Dynamic and Transient Behaviour of Standard Test Bus System Under Various Disturbances

Major Project Report

Submitted in Partial Fulfillment of the Requirements

for the Degree of

MASTER OF TECHNOLOGY

IN

ELECTRICAL ENGINEERING

(Electrical Power Systems)

By

SHALEEN DAVE

13**MEEE**28

DEPARTMENT OF ELECTRICAL ENGINEERING

INSTITUTE OF TECHNOLOGY

NIRMA UNIVERSITY

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Undertaking For Originality of the Work

I, **Shaleen Dave** (**Roll No.13MEEE28**), give undertaking that the Major Project entitled **''Dynamic and Transient Behaviour of Standard Test Bus System Under Various Disturbances''** submitted by me, towards the partial fulfillment of the requirement for the degree of Master of Technology in Electrical Power Systems, Electrical Engineering, under Institute of Technology, Nirma University, Ahmedabad is the original work carried out by me and I give assurance that no attempt of plagiarism has been made. I understand that in event of any similarity found subsequently with any published work or any Dissertation work elsewhere; it will result in severe disciplinary action.

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Place :- Ahmedabad

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Project Guide

Prof. C.R.Mehta

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Certificate

This is to certify that the Major Project Report entitled **"Dynamic and Transient Behaviour of Standard Test Bus System Under Various Disturbances"** submitted by **Shaleen Dave (13MEEE28)** towards the partial fulfillment of the requirements for the award of degree in Master of Technology (Electrical Engineering) in the field of Electrical Power Systems of Nirma University is the record of work carried out by him under our supervision and guidance. The work submitted has in our opinion reached a level required for being accepted for examination. The results embodied in this major project work to the best of our knowledge have not been submitted to any other University or Institution for award of any degree or diploma.
Date:

....

Project Guide

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"To achieve something that we had never before, we need to do something better which we have never done before"

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Abstract

The renewable energy generation is increasing day by day. The renewable resources like small hydro plants, wind farms, solar plants, and biogas plants are used to generate electrical energy. The generation through renewable energy sources have been increased exponentially in last decade because of the adverse effects of conventional plants. India is the fifth largest wind generating country in the world. Initially generation through RES was distributed i.e. not connected to grid but as the penetration is increased drastically the concept of integration of renewable energy resources will be most significant in near future. Due to large penetration of renewable sources, the issues of operation, control, power quality, fault analysis, protection and relay co-ordination opens the new area for the researchers. As renewable energy generation is not continuous in nature and also plants are away from the load centers it creates various challenges while integrating with conventional system.

In this project WSCC 9-bus system is considered as standard test bus system. Simulation work is carried out in PSCAD/EMTDC software. In this standard test bus system load flow analysis under steady state condition is performed. Analysis of the different types of faults (symmetrical and unsymmetrical) at different locations are carried out. Moreover the fault current is measured with and without wind generation. The solution to the problem allows the decision maker to quickly reach an optimal decision when considering the interconnection of renewable energy sources to a grid.

Abbreviations

RE .... Renewable Energy
RES .... Renewable Energy Sources
DG .... Distributed Generation
SFCL .... Superconducting Fault Current Limiter
FRT .... Fault Ride Through
SSSC .... Static Synchronous Series Compensator
DFIG .... Doubly Fed Induction Generator
MG .... Micro Grid
WG .... Wind Generation
ESS .... Energy Storage System
PV .... Photovoltaic
SCIG .... Squirrel Cage Induction Generator
WRIG .... Wound Rotor Induction Generator
PMSG .... Permanent Magnet Synchronous Generator
WPP .... Wind Power Plant
STATCOM .... Static Compensator

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Chapter 1

Introduction

1.1 Renewable Energy Sources in India

- Renewable energy in India is a fast developing sector. India is the first country in the world to set up a ministry of non-conventional energy resources[11].
- As per the ministry of power total installed capacity of power generation in India is $2, 28, 721$ MW. Among them about 68.19% of the electricity is generated in India by thermal power plants, 17.39% by hydro power plants, 2.08% by nuclear power plants and 12.32% by Renewable Energy Sources[11].
- India is heavily dependent on fossil fuels for its energy requirements. Most of the power generation is produced by coal and mineral oil-based power plants which contribute heavily to greenhouse gases emission. According recent surveys pollution kills more than 300,000 people every year in India.

Table 1.1: Total Power sources

Fuel	MW	Percentage
Coal	134,388.38	58.75
Gas	20,380.84	8.91
Oil	1,199.76	0.52
Total Thermal	155968.99	68.19
Hydro (Renewable)	39,788.40	17.39
Nuclear	4,781.00	2.08
RES (MNRE)	28,184.36	12.32
Total	2,28,721.74	100.00

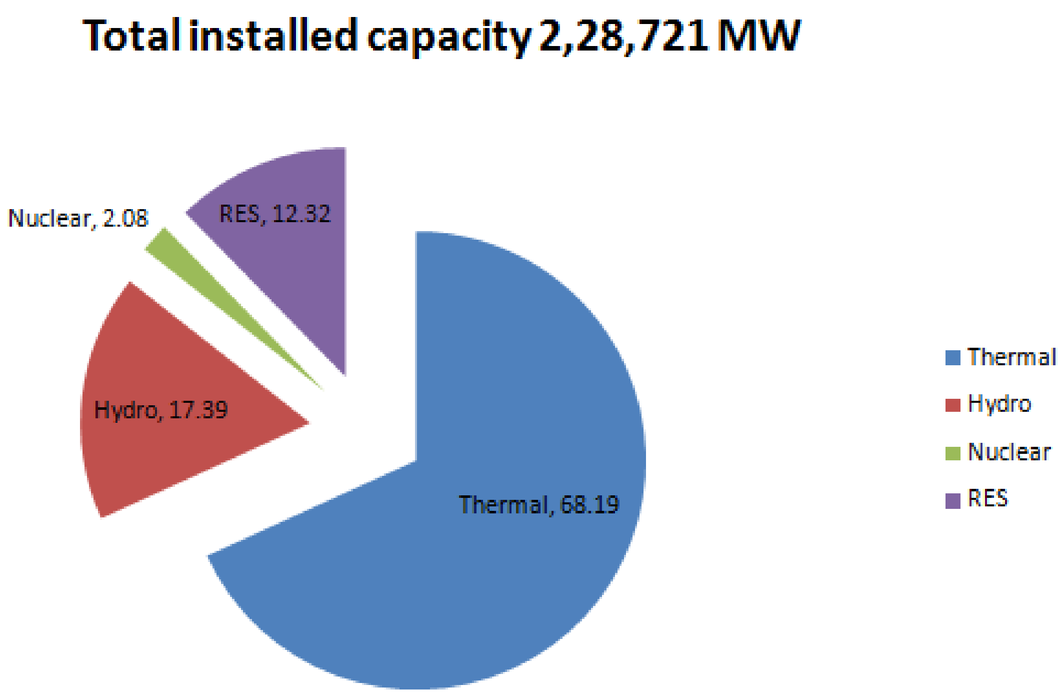
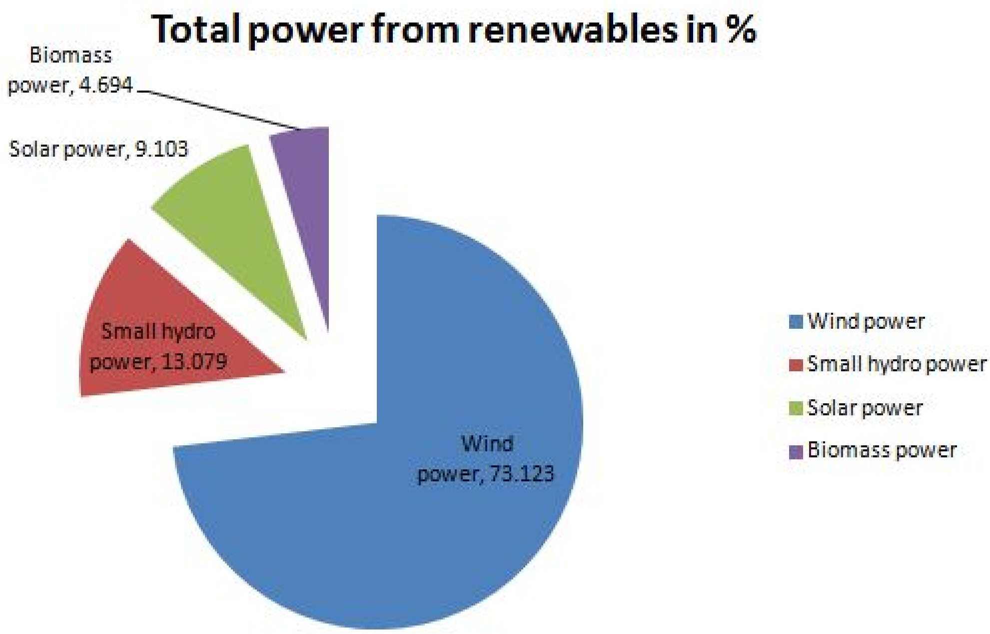


Table 1.2: Total Power from renewable sources

Sources	MW	Percentage
Wind power	21,262	73.123
Small hydro power	3803	13.079
Solar power	2647	9.103
Biomass power	1065	4.693
Total	28177	100



1.1.1 Key Drivers for Renewable Energy

- The demand supply gap, especially as population increases.
- Environment concern.
- The need to strengthen India's energy sector.
- A feasible solution for rural electrification.

Recently, electric energy sector emphasized the importance of using renewable resources as a clean supply of electric energy. Most of these DG facilities were based on either wind energy or solar energy; both of them are unpredictable and intermittent power resources. Due to regulatory, social and environmental issues, as well as technological development the electricity world is facing challenges. In particular, a system approach able to manage intermittent energy supply from distributed power plants, leading to a steady supply of electricity is necessary. RES generation makes power flows in the grid to be more difficult to be predicted and controlled. In such a case, management of power flow turns out to be a key factor for integrating scattered and decentralized RES generation into the grid.

1.2 Problem Identification

The voltage profile of the power system can be managed if the ability of compensating the reactive power of a distributed generation resource is increased. Power system functionality may be degraded without this ability of performance. Reactive power (VAR) is required to maintain the voltage level throughout the transmission line. Different distributed energy resources are used to maintain voltage drops. Due to intermittent nature of RES, the distributed generators produce the fluctuating electric power. These fluctuations have a negative impact on stability and power quality of the system. These impacts are increased as the level of penetration through RES is increased. Due to the penetration of RES in the system following parameters will be affected:

- Short circuit current level of the system
- Voltage level of the system
- Power quality
- Protection scheme

1.3 Objective

The objective is to assess the RES impact on the system in terms of active power, reactive power, different types of faults and fault current level, and where the requirement of protection, compensation in the case of different types of renewable sources, which can help in better operation of power system. This project discusses about the penetration of wind generation in WSCC 9-bus 3-machine system.

1.4 Scope of Work

- Develop a standardized model of WSCC 9-bus 3-machine system in PSCAD software and to observe load flow analysis under steady state condition for conventional case.
- Observe active power, reactive power, voltage results at each bus in steady state condition.
- Creating the fault at different locations (Generator side, Bus fault, load end) monitoring the fault current, active and reactive power in the same conventional case. Comparison of fault current with the change in line length.
- Replacement of conventional generator by wind source and analyzing the effects of fault current level on the system. Comparison of fault current with the change in line length and speed variation in wind generation

1.5 Organization of Thesis

The work carried out during the dissertation is divided into six chapters.

