

L_m magnetizing inductance;

The slip, S , equals

$$S = \frac{\omega_1 - \omega_r}{\omega_1} = \frac{\omega_2}{\omega_1} \quad (4.1)$$

Where ω_r is the rotor speed and ω_2 is the slip frequency. Moreover, if the air gap flux, stator flux and rotor flux are defined as

$$\psi_m = L_m (I_s + I_r). \quad (4.2)$$

$$\psi_s = L_{s\lambda} I_s + L_m (I_s + I_r) = L_{s\lambda} I_s + \psi_m. \quad (4.3)$$

$$\psi_r = L_{r\lambda} I_r + L_m (I_s + I_r) = L_{r\lambda} I_r + \psi_m. \quad (4.4)$$

Equations (4.1) - (4.3) that describe the equivalent circuit can be rewritten as

$$V_s = R_s i_s + j\omega_1 \psi_s. \quad (4.5)$$

$$\frac{V_r}{s} = \frac{R_r}{s} I_{sr} + j\omega_1 \psi_r. \quad (4.7)$$

The resistive losses of the induction generator are given by;

$$P_{loss} = 3(R_s (I_s)^2 + R_r (I_r)^2). \quad (4.8)$$

And the electro-mechanical *Torque*, T_e , can be expressed as

$$T_e = 3n_p I_m [\psi_m i_r^*] = 3n_p I_m [\psi_r I_R^*]. \quad (4.9)$$

Where n_p is the number of pole pairs

The power flow equations of the DFIG system, stator apparent power S_s and rotor apparent power S_r can be found as

$$S_s = 3V_s i_s^* = 3R_s |I_s|^2 + j3\omega_1 L_{s\lambda} |I|^2 + j3\omega_1 \psi_m I_s^*. \quad (4.10)$$

$$S_r = 3V_r i_r^* = 3R_r |I_r|^2 + j3\omega_1 L_{r\lambda} |I|^2 + j3\omega_1 \psi_m I_r^*. \quad (4.11)$$

Rewriting equations (4.13) and (4.14)

$$S_s = 3R_s |I_s|^2 + j3\omega_1 L_{s\lambda} |I|^2 + j3\omega_1 \frac{|\psi_m|^2}{L_m} - j3\omega_1 \psi_m I_s^*. \quad (4.12)$$

$$S_r = 3R_r |I_r|^2 + j3\omega_1 L_{r\lambda} |I|^2 + j3\omega_1 \frac{|\psi_m|^2}{L_m} - j3\omega_1 \psi_m I_r^*. \quad (4.13)$$

Now the stator and rotor power can be determined as

$$P_s = R_e [S_s] = 3R_s |I_s|^2 + 3\omega_1 I_m [\psi_m I_r^*] \approx 3\omega_1 I_m [\psi_m I_r^*]. \quad (4.14)$$

$$P_r = R_e [S_r] = 3R_r |I_r|^2 + 3\omega_1 I_m [\psi_m I_r^*] \approx 3\omega_1 I_m [\psi_m I_r^*]. \quad (4.15)$$

The approximations are made because the resistive losses and the magnetizing losses have been neglected. Finally, the mechanical power produced by the DFIG can be determined from the above equations as the sum of the stator and rotor power.

$$P_{mech} = 3\omega_1 I_m [\psi_m I_r^*] - 3\omega_1 I_m [\psi_m I_r^*] = 3\omega_1 I_m [\psi_m I_r^*]. \quad (4.16)$$

4.2 Rotor Side Converter

The aim of the rotor side converter is to control independently the active and reactive power. The active and reactive powers are not controlled directly, but by controlling the impressed rotor current. The rotor side converter operates in a stator flux d - q reference frame, where the rotor current is split into a parallel and orthogonal component to the stator flux, respectively. A very fast inner control loop regulates the active and the reactive component of the rotor current. The current set points are defined by the slower outer control loop regulating the active and reactive power. In order to decouple these two parameters, generator quantities are calculated using vector control technique in a synchronous reference

frame fixed to the stator flux [10]. The controller provides set point values of the quadrature and direct axis component of the rotor current (i_{qr} and i_{dr}). The control of active power is realized according to the control diagram as illustrated in Fig. 4-4 [10].

In normal operation the aim of the rotor side converter controller is to control active and reactive power independently. The reference active power is provided by a maximum power tracking depending on the actual generator speed, which assures operation with maximum aerodynamic efficiency. During normal operation the reference reactive power is usually set to zero. For high wind speeds the speed of the turbine is limited to its rated speed, which implies indirectly that the power is limited to its rated value, too. This is realized by means of a speed controller interacting with the pitch mechanism. [10].

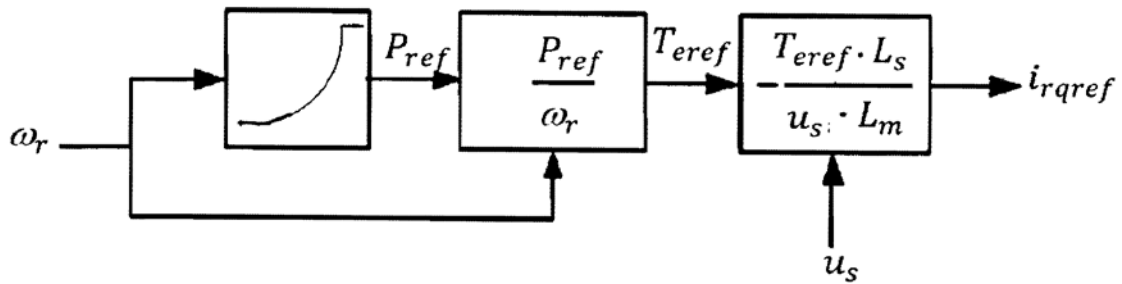


Figure 4-4 Rotor speed and active power control

It can be concluded that machine side converter behaves as a controlled current source providing power control through rotor current regulations. The implementation of the active and reactive power control is done by generating a reference current vector i_{dqr_ref} Which is proportional to the reactive power, Q_{ref} and the torque command, T_e .

The Field oriented control (also known as FOC) is the most popular among all Induction motor control mechanisms. This method is responsible for transforming the three-phase time

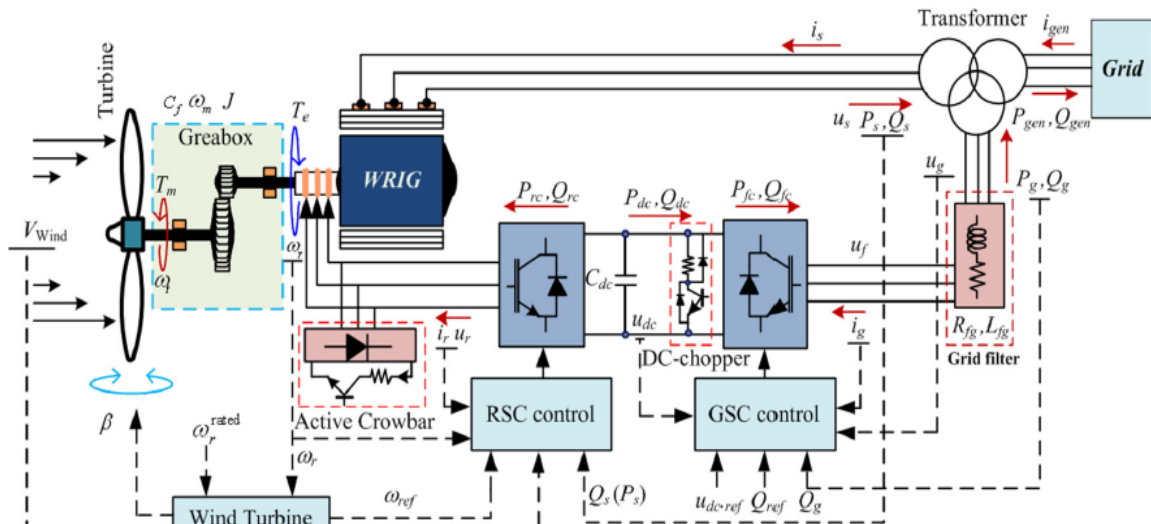


Figure 4-5 Doubly fed induction generator with converters connected to a grid. [24]

variant model, into a two coordinate (d and q co-ordinates) time invariant model. Fig. 4-5 shows the detailed block diagram of DFIG with the converters and the power flow variables according to the Simulink model. The back-to-back converter consists of two converters, i.e., machine-side converters a dc-link capacitor placed, as energy storage, in order to the voltage variations (or ripple) in the dc-link voltage small. With the machine-side converter it is possible to control the torque or the speed of the DFIG and also the power factor at the stator terminals, while the main objective of the grid-side converter is to keep the dc-link voltage.

