Modeling and Stability analysis of proposed Wind Farm at Búrfell, Iceland

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2014

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This thesis is submitted in partial fulfillment of MS degree in Electrical and Computer Engineering.

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Reykjavik, August 2014.

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Bibliographic information:
Abdul Rehman, 2014, Modelling and Stability Analysis of proposed wind farm at **Búrfell** , Master's thesis, Faculty of Electrical and Computer Engineering, University of Iceland, pp. 102.

Printing: Háskólaprent ehf., Falkagata 2, 107 Reykjavík Reykjavik, Iceland,
Reykjavik, Iceland, December 2014

Abstract

Wind energy is clean and renewable source of energy and it's impact on the nature is as minimum as compared to other sources of energy. There is a lot of potential available in Iceland ready to be exploited.
A wind turbine generator system consists of various components. Each component is modeled and extensively studied. It is found that the turbine inertia and stiffness play a great role in wind turbine torque stability.
Since the wind speed is not uniform, therefore, the available power is also not constant. The frequency of AC also depends on the generator speed and it needs to be constant when the generator is connected to the power grid which is not possible in variable speed generator system. This problem is resolved by using rectifier and inverter.
Rectifier converts AC into DC. Rectifier also controls the amount of power extracted from the turbine. It is necessary to maintain the smooth operation of the turbine. Therefore, rectifier controller is used.
Rectifier controller ensures the smooth operation of wind turbine by controlling the extraction of power and maintain the DC voltages. This is achieved by controlling the power extraction using Park Transformation[20] with PI controller.
Inverter converts AC into DC. It controls the power flow to the grid by controlling the output frequency and ensures to maintain the DC voltages. It also eliminated the interfacing problem with power grid as it generates the AC voltage of frequency compatible to the power grid. It is accomplished by Inverter control unit.
Inverter control unit controls the flow of power from DC bus to the power grid by controlling frequency. This is achieved by Park Transformation[20] with PI controller.
To ensure the unidirectional flow of power, a diode is used at DC bus. The WTGS takes some time initially to build up the voltages and once enough torque and speed is achieved it runs smoothly. In stability point of view, based on extensive simulation, the WTGS has proven to be stable even under faulty conditions.

Abbreviations

WTGS	:	Wind Turbine Generator System
WT	:	Wind Turbine
SCC	:	Short Circuit Current
PMSG	:	Permanent Magnet Synchronous Generator
PI controller	:	Proportional Integral controller

Acknowledgment

I am deeply grateful to my Project advisor, Mr. Magni Þ. Pálsson for his detailed and constructive comments, and his important support throughout this work. Beside my advisor, I would like to thank faculty of Electrical and Computer Engineering, its management, specially Dr. Helgi Þorbergsson for assisting me during my studies.

Dedicated to my family for their love and
unconditional support.

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Chapter 1

Introduction

Social, Environmental and Economic sustainability are the factors which play an important role in choosing the energy sources of a society. All three of these factors should be equally balanced for a stable and sustainable supply of energy. In the last century climate change, pollution and rising fossil fuel prices have increased the interest in renewable energy sources. Renewable energy is generally defined as energy that comes from resources which are naturally replenished on a human timescale such as sunlight, wind, rain, tides, waves and geothermal heat. Currently almost 16% of world energy supply comes from renewable energy resources. With increased investment in renewable energy sources and the technology development the percentage of renewable energy in world energy use is continuously increasing.
There are three generations of renewable energy technologies developed in last century.

- First generation technologies are hydropower, biomass and geothermal.
- Second generation technologies are solar heating , photovolatics , wind-power and advanced biofuels.
- Third generation technologies are under development they include biomass gasification, hot-dry-rock geothermal power and ocean energy

Investment in renewable energies was almost $250 billion during 2012. European countries took initiatives in this field by making renewable friendly policies. These policies spurred most of the growth in recent years. China, India and Brazil are emerging economies which are investing heavily in renewable technologies.
The use of wind energy in running of turbines for electrical power or mechanical power for water pumping or running of ships using wind sails etc.

Wind power is a renewable energy source and available abundantly around the world, without any greenhouse gas emissions and can be setup on little land with very little environmental impact.
Iceland is blessed with abundant renewable energy source of geothermal, hydro and wind power. During the last several decades Iceland was able to tap into most of geothermal and hydropower resources. Now termed as the world leader in renewable energy utilization, almost 85% of primary energy in Iceland is supplied by locally developed renewable energy sources. Iceland also has a huge wind energy potential which is under development only 0.1% electricity is supplied by wind energy.

1.1 Motivation

Wind turbines with full converters are being employed in large numbers of wind farms, connected through an unsymmetrical widespread collection cable network, and connected by long transmission cables to the system. In December, Landsvirkjun erected two wind turbines, in an area known as Hafið, within the construction area of Búrfell Power Station, in the south of Iceland. The turbines have a total of 2 MW of installed power. The project is part of Landsvirkjun's research and development project on the advantages of wind power in Iceland. A full fledged wind farm is planned for this area in near future There are also new plans about the installation of more generators around Iceland. This growth will cause changes in power flow and dynamics characteristic of the power system that have to be taken into account for the development of wind energy in Iceland. Landsnet needs to study affect of wind farms on stability of the grid. A dynamic simulation model of Wind Farm in Búrfell is proposed with Matlab/Simulink with the objective of doing a dynamic study of the system taking into account all the changes planned in generation and grid. This study let us analyze the dynamic behavior of the wind power plant with small and severe disturbances in the power system. The dynamic study will take into account the most important parts of the Wind Farm like Turbine, Governor, Generator, Back to Back converter, transformers and transmission lines to get a good approximation of the systems and acceptable results

1.2 Objective

The main objective of this work is to contribute to the topic of wind energy systems modeling and stability analysis by developing a PMSG Gear-less wind turbines based wind farm model and do a stability analysis with respect to Icelandic national grid. When increasing the integration of wind power, both the steady-state and the dynamic behavior of the system are affected. Since wind power facilities often are located in areas with weak networks (low short circuit capacity), disconnection of generators leading to power outage might occur at small disturbances. *The main objective is the focus on how different types of wind power facilities affect a network's dynamic stability when exposed to small disturbances.*

1.3 Contributions

This thesis will contribute to the research in the field of wind energy development in Iceland. The main contributions are as follows.

- Dynamic model of a PMSG gear-less turbine based wind farm.
- Stability studies for the Wind farm with respect to Icelandic Grid.
- Wind farm model based on single type of WT.
- How are faults ride-through qualities of Wind Turbines?

1.4 Scope of Thesis

The scope of the research is to study wind power integration to Icelandic national grid. Earlier research work by Landsvirkjun has showed that búrfel is ideal location for a wind farm so a wind farm is modeled at that location. and tied to an equivalent model of Icelandic grid . Power system stability analysis will be performed on the wind farm and the grid as a whole.

1.5 Literature Survey

An extensive research was done on working of wind turbines. several research papers were consulted for different design problems during the modeling phase. Data was provided by Landsnet to design an equivalent model of Iceland national grid. Earlier research done on wind energy integration by different EU countries was studied and provided the basis for this thesis.
The search engines "science direct", "leitir.is" and "skemman.is" were used, These search engines have access to all databases of Nordic Libraries and most of the international research journals. The word used for research were

"wind power integration" and "wind turbine modeling" . It was bit difficult to find specific data in the openly accessible journals since actual modeling of the system was not explained in any of the papers. In order to solve some problems in the model some literature from Matlab central help was also studied. More than 10 year old research paper or articles were not consulted since rapid advancement of wind power technology in last decade have made them not desirable for this thesis.

1.6 Thesis Layout

The layout of this thesis is as follows,

- In chapter one, Introduction about the wind energy and motivation, objective and scope of thesis have been discussed briefly.
- In chapter two, Iceland's National Grid that is the present scenario which is considered in this thesis for case study has been described.
- In chapter three, the model of Wind Turbine Generator System and its components are explained briefly. This mathematical model has been implemented in MATLAB Simulink.
- In chapter four, the results of extensive simulation for different cases have been shown and described.
- In chapter five, based on the simulation results, a conclusion has been drawn. The future scope of Wind-Turbines in Iceland's National power grid has also been described.

Chapter 2

Iceland's National Power System

The electrical power generation system of Iceland consist of different types of power plants including geothermal, hydro and small wind power capacity is also recently brought online. Wind energy is a renewable source of energy and the impact of wind turbines on the nature is minimum as compared to the other sources of energy. A recent research has shown that there are a number of areas in Iceland that can be exploited for wind energy extraction[29]. The proposed wind turbines are supposed to be installed at Búrfell. The Iceland's national power system in shown in Figure 2.1.

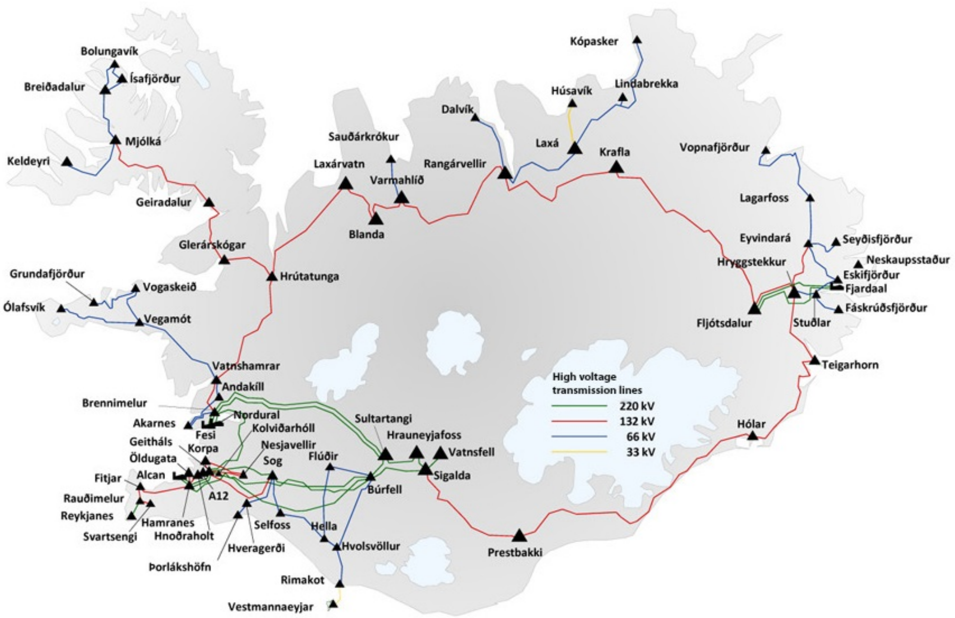

Figure 2.1: Iceland's Electrical System[27]

Chapter 3

System Modeling

3.1 Transmission System

Landsnet is the monopoly operating all the major transmission system infrastructure in Iceland. The voltages used are mostly 66 KV and higher, There are a few 33 KV lines owned by landsnet as well. All the substations are owned and operated by landsnet. Most of the grid operates at 132 KV and highest voltage in the grid is 220 KV. The newly constructed lines for the south-west were built as a 420 KV line. As per orkustofnan regulations all the power plants 7 MW or higher must be connected to the grid. There are 19 locations where power is being supplied to the grid and 61 locations where grid supplies to the consumers The single line diagram of simplified Iceland's southern power grid is shown in the Figure **??**. There are four buses in the power network. The bus 1 is of $132KV$ and it is connected to bus 4 through a transmission line of $100Km$. It is also connected to the bus 2 through a transformer of $220KV/132KV, 150MVA$. There is also a generator of $132KV, 1400MVA$ connected to bus 1. This bus is selected as PV bus. The bus 2 is of $220KV$. There is a generator of $220KV, 4000MW$ connected to this bus. It is also connected to bus 3 through a transmission line of $100Km$. This bus is under consideration for WTGS installation, therefore, it is selected as swing bus.
Bus 3 is connected to a load of $220KV, 1000MW$ with power factor of 0.95 and to the bus 4 through a transformer of $220KV/132KV, 150MVA$. This bus is also selected as PV bus.
Bus 4 is of $132V$ and it is connected to a power generator of $132KV, 1400MVA$. It is also connected to the bus 1 through a transmission line of $100Km$. This bus is also selected as PV bus.

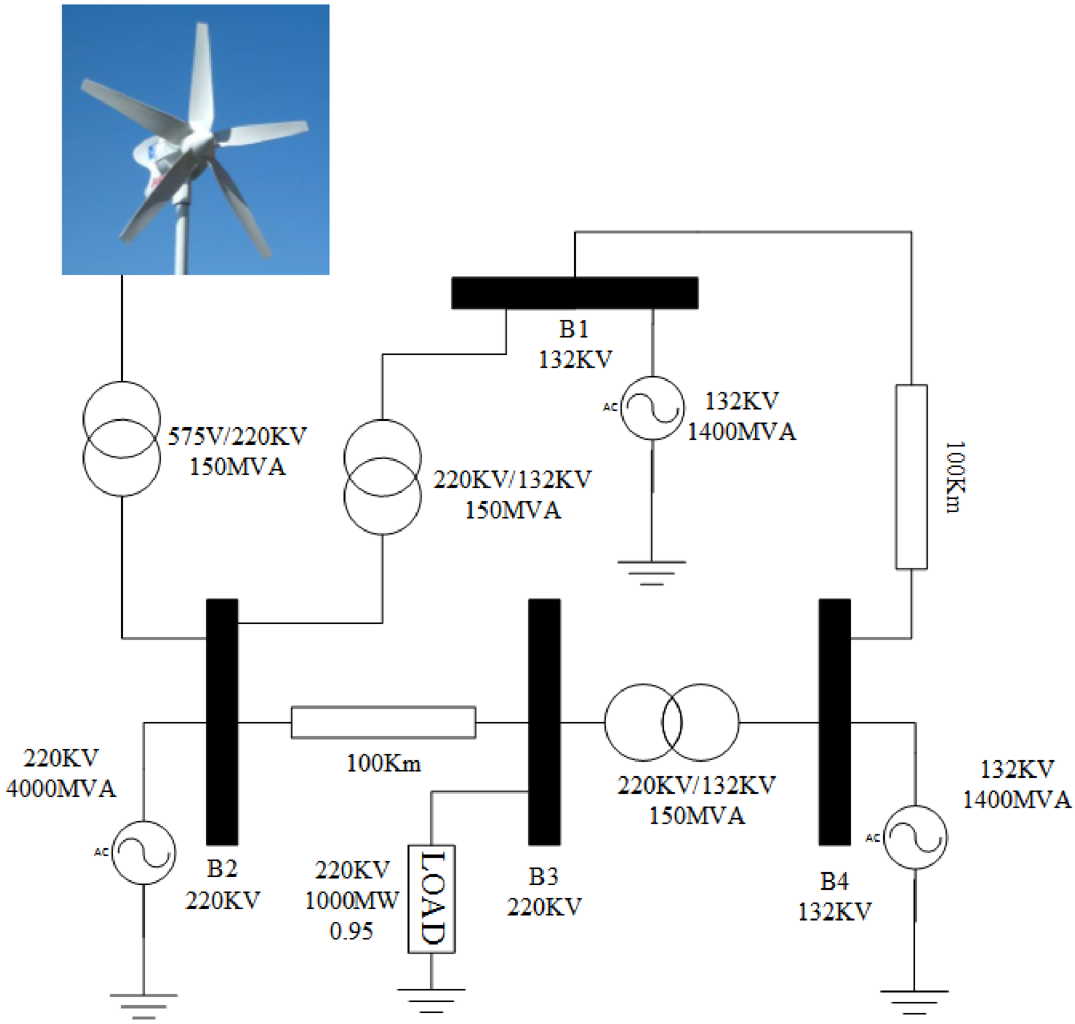

Figure 3.1: Single Line Diagram of Iceland's Power System

3.2 Wind turbine

Wind turbines have been used for centuries and still these are the best means of harvesting energy from the wind as they need little maintenance and have long service life of more than half a century. Today, these machine have to prove their efficiency and cost effectiveness with other means of energy. For this, each parameter of wind turbine needs to be optimized. Extensive study and research have been done in this regard to maximize its output power and efficiency[23].

3.2.1 Ideal Model

Wind has the kinetic energy that needs to harvested. This kinetic energy can be represented as

$$U = \frac{1}{2} m V_w^2 \tag{3.1}$$

Where U is the kinetic energy for the wind having mass m and velocity of V_w. To be specific about the wind turbine, lets say, there is packet of wind that is driving the turbine having cross sectional area A, length x and density of wind is ρ then

$$U = \frac{1}{2} (\rho A x) V_w^2 \tag{3.2}$$

Since $P_w = \frac{dU}{dt}$, so we can write

$$P_w = \frac{1}{2} \left(\rho A \frac{dx}{dt} \right) V_w^2 \tag{3.3}$$

which can also be written as

$$P_w = \frac{1}{2} \rho A V_w^3 \tag{3.4}$$

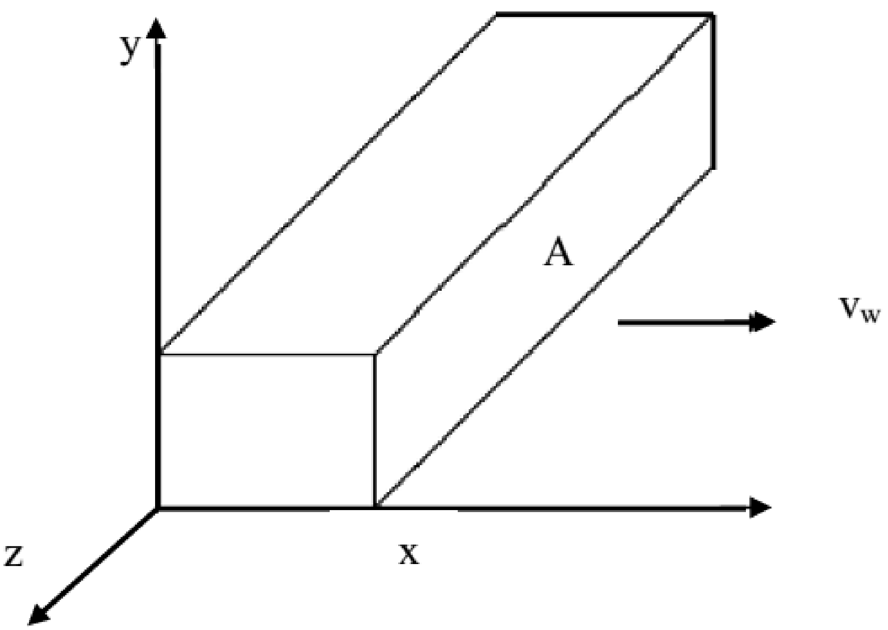

Figure 3.2: Packet of wind

The presence of turbine varies the velocity and pressure of the wind. To analyze that behavior, consider an undisturbed tube of air having diameter d_1, velocity V_{w_1} and pressure p_1 is approaching to the turbine. As the air approaches, the velocity decreases, pressure increases and its diameter approaches to the diameter of turbine d_2. This increase in pressure builds up a potential energy. In other words, the kinetic energy is converted into potential energy. This potential energy is maximum in front of the turbine. After the turbine, the pressure suddenly decreases and tends to attain the pressure equal to atmospheric pressure. This results in further decrease in the velocity of air. Once the lowest velocity is achieved, the velocity tends to increase back to normal i.e. $V_{w_1} = V_{w_4}$. This can be illustrated in the Figure 3.3.

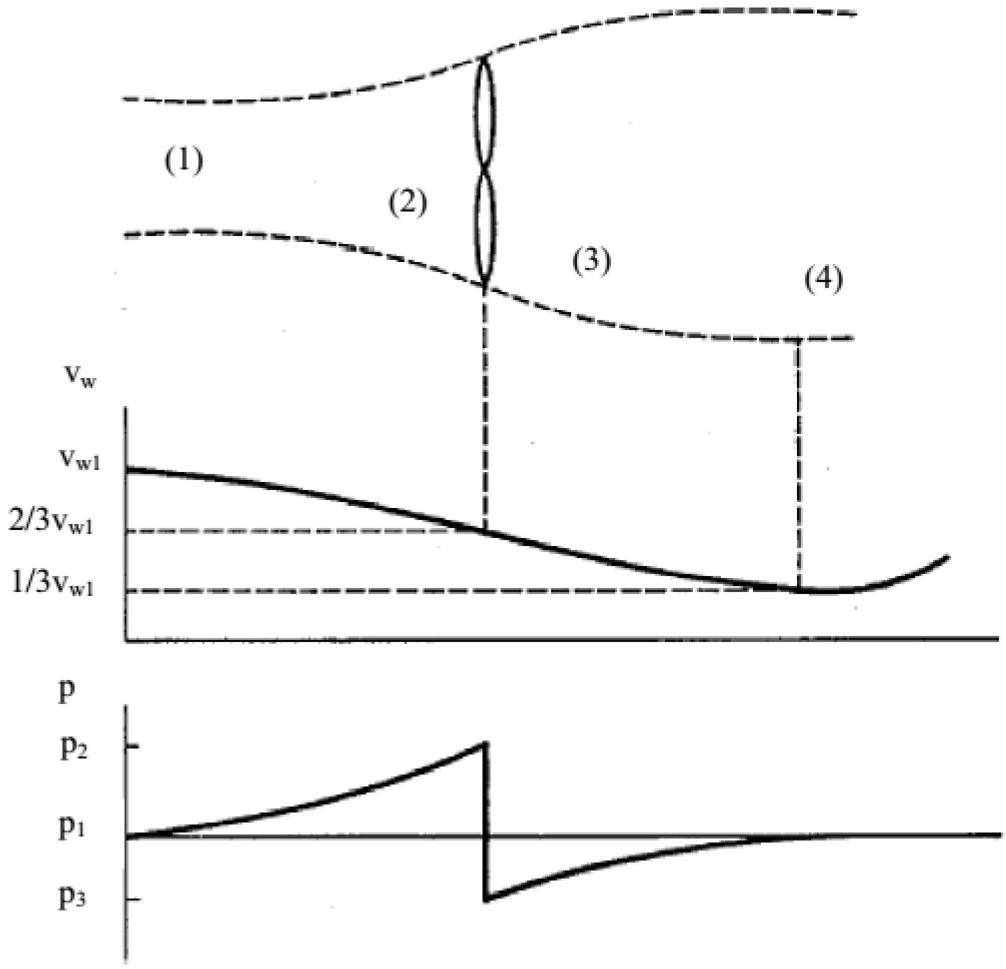

Figure 3.3: Air flow through an ideal wind turbine

The velocities and pressures at different points can be represented as:

$$\left.\begin{array}{c} V_{w_2} = V_{w_3} = \frac{2}{3}V_{w_1} \\ V_{w_4} = \frac{1}{3}V_{w_1} \\ A_2 = A_3 = \frac{3}{2}A_1 \\ A_4 = 3A_1 \end{array}\right\} \tag{3.5}$$

In this way, the total mechanical power extracted from air can be expressed as

$$P_{m,ideal} = P_1 - P_4 \tag{3.6a}$$

$$P_{m,ideal} = \frac{1}{2}\rho(A_1 V_{w_1}^3 - A_4 V_{w_4}^3) \tag{3.6b}$$

$$P_{m,ideal} = \frac{1}{2}\rho(\frac{8}{9}A_1 V_{w_1}^3) \tag{3.6c}$$

It shows that $\frac{8}{9}$ is the original power of air that is extracted by the turbine. In this derivation of mechanical power, it is assumed that the cross sectional area of air tube is smaller than that of the turbine, which may lead to different results in practical system where the cross section of air packet is bigger than the cross section of wind turbine. The cross sectional area of tube is assumed be equal to the cross sectional area of turbine. If that is so, then the extracted mechanical power is as follows.

$$P_{m,ideal} = \frac{1}{2}\rho\left[\frac{8}{9}\left(\frac{2}{3}A_2\right)V_{w_1}^3\right] \tag{3.7a}$$

$$P_{m,ideal} = \frac{1}{2}\rho\left(\frac{16}{27}A_2 V_{w_1}^3\right) \tag{3.7b}$$

The fraction $\frac{16}{27} = 0.593$ is called Betz Coefficient. It shows that the wind turbine cannot extract more than 59.3% of total wind power. A good fraction from 35% to 40% can be achieved under optimum conditions. Although, it can also be as high as 50%. The fraction 40% is considered sufficient while considering the constantly changing wind speed, direction and frictional losses due to roughness of blade surface[25].

3.2.2 Practical Model

The fraction of power extracted from the power of wind by a practical wind turbine is called *Coefficient of Performance* or *Power Coefficient*. It is denoted by C_p. The actual power output from a practical turbine can be written as:

$$P_m = C_p \left(\frac{1}{2} \rho A V_w^3 \right) = \frac{1}{2} \rho \pi R^2 V_w^3 C_p(\lambda, \beta) \tag{3.8}$$

where, R is the radius of the wind turbine blade(m), V_w is the wind speed (m/sec) and ρ is the density of air. The Power Coefficient is not constant, it depends on the wind speed, rotational speed of turbine and the performance of blade such as angle of attack and pitch angle. In general,it can be said that the Power Coefficient is the function of tip speed ration λ, blade pitch angle β (deg). The tip ratio λ can be written as:

$$\lambda = \frac{\omega_R R}{V_w} \tag{3.9}$$

where ω_R is the mechanical angular velocity of the turbine rotor (rad/s) and V_W is the wind speed (m/sec). If the rotational speed is given in terms of 'n' (rpm) then ω_R can be found as:

$$\omega_R = \frac{2\pi n}{60} \tag{3.10}$$

3.3 Wind Turbine Generator System

A wind turbine generator system (WTGS) extracts the energy present in the wind and converts it into electrical energy. Since the wind is highly changing, therefore, there must be a control system and mechanism such that it should optimize the operation and maximize the output of WTGS. A general scheme is shown in Figure 3.4.

There are two types of WTGS:

1. Fixed Speed WTGS
2. Variable Speed WTGS

Each system has its own merits and demerits. Both are discussed briefly in [25].