- **Chapter 1** describes the scenario of the various renewable sources and problems occurring while inter connecting power system. It also includes problem identified and the scope of work.
- **Chapter 2** gives a brief description about literature survey.
- **Chapter 3** gives a brief description about the wind generation, types of wind turbines such as SCIG, WRIG, DFIG, PMSG. It also discusses about the wind components and the requirements of connecting the wind farm into power system.
- **Chapter 4** presents the simulation results of the WSCC 3 machines 9 bus system under steady-state condition. This chapter also includes the results of fault analysis at different locations in the standard test system. Further, effect of line length in fault current has been discussed.
- **Chapter 5** presents simulation results of the 9 bus system when one of the synchronous generator is replaced by a wind source. This chapter also includes the results of fault analysis at different locations in the same system. Effect of change in line length in fault current and speed variation in wind generation has been discussed.
- **Chapter 6** includes conclusion and future work.

Chapter 2

Literature Survey

The most important part of any studies is to understand the given concepts and the importance of the topic. This is achieved by survey of specious literature available in IEEE and Science Direct. This section describes about some important papers to understand the concept of distributed generation in case of renewable energy sources and their impact on power system.

- **G.D. Anbarasi Jebaselvi S. Paramasivam**[1] The paper entitled *"Analysis on renewable energy systems"* gives information about the most alarming feature today is how to manage the energy demand and crucial climate change. This paper includes how to penetrate renewable energy sources gradually into the global energy market. Renewable sources are the best alternative to conventional fuels because of their abundant potential, non-pollutant nature and are exceedingly eco-friendly with the environment. This paper overviews the performance analysis of hybrid power systems, control methodologies and modeling techniques so as to get an optimum output power. Paper also includes control strategies, modeling techniques, fault analysis and management technique in hybrid power systems.

- **Alejandro Roln Joaqun Pedra Felipe Crcoles**[2] The paper entitled *"Detailed study of DFIG-based wind turbines to overcome the most severe grid faults"* describes the effects of voltage sags caused by faults on doubly-fed induction generators to overcome grid faults. It is noticed that sag duration influence is periodical. Sag effects depend on duration and depth and on the fault-clearing process as well. Two approaches of the model are compared: the first most accurate approach, discrete sag, considers that the fault is cleared in the successive natural fault-current zeros of affected phases, leading to a voltage recovery in several steps; the second least accurate approach, abrupt sag, considers that the fault is cleared instantaneously in all affected phases, leading to a one-step voltage recovery. By comparing both sag model it is evident that the sag effects are smoothen by the faut clearing process.

- **Duong Minh Bui, Keng Yu Lien, Shi-Lin Chen,Ying-chen Lu**[3] The paper entitled *"Investigate dynamic and Transient characteristics of the micro-grid operation and develop a fast-scalable-adaptable algorithm for fault protection system"* discusses the dynamic and transient behaviors with two different modes of operations of MG namely, grid connected and islanded modes. Transient characteristics of the MG are surveyed through staged fault tests (i.e. single phase and three-phase to ground faults), dynamic properties are investigated in cases of power change of sources or loads. A fast adaptive scalable fault protection algorithm has been developed to improve the operation reliability of the MG for both the islanded and grid connected modes.

- **Mariam E. Elshiekh, Diaa-EldinA. Mansour**[4] The paper entitled *"Improving Fault Ride-Through Capability of DFIG-Based Wind Turbine Using Super-conducting Fault Current Limiter"* discusses With the increase in penetration of wind energy, there is a need to keep wind turbines connected to the grid during grid faults. The super-conducting fault current limiter (SFCL) is used to reduce fault current level at the stator side and improve the fault ride-through (FRT) capability of the system. A doubly fed induction generator (DFIG) is used as a wind turbine generator, where the system is simulated using PSCAD/EMTDC software.

- **Ali Hooshyar Maher Abdelkhalek Azzouz Ehab F. El-Saadany**[5] The paper entitled *"Three-Phase Fault Direction Identification for Distribution Systems With DFIG-Based Wind DG"* discusses that conventional directional elements malfunction during three phase short-circuits when a distribution system incorporates DFIG-based wind DG. The mal operation is due to the exclusive fault behavior of DFIGs, which affects the existing relaying practices. The paper also proposes a fault current classification technique that replaces the conventional directional element during problematic conditions and provides accurate fault direction quickly based on wave shape properties of the current. The fault current frequency for DFIG-based wind DGs, however, may considerably deviate from the nominal frequency depending on wind speed. On this basis, this paper demonstrated the impossibility of finding fault direction through the common method of phase angle comparison between the current and voltage phasors.

- **Rashad M. Kamel**[6] The paper entitled *"Effect of wind generation system types on Micro-Grid (MG) fault performance during both stand alone and grid connected modes"* discusses there are three types of wind generation (WG). The first type is Fixed speed Wind Generation (FSWG) system, which have squirrel cage induction generators. Double Fed Induction Generator (DFIG) is used in the second type. Full Converter Wind Generation (FCWG) system, which is interfaced with Micro-Grid (MG) through a back to back converter referred as third type. During fault occurrence each WG has its own characteristics determined by its generator and micro grid earthing system. The main aim of this paper is to investigate and estimate how the fault performance of MG during both stand alone and grid-connected modes is influenced by the type of WG. During the island mode, it is found that the fault performance of the MG system mainly depends on the type of the employed WG.

- **RalSarrias-Mena, Luis M. Fernndez-Ramrez, Carlos A. Garca-Vzquez, Francisco Jurado**[7] The paper entitled *"Improving grid integration of wind turbines by using secondary batteries"* discussed two different hybrid configurations are modeled in MATLAB/Simulink, consisting on a doubly fed induction generator driven wind turbine and electrochemical batteries as ESS. They are simulated and compared under various operating conditions (i.e. real fluctuating wind speed input with variable active and reactive power grid demand, voltage sags, three-phase and single-phase fault to ground, and overvoltage). A conventional wind turbine without ESS is also considered as a base-case in order to highlight the main benefits of the hybrid schemes. The results show that by implementing one of the presented control strategies, it is possible to enhance the response to faults of the hybrid systems, achieving higher active power injection and helping the recovery to steady-state, thus improving the grid connection capabilities of hybrid wind farms.

- **Maryam Bahramipanah, Zegros shahooei**[8] The paper entitled *"Coordination of generators and existing energy storage with wind farms in order to reduce the transient effect"* discusses about the control method to coordinate existing generators and energy storage systems to response the transient changes. The power output fluctuations will be reduced by use of ESS. Thus, wind farm with ESS will enhanced the power system performances.

2.1 Summary

This chapter gives a brief description about the literature survey of wind generation while penetrating in the power system. It also discusses about the current issues regarding wind integration.

Chapter 3

Wind Generation

Now-a-days global warming is to find the most burning issue in many of the climate summit. Many researchers, scientists are working their own relevant areas to reduce the effective mitigation of climate effect due to global warming by using different techniques. The electricity system is observed as being easier to transfer to low-carbon energy sources than more challenging sectors of the economy such as surface and air transport. Hence the use of cost-effective and reliable low-carbon electricity sources is becoming an important objective of the energy policy in many countries. This is only possible through the use of renewable resources as the main sources for the generation of electricity. The electricity produced from wind has increased significantly in recent years. Therefore, today's wind turbines, which are centralized in wind farms, have a major impact on the production of electricity. The merge of several wind turbines into bigger units in wind parks for increasing the production from wind power. Different types of wind turbine technology is used to reach fastest growth in the world market. The basic concepts of the turbines, maximum power extractable from wind, characteristics of wind turbine are also the part of this chapter.

3.1 Wind Turbines

Wind turbines produce electricity by using the power of the wind to drive a generator. Wind passes over the blades, generating lift and exerting a turning force. The rotating blades turn a shaft inside the nacelle, which goes into a gearbox. The gearbox increases the rotational speed to that which is appropriate for the generator, which uses magnetic fields to convert the rotational energy into electrical energy.

3.1.1 Squirrel Cage Induction Generator (SCIG) [Type A Wind turbine]

It has been the workhorse of the wind power industry, as it has an inherent torque-speed curve that fits the wind power plant (WPP) application quite naturally. Although, the over speed variations in SCIG are very small (1% to 2%), its mechanical simplicity, robust construction and relatively lower cost have made it quite popular in the wind industries for considerable amount of time[14]. In addition when the torque varies, the speed of the SCIG increases or decreases only a little, thereby resulting in less tear and wear of the gearbox. This is the most important reason for using induction generator rather than a synchronous generator in WPP.
Fixed-speed wind turbines are electrically fairly simple devices consisting of an aerodynamic rotor driving a low-speed shaft, a gearbox, a high-speed shaft and an induction (sometimes known as asynchronous) generator[14]. It is directly connected to the grid. Variable-speed wind turbines are designed to achieve maximum aerodynamic efficiency over a wide range of wind speeds. The electrical system of a variable-speed wind turbine is more complicated than that of a fixed-speed wind turbine. It is typically equipped with an induction or synchronous generator and connected to the grid through a power converter

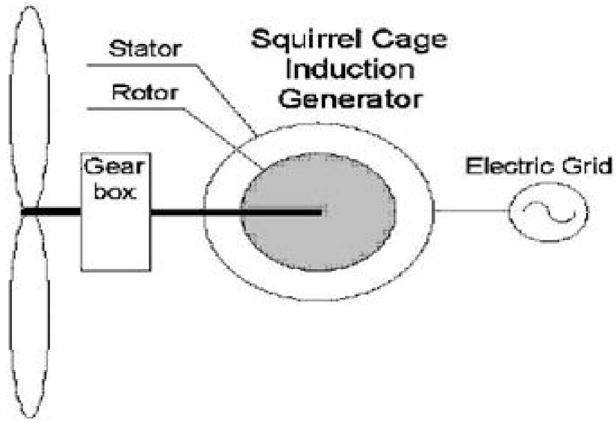


Figure 3.1: Type A SCIG

3.1.2 Wound Rotor Induction Generator (WRIG) [Type B Wind turbine]

It uses wound rotor induction generator that operates in a narrow range speed variation (up to 10% to 16%) above the synchronous speed)[14]. It overcomes many of the disadvantages of the TYPE A wind turbine. The mechanical construction of WRIG stator is similar to that of the SCIG. The unique feature of this concept is that it has a variable additional rotor resistance, which can be changed by an optically controlled converter mounted on the rotor shaft. Thus, the total rotor resistance is controllable. This optical coupling eliminates the need for costly slip rings that need brushes and maintenance.