The complexity of the mathematical model of induction motors makes it difficult to control the system with ease and accuracy. Using the FOC a structure that is similar to that of a DC machine control is commonly used. Two constants are required as reference inputs in the implementation of the FOC algorithm. These two reference inputs are the torque component (related to the q coordinate) and the flux component (related to the d co-ordinate). Since Field Orientated Control is only based on projections the control structure handles instantaneous electrical quantities. This makes the control to some extent accurate in every working operation (steady state and transient) and independent of the limited bandwidth mathematical model. The reactive power and voltage control is illustrated in Fig. 4-6

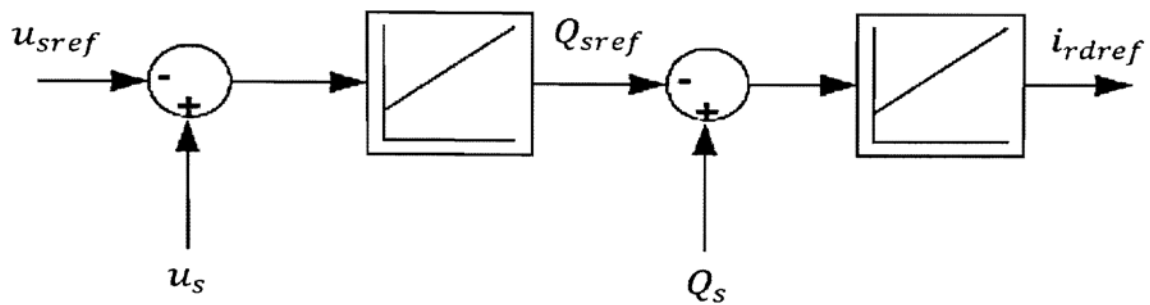


Figure 4-6 Reactive power and voltage control diagram.

4.3 Grid Side Converter

The aim of the control of the grid side converter is to maintain the dc-link capacitor voltage in a set value regardless of the magnitude and the direction of the rotor power and to guarantee a converter operation with unity power factor (zero reactive power). This means that the grid side converter exchanges with the grid only active power, and therefore the transmission of reactive power from DFIG to the grid is done only through the stator. The dc-voltage and the reactive power are controlled indirectly by controlling the grid side converter current [11]. The aim of the grid side converter controller for normal operation is

to maintain the DC-link capacitor voltage and to guarantee a converter operation with unity power factor. Detailed explanations about the control concept of the DFIG wind turbine concept for normal operation conditions can be found in [12]. In contrast to the rotor side converter the grid side converter can stay active during grid faults, when the rotor side converter is blocked by the crowbar. The grid side converter can then be used as a Voltage Compensator and contribute supplementary to reactive power supply.

4.4 DFIG Normal Operation

The control scheme of the normal operation DFIG based system is illustrated using a 153 MW wind farm consisting of six 1.5 MW wind turbines connected to a 33 kV distribution system exports power to a 230-kV grid through a 25 km, 230 kV feeder. Wind turbines using a doubly-fed induction generator (DFIG) consist of a wound rotor induction generator and an AC/DC/AC IGBT-based PWM converter. The stator winding is connected directly to the 50 Hz grid while the rotor is fed at variable frequency through the AC/DC/AC converter. The DFIG technology allows extracting maximum energy from the wind for low wind speeds by optimizing the turbine speed, while minimizing mechanical stresses on the turbine during gusts of wind. [12,13]. The DFIG is modelled using a wound rotor asynchronous generator in the stationary frame where the stator and rotor winding are excited separately. The generator is a three pole-pairs machine whose rotor is connected in Y -connection to an internal neutral point. The generator parameters are listed in Table 4-2.

The control system of the DFIG subsystem is explained in previous sections. The stator voltage, stator current, rotor current, rotor speed and DC link voltage are sensed and fed to controllers. The wind turbine information is utilized by the controller. The mechanical torque data is extracted and manipulated in the torque regulator producing the torque command [8,9].

Three main controllers perform independent functions in order to obtain the desired output:

1. Speed controller uses the MPPT curve to build the reference speed and turbine output power. The torque command is extracted by estimating that stator speed.
2. Reactive power regulator is a closed loop with feedback from the collector bus of power quality control.
3. Current regulator regulates the rotor current with respect to the reference value. The reference values are generated from torque command and the relative power regulator.

The normal operation of DFIG is simulated and the results are presented in Figure 4.7

Table 4-1 YSK15-04A generator Technical Specifications

Type	YSK15-04A
Rated power[kW]	1560
Poles	4
Voltage/V	690
Rotor voltage of open circuit/V	1650
Frequency/Hz	50
Rated speed/ rpm	1800
Speed range/ rpm	1000~2000
Factor of rated power	1.0
Rated efficiency	96.5%
Factor	0.95cap.~0.95ind.
Connection (stator/rotor)	Δ/Y
Moment of inertia/kg·m ²	67
Cool method	IC616

Table 4-2 DFIG System and model parameters

Parameter	Value
Nominal frequency [Hz]	50
Stator resistance [pu]	0.00706
Rotor resistance, R_s [pu]	0.005
Magnetization inductance, L_m [pu]	2.9
Stator leakage inductance, L_s [pu]	0.171
Rotor leakage inductance, L_r [pu]	0.156
DC link voltage, V_{dc} [V]	1200
Inertia constant [s]	5.04
Friction factor [p.u.]	0.01
DC link capacitor [μ F]	10,000
Nominal line-to-line voltage [V_{LL} , RMS]	575
Nominal output frequency [Hz]	50

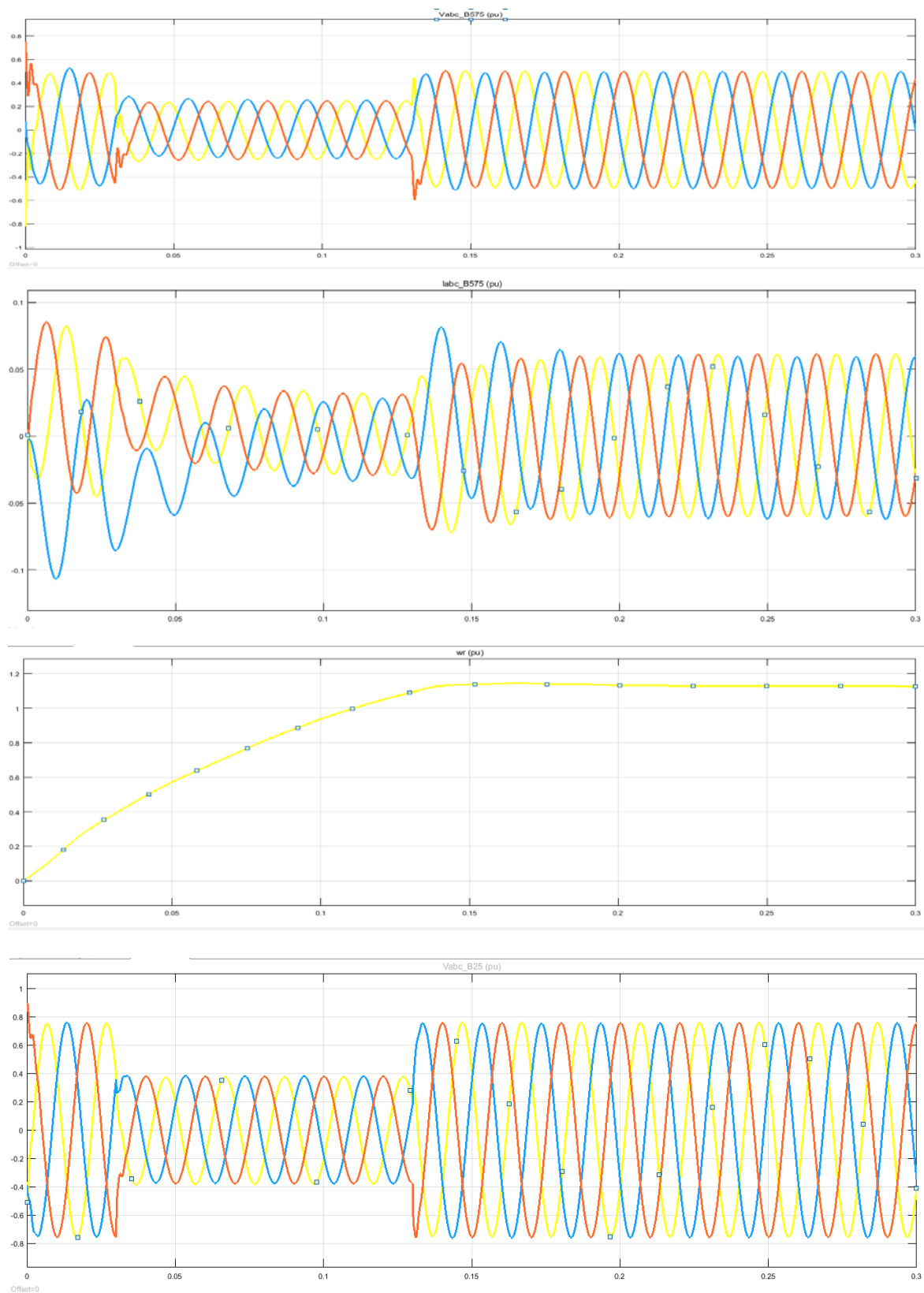


Figure 4-7 DFIG during normal operation

CHAPTER FIVE

Analysis and Results

5.1 Description

Due to the double fed induction generator's (DFIG) advantage of controlling active and reactive power independently and partial power converter, DFIG is becoming a popular type of wind power generation system. Nowadays, the grid code demands that the wind power generator possesses the ability of riding through the grid voltage sags, only when the grid voltage drops below the specific curve, the wind turbine is allowed to disconnect. DFIG wind power system has serious problems with the corresponding voltage sag as its partly power converter: depending on the depth and the conditions at the start of the sag, current, power and reactive power peaks may exceed rated values and may lead to a system shut down [22]. In general, these grid codes represent the fundamental guidelines for wind turbine manufacturers and wind farm planners. Basically, the grid code follows the counterpart categorizing wind turbine capabilities as follows