3.3.1 Fixed Speed WTGS

For fixed speed operation, induction generators are used with a gearbox to maintain the speed of generator shaft almost constant. This scheme is shown in the Figure 3.5.

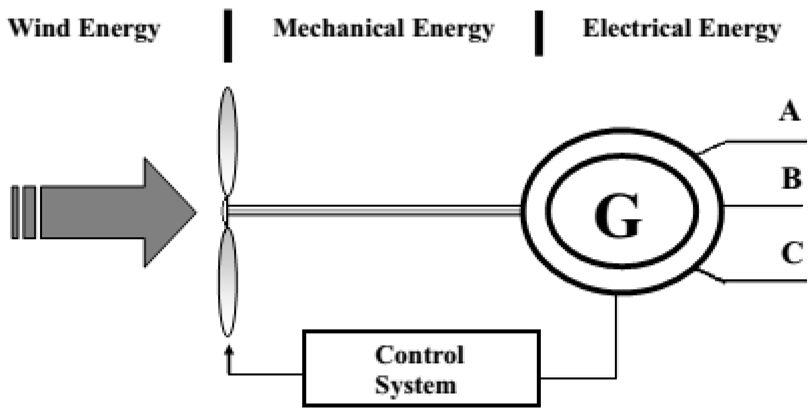

Figure 3.4: Wind Turbine Generator System

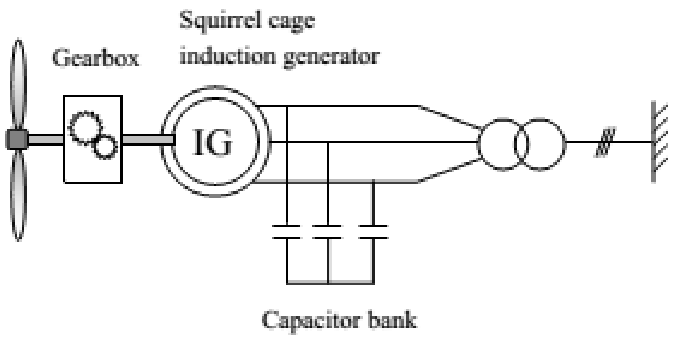

Figure 3.5: Fixed Speed WTGS Scheme

Induction generators always need to be connected to the grid as they consume creative power and produce active power. The consumption of creative power significantly drops the power factor of the generator, therefore, a reactive compensation in the form of capacitor banks is applied to keep the power factor nearly equal to one.

Its key features are:

1. It can be directly connected to the power grip.

2. Its tower support always remains under high stresses, therefore, it needs to be stronger enough to support in worst condition.

3. It needs power factor correction system to improve the power factor of the system.

3.3.2 Variable Speed

In variable speed wind turbine generator system, the generator is connected directly to the wind turbine shaft. A AC/AC converter acts as an interface between this generator of highly changing output power and the power grid. It also maintains the unidirectional flow of power from generator to the grid. The general scheme is shown in Figure 3.6.

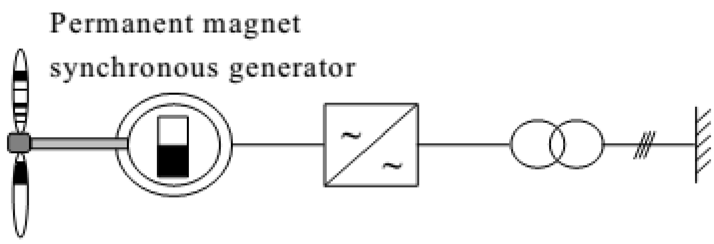

Figure 3.6: Variable Speed WTGS

Its key features are

1. It works on variable speed so it does not require a stronger structure.
2. It cannot be directly connected to the power grid, therefore, an AC/AC converter is used to match the frequency and to maintain the unidirectional flow of power.

MATLAB buit-in block for Wind Turbine is used to simulate the mechanical part of the WTGS followed by 2 Mass Model of drive train is used to introduce the effects of shaft inertia and stiffness in the torque to analyze the smooth operation of WTGS under faults. The Wind Turbine model is shown in the Figure 3.7.

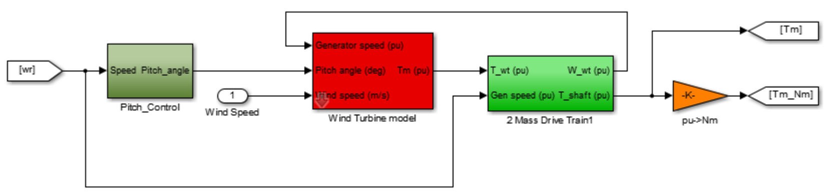

Figure 3.7: Wind Turbine Model in Simulink

3.4 PMSG

Permanent magnet synchronous generator consists of two basic parts:

- Stator: This is a stationary part that houses the armature winding.
- Rotor: This is a rotating part that houses the permanent magnet.

Permanent magnetic synchronous machine can act as motor as well as generator. When electrical power is applied to this synchronous machine, it generates output torque and vice versa. In the present case, the torque generated by wind turbine is applied to this synchronous machine and it converts the mechanical power into electrical power.
To simulate a permanent magnet synchronous generator, a synchronous machine model is used that is a built-in block in the MATLAB. In the present case, the torque is provided to the synchronous machine, so, it acts as generator and generates the voltages. It is shown in the Figure 3.8.

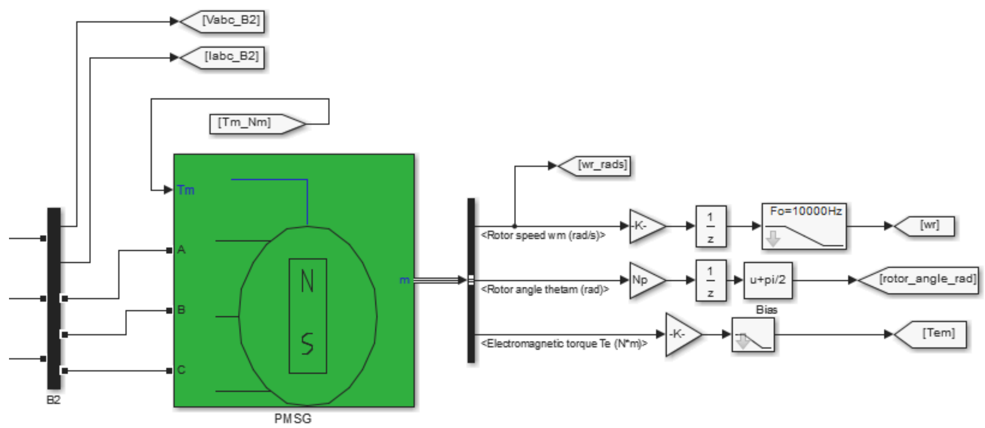

Figure 3.8: Permanent Magnet Synchronous Generator

3.5 Rectifier

The electrical power generated by PMSG is rectified into DC. The availability of power is not constant, therefore, a controlled rectifier is used. This controlled rectifier helps to control the power extraction from the generator. Turbine has a rated power, so, the extracted power should not exceed than the rated value to ensure a smooth operation of turbine at almost constant speed.

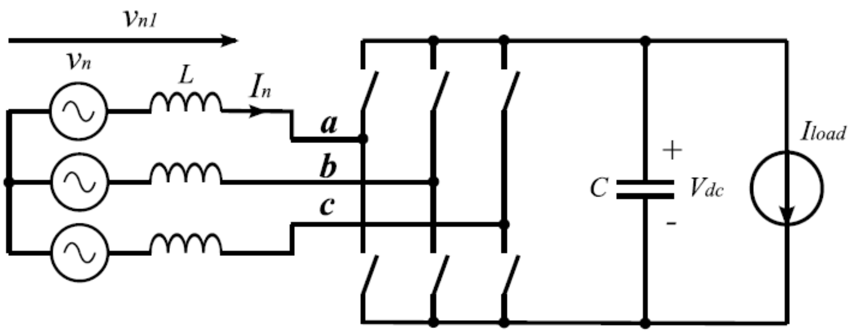

Figure 3.9: Controlled Rectifier

Figure 3.9 shows a typical controlled inverter. Since the wind speed is not constant, therefore, the torque available to drive the generator is also not constant. So, the generated voltages and frequency are not constant that may cause interfacing problems with the power system. To avoid this, all the generated voltages are rectified into DC voltages. This DC bus voltages are regulated by Rectifier controller. Controlled Rectifier model is shown in the Figure 3.10.

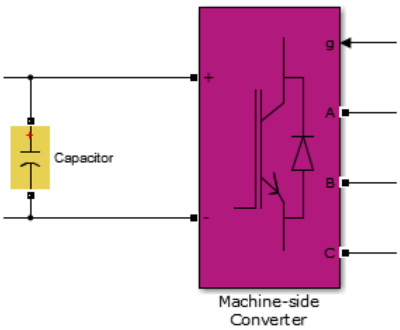

Figure 3.10: Simulink model for Controlled Rectifier

3.6 Rectifier Control

Since the availability of power is not constant, therefore, a controller is be required to control the extraction of power so that the wind turbine continues to operate smoothly. The block diagram of control strategy is shown in Figure 3.11. Rectifier Control is necessary to maintain the voltages of DC bus and to extract the power from the synchronous generator. It only allows the

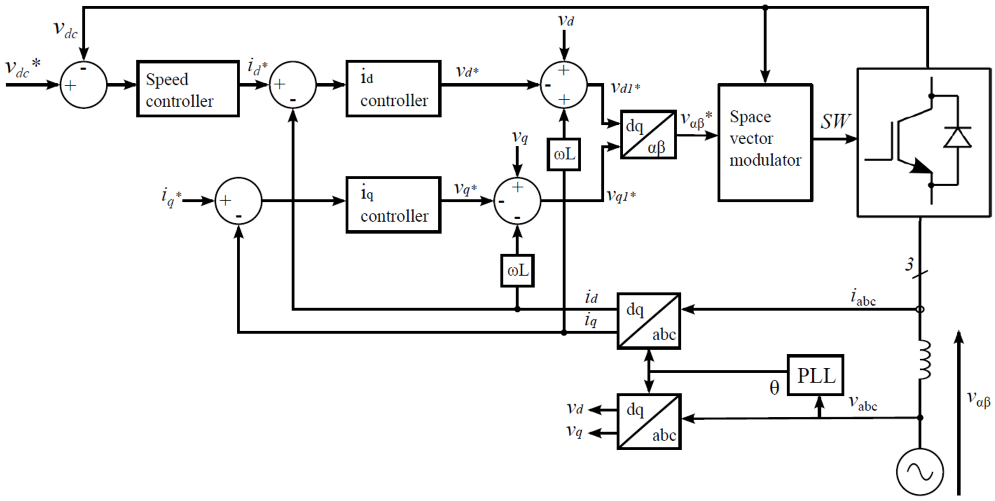

Figure 3.11: Control of Rectifier

power flow that does not significantly disturbs the rotor speed of generator and also maintain the DC bus voltages. This results in smooth operation of Wind turbine and Synchronous Generator. Park transformation is used along with the PI controller. The model of rectifier controller is shown in the Figure 3.12[22].

3.7 Inverter

To inject power into the power system, the voltage and frequency of WTGS must be compatible with the power system. To achieve this, an Inverter is used that converts the DC bus voltages into AC which is compatible with the rest of the power system. The simulink model of Inverter is shown in the Figure 3.13.

3.8 Inverter Control

To achieve the desired characteristics of inverter that it should maintain maximum flow of power by keeping the DC bus voltages almost constant, Park Transformation[20] with PI control strategy is used. The voltage control part is shown in Figure 3.14 and the current control part is shown in Figure 3.15.

Inverter Control unit controls the power flow from the DC bus to the power system. When the power is extracted from the DC bus, the DC bus

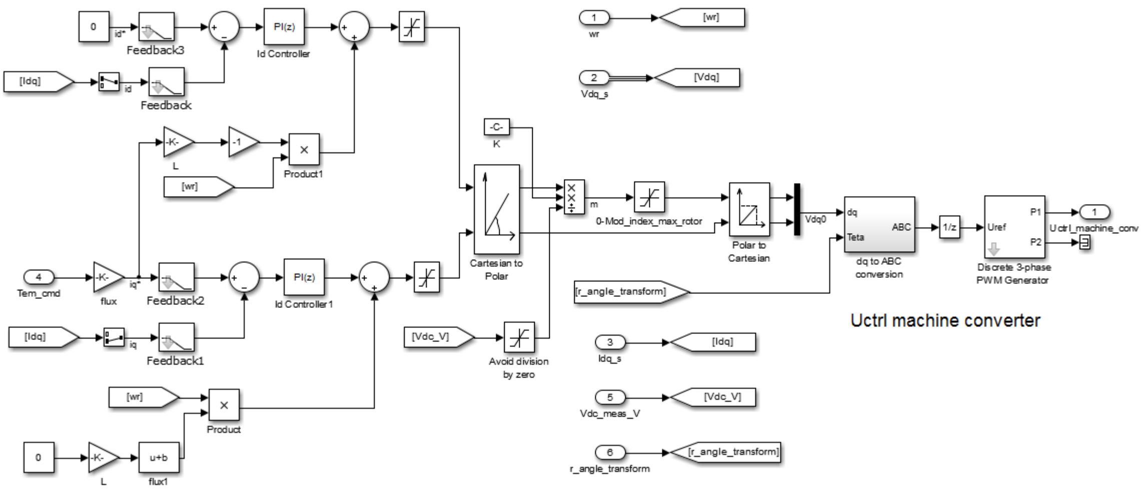

Figure 3.12: Simulink model for Rectifier Controller

voltages drops. So, this controller maintains the DC bus voltages up to a certain level that are necessary to generate AC voltages that are compatible with the power system. The simulink model of Inverter controller is shown in the Figure 3.16[24].

3.9 Inverter Protection

If the wind speed is low and DC bus voltages are not sufficient enough to generate the system compatible AC voltages then a protection system disconnects the Inverter from the power system. It connects again, if DC bus voltages are restored and the Inverter can now generate compatible AC voltages.

3.10 Unidirectional Power Flow

For generator system, the power flow must be unidirectional i.e. from the WTGS to the power system. So, to maintain the unidirectional power flow a diode is connected on the DC bus that allows flow of current only in one direction. The topology used in the simulink model is shown in the Figure ??.

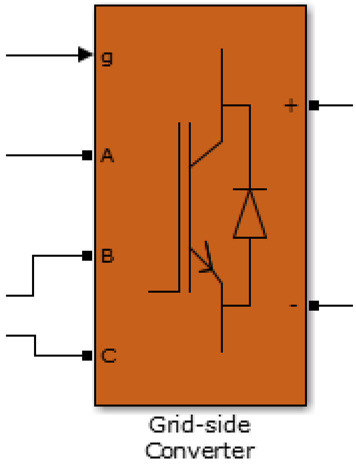

Figure 3.13: Simulink model for Inverter

3.11 WTGS Stability

Wind turbine generator system is designed and modeled in such a way that each component plays its part towards stability.

3.11.1 Pitch angle control

Pitch angle varies depending upon the speed of wind turbine under variable wind speed to ensure maximum power extraction from wind. The maximum allowable pitch angle and pitch angle changing rate is kept within limits to avoid undesirable behavior and to maintain the stability of the system.

3.11.2 Rectifier Control

The controller of rectifier is configured in such a way that it tends to draw maximum possible current from the generator by putting minimum effect on the rotor speed. In this way, the turbine runs smoothly and the system remains stable. Its output is DC voltages.

3.11.3 Inverter Control

Inverter draws power from the DC bus and converts it into AC compatible with power grid. It controls the power injection to the grid by controlling the PWM of inverter. It tends to inject the maximum possible power to the

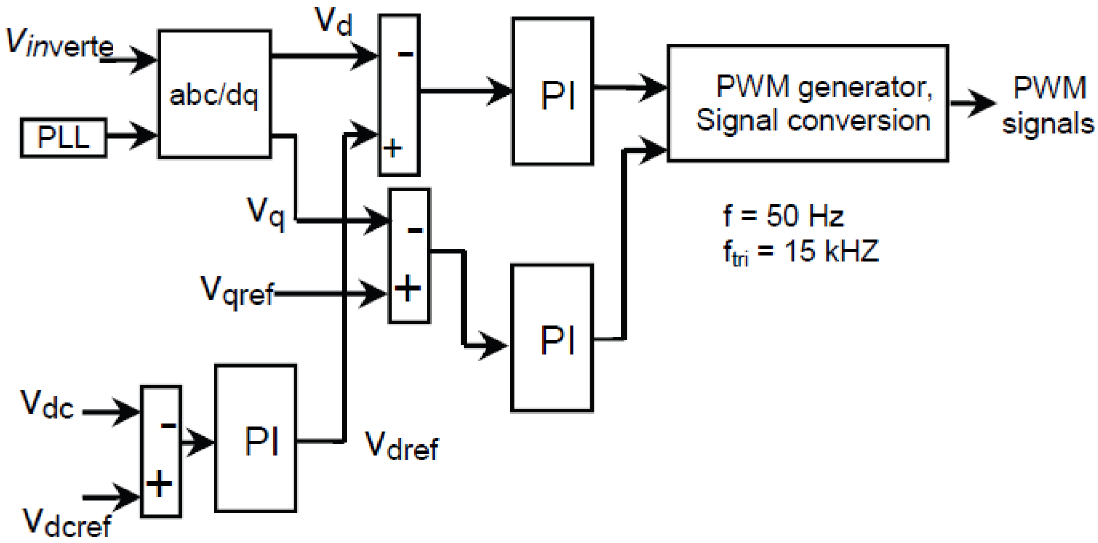

Figure 3.14: Voltage Control of Inverter

grid by keeping the DC bus voltages almost constant. In this way, the DC bus voltage remains almost same or stable. Its output is AC compatible with the power grid.

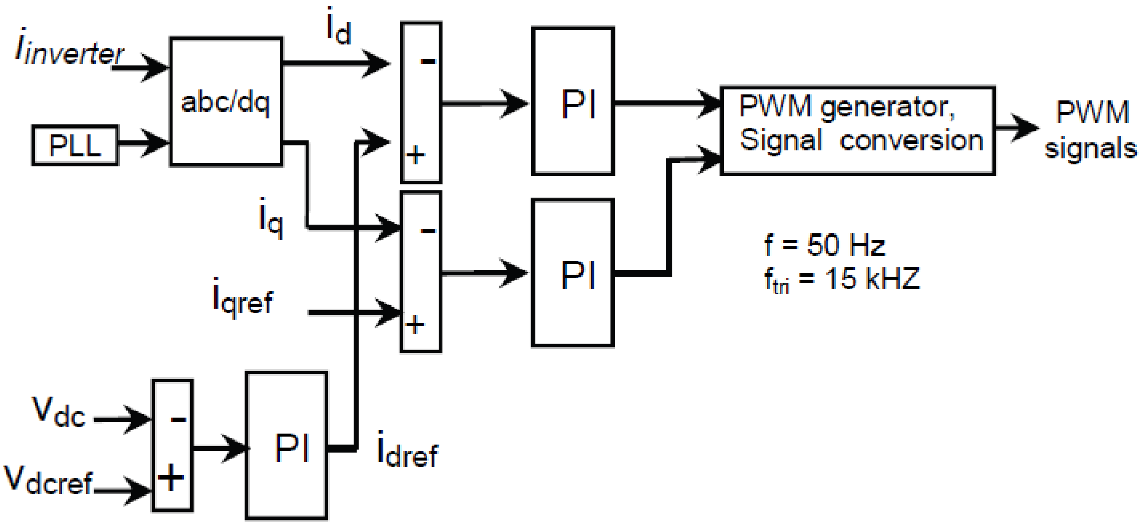

Figure 3.15: Current Control of Inverter

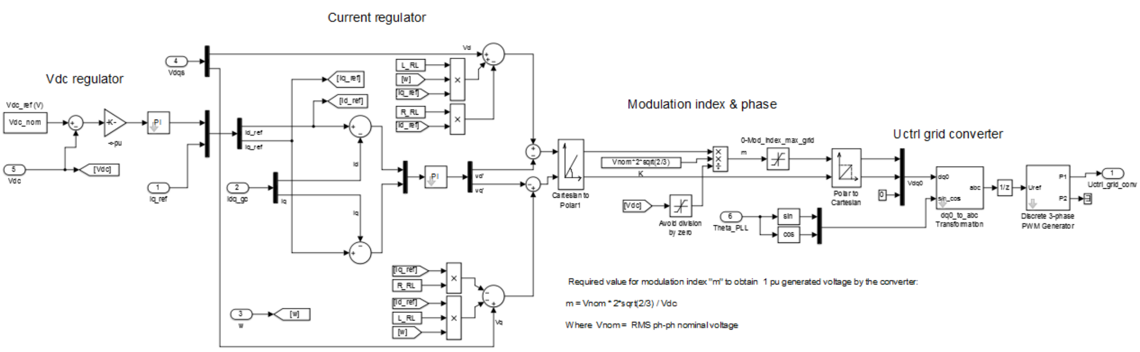

Figure 3.16: Simulink model for Inverter Controller

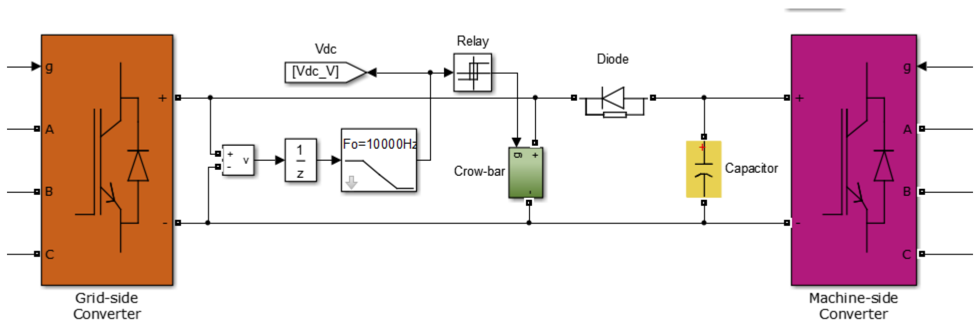

Figure 3.17: Unidirectional flow of Power

Chapter 4

Simulation Results

To analyze the stability of WTGS, numerous simulations have been performed under different circumstances. There are 8 different cases that are considered.

Case	Number of WTs	Rating of SCC
1	0	100%
2	0	60%
3	1	100%
4	1	60%
5	2	100%
6	2	60%
7	3	100%
8	3	60%

Table 4.1: Different cases for simulation

The voltages at each bus have been monitored and the simulation is carried out for $30sec$. The WTGS is connected to power system. A three phase line to ground fault has also been introduced at bus 1 for $100msec$ at the time instant of $25sec$. Further, each case is divided into two different scenarios: first with full rating of power generators and the second with 60% rating of power generators. These arrangements have been made to analyze the system completely before and after introduction of WTGS in Iceland's power system under normal, fault and after the fault conditions.
The nominal voltages of bus 1,2,3,4 and Wind Turbine bus are 132KV, 220KV, 220KV, 132KV and 575V respectively. Bus 2, where the WTGS is connected, is selected as swing bus and other buses are PV buses. A lumped load of 1000MW with 0.95 power factor is connected at bus 3. The

nominal frequency of the power system is 50 Hz. The nominal power of one Wind Turbine is 1.5MW and a transformer is used to connect this WTGS to the power grid. Each Wind Turbine is accommodated with 50MVA rating of transformer to fully support the power flow under worst conditions.

4.1 With No Wind Turbine

The power system of Iceland with no Wind Turbine is shown in Figure 4.1. This simulation has been carried to analyze the normal and under fault operation of power system without WTGS. A three phase line to ground fault occurs at Bus 1 for 100*msec* at the time instant of 25*sec*.

4.1.1 SCC With Full Rating

This part of simulation is carried out with full rating of power generators. The power system model is shown in figure 4.1 and the voltages at each bus are shown in Figure 4.2, 4.3, 4.4 and 4.5. It can be seen that the system can restore itself back to normal operation after the fault has been cleared. Hence, the power system itself is stable without WTGS.