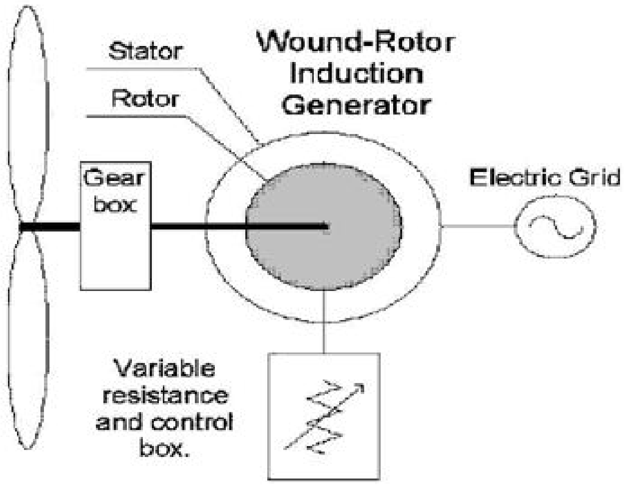


Figure 3.2: Type B WRIG

3.1.3 Doubly Fed Induction Generator (DFIG) [Type C Wind turbine]

It operates in the range of -30% to +40% of its rated speed and hence it is considered as a limited variable speed WPP[14]. DFIG combines the advantages of the induction generator as well as the variable speed feature of the synchronous generator. It is basically an induction generator with three-phase stator winding that is directly connected to the electrical grid[14]. Within limits DFIG can hold the power constant, even during fluctuating wind speed. The partial scale frequency converter performs the reactive power compensation and the smoother grid connection.

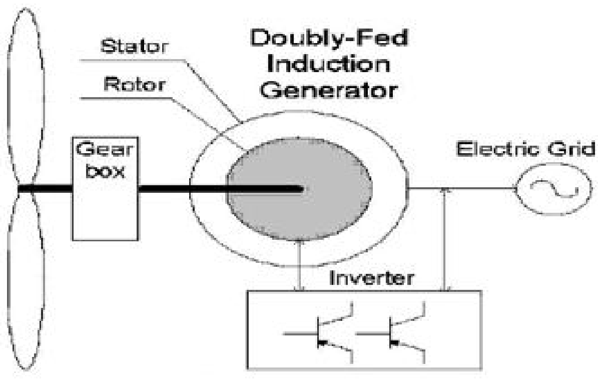


Figure 3.3: Type C DFIG

3.1.4 Permanent Magnet Synchronous Generator (PMSG) [Type D Wind turbine]

This configuration corresponds to the full variable speed wind turbine, with the generator connected to the grid through a full-scale frequency converter. The frequency converter performs the reactive power compensation and the smoother grid connection. The generator can be excited electrically (WRSG/WRIG) or by a permanent magnet (PMSG)[14]. Some full variable-speed wind turbine systems have no gearbox. In these cases, a direct driven multi pole generator with a large diameter is used. The schematic configuration is shown in Fig.3.4

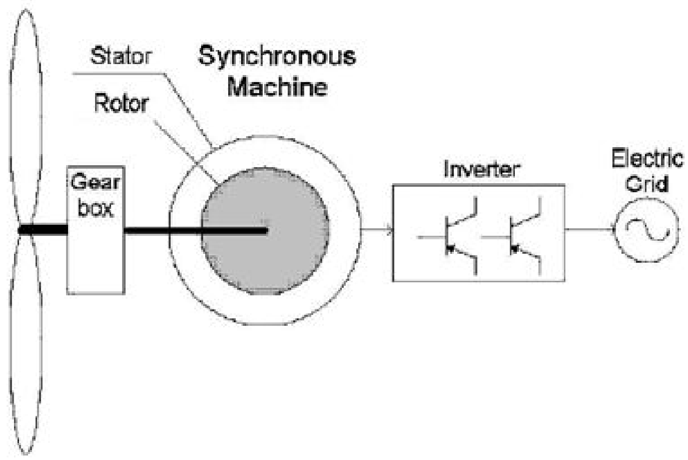


Figure 3.4: Type D PMSG

3.2 Wind Component

In PSCAD/EMTDC software, component available for wind model is given as:

- Wind Generator
- Wind Turbine
- Wind Source

3.2.1 Wind Governor

This component models a pitch angle regulator of a wind turbine. The inputs to the model are the mechanical speed of the machine Wm and the power output of the machine Pg. The output is the pitch angle of the turbine.

Input:

- Wm: Mechanical speed of the machine [rad/s]
- Pg: Power output of the machine based on the machine rating [pu]

Output:

- Beta: Pitch angle

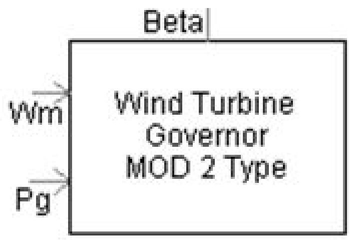


Figure 3.5: Wind Governor

3.2.2 Wind Turbine

This component models the simple mechanical physics of a wind turbine, considering blade configuration (2 or 3 blade), tip speed ratio, coefficient of power, and blade sweep area and radius[13]. Shaft dynamics are not considered in this model and it may be used together with the wind governor model. Wind speed Vw and the mechanical speed of the machine connected to the turbine W are the inputs. Beta is the pitch angle of the turbine blades and is entered in degrees. Tm and P are the output torque and power respectively in per-unit, based on the machine rating. Two type of turbines are modeled, a 2 blade (MOD 5) and a 3 blade (MOD 2)[13].

Input:

- Vw: Wind speed (must be a positive value) [m/s]

- W: Machine mechanical speed [rad/s]
- Beta: Pitch angle [deg]

Output:

- Tm: Output torque of the turbine [pu]
- P: Output power of the turbine [pu]

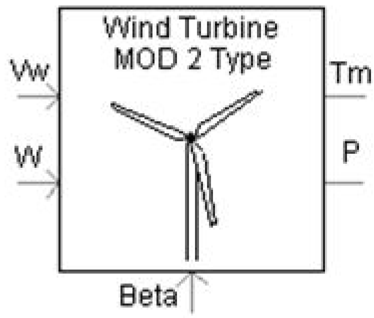


Figure 3.6: Wind Turbine

3.2.3 Wind Source

This component models the wind speed available to a wind turbine

Input:

- ES: External signal representing wind speed [m/s]

Output:

- Vw: Wind speed available to the turbine [m/s]

The external input Es can be used to input any type of wind variation that may not be defined from within the component. The user has the option to enable or disable this input[13]. Actual wind pattern recordings from field tests can be imported and be used as the wind speed to the turbine model.

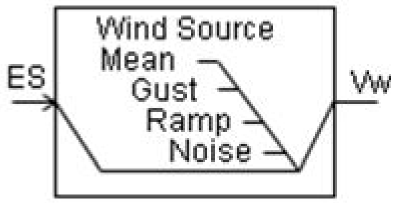


Figure 3.7: Wind Source

3.3 Requirements of Connecting The Wind Farm Into Power System

Power system operation may be affected by integration of the large scale wind power plants. To satisfy the steady state and dynamic condition of the wind turbine some grid codes have been defined so, the wind farm can be connected to the grid. Some specification have been considered for the connection[9].

- The active and reactive power should be regulated within a control range.
- The frequency variation should be within limit.
- The certain degree of voltage fluctuation must be consider.
- Wind turbine must able to withstand more than one independent faults.
- Short circuit ratio should be high.

3.4 Summary

This chapter gives a brief description about the wind generation, types of wind turbines such as SCIG, WRIG, DFIG, PMSG. It also discusses about the wind components. This chapter provides general background, lays the groundwork of whole dissertation work.

Chapter 4

Simulation Results of WSCC 9 bus system

4.1 WSCC 9-Bus System Steady State Condition

To analyze the stability of a system, an appropriate standard model which is already available is desired to be chosen. In this project popular Western System Coordinating Council (WSCC) 3 generators, 9 bus system used. This system is simulated using PSCAD/EMTDC software. The discussion in the report is based on the outcome in PSCAD. The base MVA is 100MVA and frequency is 60 Hz. PSCAD required the load flow data as inputs to all the machines.

Representation of the system can be seen in the below Figure.

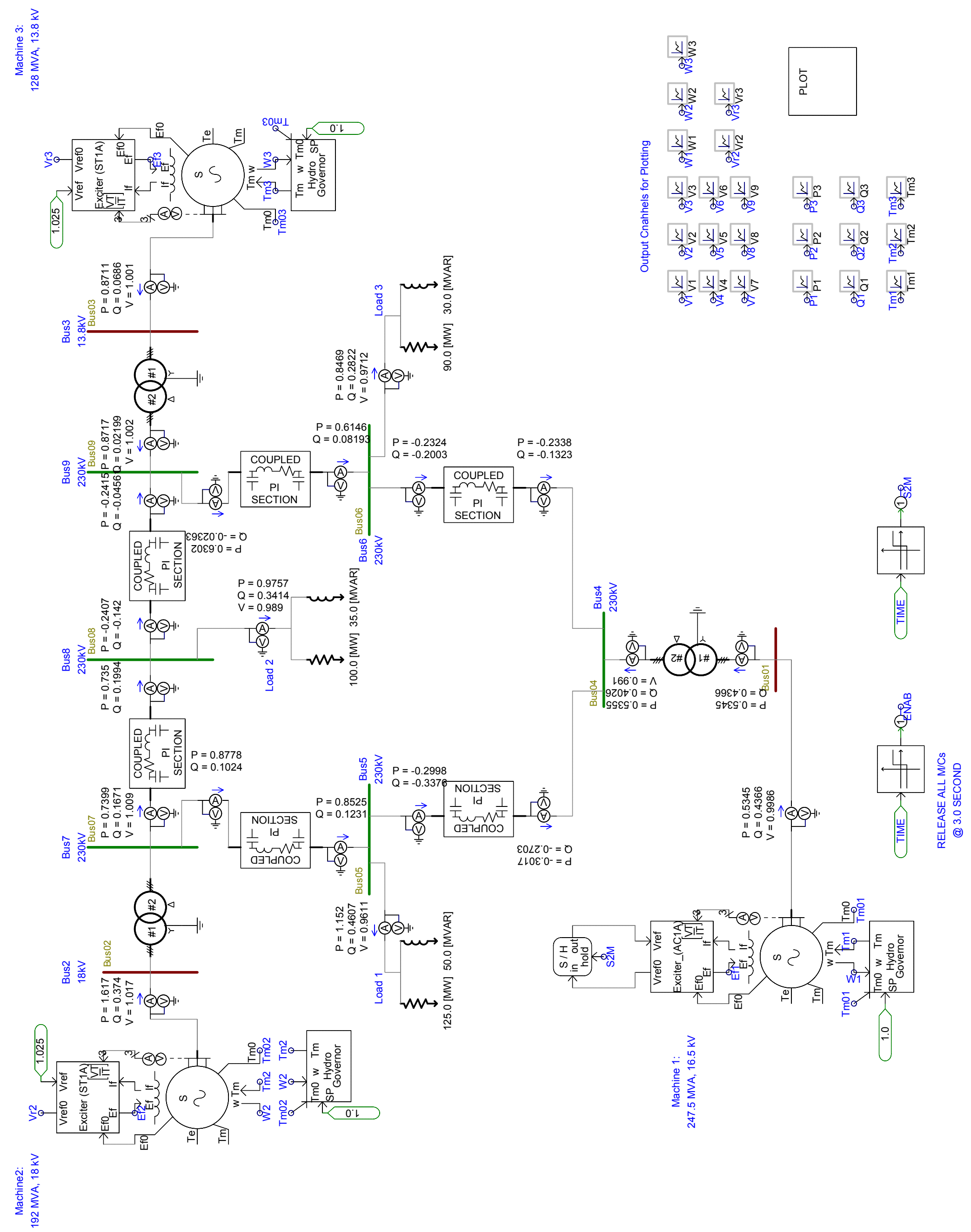


Figure 4.1: WSCC 9 bus system

4.1.1 Results of WSCC 9-bus System

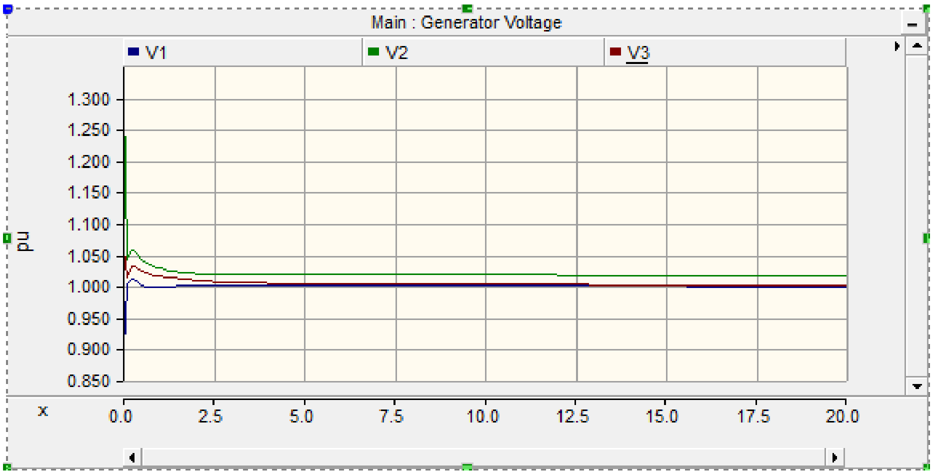


Figure 4.2: Voltages at bus 1, 2 and 3

Here the voltages of generator 1, 2 and 3 are shown in per unit. Voltages are in steady state and desire output is coming as shown in figure 4.2