- (i) Low voltage Ride-through (LVRT) requirement to keep wind turbines on the grid during faults by introducing new technologies.
- (ii) When tripping, wind turbines have to guarantee reconnection and continuation of power generation in the shortest possible time.
- (iii) The establishment of mechanisms for ascertaining and continuous monitoring of the fulfilment of grid requirements.
- (iv) Establishing intelligent system protection devices to ensure a minimum loss of wind power and to guarantee fast recovery of normal operation.

The new grid codes requirements include voltage level, Total Harmonic Distortion (THD) levels in the point of common coupling (PCC) as well as the ride through capabilities during fault events in the grid. Also, the new wind turbines/farms should contribute to regulation if active and reactive power and thereby contribute to the frequency and voltage control [25].

One of the challenges of DFIG is that it does not handle faults in the manner of conventional generator during grid disturbances. Some of the critical problems that encounter DFIG under fault conditions are the following:

- (i) rotor over current which can cause the machine side converter to be damages or to be offline due to protection.
- (ii) DC link over-voltage which can lead to capacitor failure.
- (iii) temporary loss of control of the active and reactive power causing oscillations at the DFIG output.
- (iv) reactive power compensation during voltage imbalance.

In order to avoid damage, WECS are tripped offline, separating the turbine from the grid. Thus, utilities are recognizing the need for WECS to withstand grid disturbances even if the voltage drops at the point of connection. The disturbances are classified as balanced or unbalanced. Based on the network configuration and WECS topology, the turbine may experience different situations at the turbine input terminals. The grid requires intelligent protection schemes to avoid voltage collapse and handle fault conditions in a shorter duration. Further analysis and the recommended method will be discussed in the next chapter. In this chapter, short circuit faults are introduced in the simulation to study the response of DFIG. These faults are imposed along the transmission line and are categorized either as shorted phase(s) to ground or arching between phases. In the simulation the analysis of DFIG behavior under each fault condition and undesirable fault response characteristics will be observed in the large peak currents at the initiation of the fault.

5.2 Short circuit analysis

5.2.1 Double Fed Induction Generator during Fault

Wind turbines based on DFIG have the stator windings connected directly to the grid, making the rotor winding susceptible to high currents induced during grid faults. The rotor windings are connected to the grid via a back-to-back converter, which is very sensitive to over-currents. The most common way to avoid high induced currents in the rotor side converter (RSC) is the use of a crowbar system. The crowbar system makes the DFIG behave in the same way as a conventional Squirrel Cage Induction Generator (SCIG) with higher rotor resistance expanding the critical rotor speed during the disconnection of the RSC from the rotor winding [22]. In the following sections the response of DFIG to various types of faults is analyzed and presented. The balanced (or three phase) fault is the one when all three lines are shorted to ground. It is usually rare, but can happen. When a fault occurs, it is important to isolate it by opening protective breakers. For a three-phase symmetrical fault, at the instant of fault, all three voltages reach a value of V .

$$V_a = V_b = V_c = V. \quad (5.1)$$

Addition of the three phase-currents should be zero

$$I_a + I_b + I_c = 0 \quad (5.2)$$

Another type of fault is Asymmetrical faults

1) Phase to phase faults (phase 'a' to phase 'b')

$$I_e = 0 \quad (5.3)$$

$$I_a + I_b = 0 \quad (5.4)$$

$$V_a = V_b = V \quad (5.5)$$

2) Single phase to ground faults (phase 'a' to ground)

$$V_b = 0 \quad (5.6)$$

$$I_b = I_c = 0 \quad (5.6)$$

The following simulation results illustrate the DFIG response during three phase faults in the transmission. The analysis was carried out in MATLAB Simulink® simulation environment. The fixed simulation time-step was set to $0.5e-7$ and forward Euler method was used.