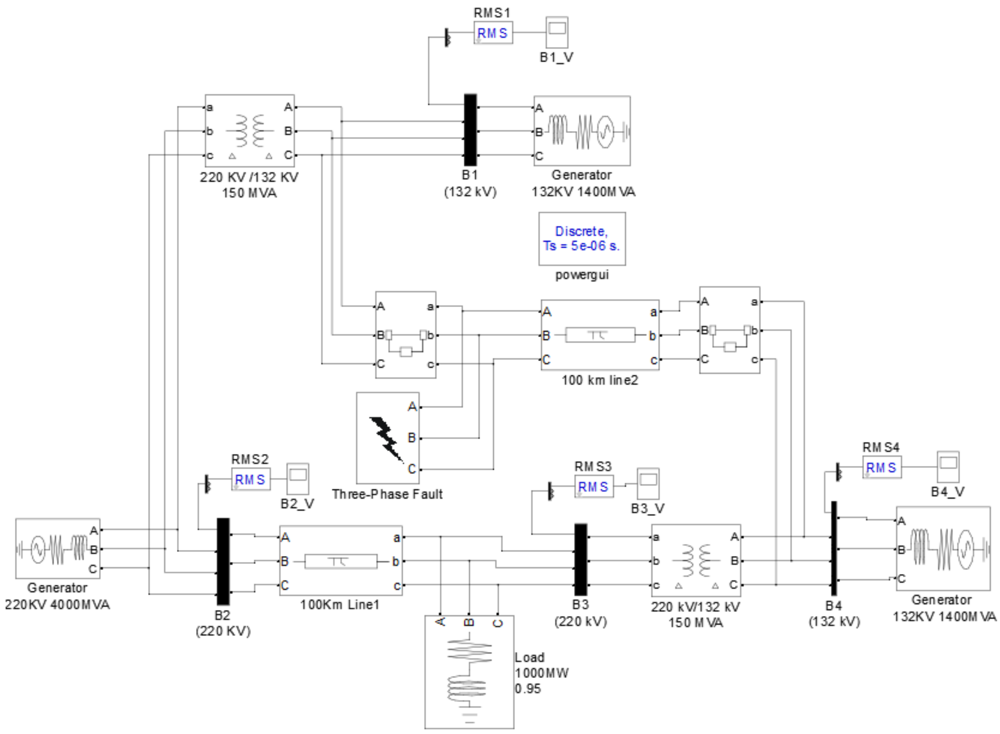

Figure 4.1: Full rating of power generators with no WTGS

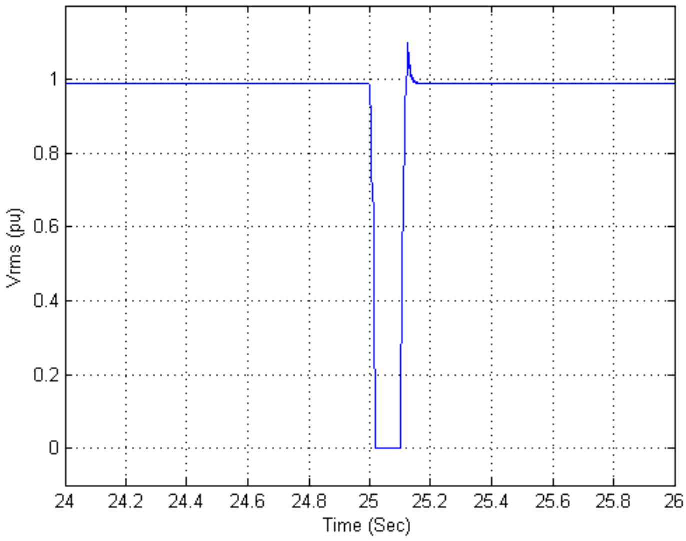

Figure 4.2: Bus 1 Voltage in Full rating of SCC with no Wind Turbine

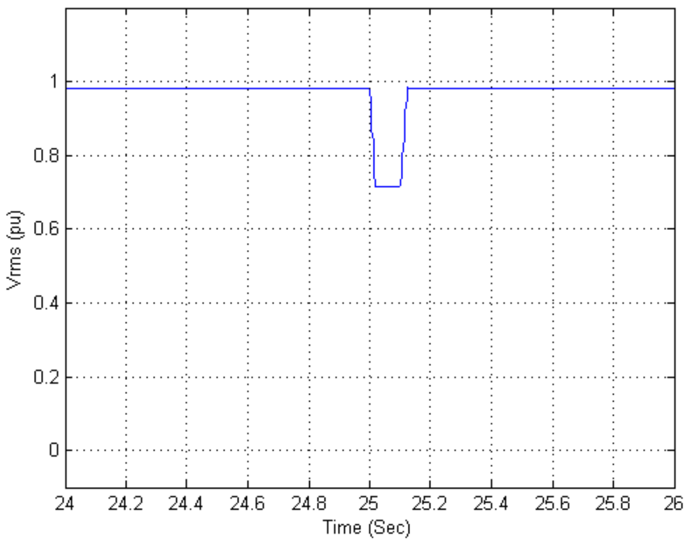

Figure 4.3: Bus 2 Voltage in Full rating of SCC with no Wind Turbine

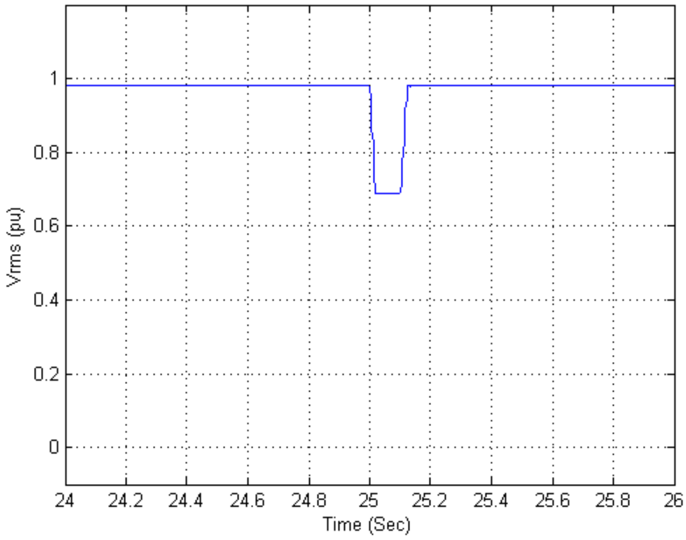

Figure 4.4: Bus 3 Voltage in Full rating of SCC with no Wind Turbine

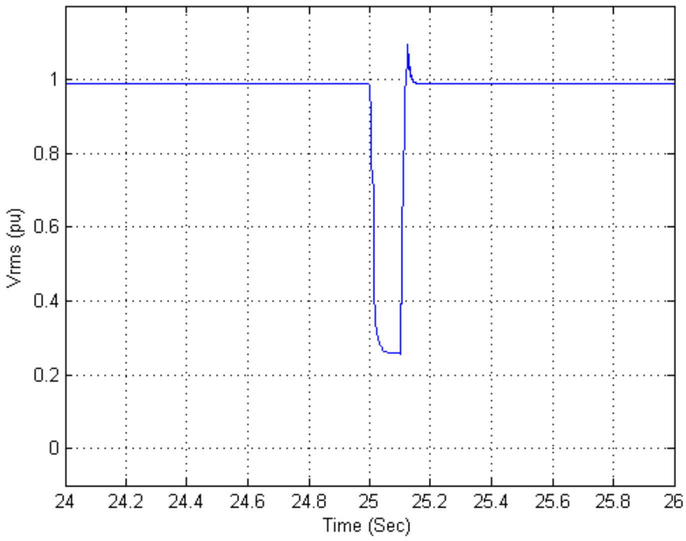

Figure 4.5: Bus 4 Voltage in Full rating of SCC with no Wind Turbine

4.1.2 SCC With 60% Rating

This simulation has been carried with 60% rating of power generators without WTGS. A three phase line to ground fault occurs at Bus 1 for 100*msec* at the time instant of 25*sec*. The power system with 60% rating of power generators is shown in Figure 4.6. The voltages at each bus are shown in 4.7, 4.8, 4.9 and 4.10. It can be seen that the system can restore itself back to normal operation after the fault has cleared. Hence, the power system itself is stable without WTGS.

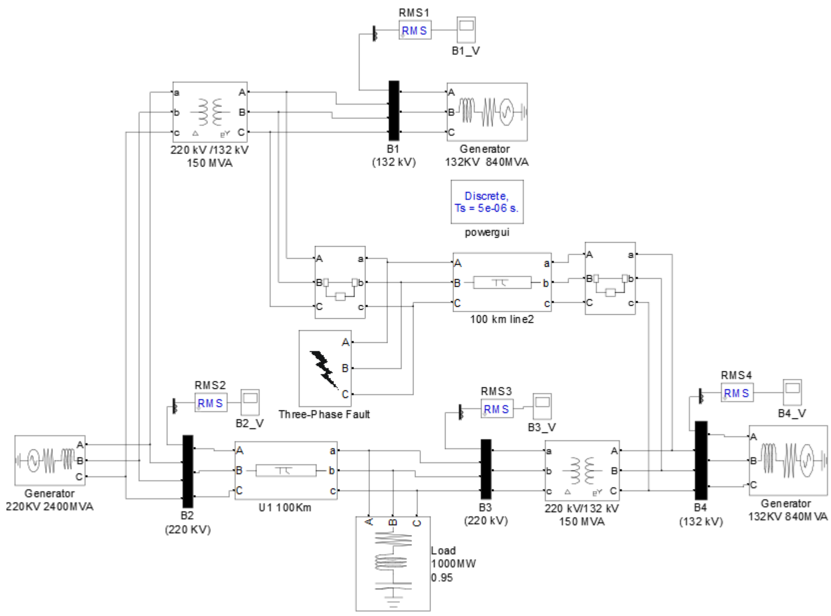

Figure 4.6: 60% rating of SCC with no WTGS

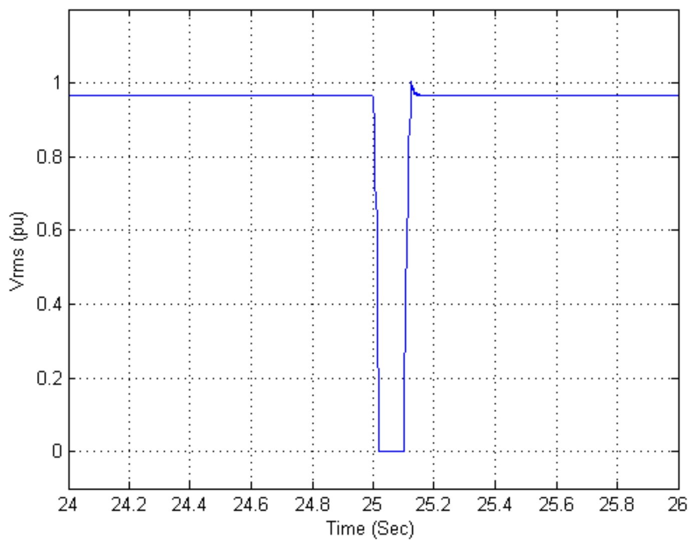

Figure 4.7: Bus 1 Voltage in 60% rating of SCC with no Wind Turbine

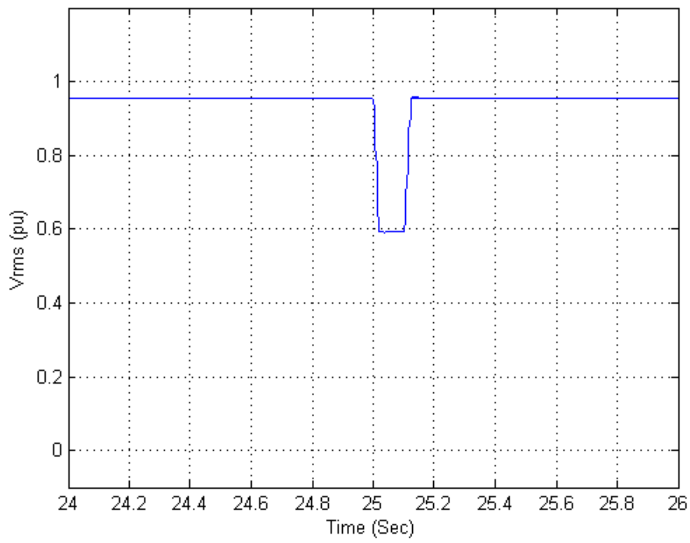

Figure 4.8: Bus 2 Voltage in 60% rating of SCC with no Wind Turbine

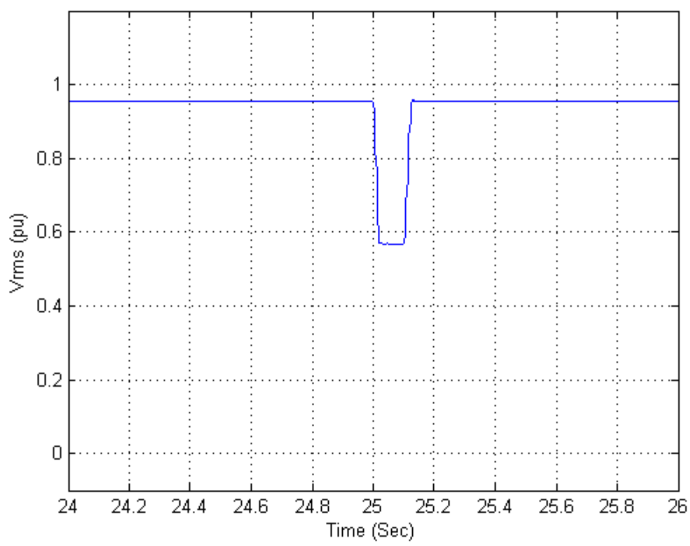

Figure 4.9: Bus 3 Voltage in 60% rating of SCC with no Wind Turbine

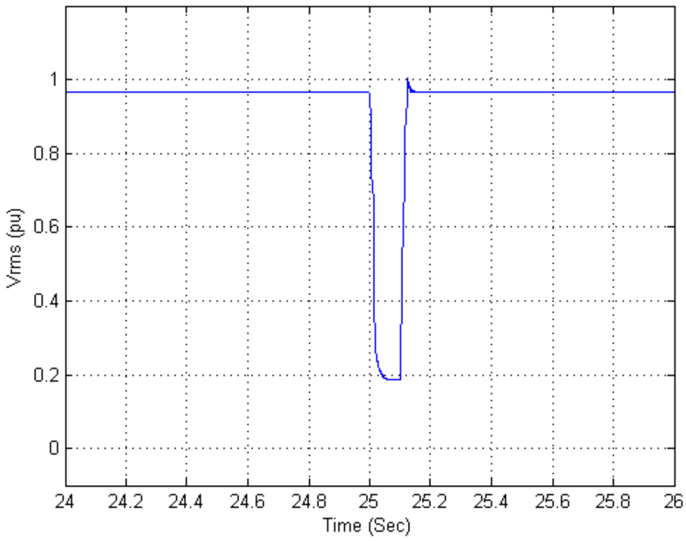

Figure 4.10: Bus 4 Voltage in 60% rating of SCC with no Wind Turbine

4.2 With One Wind Turbine

The power system of Iceland with one Wind Turbine is shown in Figure 4.11. This simulation has been carried to analyze the normal and under fault operation of power system with out WTGS. A three phase line to ground fault occurs at Bus 1 for 100*msec* at the time instant of 25*sec*.

4.2.1 SCC with 100% Rating

This part of simulation is carried out with full rating of power generators. The power system with Full rating of power generators is shown in Figure 4.11. The voltages at each bus are shown in Figure 4.12, 4.13, 4.14 and 4.15. By analyzing the rotor speed of generator, it can be ensured that the generator runs smoothly even if there is a fault in the system. The rotor speed plot is shown in Figure 4.17. Therefore, it can be concluded that the power system is stable. The power contribution by WTGS is shown in Figure 4.16. The torque generated by wind turbine is shown in Figure 4.19. It can be seen that the turbine maintains the torque even under and after fault and continues to operate normally.

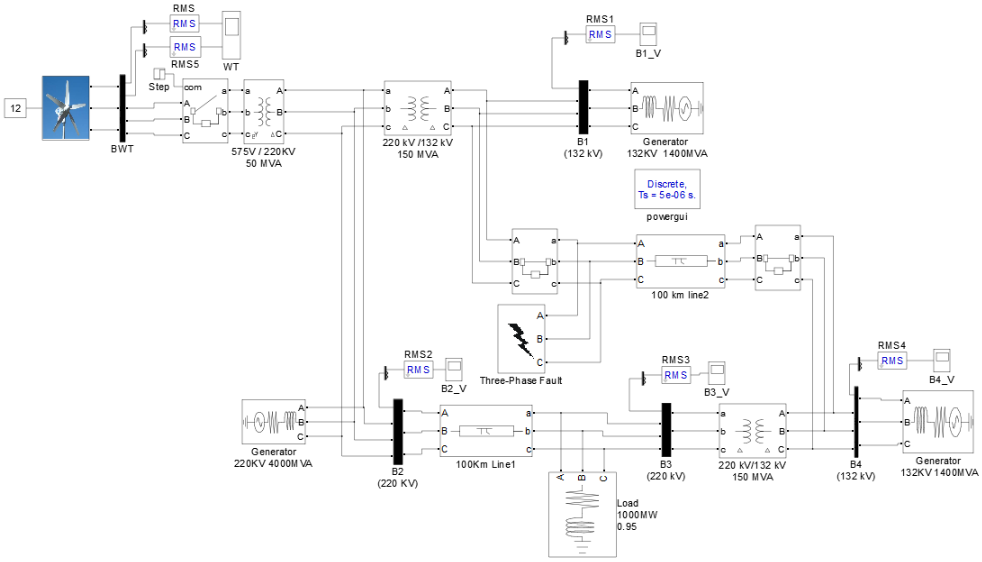

Figure 4.11: Iceland Power System with One WTGS

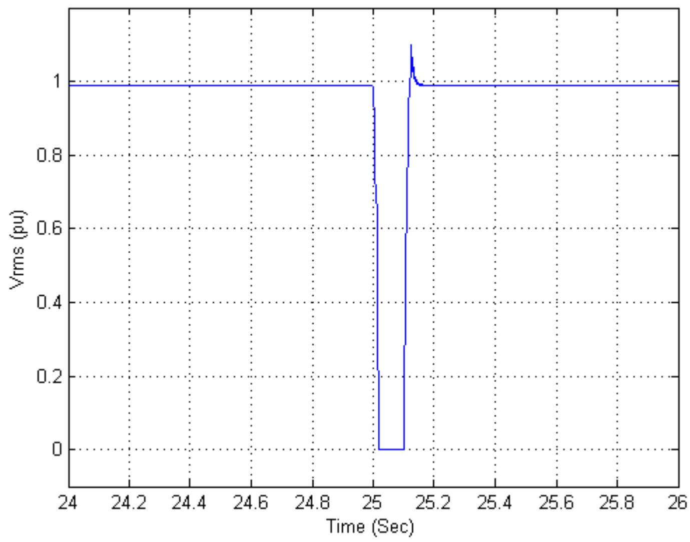

Figure 4.12: Bus 1 Voltage in Full rating of SCC with One Wind Turbine

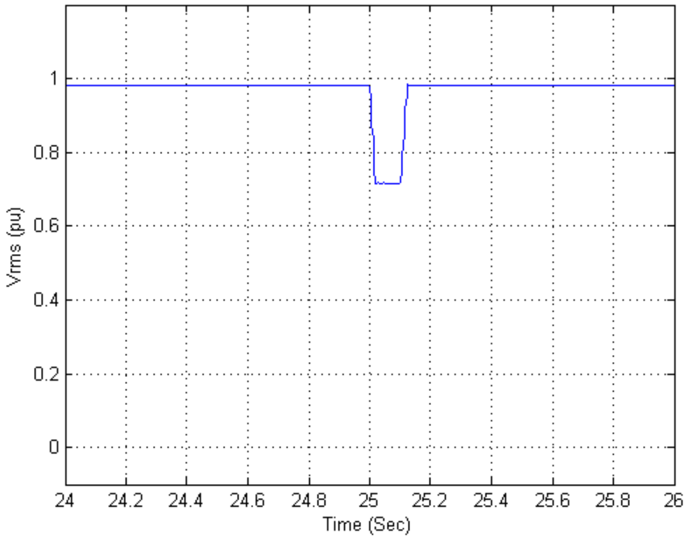

Figure 4.13: Bus 2 Voltage in Full rating of SCC with One Wind Turbine

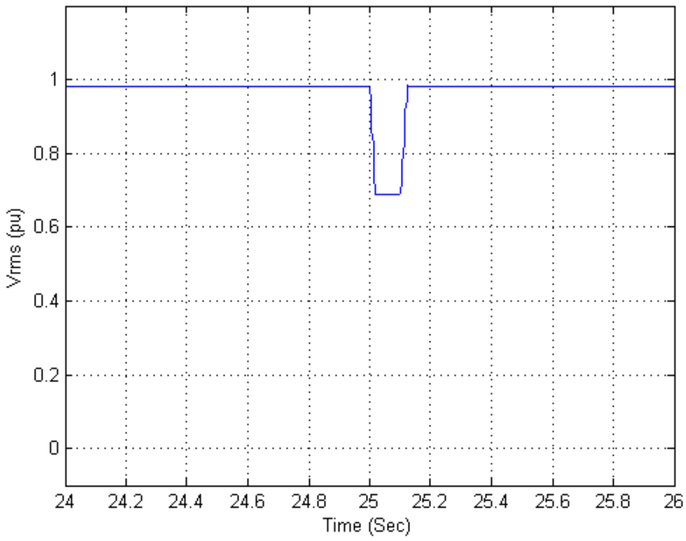

Figure 4.14: Bus 3 Voltage in Full rating of SCC with One Wind Turbine

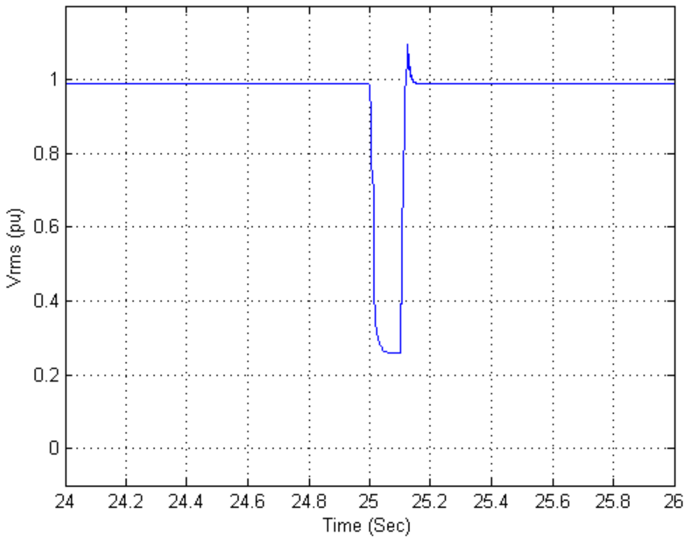

Figure 4.15: Bus 4 Voltage in Full rating of SCC with One Wind Turbine

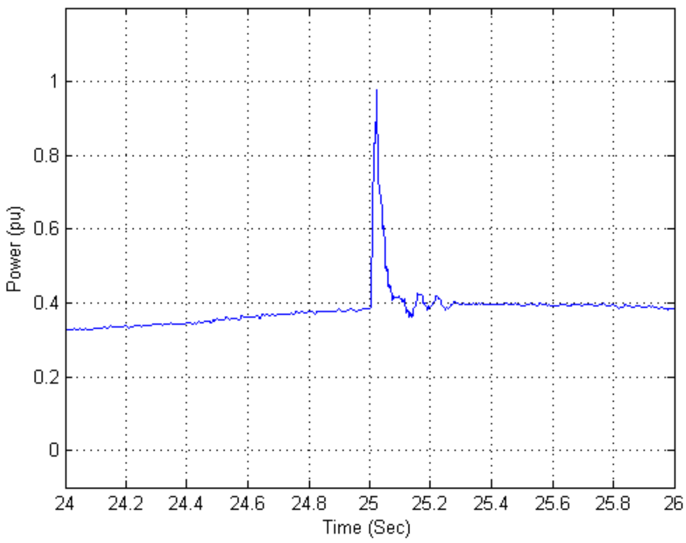

Figure 4.16: Power Injected by One Wind Turbine

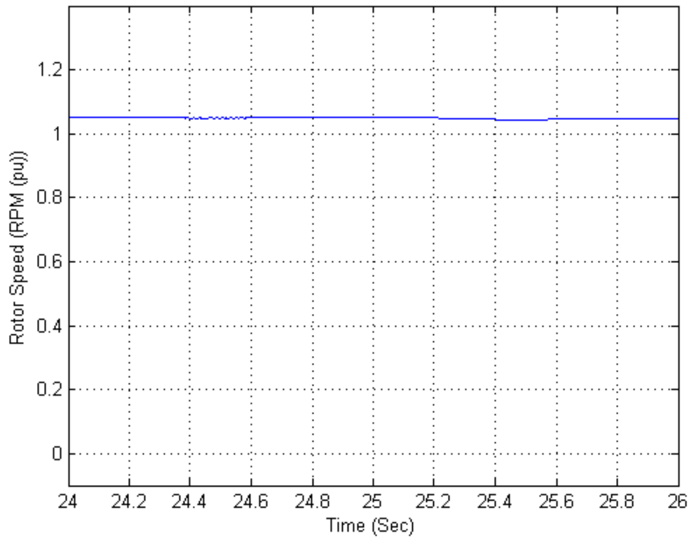

Figure 4.17: Rotor Speed of Wind Turbine

In the event of fault, the rotor speed increases and the torque of wind turbine decreases as shown in the Figure 4.18 and 4.37 respectively. It is due to the fact that the control of AC/AC converter is designed in such a way that it helps the wind turbine to run smoothly and it only permits the power flow to the power grid that can be harvested from the wind without disturbing the rotor speed[26].

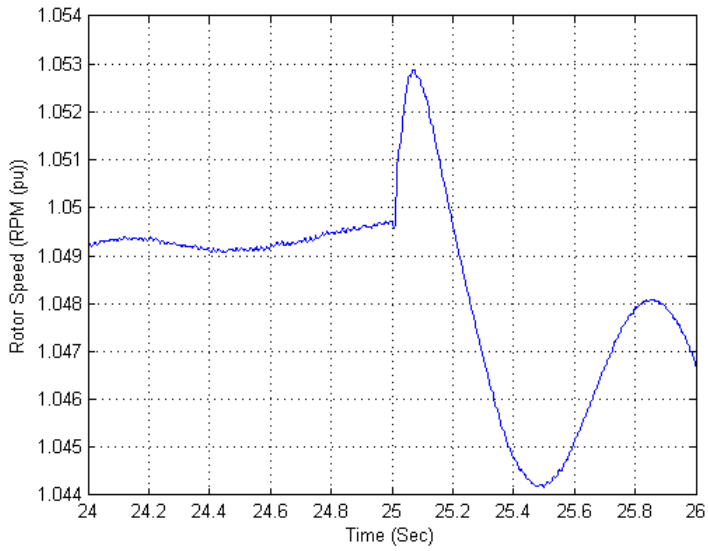

Figure 4.18: Rotor Speed of Wind Turbine

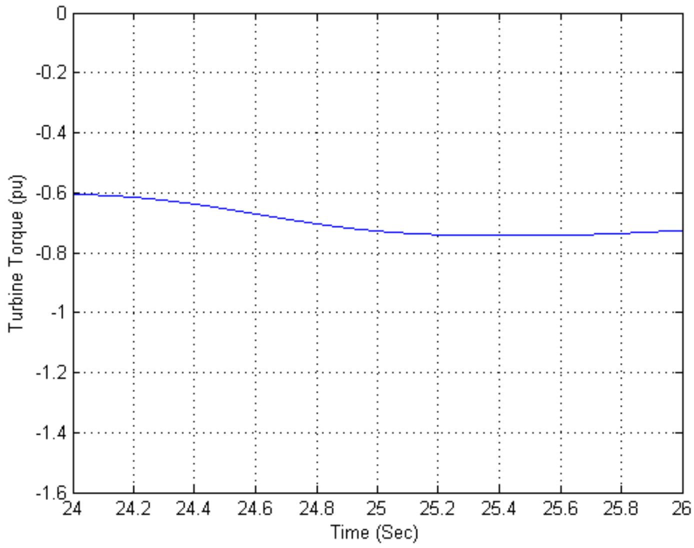

Figure 4.19: Torque of Wind Turbine

4.2.2 SCC with 60% Rating

This simulation has been carried with 60% rating of power generators with one WTGS. A three phase line to ground fault occurs at Bus 1 for 100*msec* at the time instant of 25*sec*. The power system with 60% rating of power generators is shown in Figure 4.20. The voltages at each bus are shown in 4.7, 4.8, 4.9 and 4.10. By analyzing the rotor speed of generator, it can be ensured that the generator runs smoothly even if there is a fault in the system. The rotor speed plot is shown in Figure 4.26. Therefore, it can be concluded that the power system is stable. The power contribution by WTGS is shown in Figure 4.25. It can also be noticed that the power shared by WTGS in case of 60% rating of SCC is greater than the power shared by WTGS in case of full rating of SCC. The torque generated by wind turbine is shown in Figure 4.28. It can be seen that the turbine maintains the torque even under and after fault and continues to operate normally.