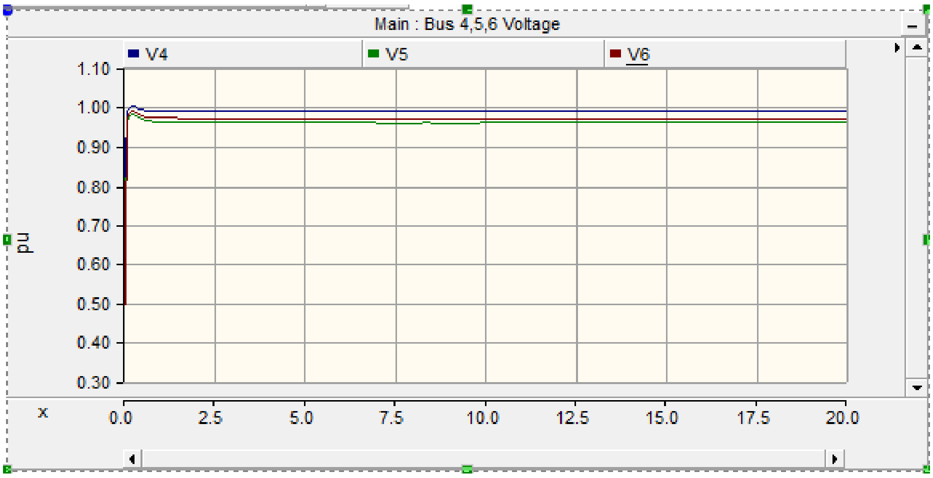


Figure 4.3: Voltages at bus 4, 5 and 6

Figure 4.3 shows the voltages of buses 4, 5 and 6 in steady state condition (pu).Values are near 1.0 pu. Voltages are in steady state after few seconds(2.2sec).

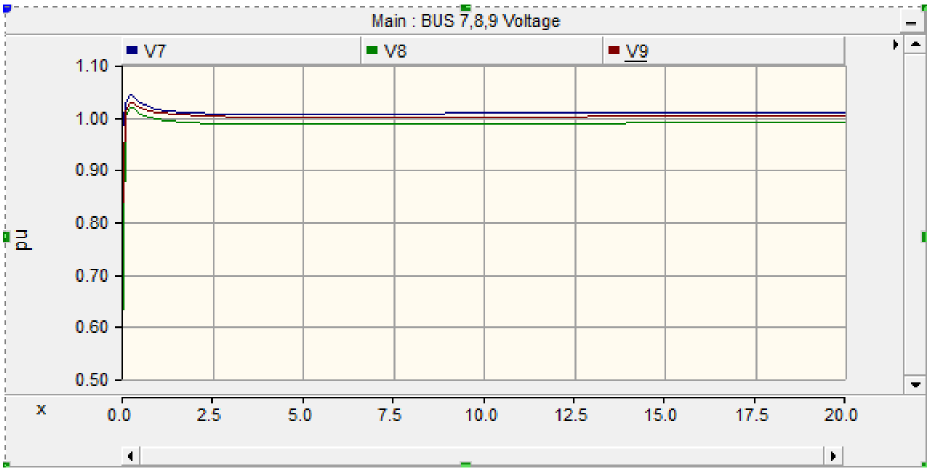


Figure 4.4: Voltages at bus 7, 8 and 9

Figure 4.4 shows the voltages of bus 7, 8 and 9 in pu, which is in steady state.

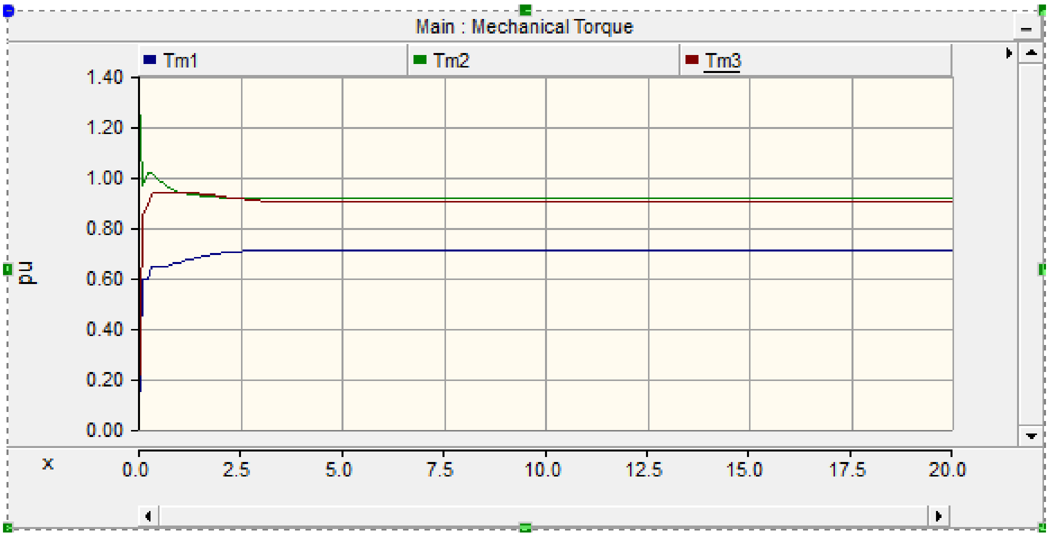


Figure 4.5: Mechanical torque of generator 1, 2 and 3

It can be seen from the results that mechanical torque of three of the generators are stable after 3 sec.

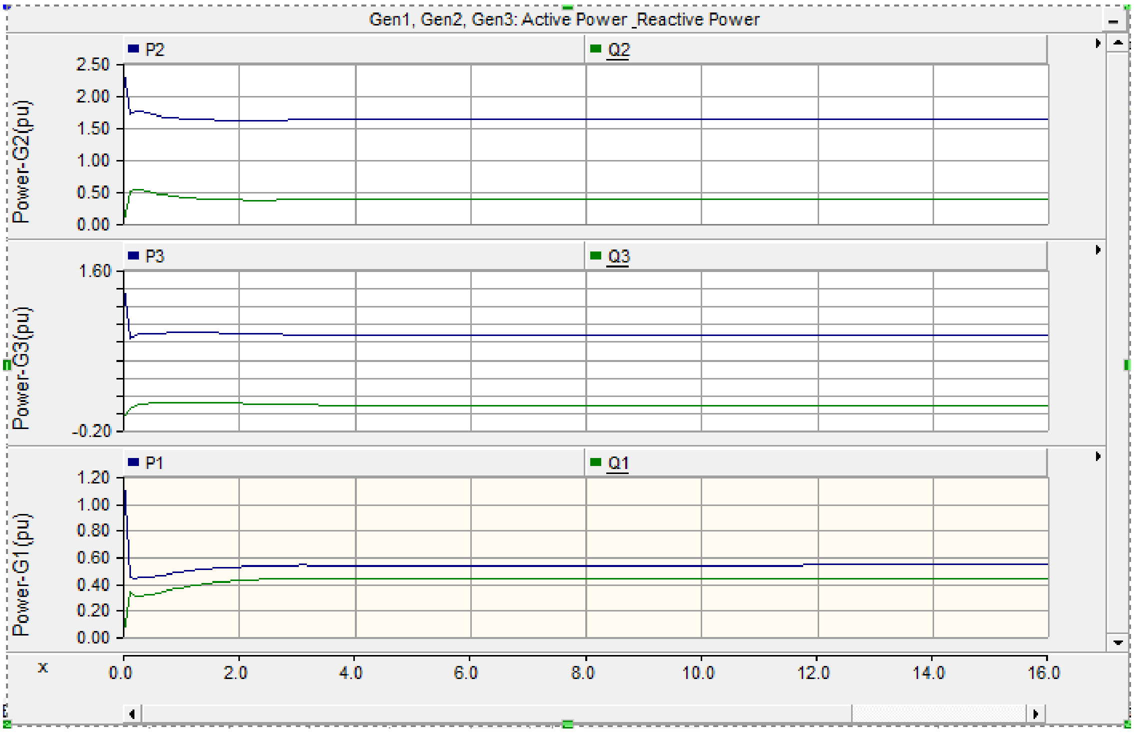


Figure 4.6: Active and Reactive power of generator 1, 2 and 3

Figure 4.6 show P1, P2, P3, Q1, Q2, Q3 are the active and reactive power of the machine 1, 2 and 3. Here generator 1 is swing generator. It can be seen from the results that active and reactive power of three of the machines are becoming stable after certain period of time the power values are satisfactory.

Table 4.1: Comparison of voltages

Bus No.	Voltage(pu)	-
-	Actual	Simulated
1	1.04	0.9986
2	1.025	1.017
3	1.025	1.002
4	1.026	0.9913
5	0.996	0.9615
6	1.013	0.9715
7	1.026	1.009
8	1.016	0.9891
9	1.032	1.002

Table 4.2: The comparison of simulated and actual results of power

Bus No.	Active Power(pu)	-	Reactive Power(pu)	-
-	Actual	Simulated	Actual	simulated
1	0.716	0.5346	0.27	0.4367
2	1.63	1.617	0.067	0.3741
3	0.85	0.8713	-0.109	0.06859

4.2 Fault Analysis of WSCC 9-Bus System

Faults are created in standard test bus system i.e. WSCC 9-bus system. Different types of faults are created at different location i.e. Generator side, load side and bus fault shown in figure.