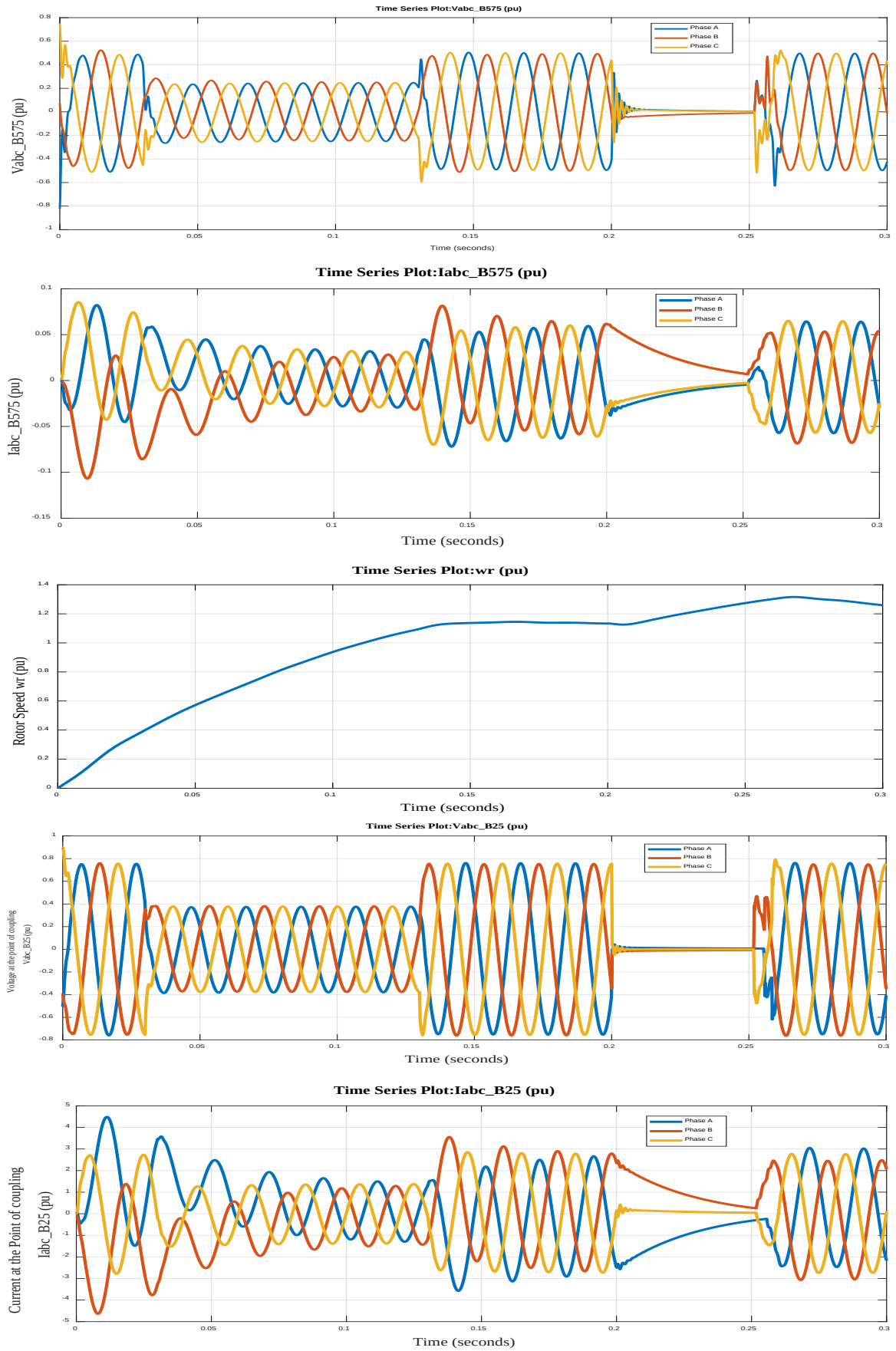


Figure 5-1 DFIG during a voltage sag at three phase faults

In Fig 5-1 the steady-state operation of the DFIG and its dynamic response to voltage sag resulting from a remote fault on the 230-kV system is plotted. The fault was introduced at $t=0.2$ s and removed at approximately $t=0.25$ s. Initially the DFIG wind farm produces to 153 MW. The corresponding turbine speed is 1pu of generator synchronous speed. The DC voltage is regulated at 1150 V and reactive power is kept at 0 Mvar. At $t=0.2$ s the positive-sequence voltage suddenly drops to 0.05 pu. causing an oscillation on the DC bus voltage and on the DFIG output power. During the voltage sag the control system tries to regulate DC voltage and reactive power at their set points (1150 V, 0 Mvar). The system recovers in 3 cycles at approximately $t=0.25$ s. Under normal operation, the DC link voltage has a steady value of approximately 1200V with some AC ripples. During fault, the capacitor voltage increases above its rated value to a peak of approximately 2000V, shown in Fig. 5-1. Also, the rotor current during fault is very high when compared with the rated value of 1pu. This can result in high stator voltage across DC link capacitor. Before the fault is applied, the active power output of the wind turbine is 0.5 pu while the reactive power output is kept constant at 0 pu. Approximately 100 ms after fault is cleared the terminal voltage is recovered (back to the steady state value) at 1 pu. This fast voltage recovery is due to the ability of DFIG to control the reactive power; damping control helps a quick recovery of DFIG after a fault on the grid.

5.2.2 Two-Phase Shorted

A two-phase fault is simulated in the same location as the three-phase fault, where only two-phases are shorted to ground. The simulation results are shown in the following figures. With unbalanced voltage, large rotor currents are induced in the rotor currents. This type of fault is not as severe as the three-phase fault, but it can still cause an interruption to the power system and damage to the devices.

A two-phase fault is applied to phase A and B of the transmission line between the transformer and B20 bus bar. This fault has caused severe disturbance in the DFIG behavior as well as the entire network. As depicted in Fig. 5-2, the DC voltage is not stable anymore and far from the rated value with a lot of harmonics, this overvoltage DC can easily damage the capacitor. The active power was lost for significant time and when it returned it shows over production due to the power in balance. It can be observed that, reactive power between $t=0.02$ s to $t=0.1$ s is not zero and its injecting undesirable power to the network. The system recovers only around $t=0.15$ s.

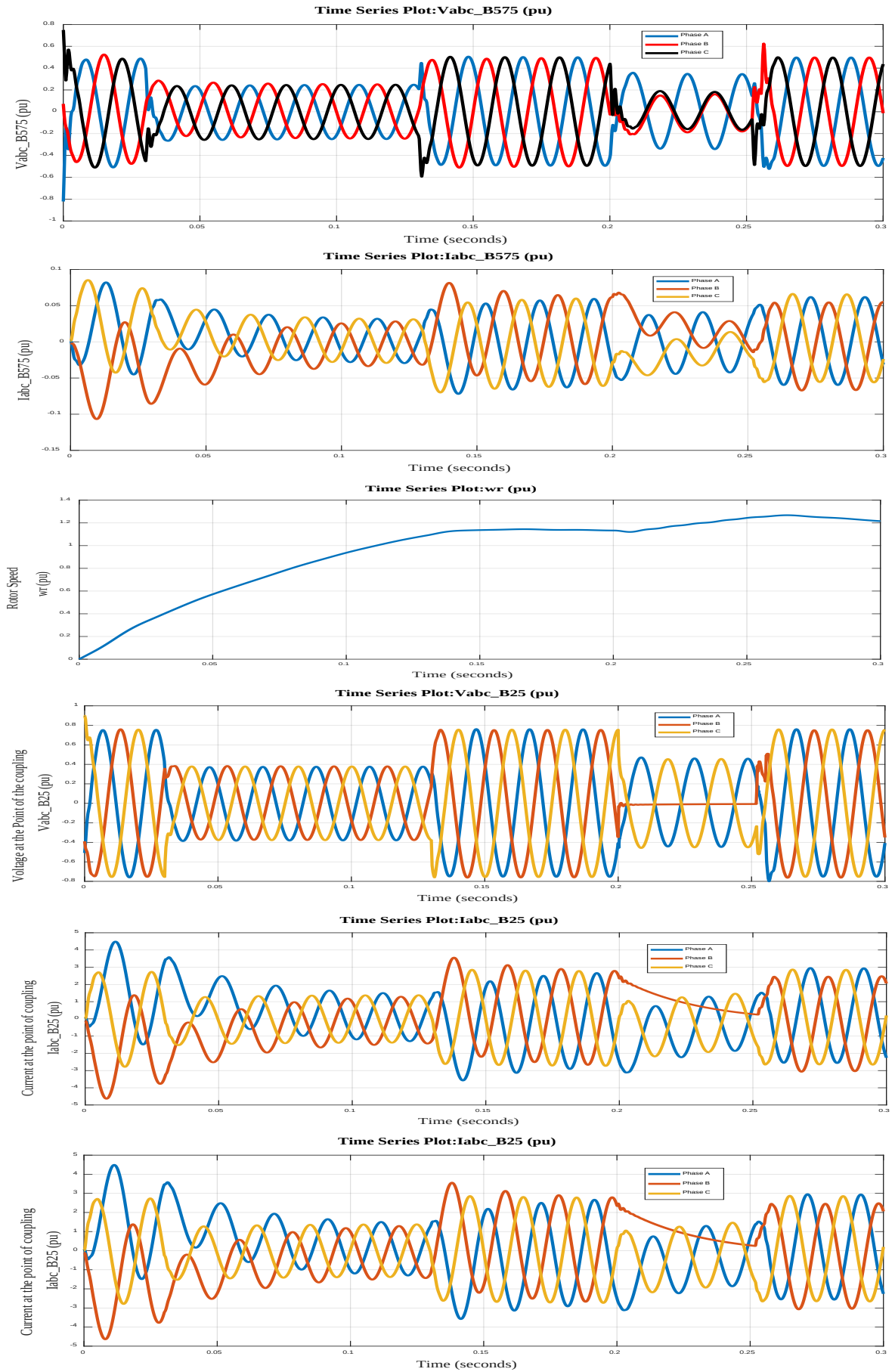


Figure 5-2 DFIG under unbalanced 2-phase fault

5.2.3 Summary of Result

In this chapter the simulations of DFIG during various types of fault in the network were analyzed and presented. The dynamic response of the DFIG under fault was observed to be different and random in nature during the random fault occurrence in the power system. During the steady-state operation of the DFIG and its dynamic response to voltage sag resulting from a remote fault on the 230-kV system is plotted. The fault was introduced at the beginning and removed approximately after 0.1sec. As a result; the DFIG wind farm produces lower power during the voltage sag. Following the voltage sag, as depicted in the previous sections, current, power and reactive power peaks have all exceeded their corresponding rated values. This could lead to entirely shut down of the system.

5.3 Transient stability Analysis

The Wind Farm Transient Stability Analysis is designed to investigate the stability limits of a power system before, during, and after system changes or disturbances. The model's dynamic characteristics of a power system, implements the user-defined events and actions, solves the system network equation and machine differential equations interactively to find out system and machine responses in time domain. From these responses, it can determine the system transient behavior, make stability assessment, find protective device settings, and apply the necessary remedy or enhancement to improve the system stability Using ETAP software. Here, it is provided that an overview on the basics of transient stability study.

This Transients are momentary events preceding the steady-state condition during a sudden change of a circuit in a power system. These momentary bursts of energy are characterized by extremely high voltages that can drive very large amounts of currents into the system for a limited time. The stability of a system refers to the ability of a system to return back to its steady state when subjected to a disturbance. The transient stability analysis determines whether the components in the system returns to their steady state in a timely manner once the disturbance or fault is cleared.

The ETAP Transient Stability Analysis program can investigate the system dynamic responses and stability limits of a power system before, during, and after the occurrence of disturbances. The studies concern on the aggregated Adama wind farm-II model shows on the figure 5.3, and its transient outputs are on the Figure 5.4.