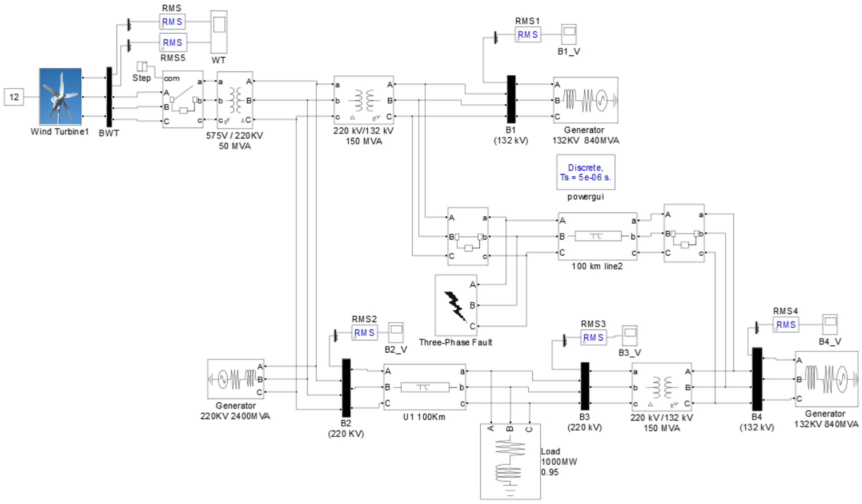

Figure 4.20: 60% rating of power generators with One WTGS

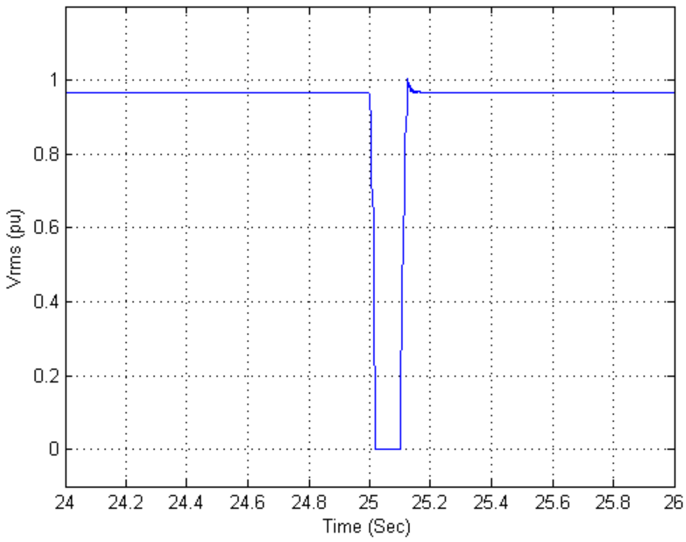

Figure 4.21: Bus 1 Voltage in 60% rating of SCC with One Wind Turbine

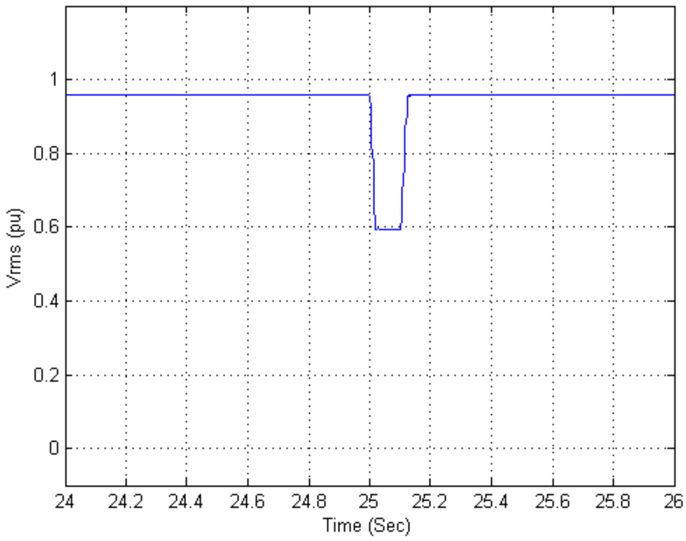

Figure 4.22: Bus 2 Voltage in 60% rating of SCC with One Wind Turbine

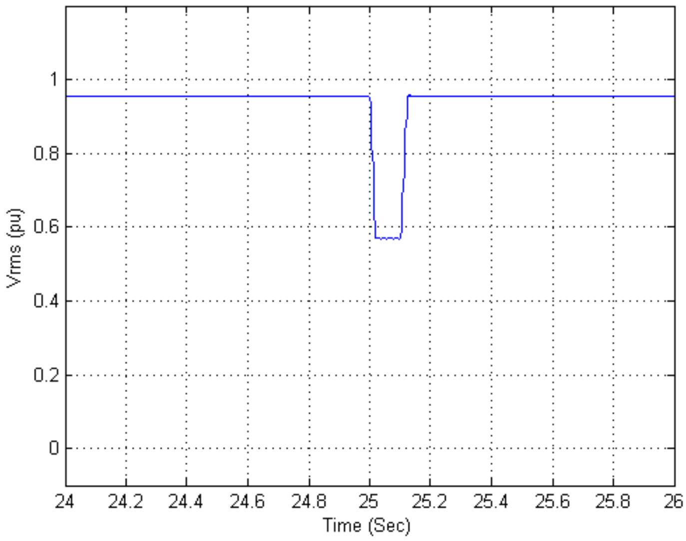

Figure 4.23: Bus 3 Voltage in 60% rating of SCC with One Wind Turbine

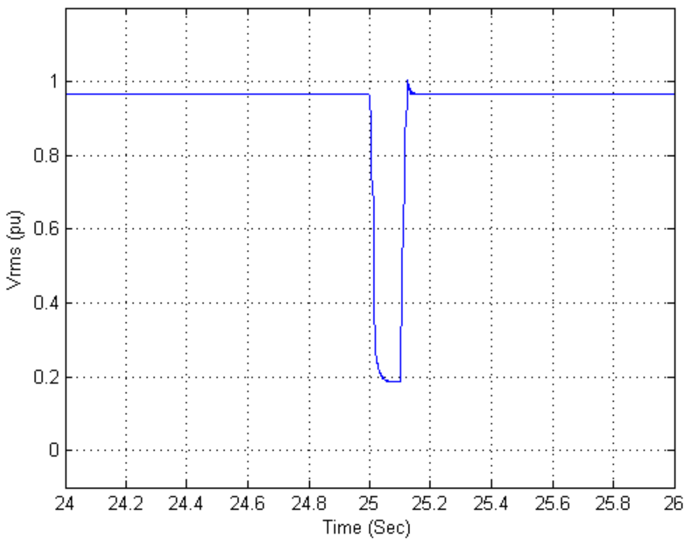

Figure 4.24: Bus 4 Voltage in 60% rating of SCC with One Wind Turbine

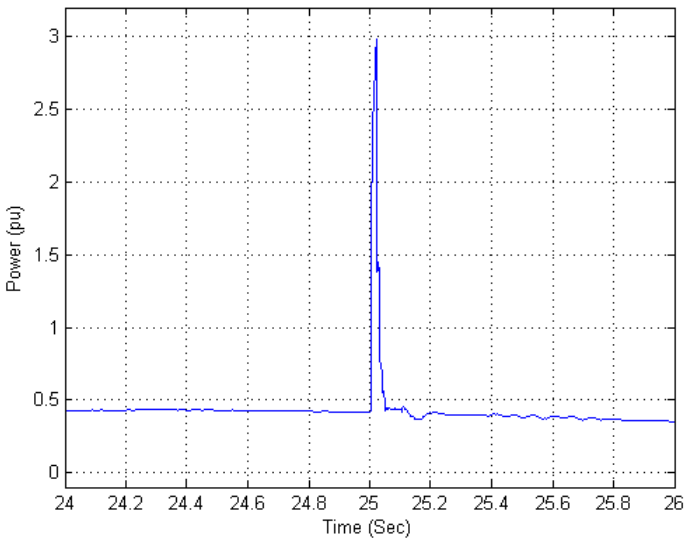

Figure 4.25: Power Injected by One Wind Turbine

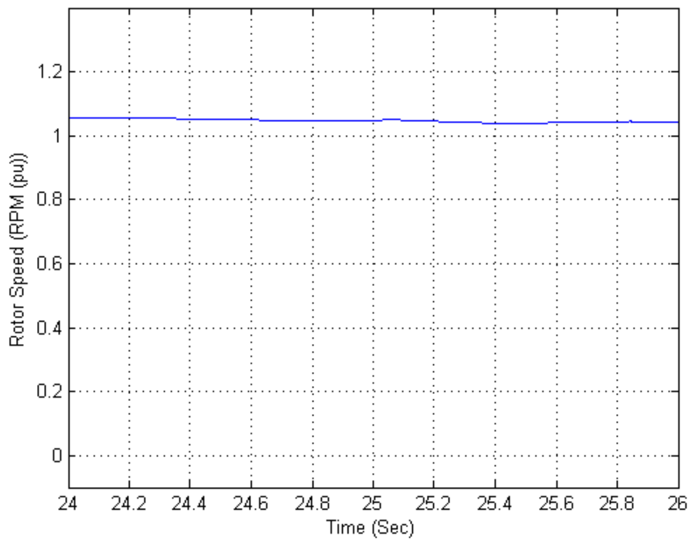

Figure 4.26: Rotor Speed of Wind Turbine

In the event of fault, the rotor speed increases and the torque of wind turbine decreases as shown in the Figure 4.27 and 4.37 respectively. It is due to the fact that the control of AC/AC converter is designed in such a way that it helps the wind turbine to run smoothly and it only permits the power flow to the power grid that can be harvested from the wind without disturbing the rotor speed[26].

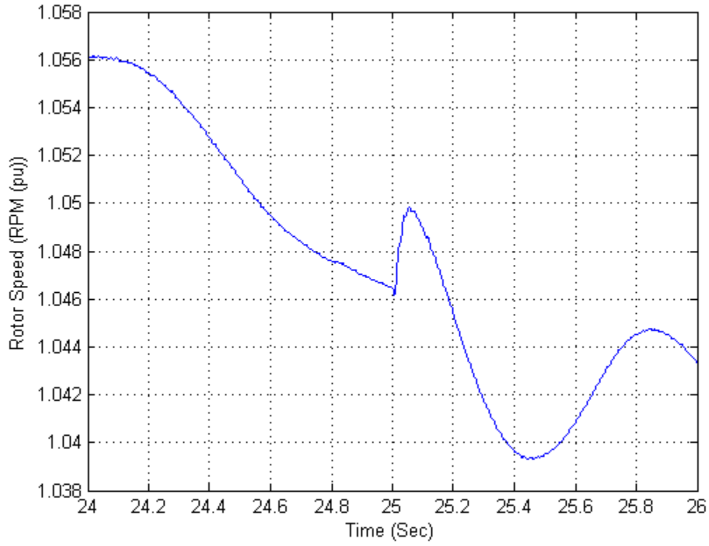

Figure 4.27: Rotor Speed of Wind Turbine

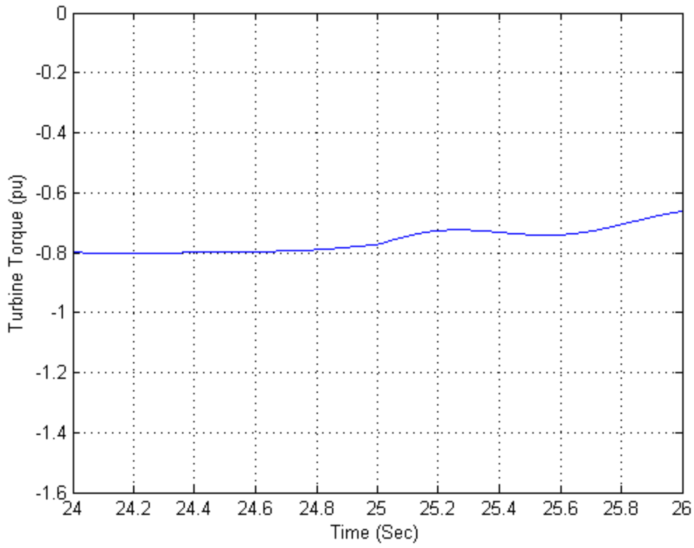

Figure 4.28: Torque of Wind Turbine

4.3 With Two Wind Turbine

The power system of Iceland with two Wind Turbines is shown in Figure 4.1. This simulation has been carried to analyze the normal and under fault operation of power system with out WTGS. A three phase line to ground fault occurs at Bus 1 for 100*msec* at the time instant of 25*sec*.

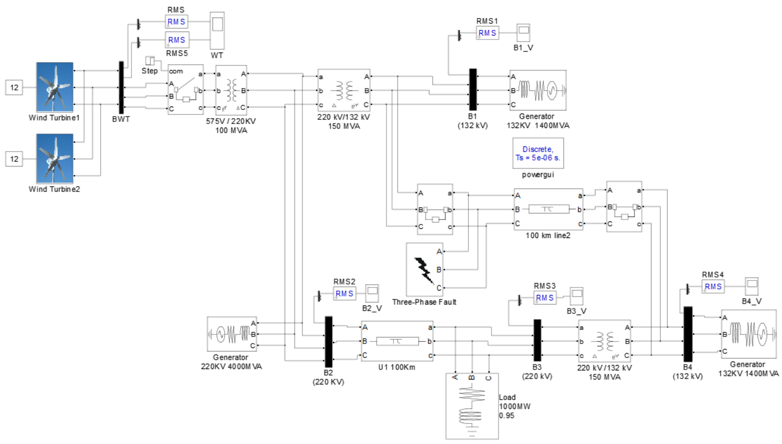

Figure 4.29: Iceland Power System with Two WTGS

4.3.1 SCC with 100% Rating

This part of simulation is carried out with full rating of power generators. The power system with Full rating of power generators is shown in Figure 4.29. The voltages at each bus are shown in Figure 4.30, 4.31, 4.32 and 4.33. By analyzing the rotor speed of generator, it can be ensured that the generator run smoothly even if there is a fault in the system. The rotor speed plot is shown in Figure 4.35. Therefore, it can be concluded that the power system is stable. The power contribution by WTGS is shown in Figure 4.34. The torque generated by wind turbine is shown in Figure 4.37. It can be seen that the turbine maintains the torque even under fault and continues to operate. After the fault is cleared, it continues to operate normally.

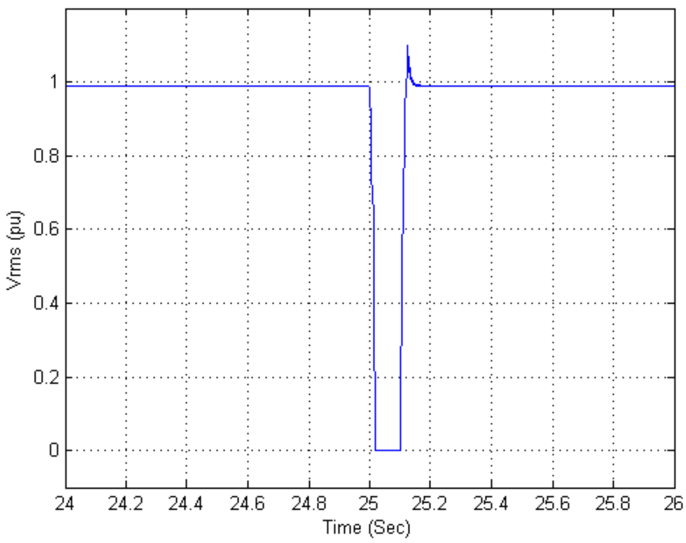

Figure 4.30: Bus 1 Voltage in Full rating of SCC with Two Wind Turbines

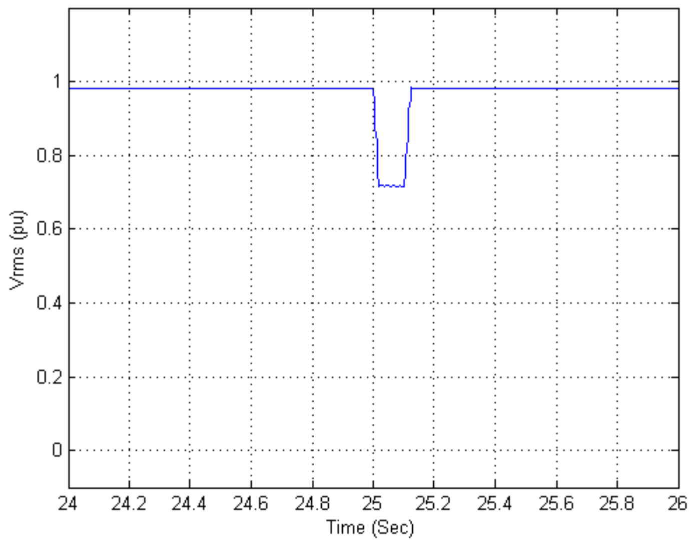

Figure 4.31: Bus 2 Voltage in Full rating of SCC with Two Wind Turbines

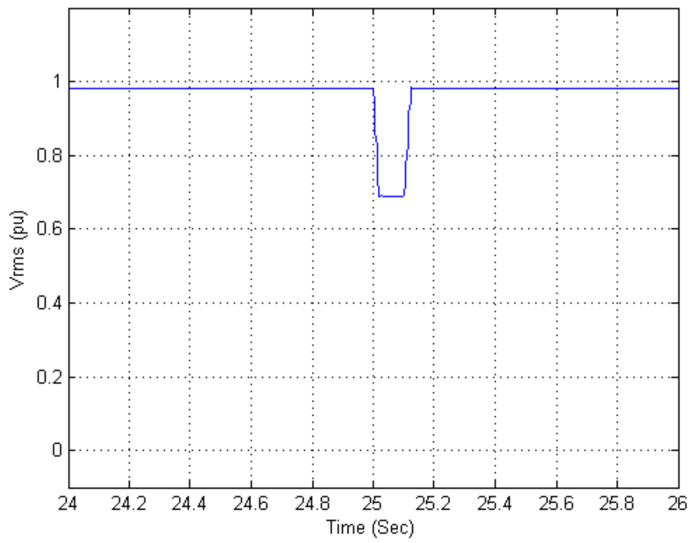

Figure 4.32: Bus 3 Voltage in Full rating of SCC with Two Wind Turbines

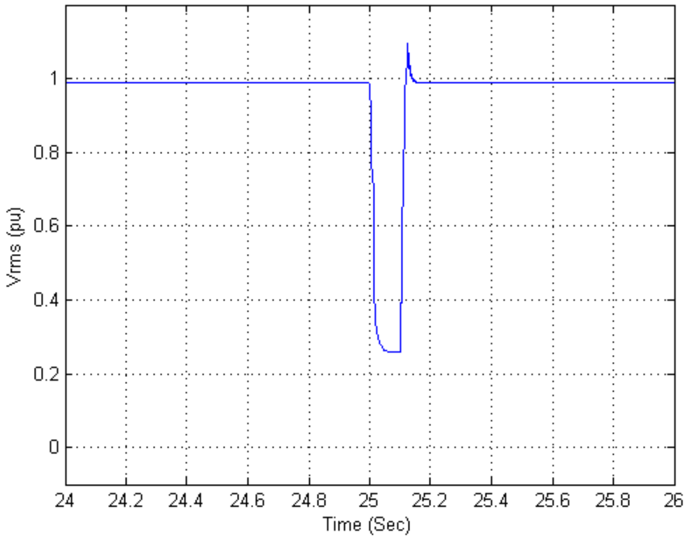

Figure 4.33: Bus 4 Voltage in Full rating of SCC with Two Wind Turbines

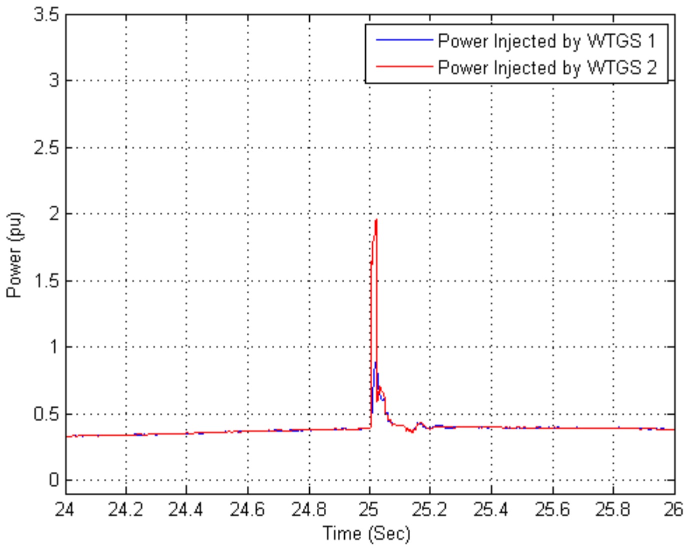

Figure 4.34: Power Injected by Two Wind Turbine

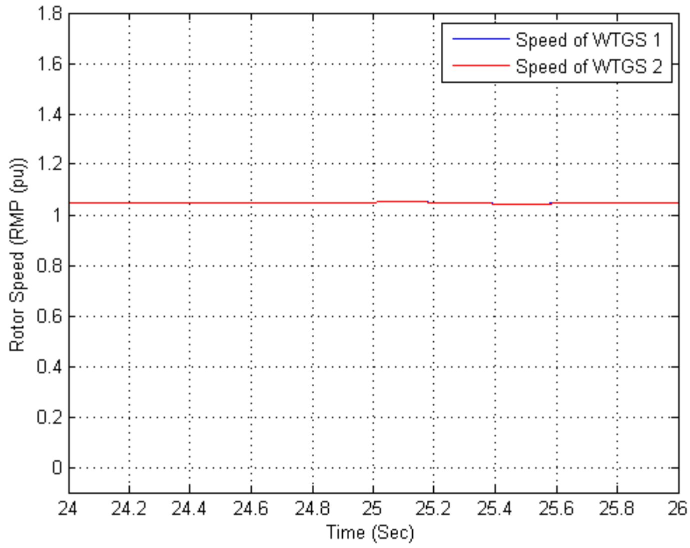

Figure 4.35: Rotor Speed of Wind Turbines

In the event of fault, the rotor speed increases and the torque of wind turbine decreases as shown in the Figure 4.36 and 4.37 respectively. It is due to the fact that the control of AC/AC converter is designed in such a way that it helps the wind turbine to run smoothly and it only permits the power flow to the power grid that can be harvested from the wind without disturbing the rotor speed[26].

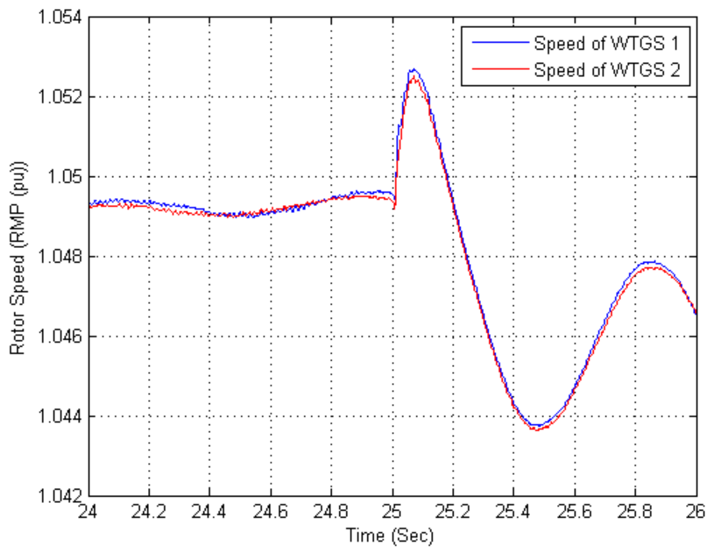

Figure 4.36: Rotor Speed of Wind Turbines

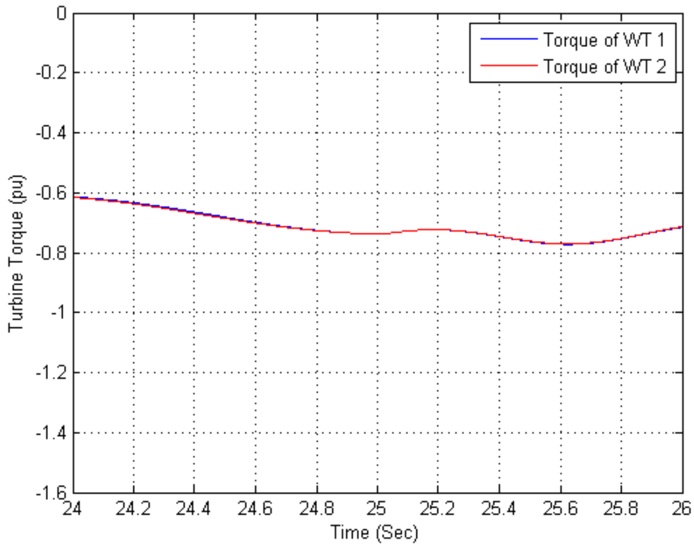

Figure 4.37: Torque of Two Wind Turbines

4.3.2 SCC with 60% Rating

This simulation has been carried with 60% rating of power generators without WTGS. A three phase line to ground fault occurs at Bus 1 for 100*msec* at the time instant of 25*sec*. The power system with 60% rating of power generators is shown in Figure 4.38. The voltages at each bus are shown in 4.39, 4.40, 4.41 and 4.42. By analyzing the rotor speed of generator, it can be ensured that the generator run smoothly even if there is a fault in the system. The rotor speed plot is shown in Figure 4.44. Therefore, it can be concluded that the power system is stable. The power contribution by WTGS is shown in Figure 4.43. It can also be noticed that the power shared by WTGS in case of 60% rating of SCC is greater than the power shared by WTGS in case of full rating of SCC.