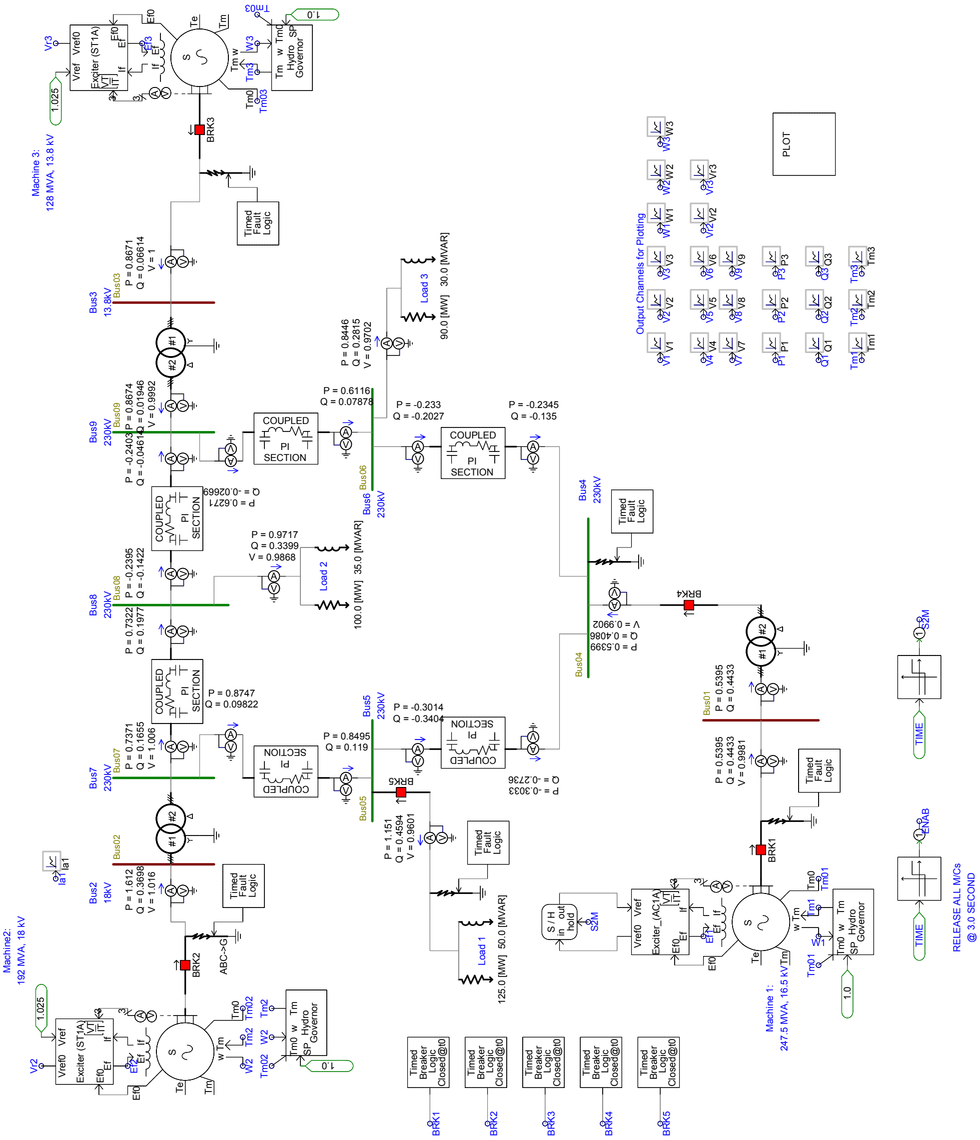


Figure 4.7: WSCC 9 bus system

Fault Created near Synchronous Generator at Bus-3

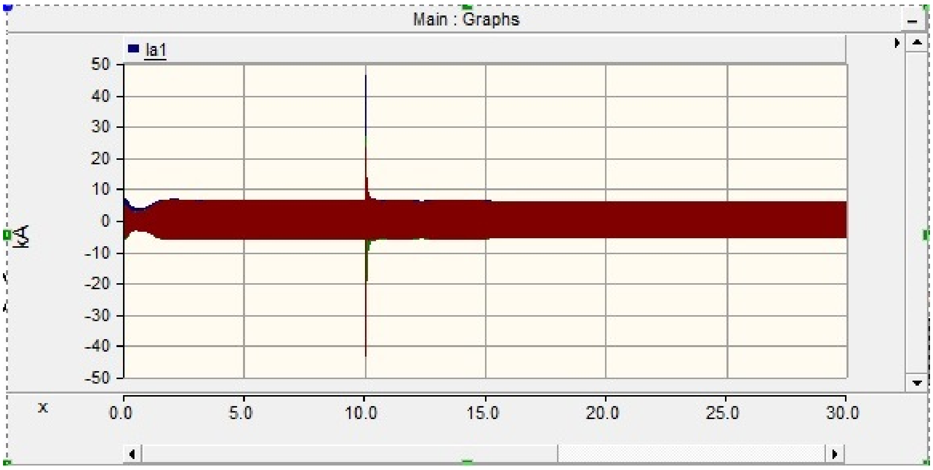


Figure 4.8: Phase to ground fault(L-G) at bus-3

Figure 4.8 shows the phase to ground (L-G) fault near machine-3. Fault current is 45.76387 kA as shown in the graph. System became stable after 15.1 sec. Thus the stable value of current is achieved.

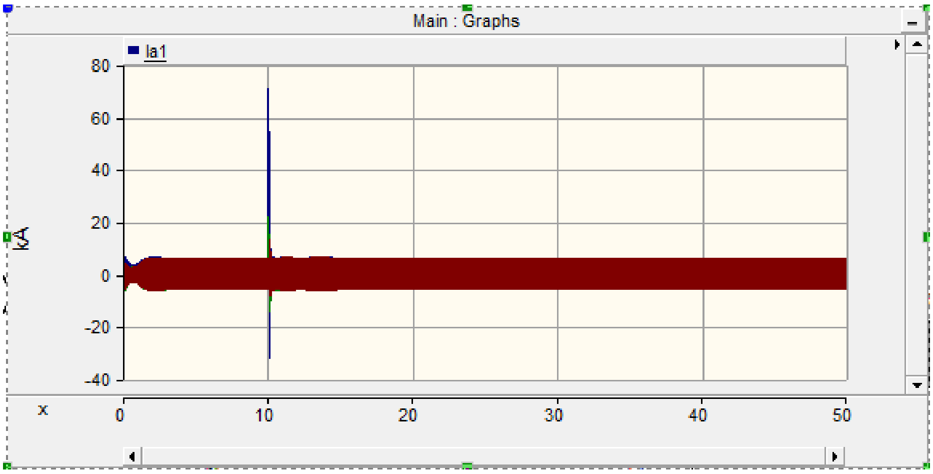


Figure 4.9: Three phase to ground fault(LLL-G) at bus-3

Figure 4.9 shows the three phase to ground (LLL-G) fault near machine-3. Fault current is 71.0924 kA as shown in the figure. Three phase to ground fault is more severe compare to two phase to ground fault. Thus a stable value is achieved depending on the system dynamics based on generation and load connected.

Table 4.3: Fault current at Synchronous generator-3

Types of faults	Fault current (kA)
L-G	45.76387
LL-G	62.7946
LLL-G	71.0924
LL	35.5921
LLL	47.6911

Fault Created near Synchronous Generator at Bus-2

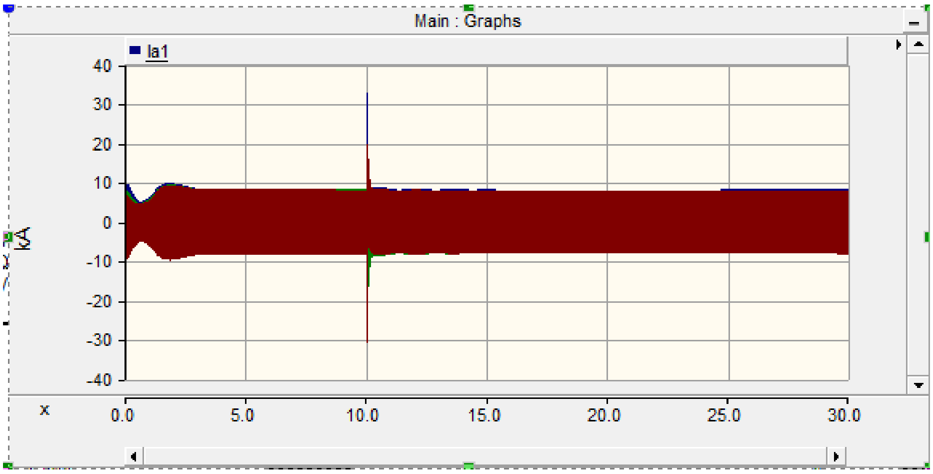


Figure 4.10: Phase to ground fault(L-G) at bus-2

Figure 4.10 shows the phase to ground (L-G) fault near machine-2. Fault current is 34.35706 kA as shown in the graph. System became stable after 15.1 sec. Thus the stable value of current is achieved.

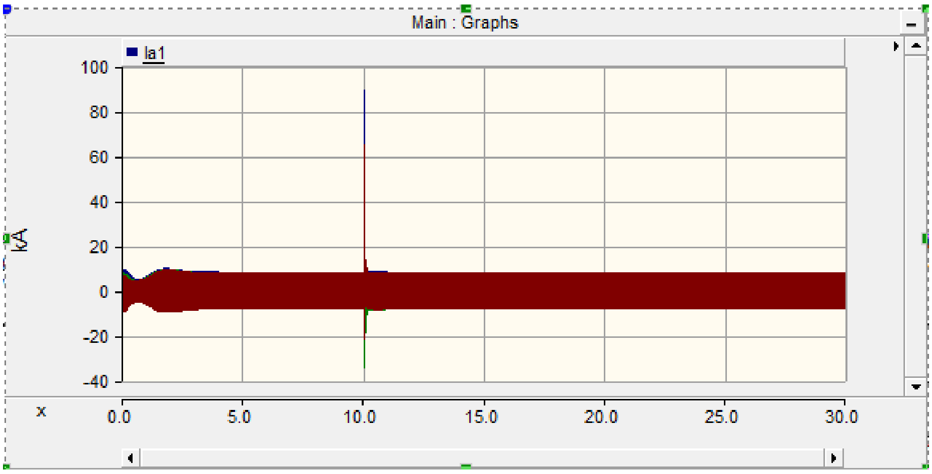


Figure 4.11: Three phase to ground fault(LLL-G) at bus-2

Figure 4.11 shows the three phase to ground (LLL-G) fault near machine-2. Fault current is 88.9988 kA as shown in the figure. Three phase to ground fault is more severe compare to two phase to ground fault. Thus a stable value is achieved depending on the system dynamics based on generation and load connected.

Table 4.4: Fault current at Synchronous generator-2

Types of faults	Fault current (kA)
L-G	34.35706
LL-G	85.40431
LLL-G	88.99880
LL	43.41779
LLL	46.7723

Fault Created near Synchronous Generator at Bus-1

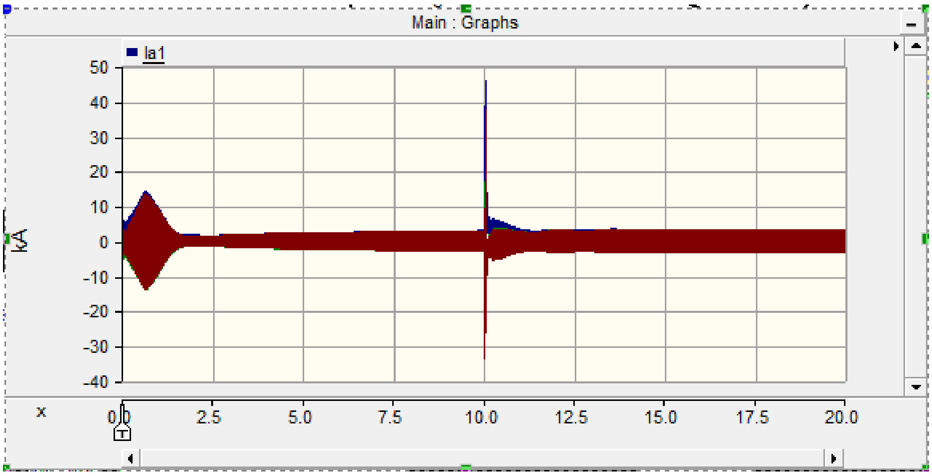


Figure 4.12: Phase to ground fault(L-G) at bus-1

Figure 4.12 shows the line to ground (L-G) fault near machine-1 which creates 47.67856 kA fault current.