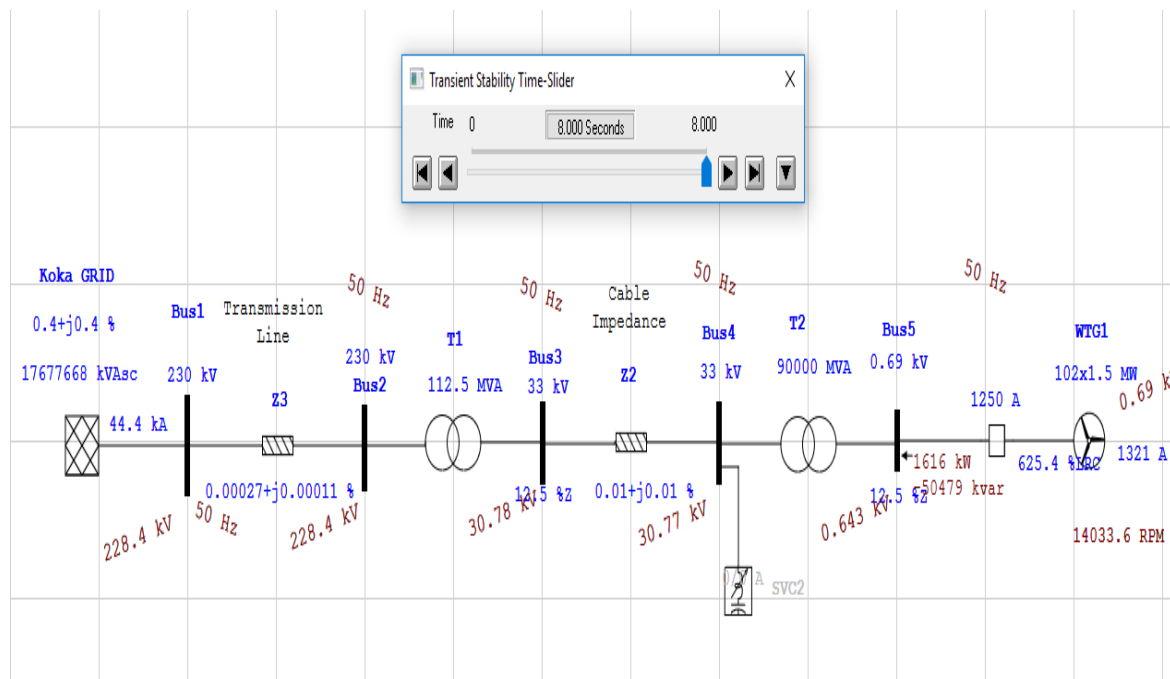


Figure 5-3 Transient stability Analysis for Adama Wind Farm Aggregated one line diagram

The transient stability of the aggregated Adama wind farm II as shown on the figure 5-3 have 5 buses one-line diagram, that used for analyze the property of the wind farm, to investigate the stability limits of a power system before, during, and after system changes or disturbances. It is the ability of the power system to maintain synchronism when subjected to a severe transient disturbance.

According to chapter 3 on the above, the fault ride through on different scenarios which is taken in to account the fault on different point of the internal system of the wind farm can be assessed on different fault time duration. The figure 5-4 shows the output of the wind farm at the terminal voltage, the wind speed, the power, the reactive power, the current and the speed of the rotor relationship simulated on ETAP software, this relation used for the study of the wind farm how to operate when different fault disturbance can occur at any time and how to ride of the faults on the transient and steady state operation.

5.3.1 Simulation result

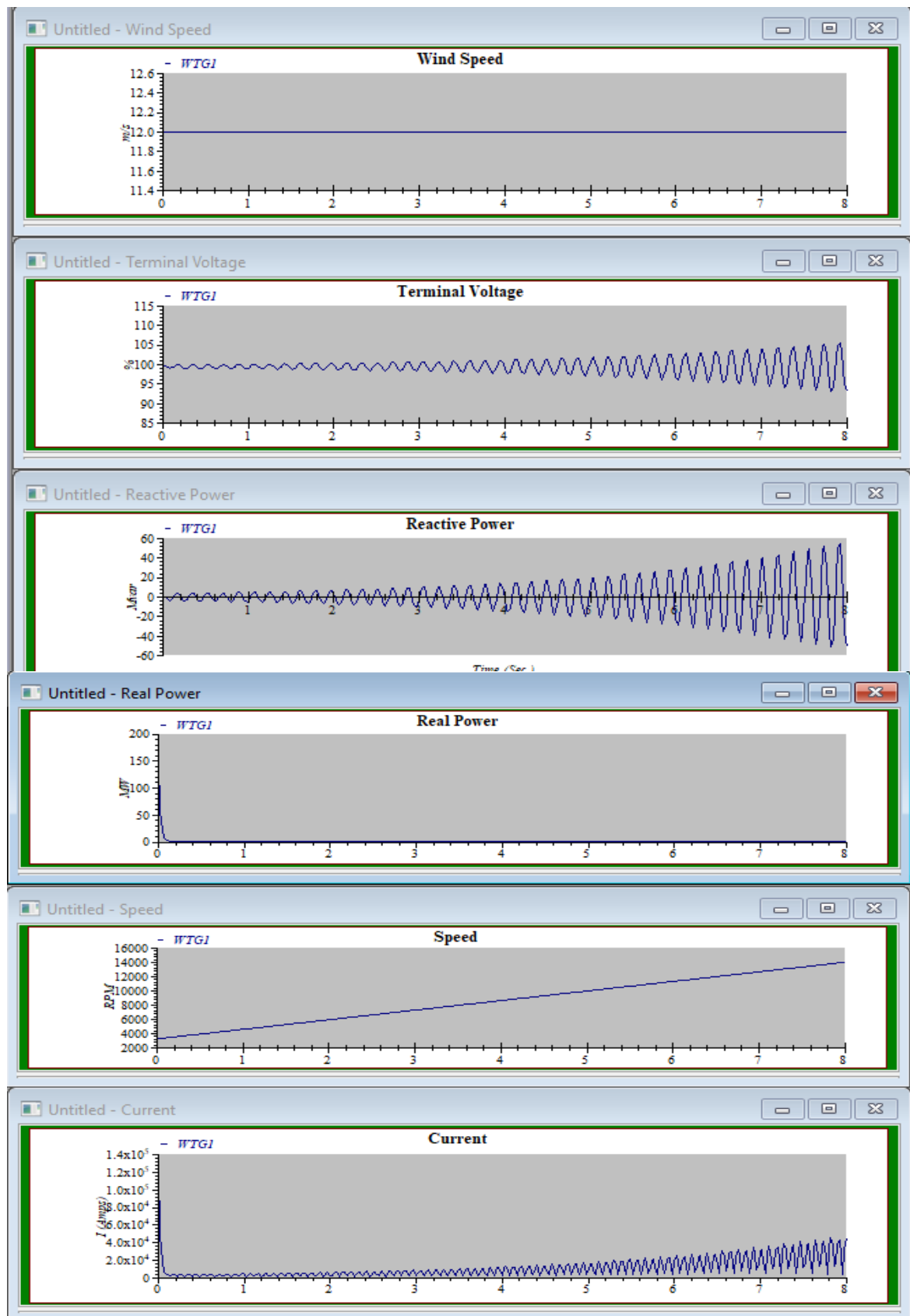


Figure 5-4 the simulation output of transient stability

5.4 Power flow Analysis

The Wind Farm Optimal Power Flow (OPF) analysis is an extremely powerful for power system design, planning, and operation. It solves power system load flow, but at the same time can optimize system operating conditions and automatically adjust control variable settings, while ensuring both equality and inequality constraints are not violated. The optimized system will reduce the installation and/or operating cost, improves its overall performance, and increases its reliability and security. Besides minimizing the operating and installation cost, the Analysis also provides a variety of other choices of optimization objectives, which covers virtually all the optimization criteria for a real power system. Any practical control means in a power system such as transformer LTC, generator AVR control, shunt and series compensations, and load shed can all be considered in the calculation. Constraints for bus voltage, branch flow in different types (MVA, MW, Mvar, and Amp), as well as control variables are also available for users to select and enforce. By using state-of-the-art optimization algorithms and advanced programming techniques, this analysis is proven very capable, robust, and effective. The power analysis of the Adama wind Farm-II using aggregated one-line diagram is shown in figure 5.3 and the output of the one-line diagram shown on table 5.1.