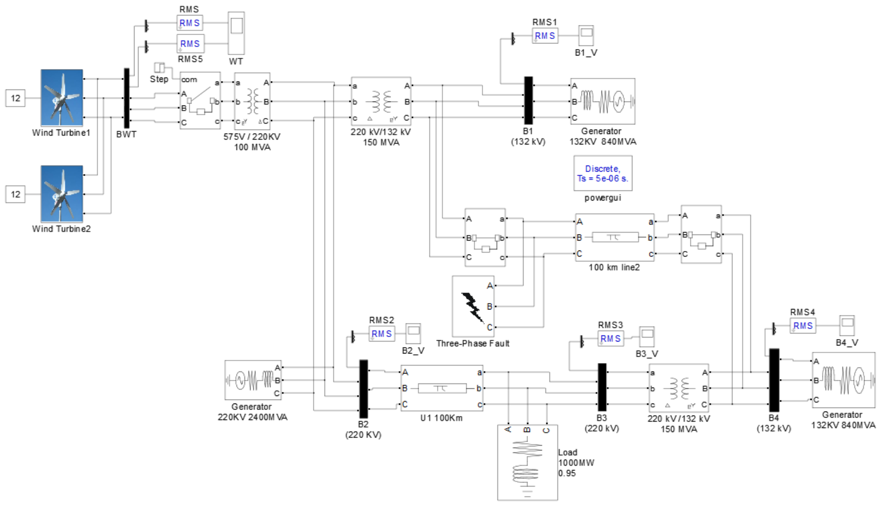

Figure 4.38: 60% rating of power generators with Two WTGS

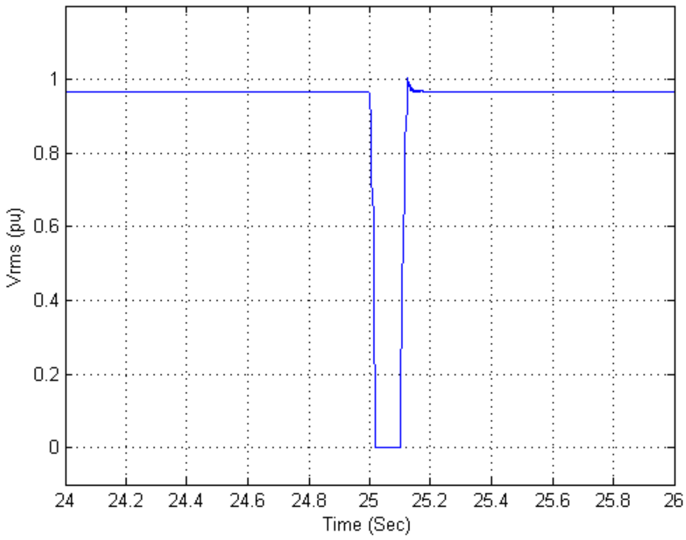

Figure 4.39: Bus 1 Voltage in 60% rating of SCC with Two Wind Turbines

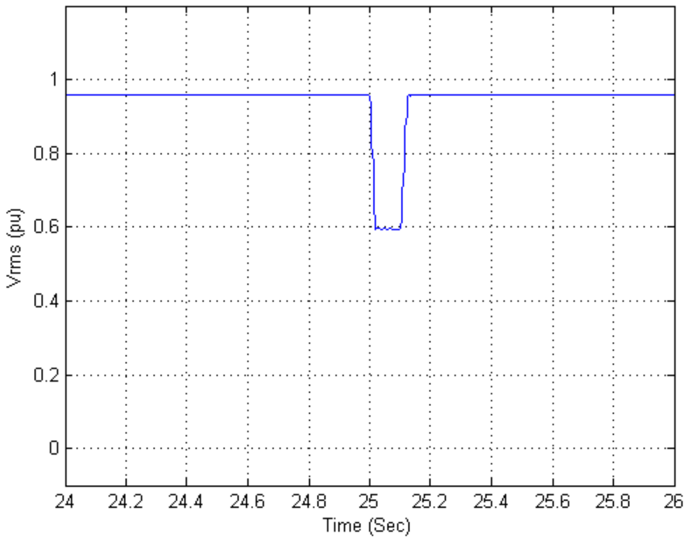

Figure 4.40: Bus 2 Voltage in 60% rating of SCC with Two Wind Turbines

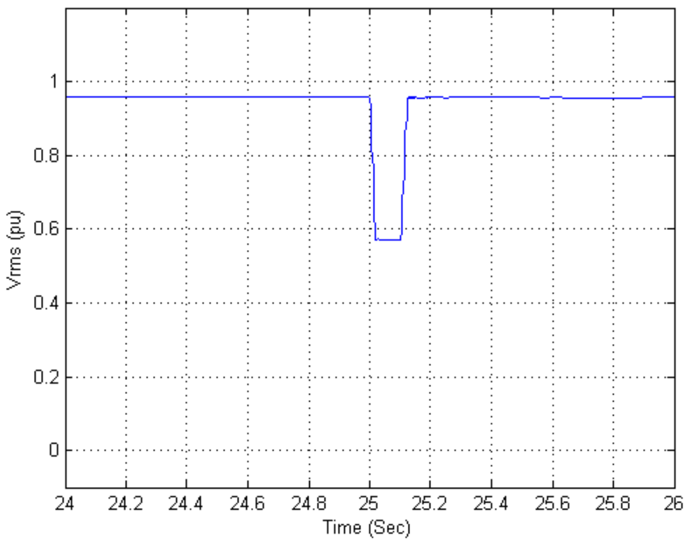

Figure 4.41: Bus 3 Voltage in 60% rating of SCC with Two Wind Turbines

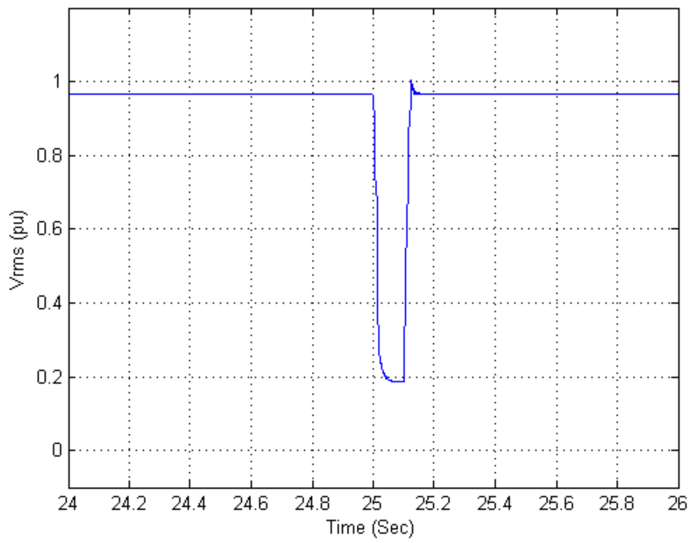

Figure 4.42: Bus 4 Voltage in 60% rating of SCC with Two Wind Turbines

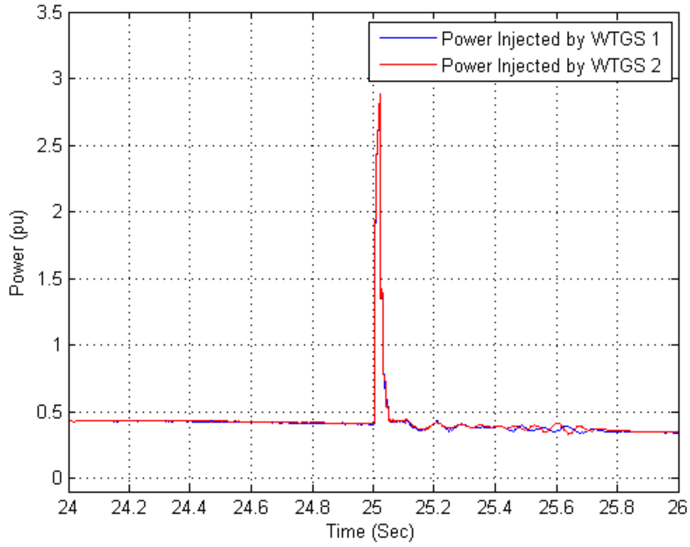

Figure 4.43: Power Injected by Two Wind Turbine

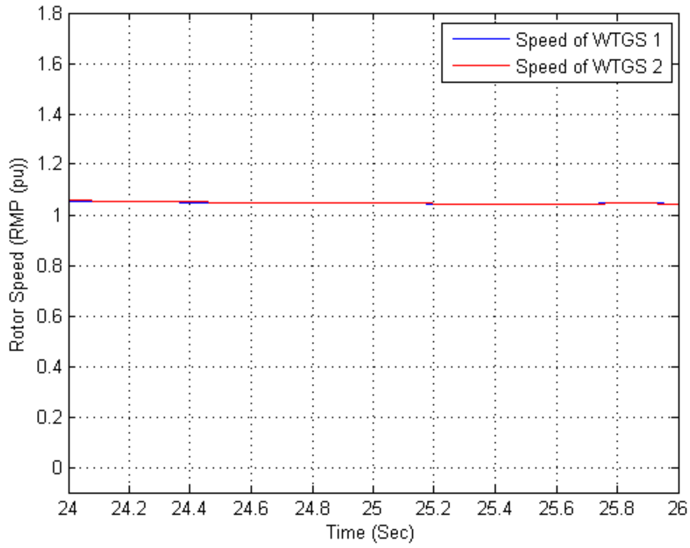

Figure 4.44: Rotor Speed of Wind Turbine

In the event of fault, the rotor speed increases and the torque of wind turbine decreases as shown in the Figure 4.45 and 4.37 respectively. It is due to the fact that the control of AC/AC converter is designed in such a way that it helps the wind turbine to run smoothly and it only permits the power flow to the power grid that can be harvested from the wind without disturbing the rotor speed[26].

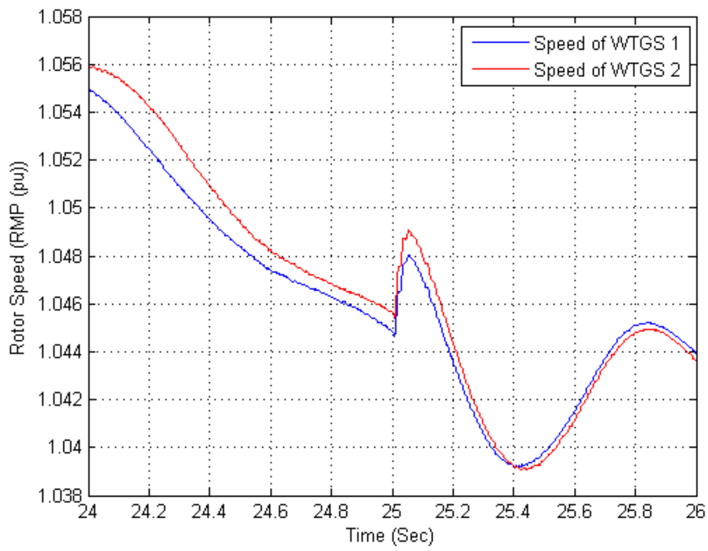

Figure 4.45: Rotor Speed of Wind Turbine

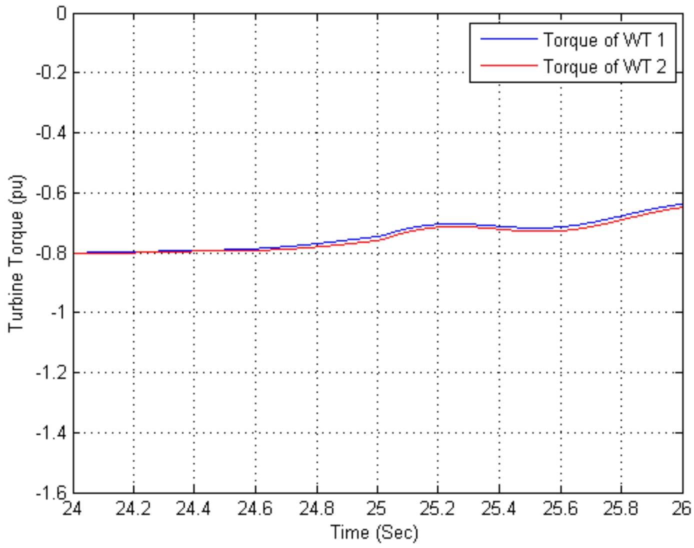

Figure 4.46: Torque of Two Wind Turbines

4.4 With Three Wind Turbine

The power system of Iceland with three Wind Turbines is shown in Figure 4.47. This simulation has been carried to analyze the normal and under fault operation of power system with out WTGS. A three phase line to ground fault occurs at Bus 1 for 100$msec$ at the time instant of 25sec.

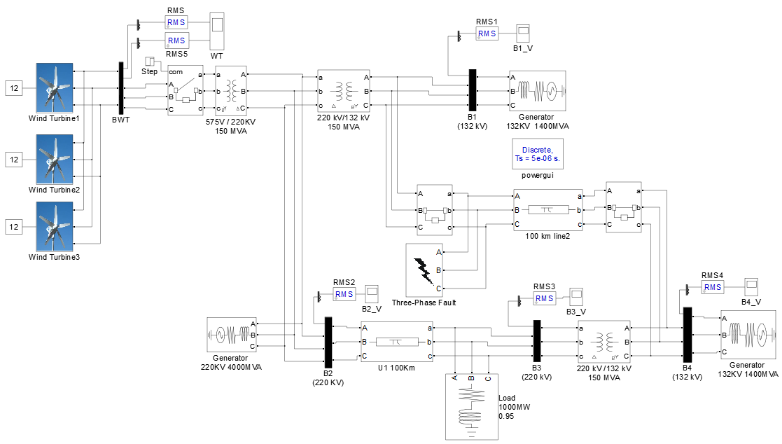

Figure 4.47: Iceland Power System with Three WTGS

4.4.1 SCC with 100% Rating

This part of simulation is carried out with full rating of power generators. The voltages at each bus are shown in Figure 4.48, 4.49, 4.50 and 4.51. By analyzing the rotor speed of generator, it can be ensured that the generator run smoothly even if there is a fault in the system. The rotor speed plot is shown in Figure 4.53. The rotor speed with magnified scale is shown in Figure 4.55. Therefore, it can be concluded that the power system is stable. The power contribution by WTGS is shown in Figure 4.52. The torque generated by wind turbine is shown in Figure 4.56. It can be seen that the turbine maintains the torque even under fault and continues to operate. After the fault is cleared, it continues to operate normally.

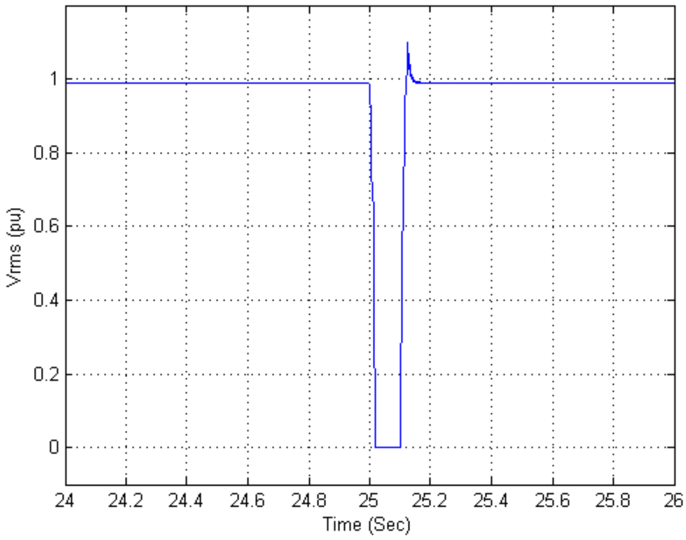

Figure 4.48: Bus 1 Voltage in Full rating of SCC with Three Wind Turbine

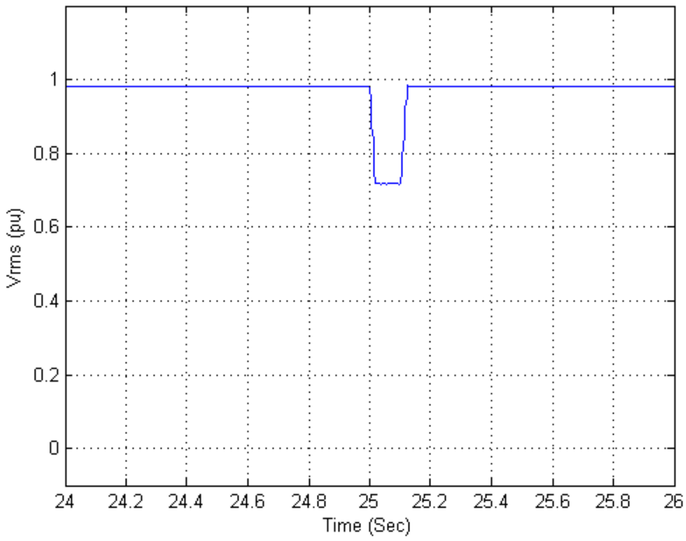

Figure 4.49: Bus 2 Voltage in Full rating of SCC with Three Wind Turbines

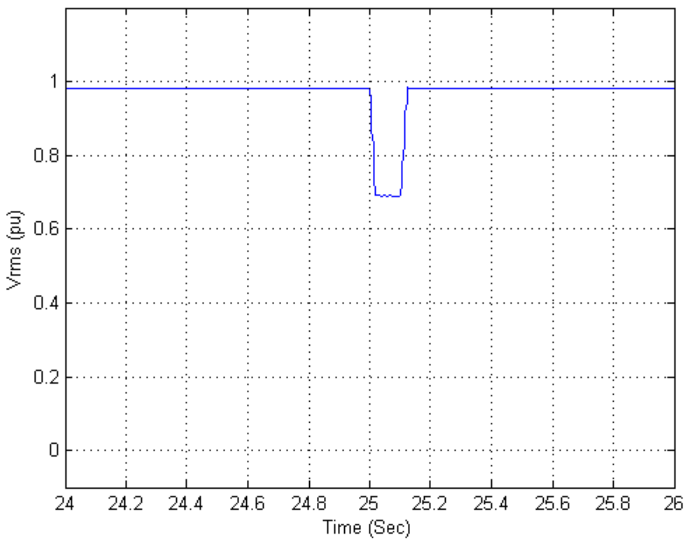

Figure 4.50: Bus 3 Voltage in Full rating of SCC with Three Wind Turbines

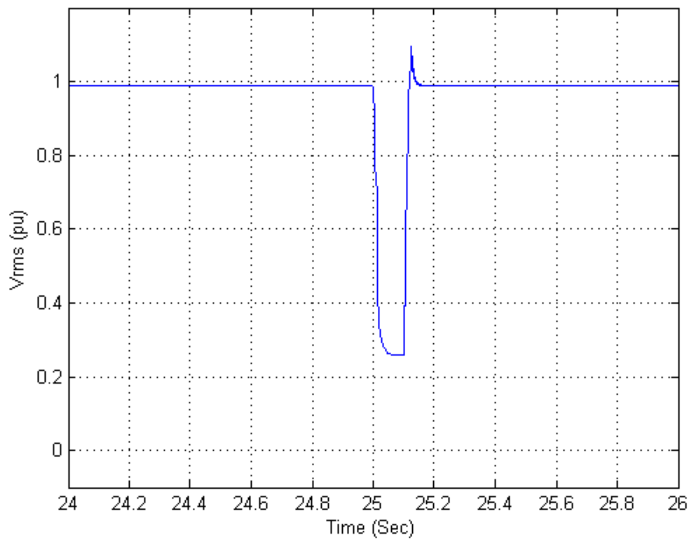

Figure 4.51: Bus 4 Voltage in Full rating of SCC with Three Wind Turbines

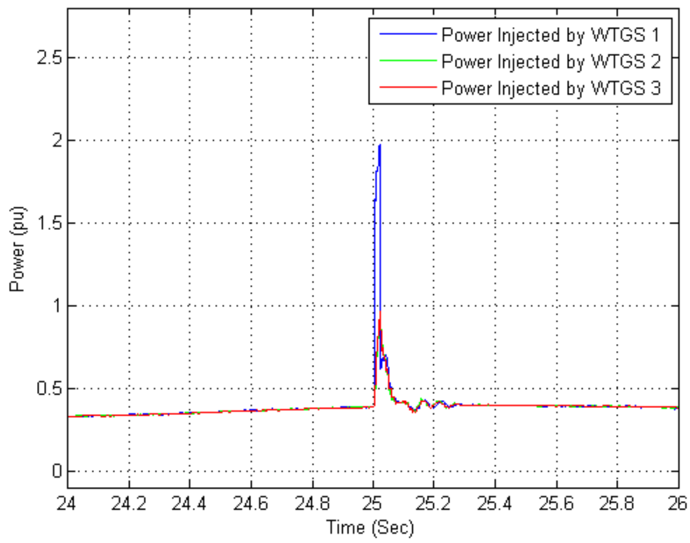

Figure 4.52: Power Injected by Three Wind Turbine

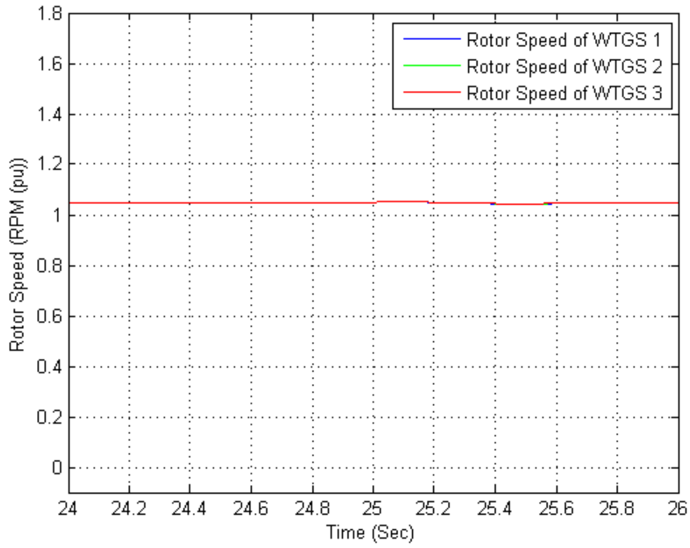

Figure 4.53: Rotor Speed of Wind Turbines

In the event of fault, the rotor speed increases and the torque of wind turbine decreases as shown in the Figure 4.54 and 4.65 respectively. It is due to the fact that the control of AC/AC converter is designed in such a way that it helps the wind turbine to run smoothly and it only permits the power flow to the power grid that can be harvested from the wind without disturbing the rotor speed[26].