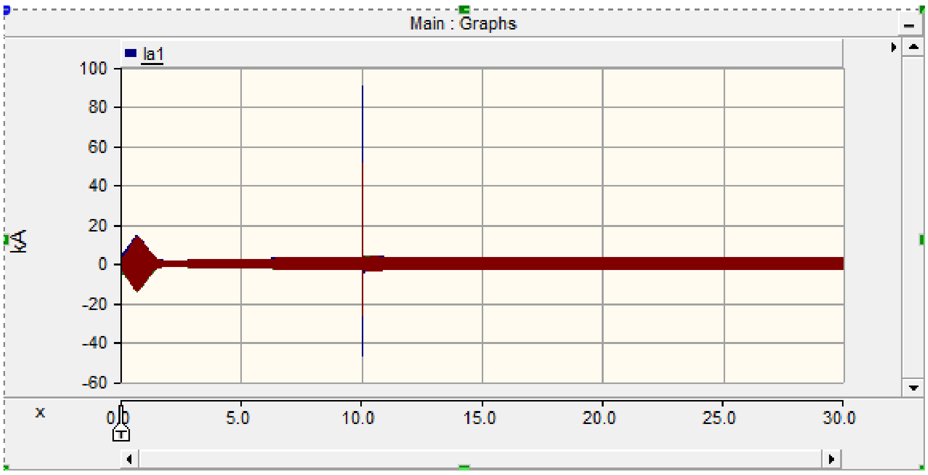


Figure 4.13: Three phase to ground fault(LLL-G) at bus-1

Figure 4.13 shows the three phase to ground (LLL-G) fault near machine-3. Fault current is 88.9988 kA as shown in the figure. Three phase to ground fault is more severe compare to two phase to ground fault. Thus a stable value is achieved depending on the system dynamics based on generation and load connected.

Table 4.5: Fault current at Synchronous generator-1

Types of faults	Fault current (kA)
L-G	47.67856
LL-G	85.25911
LLL-G	90.47033
LL	31.14049
LLL	38.550799

Fault Created at Bus-4

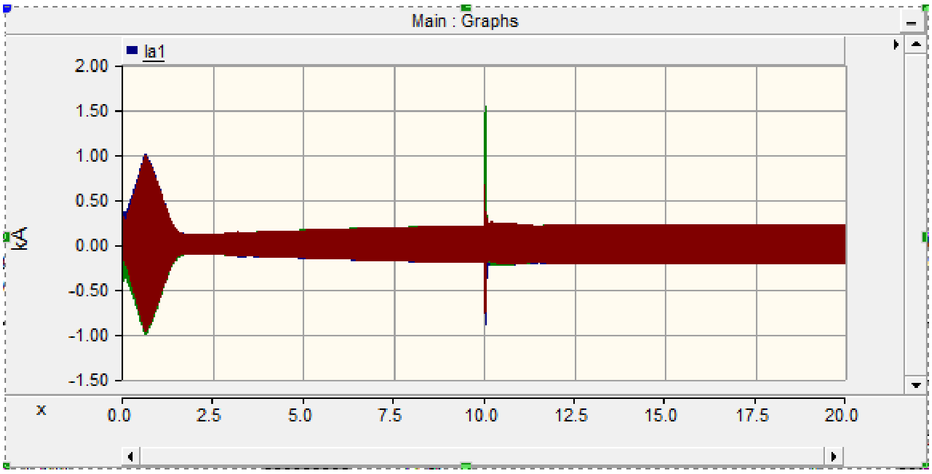


Figure 4.14: Phase to ground fault(L-G) at bus-4

Figure 4.14 shows the line to ground (L-G) fault at bus-4 which creates 1.54 kA fault current. System became stable after 12 sec.

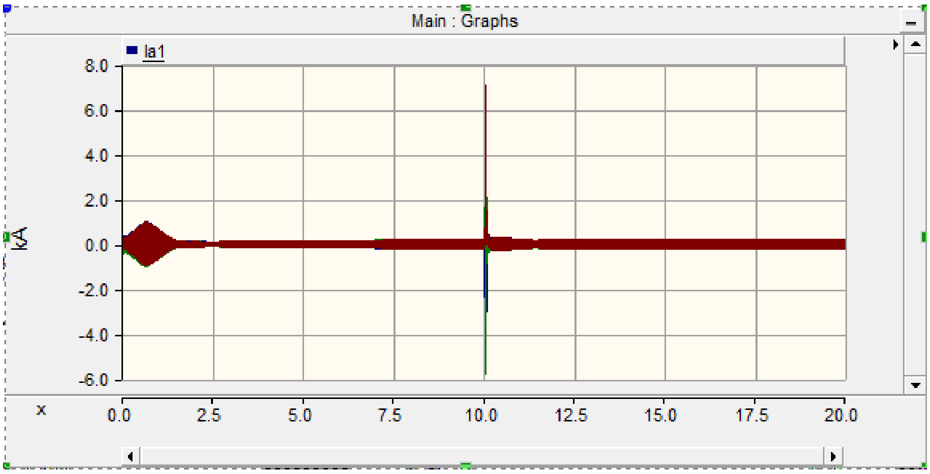


Figure 4.15: Three phase to ground fault (LLL-G) at bus-4

Figure 4.15 shows the three phases to ground (LLL-G) fault at bus-4. Magnitude of Fault current is 7.10136 kA as shown in the graph. Three phase to ground fault is most severe than other faults. Stable value is achieved depending on the system dynamics based on generation and load connected. System became stable after 11.3 sec.

Table 4.6: Fault current at bus-4

Types of faults	Fault current (kA)
L-G	1.5390
LL-G	4.15171
LLL-G	7.10136
LL	3.4171
LLL	3.7821

Fault Created at Load-1 Side

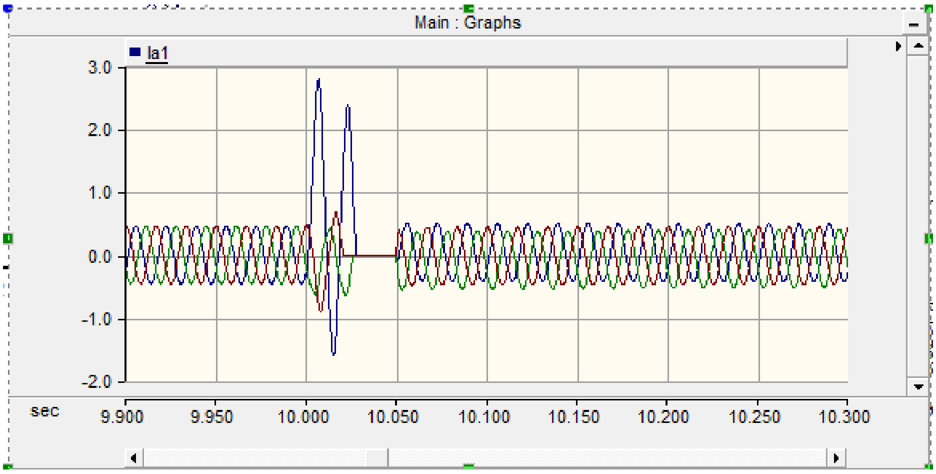


Figure 4.16: Phase to ground fault(L-G) at load-1

Figure 4.16shows the phase to ground (L-G) fault at load-1 side which creates 2.7928 kA fault current. When fault is clear from the system it will try to regain equilibrium position. System became stable at 11.3 sec.

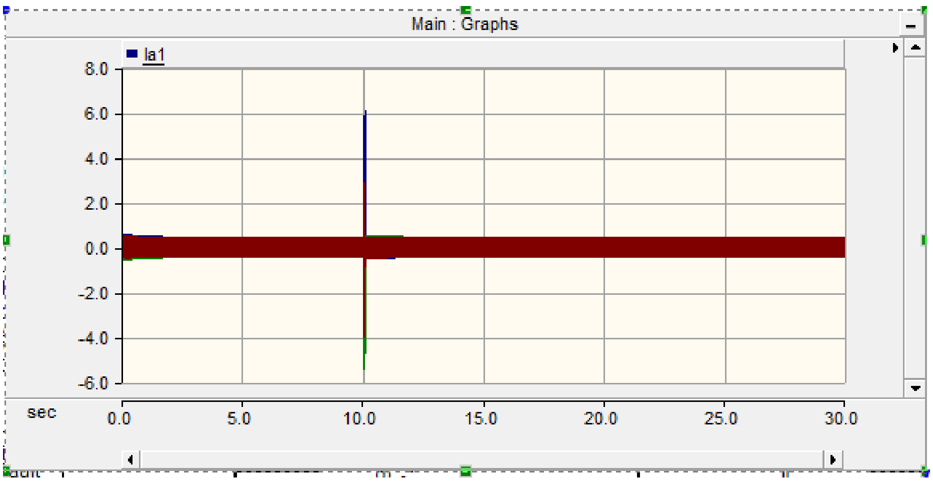


Figure 4.17: Three phase to ground fault(LLL-G) at load-1

Figure 4.17 shows the three phases to ground (LLL-G) fault at load-1 side. Magnitude of Fault current is 6.0604 kA as shown in the graph. Three phase to ground fault is most severe than other faults. Stable value is achieved depending on the system dynamics based on generation and load connected. System became stable after 11.3 sec.

Table 4.7: Fault current at load-1 side

Types of faults	Fault current (kA)
L-G	2.79283
LL-G	5.72577
LLL-G	6.06036
LL	2.00209
LLL	2.27964

4.2.1 Effect of Line Length in Fault Current

In WSCC 9-bus system line connected between bus 7-8 is increased by 10 km. Impedance is increased due to increase in line length so, the Fault current is reduced. That comparison is shown in table.

Table 4.8: Comparison of fault current with line length of 10km at machine-1

Types of faults	Fault current(kA) with 1km line	Fault current(kA) with 10km line
L-G	47.67856	35.4752
LL-G	85.25911	77.6292
LLL-G	90.47033	79.0176
LL	31.14049	22.35143
LLL	38.550799	26.85412

Table 4.9: Comparison of fault current with line length of 10km at machine-2

Types of faults	Fault current(kA) with 1km line	Fault current(kA) with 10km line
L-G	34.35706	25.2544
LL-G	85.40431	64.2135
LLL-G	88.99880	66.8234
LL	43.41779	35.462
LLL	46.7723	38.825

Table 4.10: Comparison of fault current with line length of 10km at machine-3

Types of faults	Fault current(kA) with 1km line	Fault current(kA) with 10km line
L-G	45.76387	29.256
LL-G	62.7946	45.235
LLL-G	71.0924	52.023
LL	35.5921	21.594
LLL	47.6911	33.436

Table 4.11: Comparison of fault current with line length of 10km at bus-4

Types of faults	Fault current(kA) with 1km line	Fault current(kA) with 10km line
L-G	1.5390	1.02569
LL-G	4.15171	2.5672
LLL-G	7.10136	4.2519
LL	3.4171	2.1009
LLL	3.7821	2.2183

Table 4.12: Comparison of fault current with line length of 10km at load-1 side

Types of faults	Fault current(kA) with 1km line	Fault current(kA) with 10km line
L-G	2.79283	1.95489
LL-G	5.72577	2.8764
LLL-G	6.06036	3.1240
LL	2.00209	1.4921
LLL	2.27964	1.7826

As shown in above tables fault current is reducing by increasing the line length. As the line length increases the reactance of a line will increase that will reduce the fault current. At different locations the effects of a change in current magnitude is different.