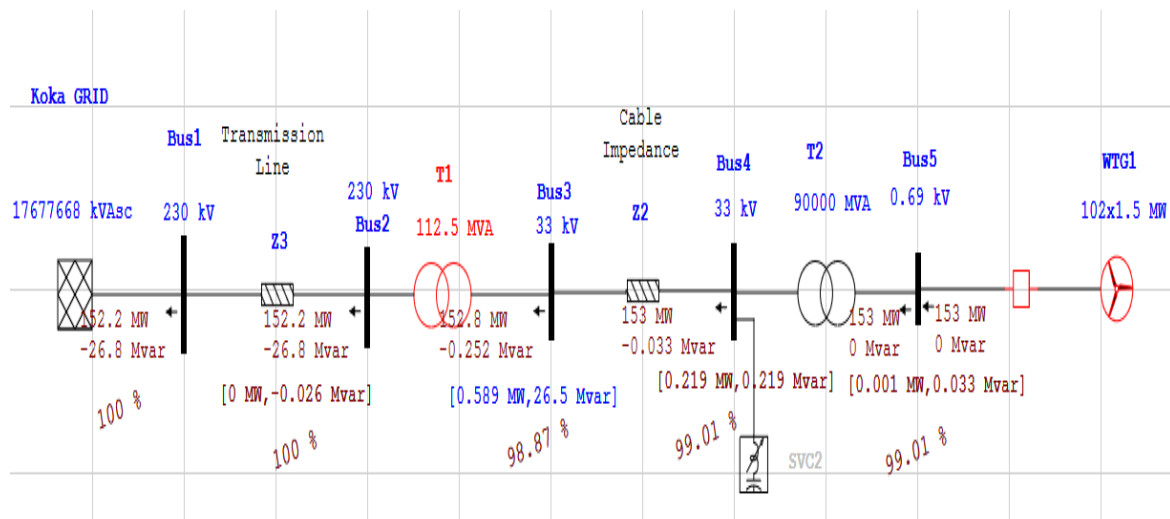


Figure 5.3 The power flow Analysis of the Adama wind Farm II an aggregated one-line diagram

Table 5.1 The output Power Flow Analysis result of the Aggregated one-line diagram

LOAD FLOW REPORT @ T = 0.000-

Bus		Voltage		Generation		Load		Load Flow				
ID	kV	% Mag.	Ang.	MW	Mvar	MW	Mvar	ID	MW	Mvar	Amp	%PF
* Bus1	230.000	100.000	0.4	0	0	0	0	Bus2	-152.190	26.751	387.9	-98.5
								Koka GRID	152.190	-26.751	387.9	-98.5
Bus2	230.000	100.000	0.4	0	0	0	0	Bus1	152.191	-26.778	387.9	-98.5
								Bus3	-152.191	26.778	387.9	-98.5
Bus3	33.000	98.869	10.3	0	0	0	0	Bus4	-152.780	0.252	2703.5	100.0
								Bus2	152.780	-0.252	2703.5	100.0
Bus4	33.000	99.011	10.4	0	0	0	0	Bus3	152.999	-0.033	2703.5	100.0
								Bus5	-152.999	0.033	2703.5	100.0
Bus5	0.690	99.011	10.4	0	0	0	0	Bus4	153.000	0.000	129299.8	100.0
								WTG1	-153.000	0.000	129299.8	100.0
Koka GRID	230.000	99.501	0.0	-151.235	27.706	0	0	Bus1	-151.235	27.706	387.9	-98.4
WTG1	0.690	125.280	48.2	153.000	118.614	0	0	Bus5	153.000	118.614	129299.8	79.0

* Indicates a voltage regulated bus (voltage controlled or swing type machine connected to it)

Indicates a bus with a load mismatch of more than 0.1 MVA

LOAD FLOW REPORT @ T = 100.000-

Bus		Voltage		Generation		Load		Load Flow				
ID	kV	% Mag.	Ang.	MW	Mvar	MW	Mvar	ID	MW	Mvar	Amp	%PF
Bus1	230.000	99.324	0.1	0	0	0	0	Bus2	-1.552	45.388	114.8	-3.4
								Koka GRID	1.552	-45.388	114.8	-3.4
Bus2	230.000	99.324	0.1	0	0	0	0	Bus1	1.552	-45.415	114.8	-3.4
								Bus3	-1.552	45.415	114.8	-3.4
Bus3	33.000	94.249	0.3	0	0	0	0	Bus4	-1.603	43.089	800.4	-3.7
								Bus2	1.603	-43.089	800.4	-3.7
Bus4	33.000	94.209	0.3	0	0	0	0	Bus3	1.622	-43.071	800.4	-3.8
								Bus5	-1.622	43.071	800.4	-3.8
Bus5	0.690	94.202	0.3	0	0	0	0	Bus4	1.623	-43.068	38281.5	-3.8
								WTG1	-1.623	43.068	38281.5	-3.8
Koka GRID	230.000	99.501	0.0	-1.468	45.472	0	0	Bus1	-1.468	45.472	114.8	-3.2
WTG1	0.690	71.498	1.0	1.623	-32.671	0	0	Bus5	1.623	-32.671	38281.5	-5.0

* Indicates a voltage regulated bus (voltage controlled or swing type machine connected to it)

Indicates a bus with a load mismatch of more than 0.1 MVA

CHAPTER SIX

Conclusion and Future Work

6.1 Conclusion

Through this research, it is shown that:

- A large Scale Adama wind farm using SANY DFIG wind turbines can be consistently aggregated to one equivalent machine for load flow and transient stability studies.
- The low voltage ride-through response can be improved by inserting a self-impedance between the faulted feeder and the rest of the large wind farm during the fault. This impedance will reduce the number of wind turbines tripping during the fault, and increase the voltage stability of the wind farm.

In the research simulation, a large wind farm with a large number of buses has been aggregated to an equivalent wind farm with 5 buses. And the large wind turbines, and transformers also equivalenced to one system. This represents a reduction in size of the large wind farm by and is an important savings of resources and time.

The aggregated wind farm models consist of only one equivalent wind turbine including the detailed controller models as well as the representation of the mechanical system. The equivalent cable impedance between the aggregated machine and the connection point is defined in a way that the transient short-circuit contribution of the aggregated model at the point of common coupling is equal to the short- circuit contribution of the complete wind farm model.

In this paper, just variable speed wind generators have been analyzed (DFIGs) and it has been shown that this technology is able to improve transient stability margins, when being equipped with low voltage ride-through capability, reactive current boosting and ideally with fast voltage control. In the event of a large disturbance resulting in a significant dip in voltage close to the wind turbine it was accepted practice to trip the wind turbine. This action was based on the reasoning that distribution systems being supplied by radial systems could result in the wind farm being connected to the system following the disturbance and result in an islanded operation, which could cause unacceptable overvoltage conditions. With the evolution of wind turbine technology and the development of large wind farms connected to the bulk transmission network, the issue of voltage ride through sometimes also referred to as low voltage ride through or fault ride through, became an important operating issue.

This led to the development of voltage ride through requirements in various parts of the world, which requires wind farms to remain online in the presence of severe voltage disturbances for a specified period of time and with a defined voltage profile. The regulations require wind plants to remain in service during three-phase faults with normal and for single line to ground faults with delayed clearing. The regulations also require the subsequent postfault voltage to return to the pre-fault voltage level unless the clearing of the fault effectively disconnects the wind generator from the system. In the event that a fault persists for a period greater than the clearing duration specified, or the postfault voltage does not recover to the specified value, the wind park may disconnect from the transmission system. Wind generating plants must remain connected during such faults with voltage levels down to zero volts as measured at the high side of the point of interconnection (POI).

6.2 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 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 increases 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.

Reference

- [1]. F. Shewarega, I. Erlich, and J. L. Rueda, "Impact of large offshore wind farms on power system transient stability," IEEE PES Power Systems Conference and Exposition, p. 8, 2009.
- [2]. Andreas Petersson, "Analysis, Modeling and Control of Doubly - Fed Induction Generators for Wind Turbines"; PhD Theses, Chalmer University of Technology, Gutenberg, Sweden, 2005.
- [3]. G. Bekele and A. Abdela, "Investigation of wind farm interaction with Ethiopian electric power corporation's grid," Energy Procedia, vol. 14, no. 0, pp. 1766–773, 2012.
- [4]. Getachew Biru and Mesfin Megra "Impact of large scale wind power integration on Ethiopian power system transient stability"; MSC Thesis, Adama Science and Technology University, Adama, Ethiopia, March 22, 2017.
- [5]. O. A. Lara, N. Jenkins, J. Ekanayake, P. Cartwright, M. Hughes, "Wind Energy Generation: Modelling and Control". Chichester, UK: Wiley, 2009.
- [6]. Yazdani, R. Iravani, "Voltage-Sourced Converters in Power Systems: Modeling, Control, and Applications". Hoboken, New Jersey: IEEE/Wiley, 2010.
- [7]. W. Leonhard, "Control of Electrical Drives". New York, USA: Springer, 3rd ed., 2001.
- [8]. J. G. Slootweg, W.L. Kling, "Aggregated Modeling of Wind Parks in Power System", Power Engineering Society Summer Meeting, 2002 IEEE, Volume 1, 25-25 July 2002 Page(s):503 – 508 vol.1
- [9]. M. Poller, S. Achilles, "Aggregated Wind Park Models for Analyzing Power System Dynamics", online: <http://www.digsilent.de/Consulting/Publications>
- [10]. K. Elkington, V. Knazkins, M. Ghandhar, "On the Rotor Angle Stability of Power Systems with Doubly Fed Induction Generators", Power Tech, 2007 IEEE Lausanne, 1-5 July 2007 Page(s):213 – 218
- [11]. Martinez De Alegria, 1.L. Villate, 1. Andreu, 1. Gabiola and P. Ibanez, "grid connection of doubly fed induction generator wind turbines", Bilbao, Spain, 2008
- [12]. R. Pena, 1. C. Clare and G. M. Asher, "Doubly fed induction generator using back-to-back PWM converters and its application to variable-speed wind-energy generation", in Proceedings Electrical Power Applications, vol. 143, 1996, P. 231-242