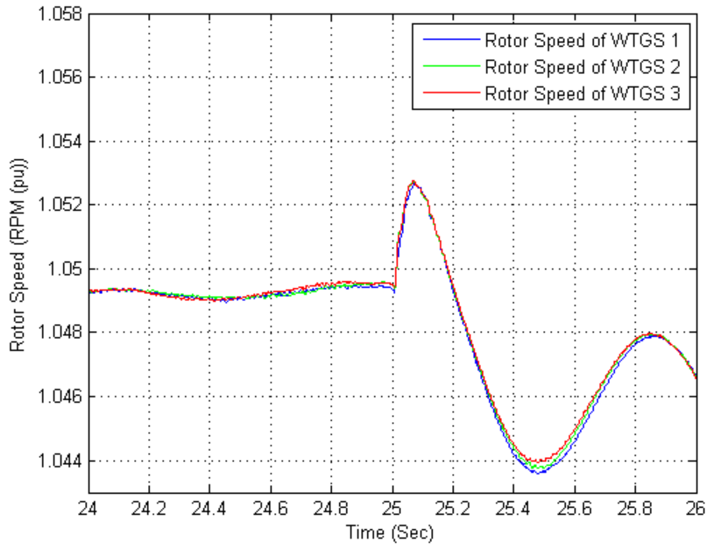

Figure 4.54: Rotor Speed of Wind Turbines

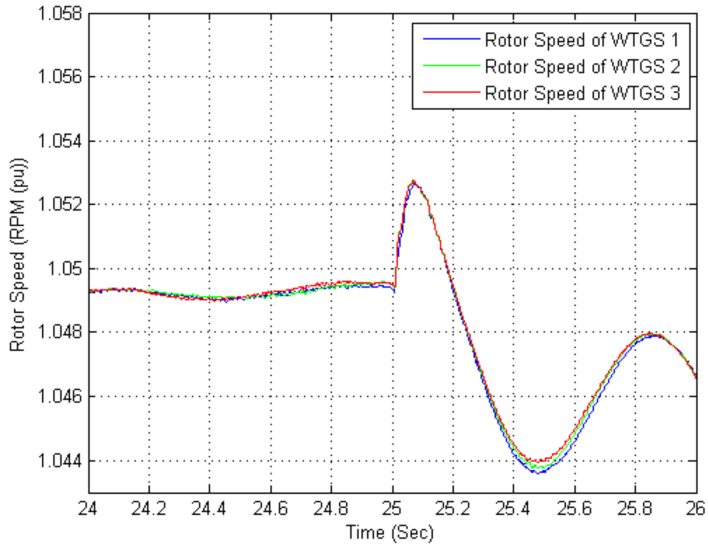

Figure 4.55: Rotor Speed with Magnified Scale

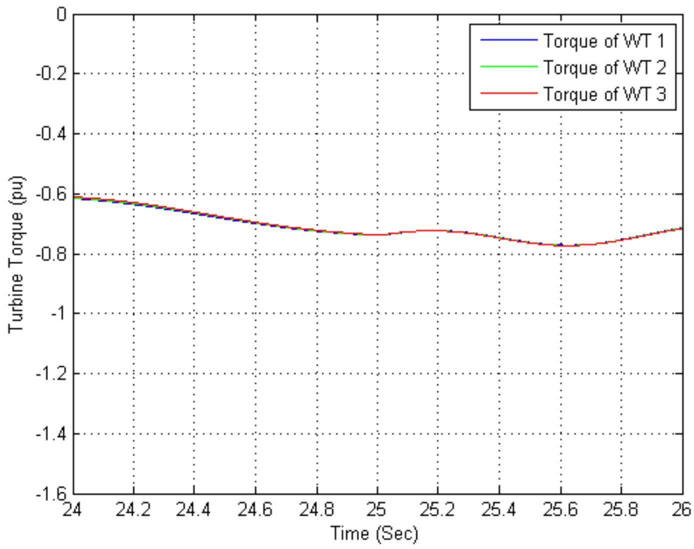

Figure 4.56: Torque of Three Wind Turbines

4.4.2 SCC with 60% Rating

This simulation has been carried with 60% rating of power generators without WTGS. A three phase line to ground fault occurs at Bus 1 for 100*msec* at the time instant of 25*sec*. The power system with 60% rating of power generators is shown in Figure 4.57. The voltages at each bus are shown in 4.58, 4.59, 4.60 and 4.61. By analyzing the rotor speed of WTGS, it can be ensured that the WTGS runs smoothly even if there is a fault in the system. The rotor speed plot is shown in Figure 4.63. Therefore, it can be concluded that the power system is stable. The power contribution by WTGS is shown in Figure 4.62. It can also be noticed that the power shared by WTGS in case of 60% rating of SCC is greater than the power shared by WTGS in case of full rating of SCC. The torque generated by wind turbine is shown in Figure 4.65. It can be seen that the turbine maintains the torque even under fault and continues to operate. After the fault is cleared, it continues to operate normally.

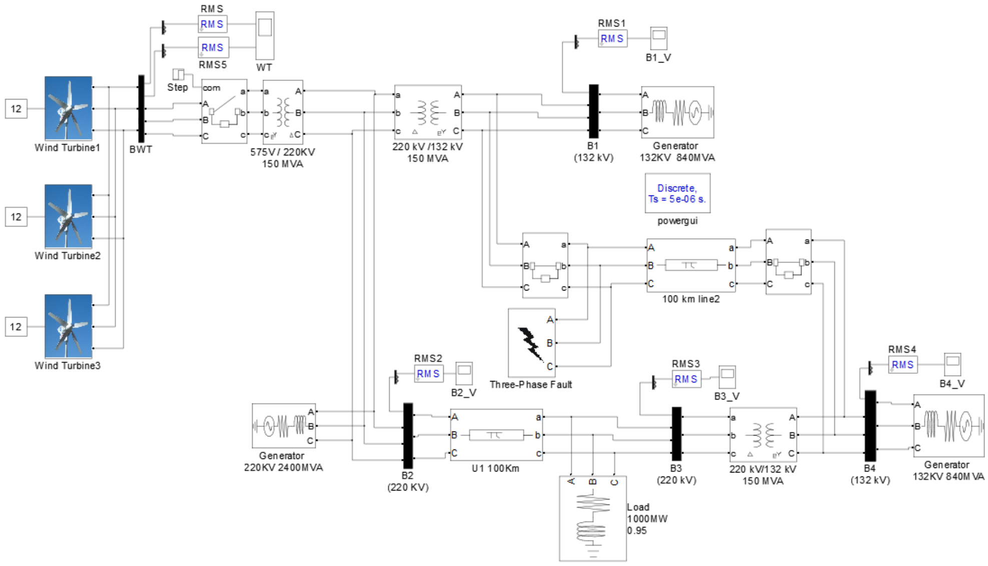

Figure 4.57: 60% rating of power generators with Three WTGS

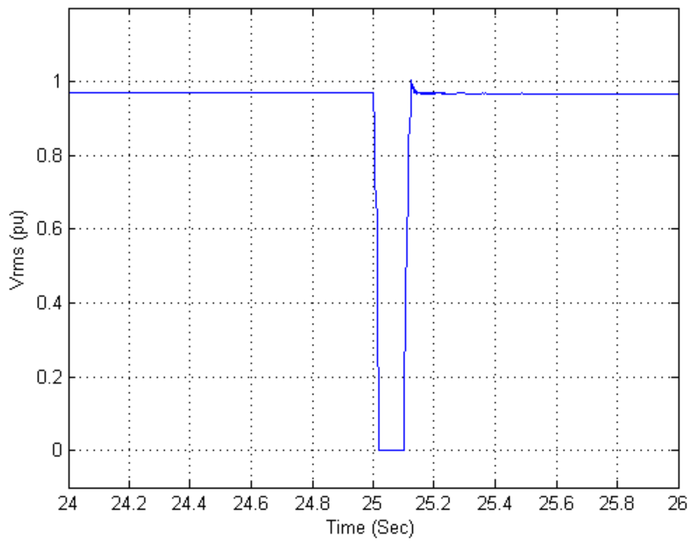

Figure 4.58: Bus 1 Voltage in 60% rating of SCC with Three Wind Turbines

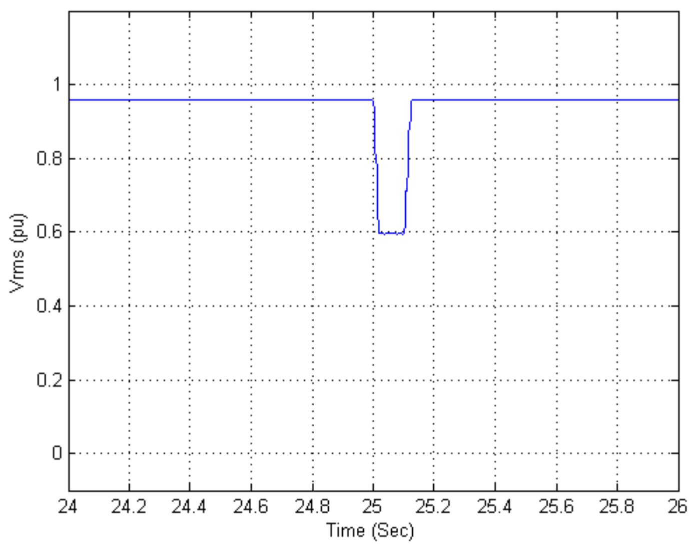

Figure 4.59: Bus 2 Voltage in 60% rating of SCC with Three Wind Turbines

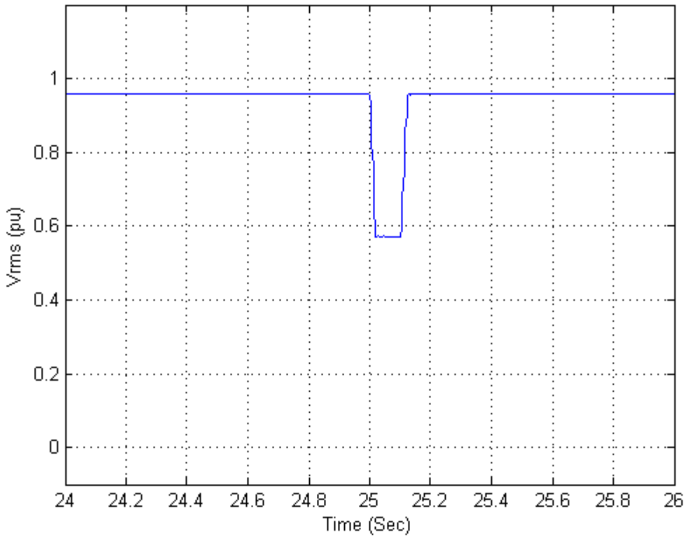

Figure 4.60: Bus 3 Voltage in 60% rating of SCC with Three Wind Turbines

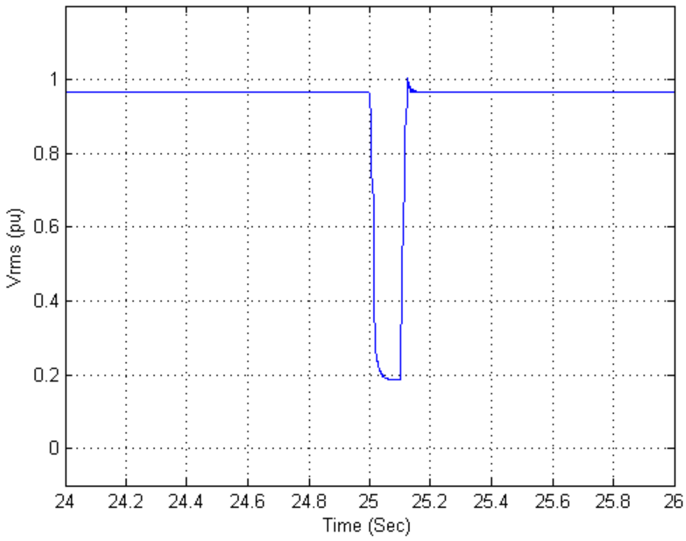

Figure 4.61: Bus 4 Voltage in 60% rating of SCC with Three Wind Turbines

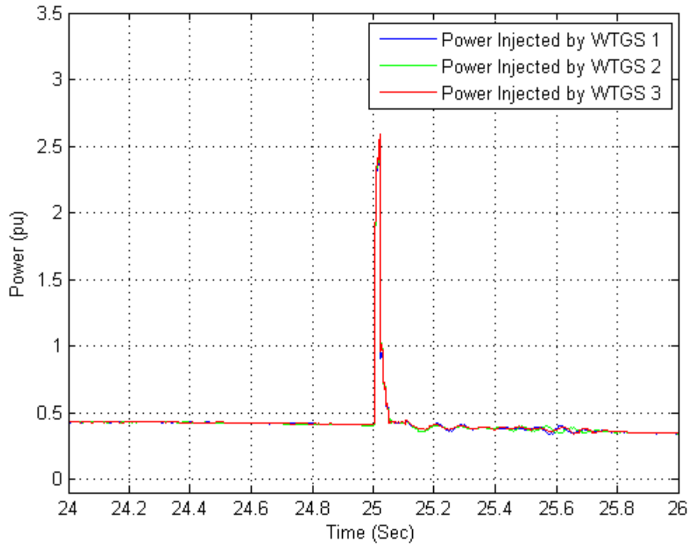

Figure 4.62: Power Injected by Three Wind Turbine

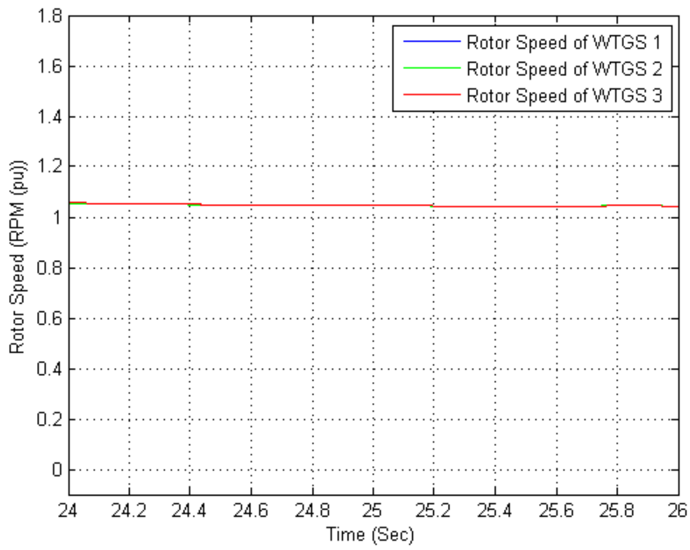

Figure 4.63: Rotor Speed of Wind Turbines

In the event of fault, the rotor speed increases and the torque of wind turbine decreases as shown in the Figure 4.64 and 4.65 respectively. It is due to the fact that the control of AC/AC converter is designed in such a way that it helps the wind turbine to run smoothly and it only permits the power flow to the power grid that can be harvested from the wind without disturbing the rotor speed[26].

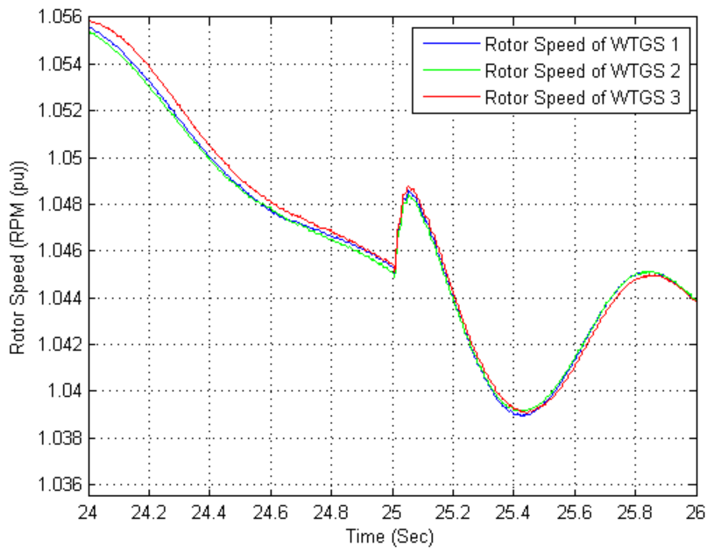

Figure 4.64: Rotor Speed of Wind Turbines

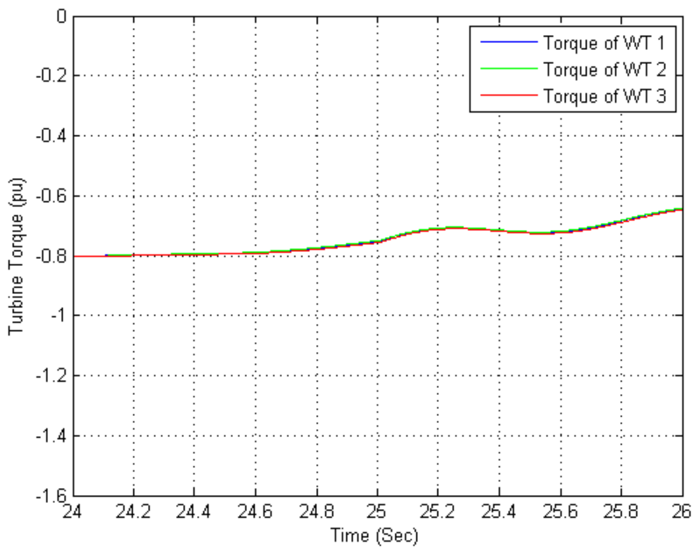

Figure 4.65: Torque of Three Wind Turbines

4.5 Comparison of Different Cases

To draw a conclusion, it is necessary to compare the results of simulation.

4.5.1 Impact of WTs with 100% Rating of SCC

Wind turbines are dynamic sources of energy. They may affect the system stability. A comparison among the bus voltages is shown in Figure 4.66, 4.67, 4.68 and 4.69. Figure 4.66 shows the voltages of bus 1. In case 1, when there is no WTGS connected to grid, the voltages at bus 1 are approximately $0.9894V_{pu}$. But in case 3, with the introduction of one WTGS into the power grid, the voltages at this bus increase to $0.9896V_{pu}$ approximately. Similarly in case 5 and case 7, voltages are increased to approximately $0.9898V_{pu}$ and $0.99V_{pu}$ respectively. This implies that with each introduction of WTGS into the power grid, the voltages at bus 1 improves.

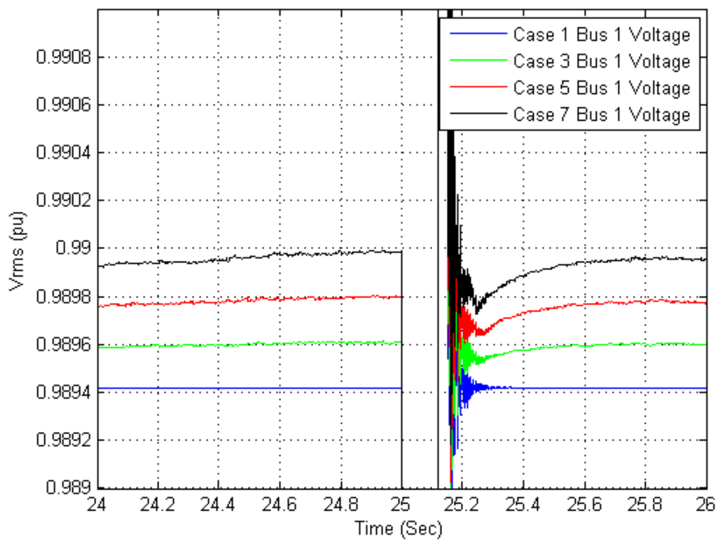

Figure 4.66: Bus 1 Voltages with 100% SCC rating

Similar behavior can observed at bus 2, bus 3 and bus 4 in Figure 4.67, 4.68 and 4.69 respectively.

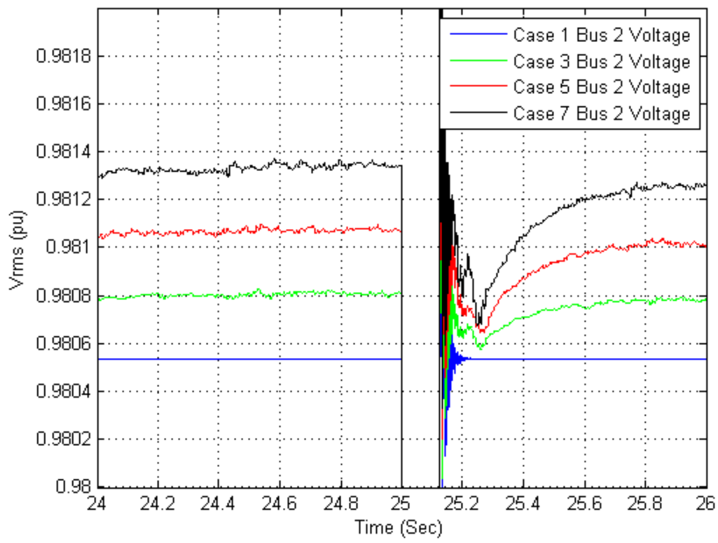

Figure 4.67: Bus 2 Voltages with 100% SCC rating

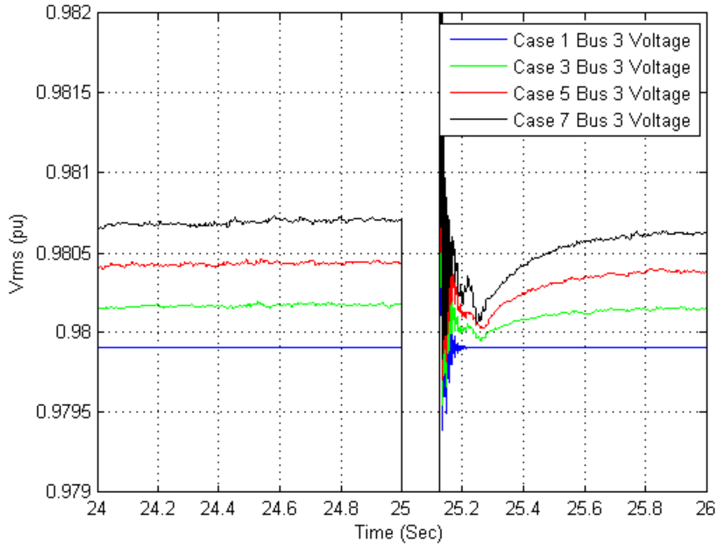

Figure 4.68: Bus 3 Voltages with 100% SCC rating

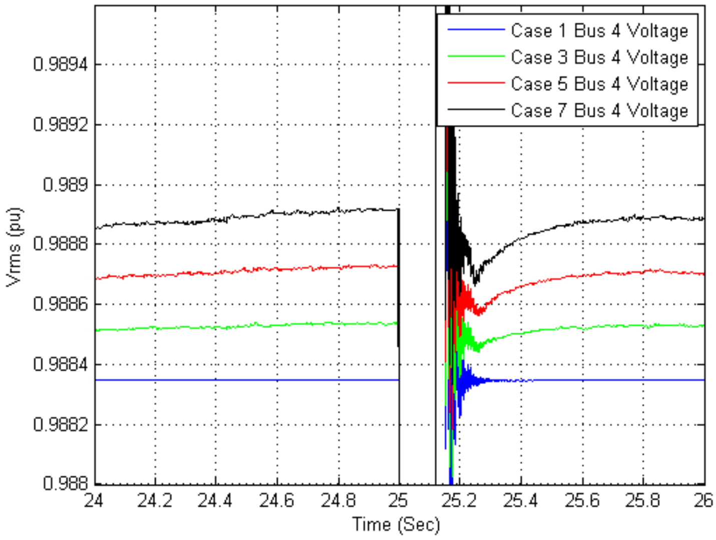

Figure 4.69: Bus 4 Voltages with 100% SCC rating

It can be seen clearly that the voltages are recovered back to normal after the fault. So, it can be concluded that with each contribution of WTGS, the system voltages improve and their behavior under and after faulty conditions remains stable. Hence, the WTGS system has successfully ridden through the fault.

4.5.2 Impact of WTs with 60% Rating of SCC

If the short circuit current rating of all the generators is decreases up to 60% of the nominal value, the impact of WTGS becomes more prominent. A comparison among the different bus voltages is shown in Figure 4.70, 4.71, 4.72 and 4.73.
Figure 4.70 shows the voltages of bus 1. In case 2, when there is no WTGS connected to grid, the voltages at bus 1 are approximately $0.9668V_{pu}$. But in case 4, with the introduction of one WTGS into the power grid, the voltages at this bus increase to $0.9674V_{pu}$ approximately. Similarly in case 6 and case 8, voltages are increased to approximately $0.9678V_{pu}$ and $0.9684V_{pu}$ respectively. This implies that with each introduction of WTGS into the power grid, the voltages at bus 1 improves.

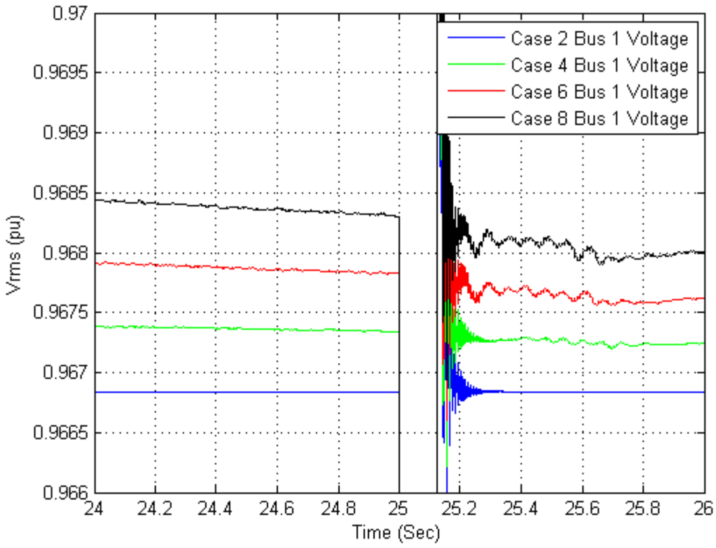

Figure 4.70: Bus 1 Voltage with 60% SCC rating

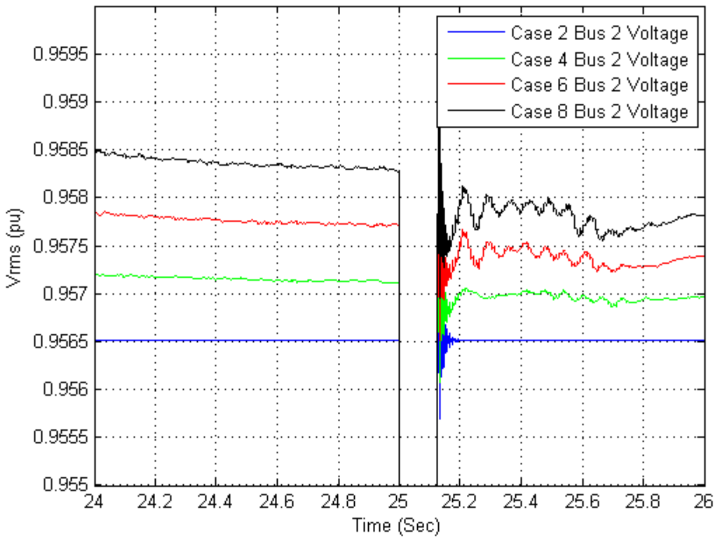

Figure 4.71: Bus 2 Voltage with 60% SCC rating

Similar behavior can observed at bus 2, bus 3 and bus 4 in Figure 4.71, 4.72 and 4.73 respectively.