4.3 Summary

This chapter includes the simulation results of the WSCC 3 machines 9 bus system under steady-state condition. Also fault analysis at different locations in the standard test system has been done. Further, effect of line length in fault current has been discussed.

Chapter 5

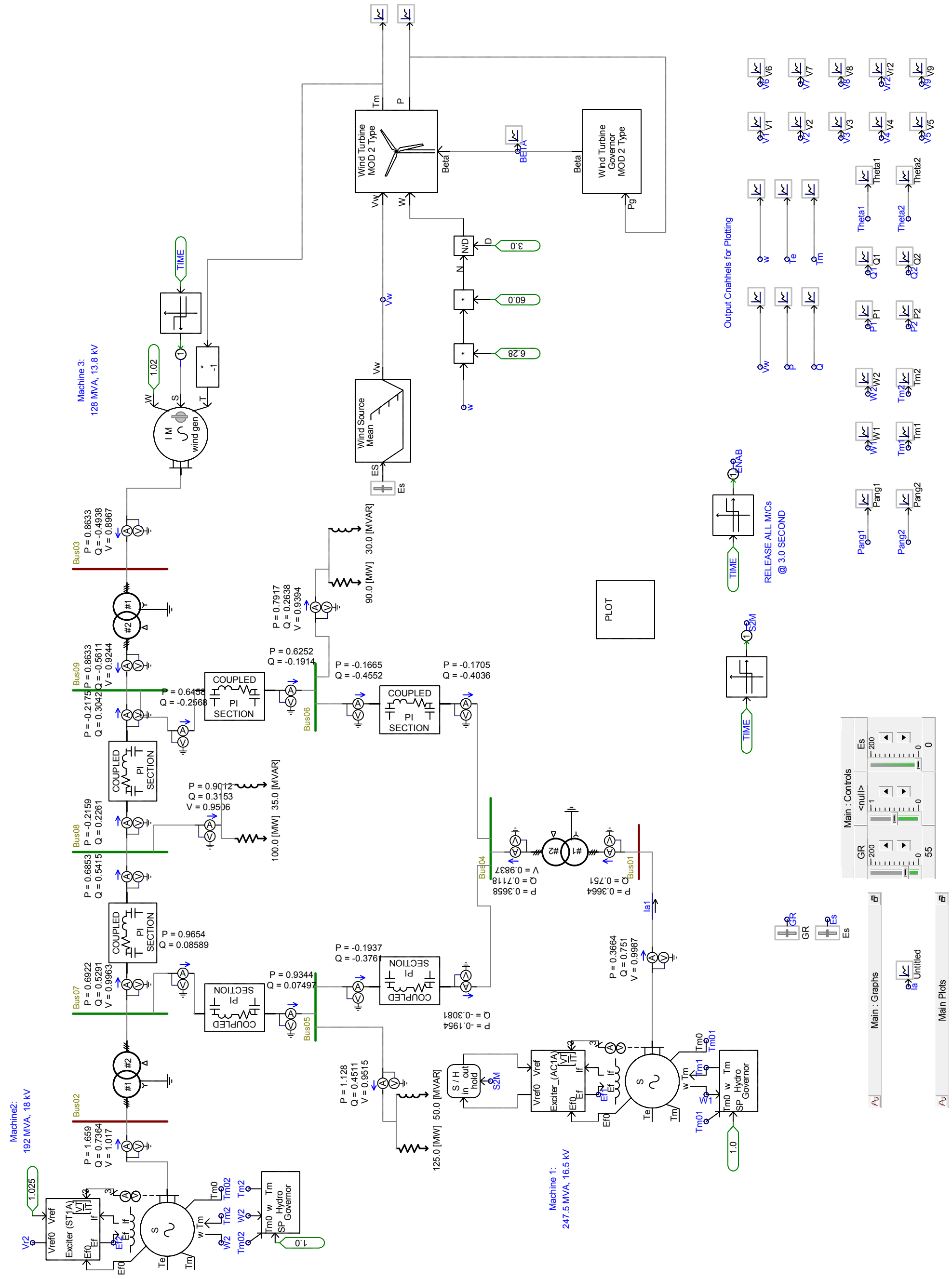
Simulation Results of 9-Bus System with Wind Integration

5.1 9-Bus System with Wind Integration

To analyze the stability and dynamic behavior of a system, wind model is integrated in the WSCC 9-bus system. This system is simulated using PSCAD/EMTDC software. The discussion in the report is based on the outcome in PSCAD.
Specification of wind model

Table 5.1: Wind data

Rated RMS phase voltage	8.08 kV
Rated RMS phase current	4.123 kA
Rated frequency	60 Hz
Rated MVA	128
Angular speed	376.99 rad/sec


Machine2:
192 MVA, 18 kV
Machine 1:
247.5 MVA, 16.5 kV
Machine 3:
128 MVA, 13.8 kV
Bus02
Bus07
Bus08
Bus09
Bus03
Bus05
Bus06
Bus04
Bus01
COUPLED
PI
SECTION
Exciter (ST1A)
Exciter_(AC1A)
Hydro
Governor
Wind Source
Mean
Wind Turbine
MOD 2 Type
Wind Turbine
Governor
MOD 2 Type
Output Channels for Plotting
RELEASE ALL M/Cs
@ 3.0 SECOND
PLOT
Main : Controls
Main : Graphs
Main Plots
125.0 [MW] 50.0 [MVAR]
100.0 [MW] 35.0 [MVAR]
90.0 [MW] 30.0 [MVAR]
P = 1.659
Q = 0.7364
V = 1.017
P = 0.3664
Q = 0.751
V = 0.9987
P = 0.8633
Q = -0.4938
V = 0.8967

5.1.1 Results Obtained

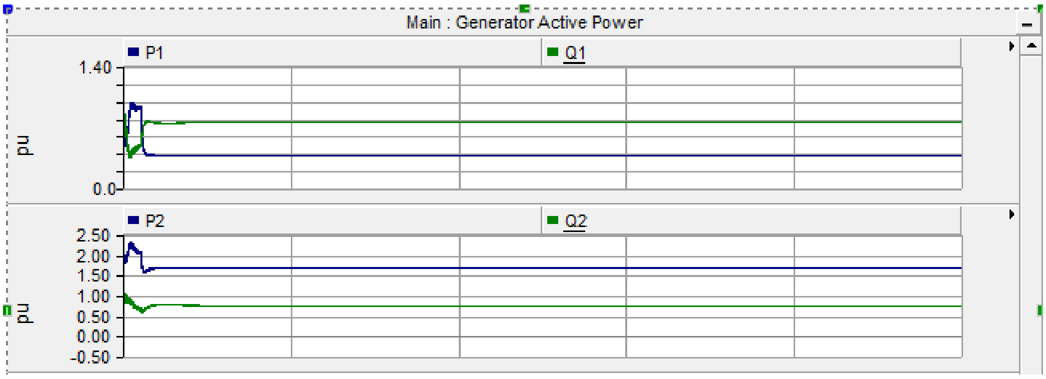


Figure 5.2: Active and Reactive Power of wind generator

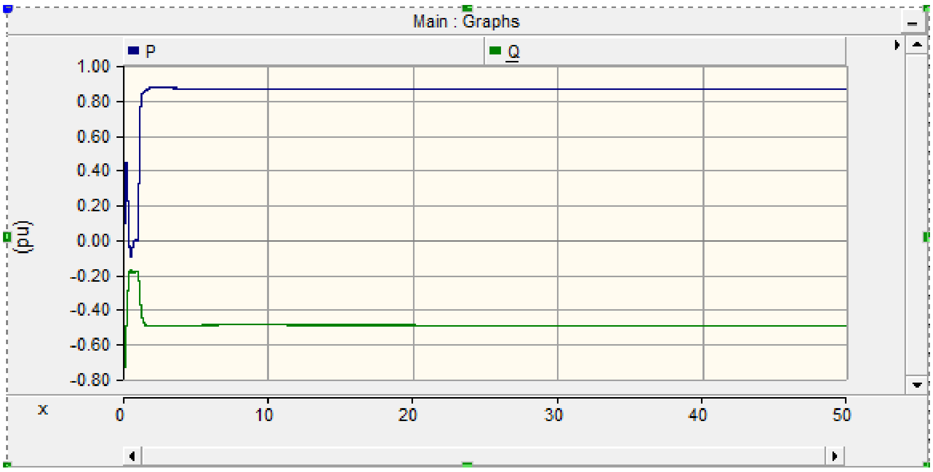


Figure 5.3: Active and Reactive Power of generator 1 and 2

Figure 5.2 shows P1, P2,Q1, Q2 are the active and reactive powers of the machine 1, 2 and figure 5.2 shows the active and reactive powers of the wind generator. Reactive power of wind generator is drawn from the system shown in figure. It can be seen from the results that active and reactive power of three of the machines are becoming stable after certain period of time, the power values are satisfactory.

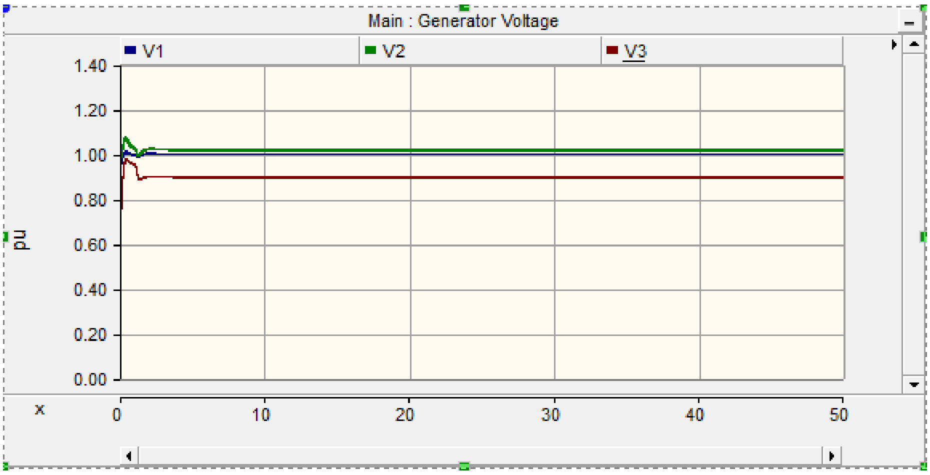


Figure 5.4: Voltages of generator 1, 2 and 3

Here in figure 5.4 the voltages of generator 1, 2 and 3 are shown in per unit. Wind is connected at bus-3. Voltages are in steady state condition as shown in figure.