- [13]. S. Seman, J. Niiranen, S. Kanerva, and A. Arkkio, "*Analysis of 1.7 MVA Doubly Fed Wind-Power Induction Generator during Power Systems Disturbances*", IEEE Transactions on Power Systems, 2006
- [14]. Seman, S., Niiranen, J., Arkkio, A. 2006. "*Ride-Through Analysis of Doubly Fed Induction Wind-Power Generator under Unsymmetrical Network Disturbance*", IEEE Transaction on Power Systems, Accepted for future publication, 7 p
- [15]. G. Tsourakis and C. D. Voums, "*Simulation of Low Voltage Ride Through Capability of Wind Turbines with DFIG*",
- [16]. S. R. Pena, J. C. Clare, and G. M. Asher, "*Doubly fed induction generator using back-to-back converters and its application to variable-speed wind-energy generation*," Proc. Inst. Elect. Eng., Elect. Power Appl., vol. 143, no. 3, pp. 231-241, May 1996
- [17]. Jouko Niiranen, Slavomir Seman, Jari-Pekka Matsinen, Reijo Virtanen and Antti Vilhunen; "*Low voltage Ride Through Testing of Wind Turbine Drives*", ABB, 2nd Edition of IEC 61400-21
- [18]. Rabelo, B.; Clare, J.C; Asher, G.M.; "*Doubly fed induction generator using back-to-back P\VM converters and its application to variable speed wind-energy generation*"; IEEE Proceedings on Electrical Power Application, Vol.143, No.3, 1996.
- [19]. S. Bernard, "*Investigation of different Methods to Control a Small Variable Speed Wind Turbine with PMSM Drives*"; Journal of Energy Resources Technology, Vol. 129, No.3, 2007[20].
- [20]. Rotsenko K.; "*Flexible Power Flow Control for Brushless Doubly Fed Induction Generator*"; Thesis, Ryerson University, Toronto, Ontario, 2007.
- [21]. Ramroop, AD Shoba; "*Fault Detection of Fault Ride Through for Doubly-Fed Induction Generator Based Wind Energy Systems*"; Thesis, Ryerson University, Toronto, Ontario, 2008.
- [22]. A Petersson, L. Hamefors and T. Thiringer, "*Comparison between stator-flux and grid-flux oriented rotor current control of doubly-fed induction generators*", Proceedings of the 35th Annual IEEE Power Electronics Specialists Conference - PESC'04. Volume 1, 20-25 June 2004 pp. 482 – 486
- [23]. Tanuj Mishra; "*Dynamic Performance Estimation of DFIG wind turbine under Balance and Unbalance grid fault condition*", Thesis, National Institute of Technology, Rourkela.

- [24]. Vandai Le, Xinran Li, Yong Li, Tran Le Thang Dong and Caoquyen Le,” *An Innovative Control Strategy to Improve the Fault Ride-Through Capability of DFIGs Based on Wind Energy Conversion Systems*” November 2015.
- [25]. J.-h. H. Zhang, “*Development and planning of wind power in China,*” in Power and Energy Society General Meeting, 2010 IEEE, Minneapolis, 2010.
- [26]. M. Yin, X. Ge and Y. Zhang, “*Major problems concerning China's large-scale wind power integration,*” in Power and Energy Society General Meeting, 2011 IEEE, 2011.
- [27]. Q. Zhang, “*The current state, problems and development strategies of the wind power industry in the three northeast provinces of China,*” in World Non-Grid-Connected Wind Power and Energy Conference (WNWEC), 2010, Nanjing, 2010.
- [28]. H. Chen, “*Power grid is getting ready for the development of wind power in China,*” in IPEC, 2010 Conference Proceedings, Singapore, 2010.
- [29]. Z. Xia, “*Influences on CPS frequency evaluation indexes after large scale wind power joining up to East China power grid,*” in Electric Utility Deregulation and Restructuring and Power Technologies (DRPT), 2011 4th International Conference on, Weihai, Shandong, 2011.
- [30]. Wikipedia, “*Wind power in the United States,*” 2012. [Online]. Available: http://en.wikipedia.org/wiki/Wind_power_in_the_United_States. [Accessed 13 10 2012].
- [31]. US Department of Energy, “20% wind energy by 2030 “*Increasing Wind Energy's contribution to the U.S. Electricity supply,*” US Department of Energy, 2008.
- [32]. N. Abdel-Karim, “*Operational sensitivities of Northeastern US grid to wind power integration scenarios,*” in Power and Energy Society General Meeting, 2010 IEEE, Minneapolis, 2010.
- [33]. N. W. Miller, “*Frequency responsive wind plant controls: Impacts on grid performance,*” in Power and Energy Society General Meeting, 2011 IEEE, San Diego, CA, 2011.
- [34]. H. L. Durrwachter, “*Integration of Wind Generation In to the ERCOT Market,*” Sustainable Energy, IEEE Transactions on, vol. 3, no. 4, pp. 862-867, 2012.

Appendix

Appendix A

WTGS parameter

Technical parameters of the 1.5MW series WTGS are shown in Table 1.

Table 1 Technical parameters of the 1.5MW series WTGS

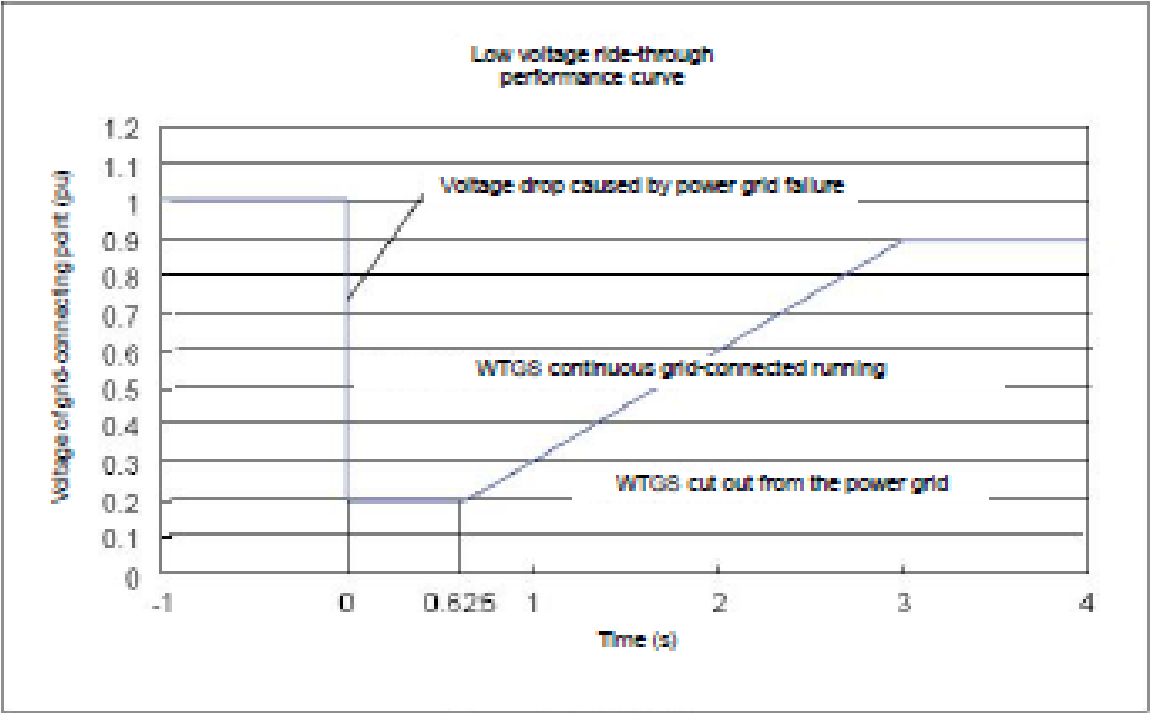
Parameter		Parameter value /description
WTGS model		SE7715
Basic parameter	Wind scale	IEC II
	Rated power (Appendix I)	1500kW
	Rated wind speed (Appendix I)	12m/s
	Cut-in wind speed (Appendix I)	3.5m/s
	Cut-out wind speed (Appendix I)	25m/s
	Survival wind speed (Appendix I)	59.5m/s
	Noise source level	≤108dB
	Anticorrosion level	Outer part conforms to C4 type corrosion of ISO12944-2 Inner part conforms to C2 or C3 type corrosion of ISO12944-2
	Working altitude	≤2000m (Common WTGS)
		≤3500m (Highland WTGS)
	Yearly availability	≥95%
	Design service life	20 years
	Height of wheel hub center	70m
	WTGS weight (excluding the towers)	94.0t
Wind rotor	Diameter	77.6m
	Sweep area (Appendix I)	4736m ²
	Rated rotating speed (Appendix I)	19rpm
	Variable pitch system	3 Independent blade variable pitch controls
	Number of blade	3
	Vane materials	GFRP (glass fiber reinforced epoxy resin)