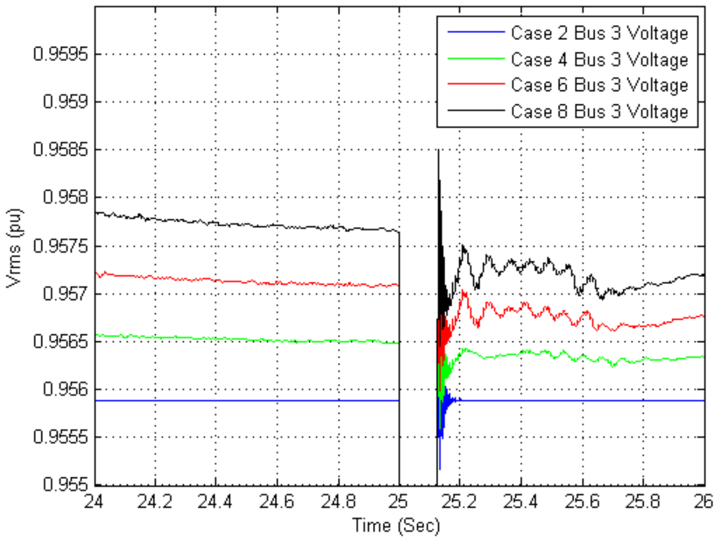

Figure 4.72: Bus 3 Voltage with 60% SCC rating

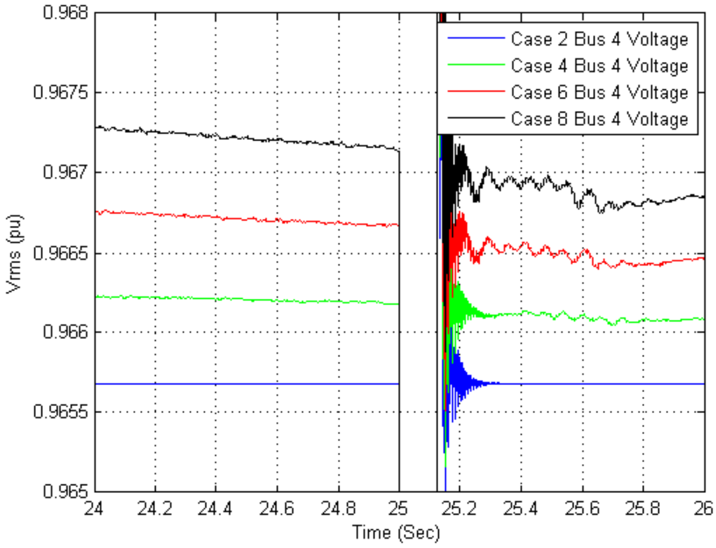

Figure 4.73: Bus 4 Voltage with 60% SCC rating

It can be seen clearly that the voltages are recovered back to normal after the fault. So, it can be concluded that with each contribution of WTGS, the system voltages improve and their behavior under and after faulty conditions remains stable. Hence, the WTGS system has successfully ridden through the fault.

4.5.3 Impact of SCC

Short circuit current (SCC) rating of a power source plays an important role in power system voltage regulation. It also determines the maximum power that can be supplied by the source to the power grid. As SCC rating decreases, the load is shifted towards the other power sources connected to the power grid but the overall capacity of power system decreases as well. So, in the event of fault, when maximum current flows through the power system, the voltage drop at different buses of power system becomes more severe.

A comparison among the voltages of different buses, for 100% and 60% rating of SCC, is shown in the Figure 4.74, 4.75, 4.76 and 4.77. It can be seen clearly that the voltage drop is significant in case of 60% rating of SCC as compared to 100% rating of SCC during fault.

Figure 4.74: Bus 1 Voltage with SCC 100% and 60% Rating

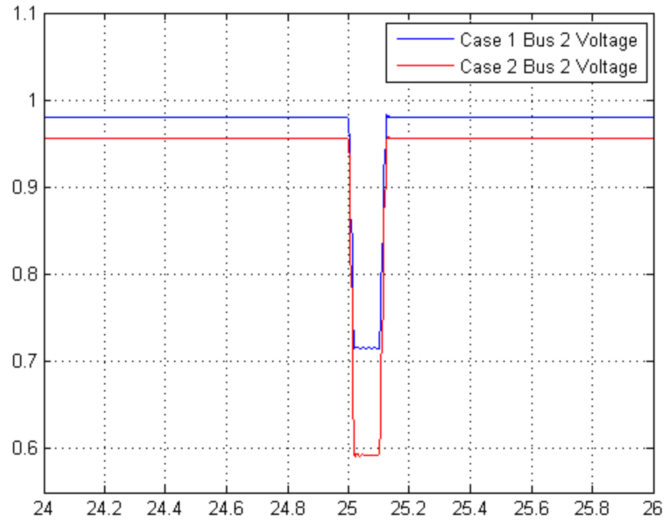

Figure 4.75: Bus 2 Voltage with SCC 100% and 60% Rating

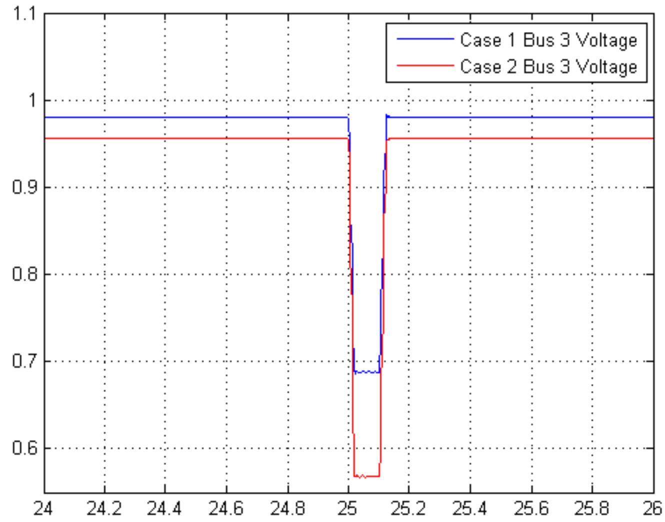

Figure 4.76: Bus 3 Voltage with SCC 100% and 60% Rating

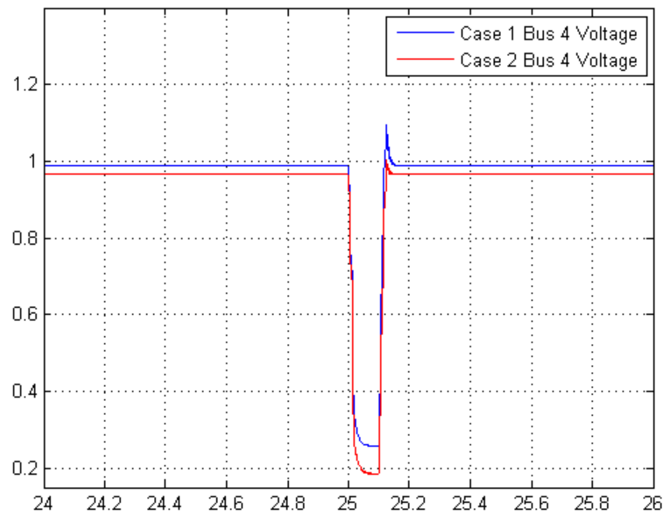

Figure 4.77: Bus 4 Voltage with SCC 100% and 60% Rating

WTGS is also connected to the power grid. It also plays its part in voltage regulation. It can be seen in the Figure 4.78 that in case 3, when SCC rating is 100%, the rotor speed of WTGS is almost uniform but in case 4, when SCC rating is 60%, the WTGS takes more time to adjust in the system as power share has increased. In the event of fault, the behavior of WTGS is almost similar. It implies that the WTGS is not affected by the SCC ratings of other sources of power connected to the grid. Hence, it can be concluded that the WTGS is immune to the power system parameters and faults.

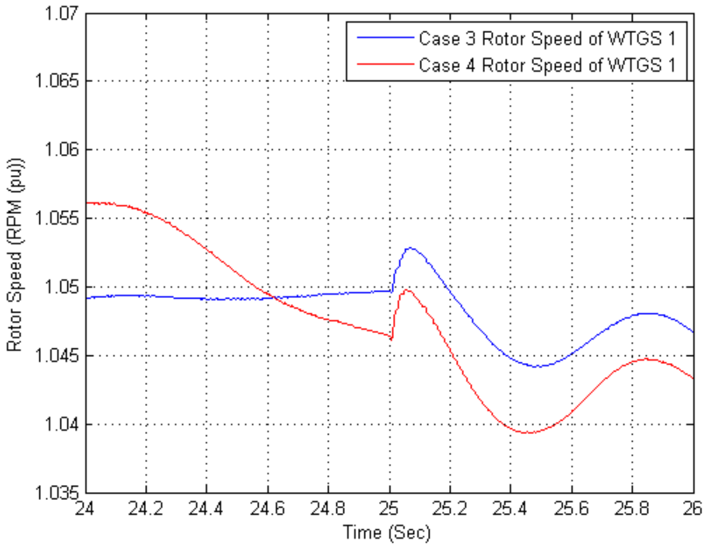

Figure 4.78: Rotor Speed of WTGS with SCC 100% and 60% Rating

Chapter 5

Conclusion and Future Work

5.1 Conclusion

WTGS is a system that extracts energy from the wind and converts it into electrical energy. To analyze the transient behavior and stability, it is modeled in Simulink MATLAB. By considering the Icelandic environment, the wind speed is found to be varying, so PMSG cannot be directly connected to the power grid due to voltage and frequency interfacing problems. This problem is overcome by an intermediate system consisting of rectifier and inverter and their control systems. The whole wind turbine generator system operates smoothly and remains stable. After extensive simulation, it is concluded that the wind turbine generator system is effective and stable source of electrical power. The wind turbine operates smoothly due to efficient modeling of rectifier control. It is observed that the turbine continues to provide rated torque at rated speed under faulty conditions. It implies that the wind turbine generator system remains stable under faulty conditions. The simulation results also show that the system continues to operate normally after the fault as if no fault has occurred.
In the comparison, it can be seen that with each contribution of WTGS, the overall bus voltages of the system improves. And in cases where SCC rating is 60% of rated value, the impact of WTGS becomes even more prominent. Immediate recovery after the fault shows that the system is responsive and immune to the faults.

5.2 Future Work

There is always room for improvement. In the present model of Wind Turbine Generator System, Park Transformation with PI controller is used to control the flow of power. The settling time of WTGS is about 80*sec*. Another possibility, as a next step in future, could be designing a more efficient and faster controller which controls the power flow with minimum effort of calculations.
The analysis in this thesis has been carried out for variable speed wind turbine yet the wind speed is assumed to be constant. In future, the analysis can be carried out for different wind speed to evaluate the performance and stability.
In practical systems, the load is also variable. In this thesis, a lumped load of constant value is used to simplify the analysis. This analysis can be extended to a dynamic load in future and the performance of WTGS can be evaluated for under load and overload conditions.
The other sources of power generation that are connected to grid, are also assumed to be constant. In Iceland's power grid, most of the power generators operates on renewable sources of energy. A renewable source of energy is highly dynamic. The analysis on WTGS to coexist with other dynamic power sources, ensuring the power stability and quality can be done in future.

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Appendix A

System Modeling Parameters

The detailed parameters that are used in Simulink blocks are elaborated here. The model initialization parameters are:

- Ts = 5e-6;
- Np = 48;
- Pnom = 40e6;
- Vnom = 575;
- Fnom = 50;
- Vdc_nom = 1150;
- R_RL = 0.003;
- L_RL = 0.3;
- Fb_time_const=0.005;