Parameter		Parameter value / description
WTGS model		SE7715
Yaw system	Yaw slewing bearing	Four-point contact ball bearing
	Brake	Hydraulic brake
	Yaw driver	4 synchronous drive motor
	Yaw speed	0.55°/s
Speed-up gearbox	Type	Level 1 planet and level 2 parallel axis
	Speed ratio	94.7
	Rated power	1660kW
	Efficiency	≥97%
Main bearing	Type	Double row self-aligning roller bearing
Generator	Type	Doubly fed Induction generator (DFIG), air cooling
	Power	1540kW
	Voltage	690V
	Rated speed	1800rpm
	Protection grade	IP54 (Collecting ring shell IP23)
	Efficiency at rated power	≥97%
	Insulation grade	H
Master control system	Nominal voltage	690V(AC)±10%
	Rated frequency	50Hz±1%
	Relative humidity of the operating environment	5%~95%
Variable pitch system	Normal variable pitch speed	5°/s
	Sudden stop variable pitch speed	10°/s
	Variable pitch angle	0~90°
Converter	Rated capacity (rotor side)	694kVA
	Rated capacity (grid side)	365kVA

Appendix B

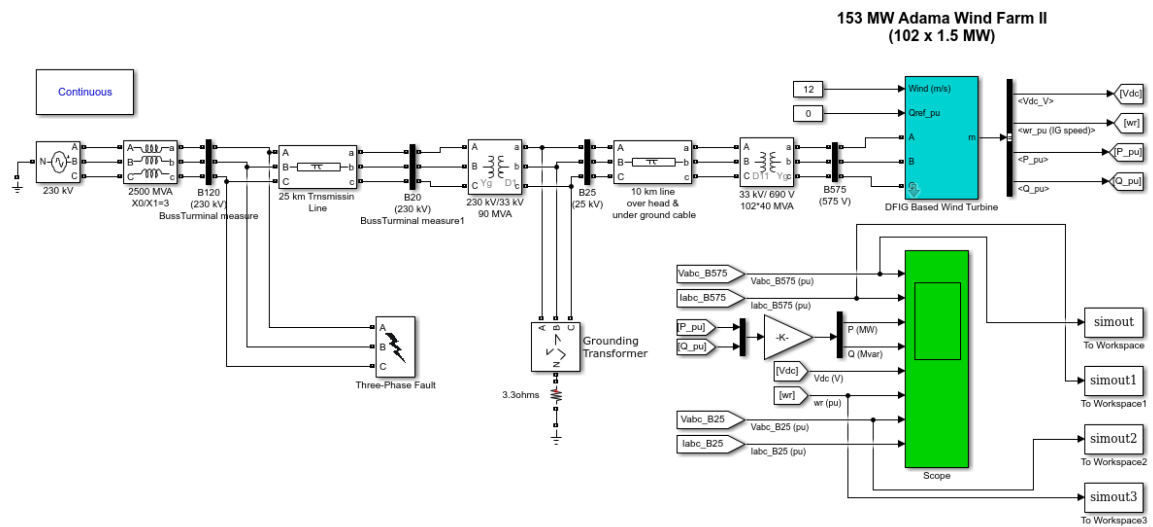
Low voltage ride-through performance

Low voltage ride-through requirement

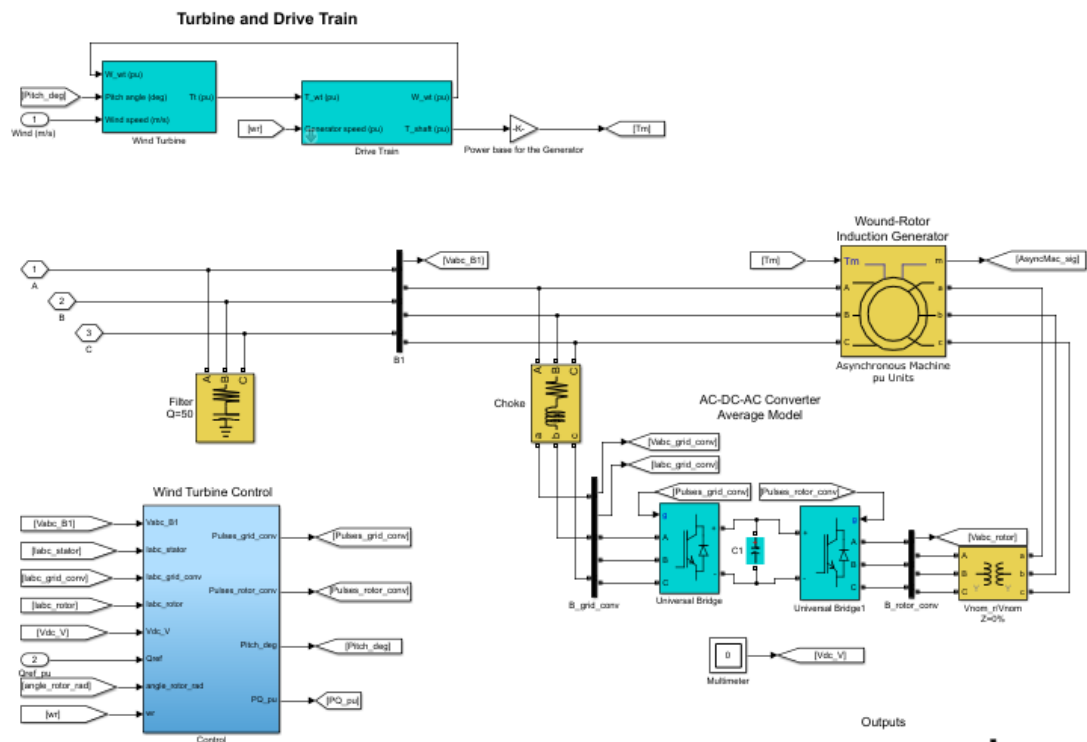


Appendix C

The over All MATLAB Simulink simulation (An Aggregated one-line diagram)



The DFIG model



Appendix D

****The MATLAB CODE for Power Coefficient versus Tip Speed Ratio λ ****

```
B=0;
for m=1:20
H(m)=1/(m+0.08*B)-0.035/(B*B*B+1);
l(m)=1/H(m);
cp(m)=0.5176*(116/l(m)-0.4*B-5)*exp(-21/l(m))+0.0068*m;
end
m=[1:1:20];
plot(m,cp(m))
grid
[cpmax,mmx]=max(cp(m))
xlabel('Tip speed ratio lmbdas')
ylabel(' Performance coefficient cp')
text(7,0.55, '0 deg')
B=2;
for m=1:20
H(m)=1/(m+0.08*B)-0.035/(B*B*B+1);
l(m)=1/H(m);
cp(m)=0.5176*(116/l(m)-0.4*B-5)*exp(-21/l(m))+0.0068*m;
end
m=[1:1:20];
hold on
plot(m,cp(m))
text(10.2,0.49 , '{2 deg}')
B=5;
for m=1:20
H(m)=1/(m+0.08*B)-0.035/(B*B*B+1);
l(m)=1/H(m);
cp(m)=0.5176*(116/l(m)-0.4*B-5)*exp(-21/l(m))+0.0068*m;
end
m=[1:1:20];
hold on
plot(m,cp(m))
text(13.2,0.3 , '{5 deg}')
B=10;
for m=1:20
H(m)=1/(m+0.08*B)-0.035/(B*B*B+1);
l(m)=1/H(m);
cp(m)=0.5176*(116/l(m)-0.4*B-5)*exp(-21/l(m))+0.0068*m;
```

```
end
m=[1:1:20];
hold on
plot(m,cp(m))
text(8,0.3 , '{10 deg}')
B=15;
for m=1:20
H(m)=1/(m+0.08*B)-0.035/(B*B*B+1);
l(m)=1/H(m);
cp(m)=0.5176*(116/l(m)-0.4*B-5)*exp(-21/l(m))+0.0068*m;
end
m=[1:1:20];
hold on
plot(m,cp(m))
text(8,0.17 , '{15 deg}')
B=20;
for m=1:20
H(m)=1/(m+0.08*B)-0.035/(B*B*B+1);
l(m)=1/H(m);
cp(m)=0.5176*(116/l(m)-0.4*B-5)*exp(-21/l(m))+0.0068*m;
end
m=[1:1:20];
hold on
plot(m,cp(m))
text(7,0.1 , '{20 deg}')
```