A.1 WTGS

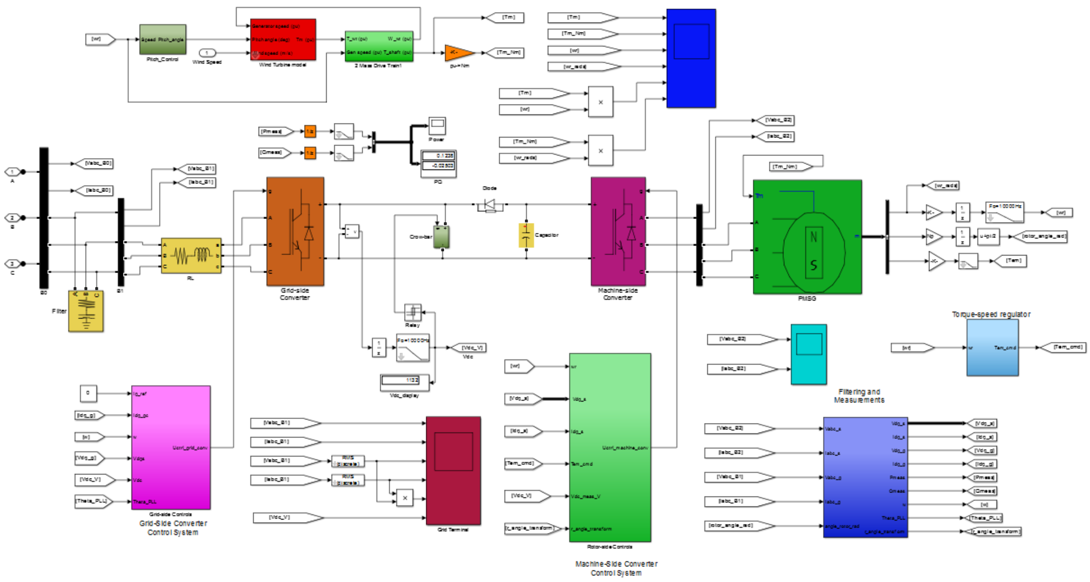

Figure A.1: Wind turbine generator system model

A.2 Wind Turbine

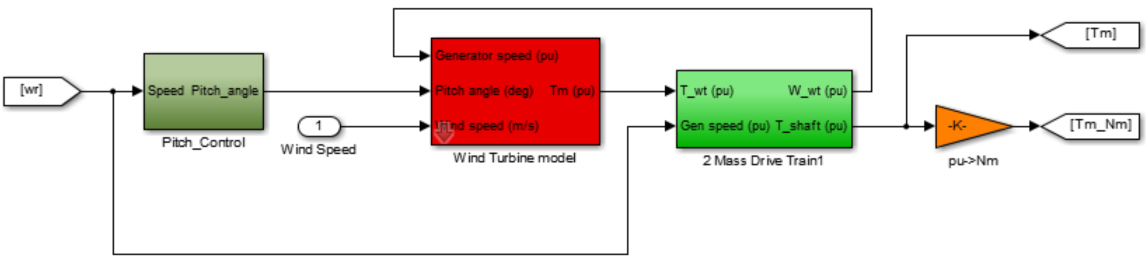

Figure A.2: Wind Turbine model

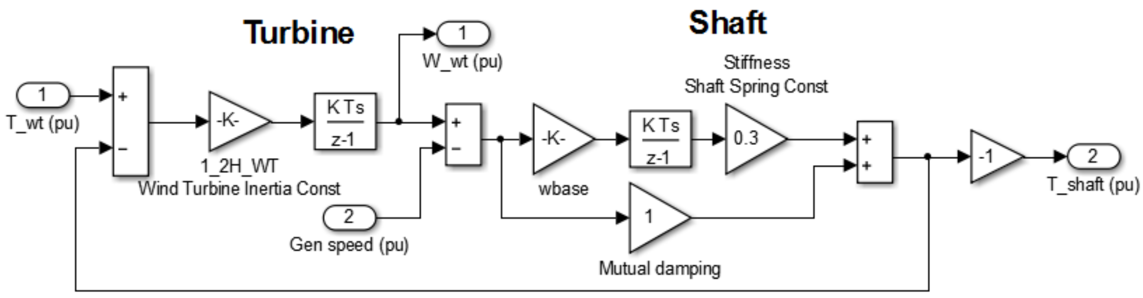

Figure A.3: 2 Mass based drive drain model

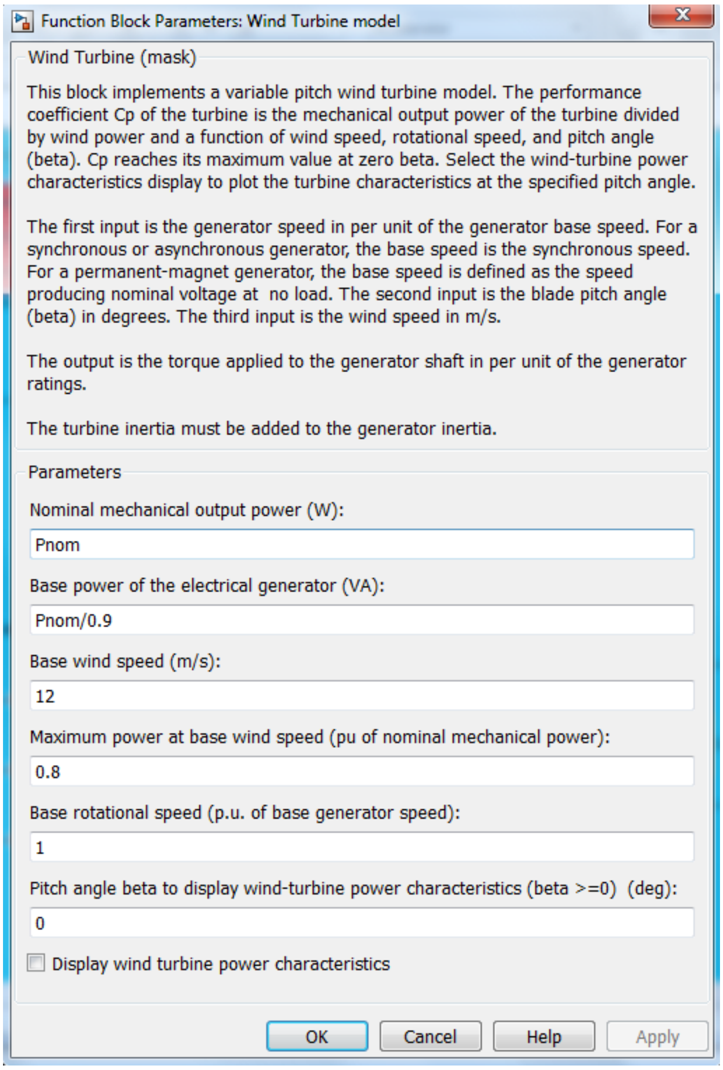

Figure A.4: Wind Turbine Simulink Block

A.3 PMSG

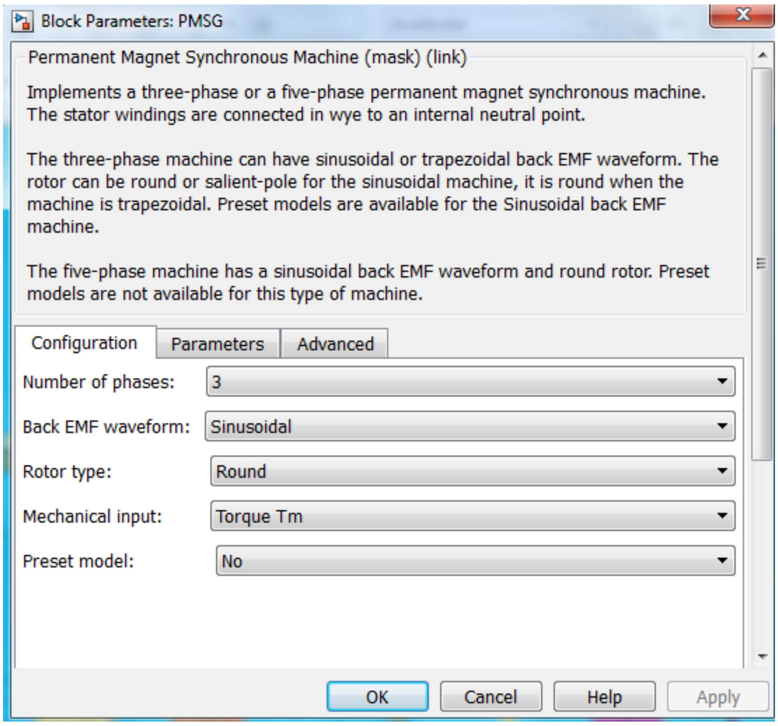

Figure A.5: PMSG configuration parameters

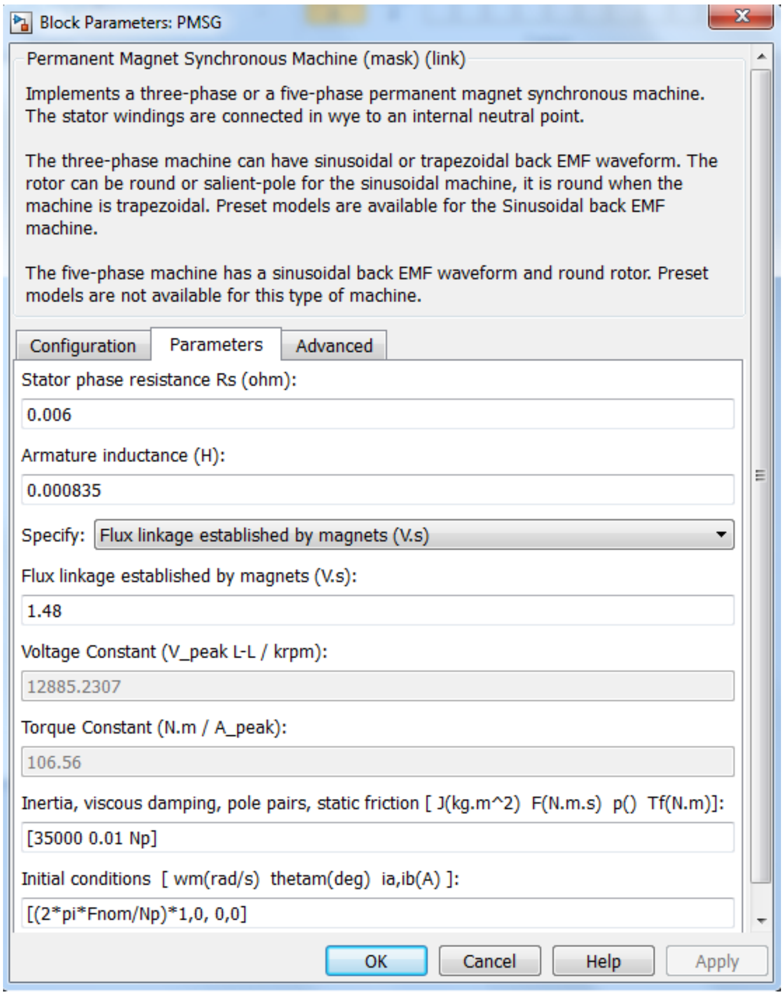

Figure A.6: PMSG parameters

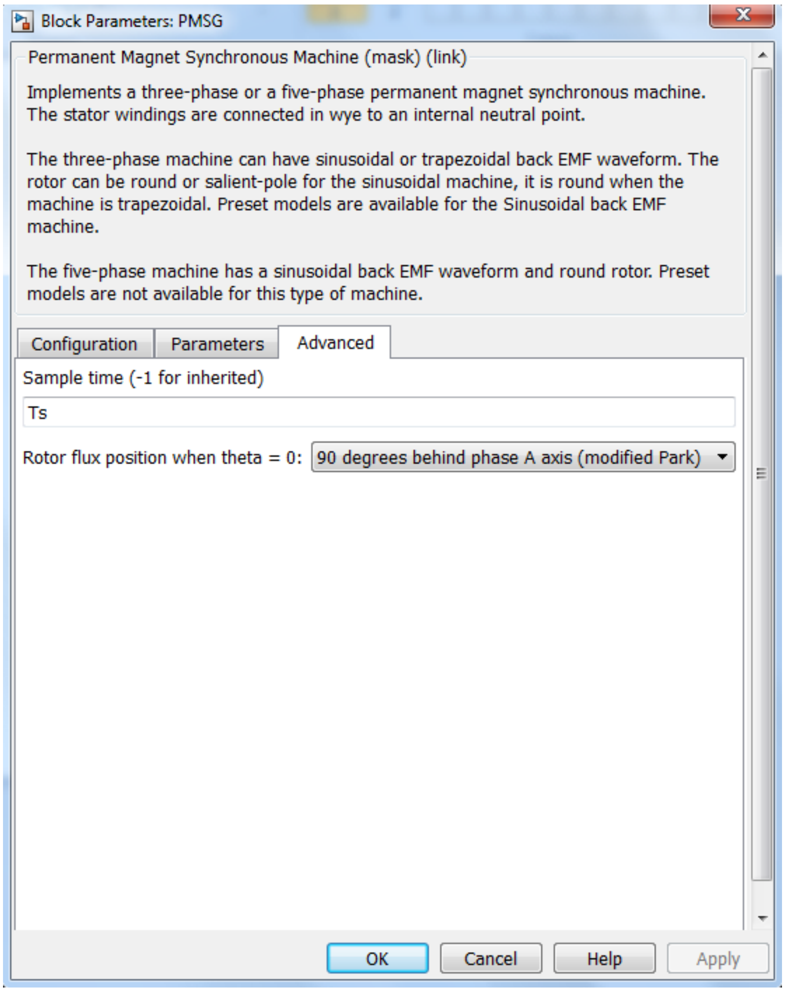

Figure A.7: PMSG advanced parameters

A.4 Rectifier Model

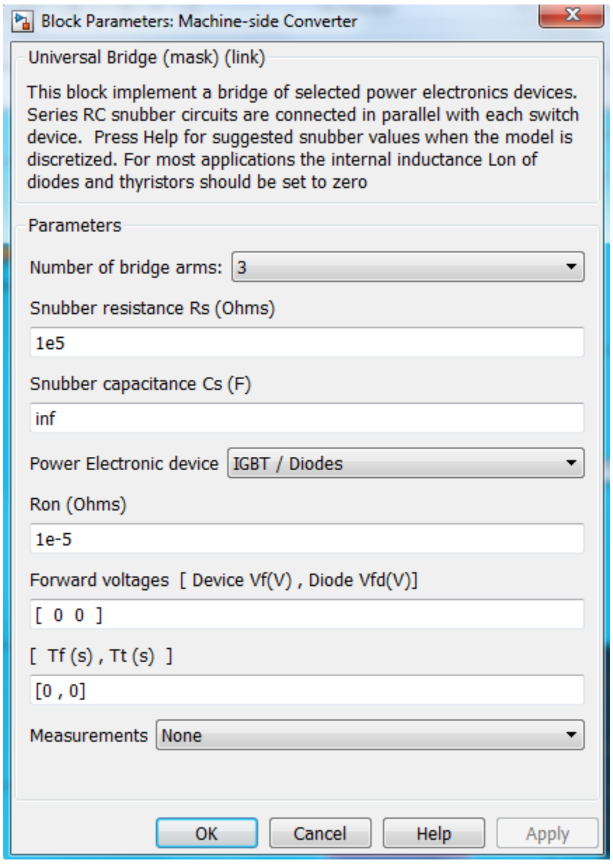

Figure A.8: Rectifier model parameters

A.5 Rectifier Control Model

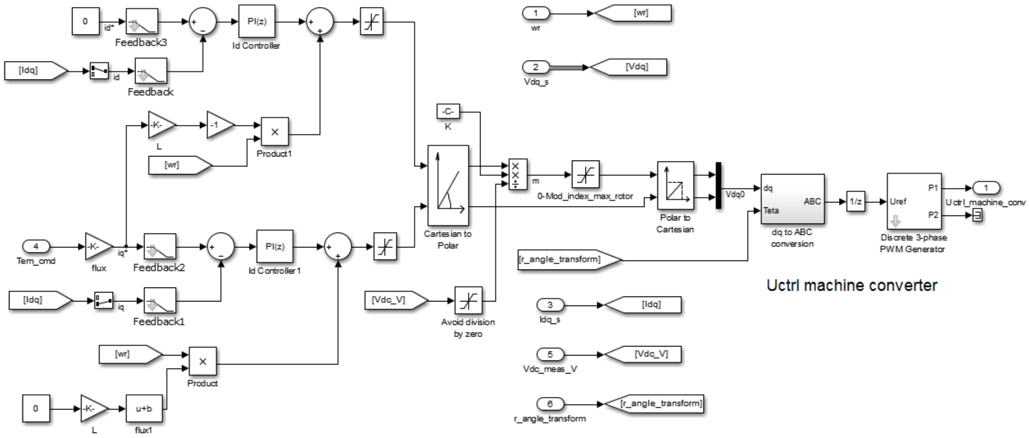

Figure A.9: Rectifier control model

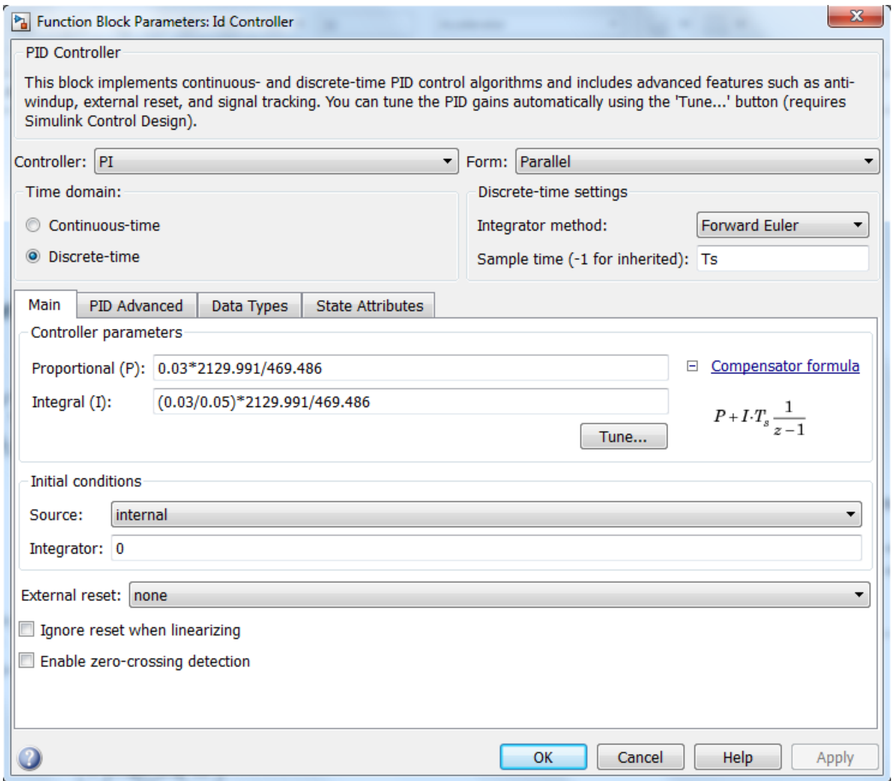

Figure A.10: Parameters of PI controller for rectifier control

A.6 Inverter Model

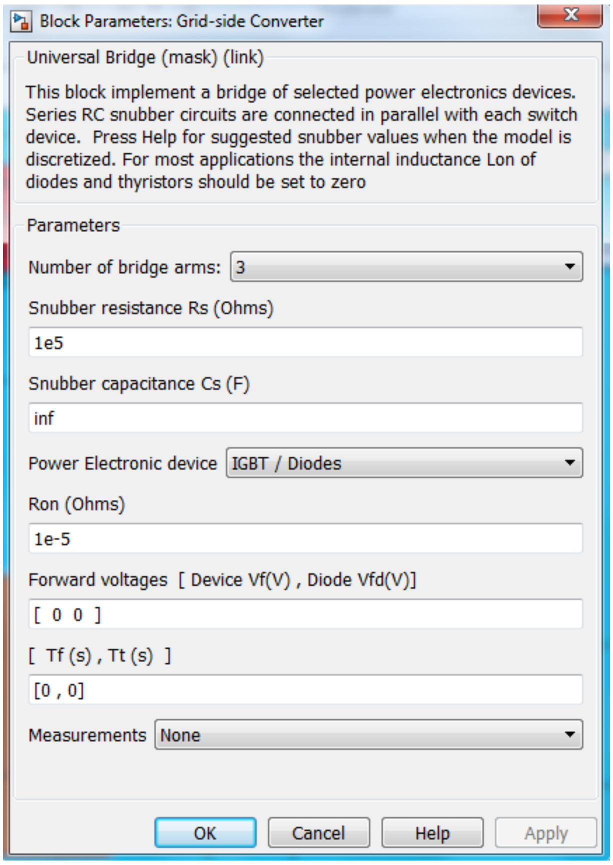

Figure A.11: Inverter model parameters

A.7 Inverter Control Model

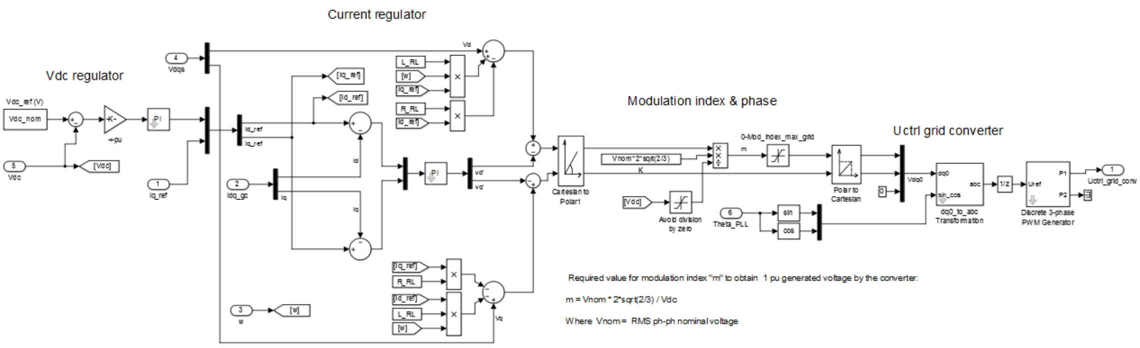

Figure A.12: Inverter control model

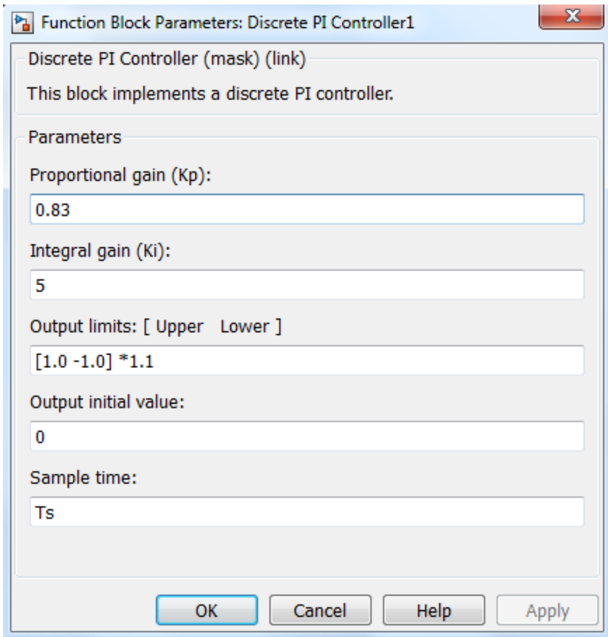

Figure A.13: Parameters of PI controller for inverter control

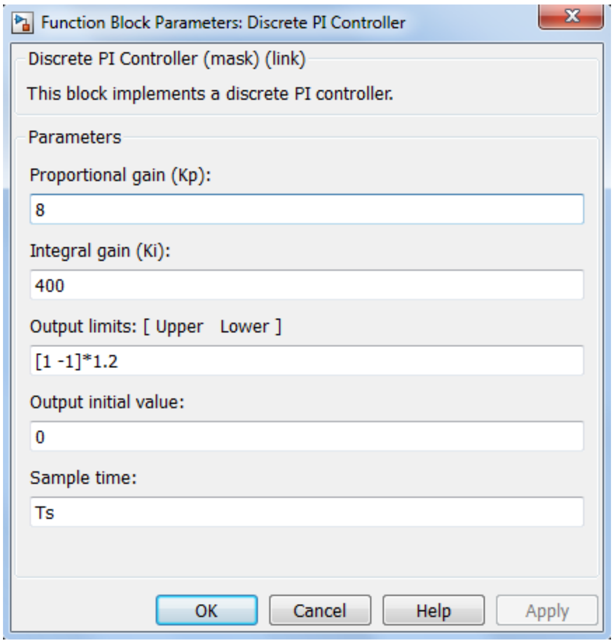

Figure A.14: Parameters of PI controller for DC voltage control

A.8 Park Transformation

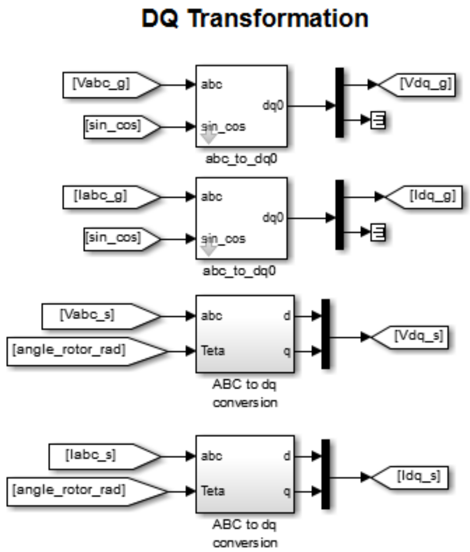

Figure A.15: ABC to dq transformation

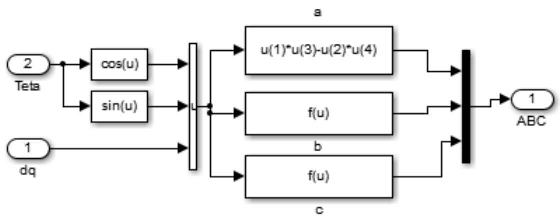

Figure A.16: dq0 to ABC transformation

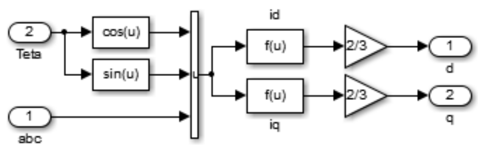

Figure A.17: ABC to dq0 transformation

A.9 PLL

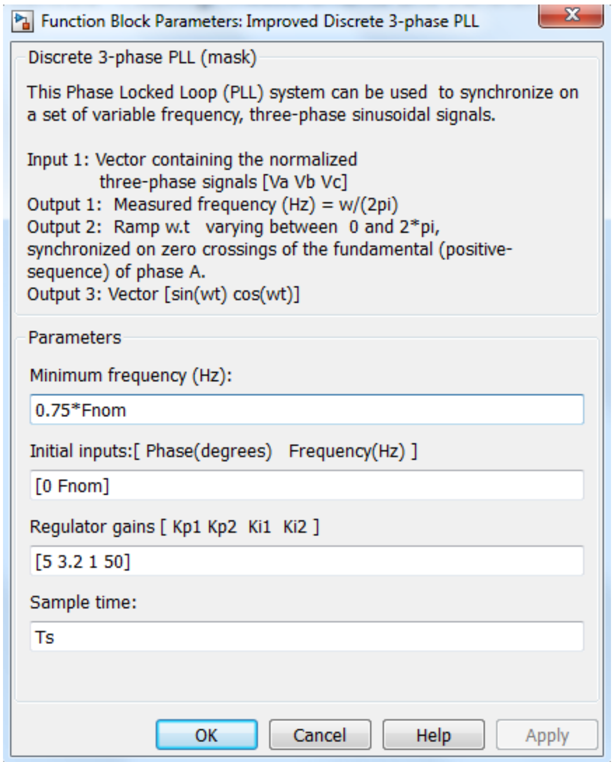

Figure A.18: PLL

A.10 PWM

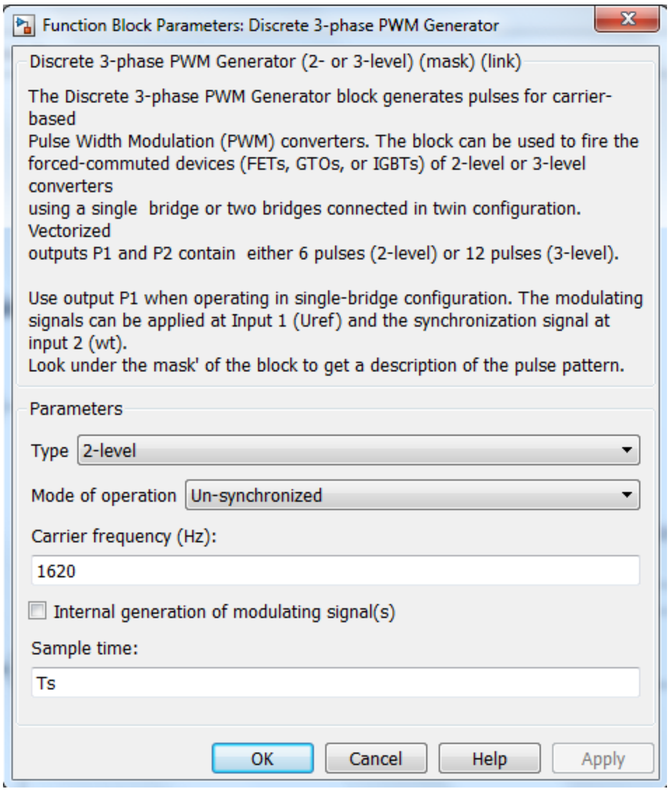

Figure A.19: PWM generator

A.11 RMS

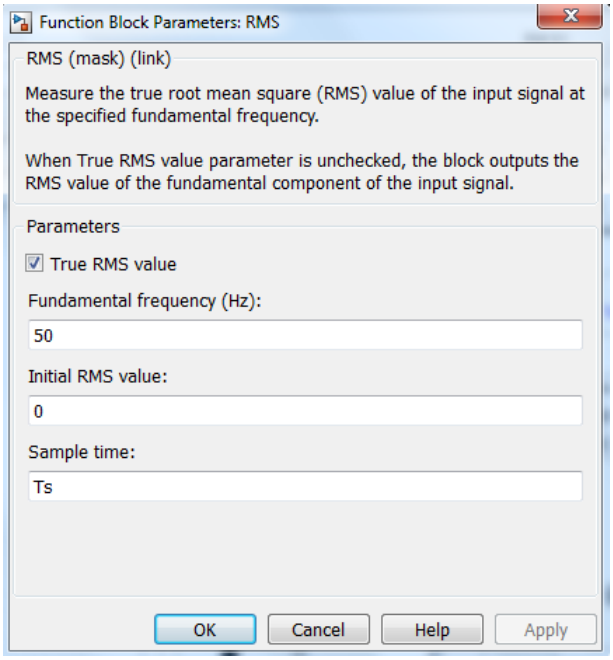

Figure A.20: RMS block parameters

A.12 Fault

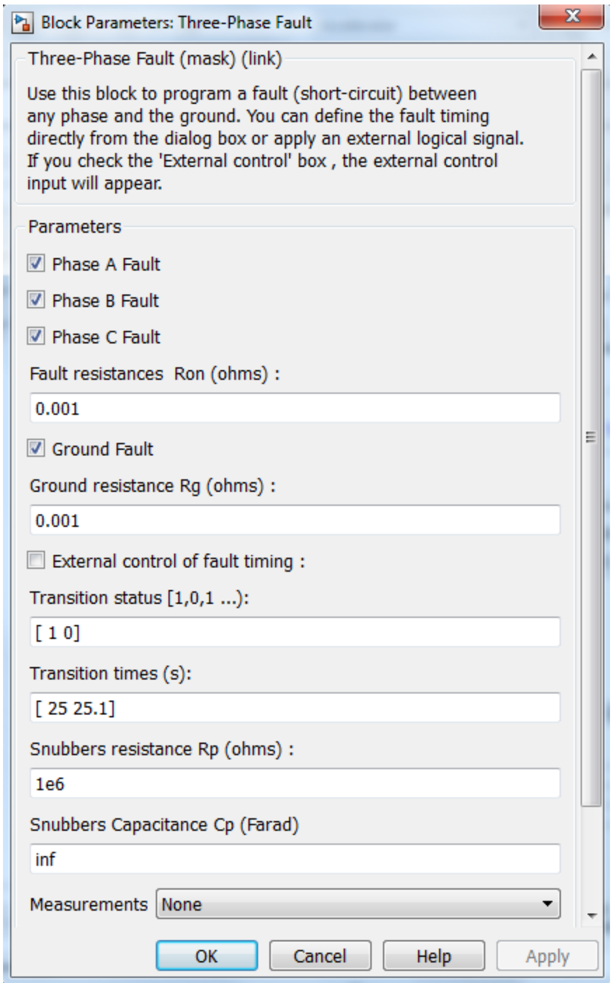

Figure A.21: Fault block parameters

A.13 Load

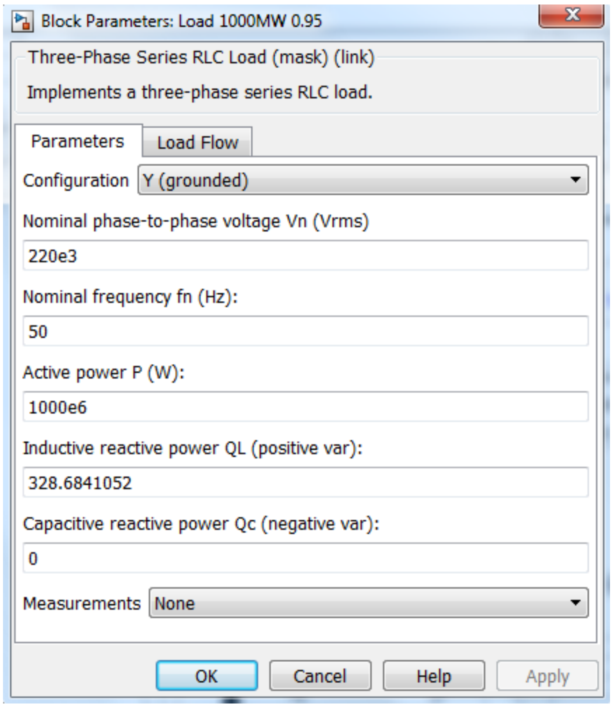

Figure A.22: Load block parameters

A.14 RL

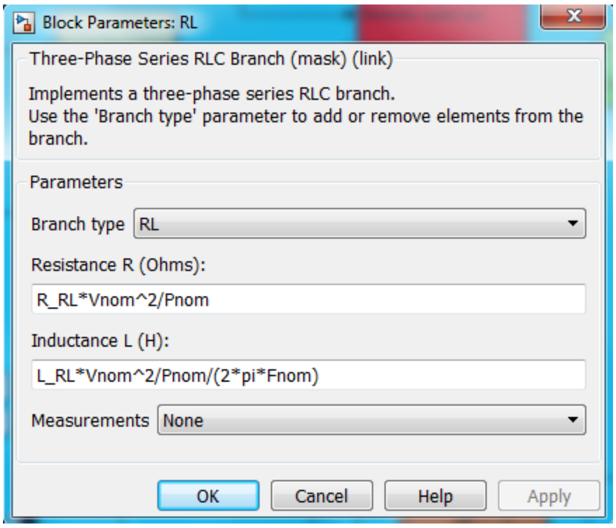

Figure A.23: RL block parameters

A.15 1400MVA, 132KV Generator

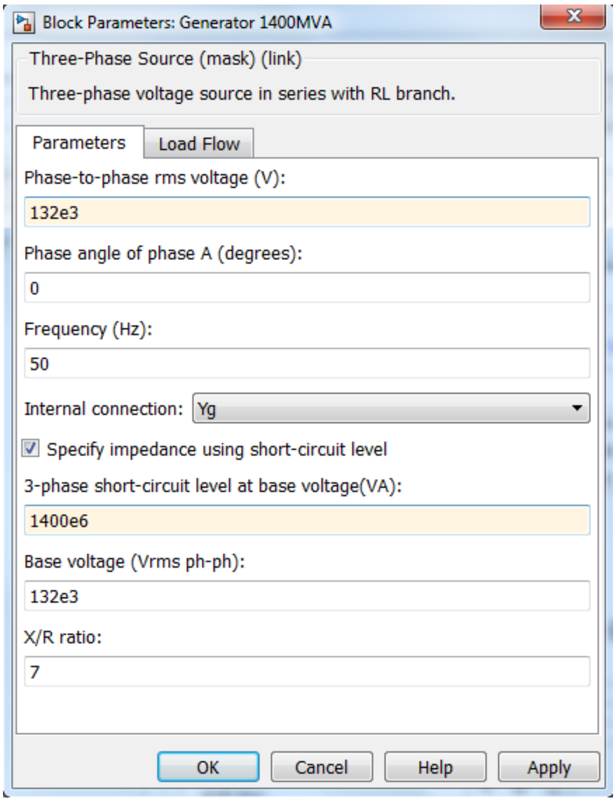

Figure A.24: 1400MVA, 132KV Generator

A.16 4000MVA, 220KV Generator

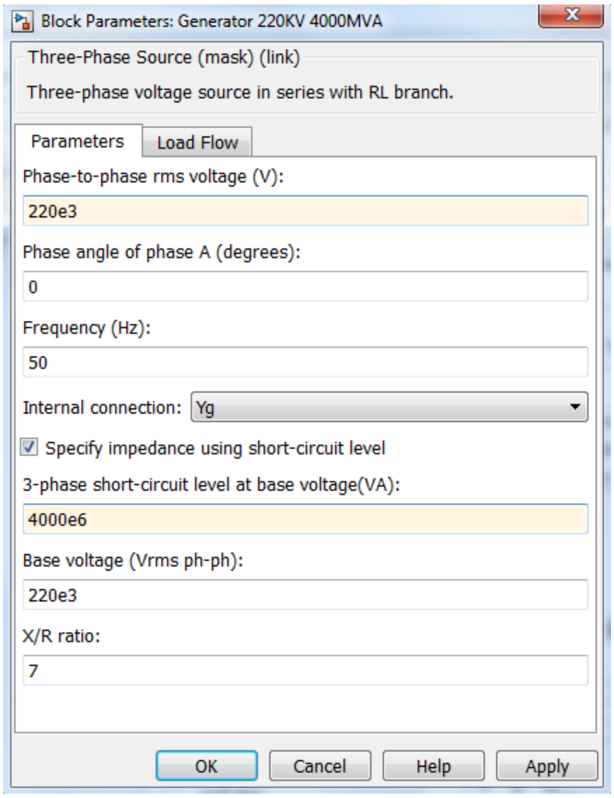

Figure A.25: 4000MVA, 220KV Generator

A.17 Transformer

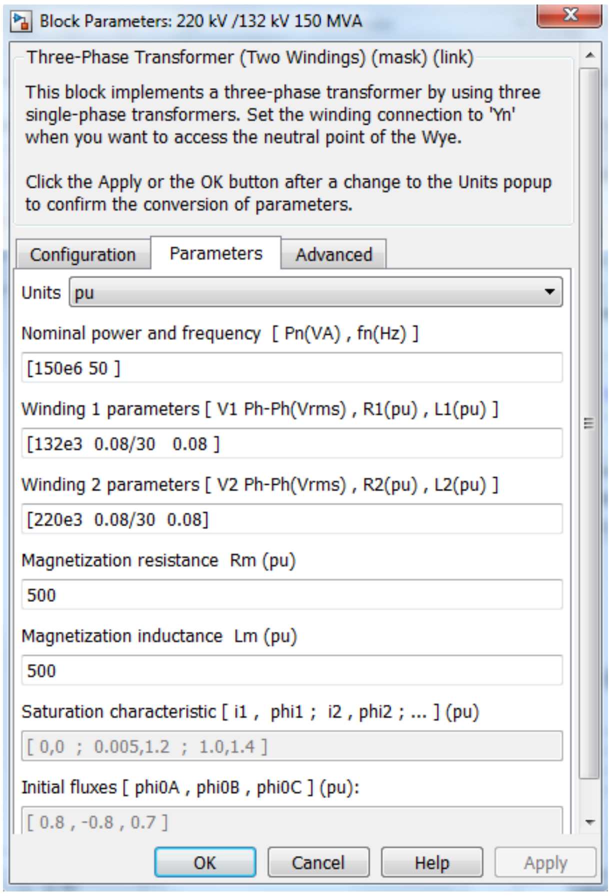

Figure A.26: Transformer block parameters