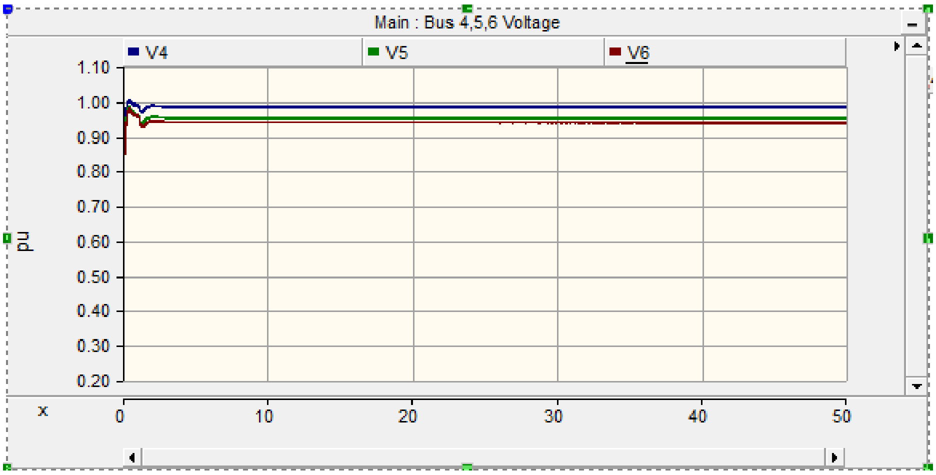


Figure 5.5: Voltages at bus 4, 5 and 6

Figure 5.5 shows the voltages of buses 4, 5 and 6 in steady state condition (pu).Values are near 0.40pu. Voltages are in steady state after few seconds (3s).

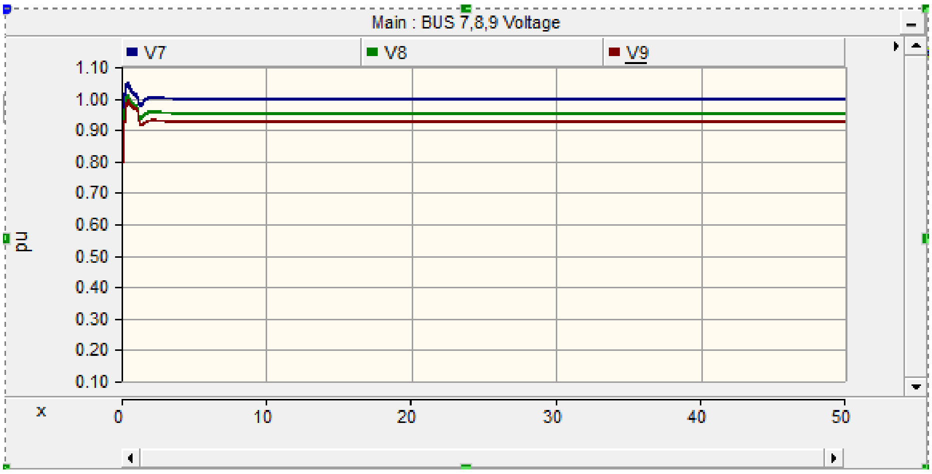


Figure 5.6: Voltages at bus 7, 8 and 9

Figure 5.6 shows the voltages of bus 7, 8 and 9 in pu, which is in steady state. Values are near 0.34 pu. Voltages are in steady state after few seconds (3s).

The comparison of actual simulated with conventional case and simulated with wind actual results of voltages and power after the wind model is integrated.

Table 5.2: Comparison of the voltages

Bus number	Actual voltages	Simulated with 9-bus	Simulated with wind
1	1.04	0.9986	0.9987
2	1.025	1.017	1.017
3	1.025	1.002	0.8967
4	1.026	0.9913	0.9837
5	0.996	0.9615	0.9515
6	1.013	0.9715	0.9394
7	1.026	1.009	0.9963
8	1.016	0.9891	0.9506
9	1.032	1.002	0.9244

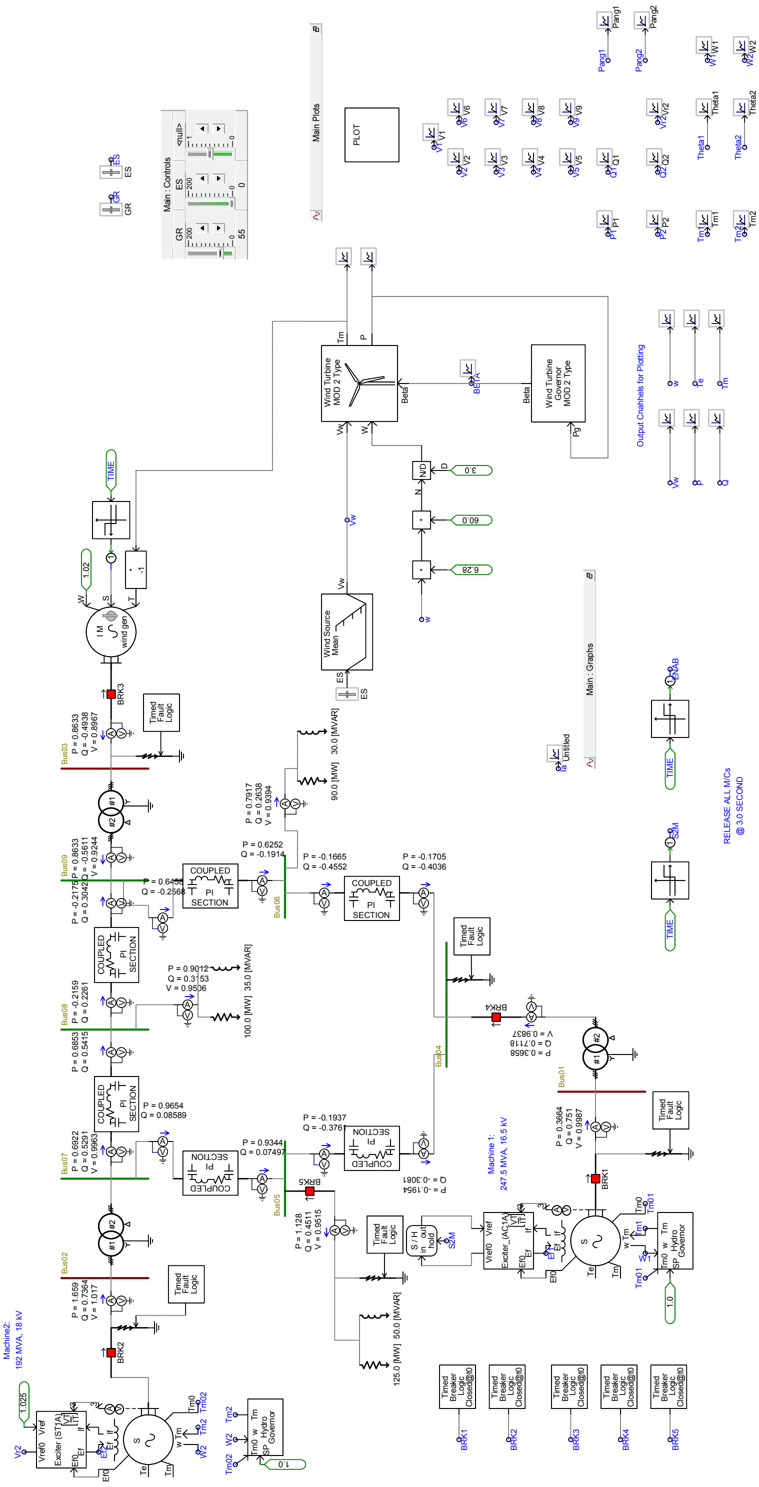
Table 5.3: Comparison of the active power

Bus	Actual P	Simulated with 9-bus	Simulated with wind
1	0.716	0.5346	0.3664
2	1.63	1.617	1.659
3	0.85	0.8713	0.8633

Table 5.4: Comparison of the reactive power

Bus	Actual Q	Simulated with 9-bus	Simulated with wind
1	0.27	0.4367	0.751
2	0.067	0.3741	0.7364
3	-0.109	0.06859	-0.4938

5.2 Fault Analysis of 9-Bus System with Wind Integration



Fault Created near Wind Generator at Bus-3

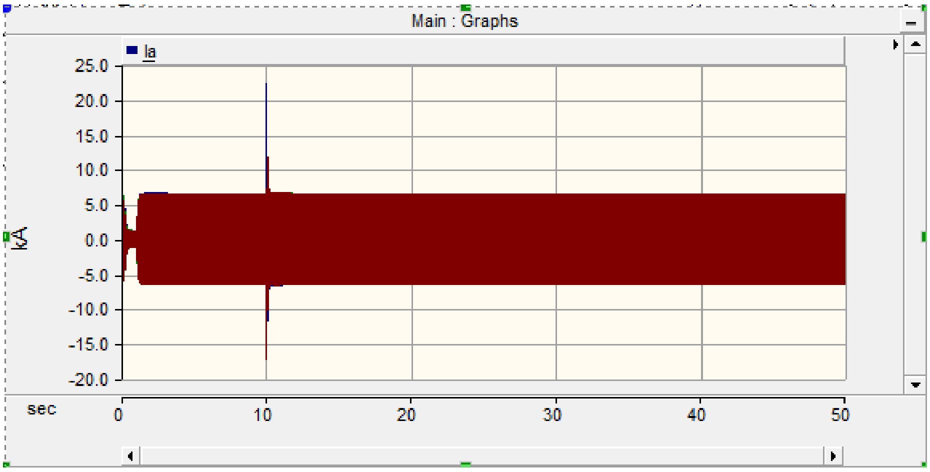


Figure 5.8: Phase to ground fault(L-G) at bus-3

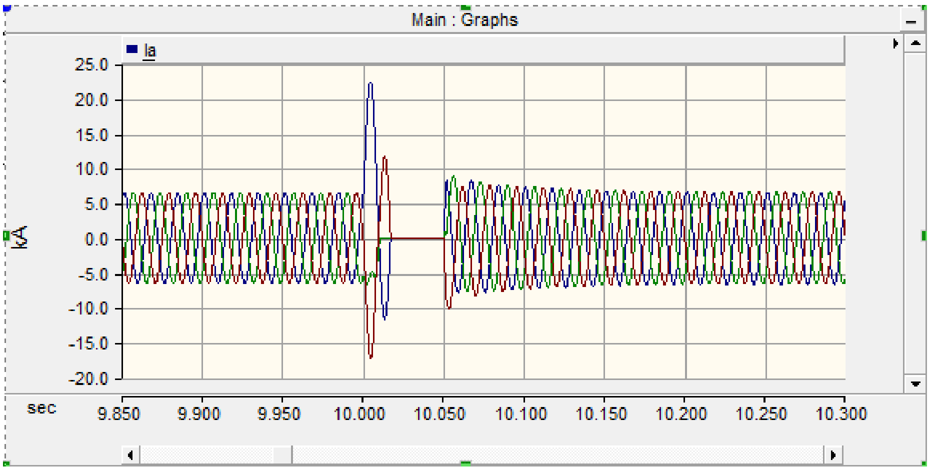


Figure 5.9: Zoomed view of phase to ground fault(L-G) at bus-3

Figures 5.8and 5.9 show the phase to ground (L-G) fault near wind farm. Fault current is 22.3351 kA as shown in the graph. System became stable after 12.0 sec. Thus the stable value of current is achieved.

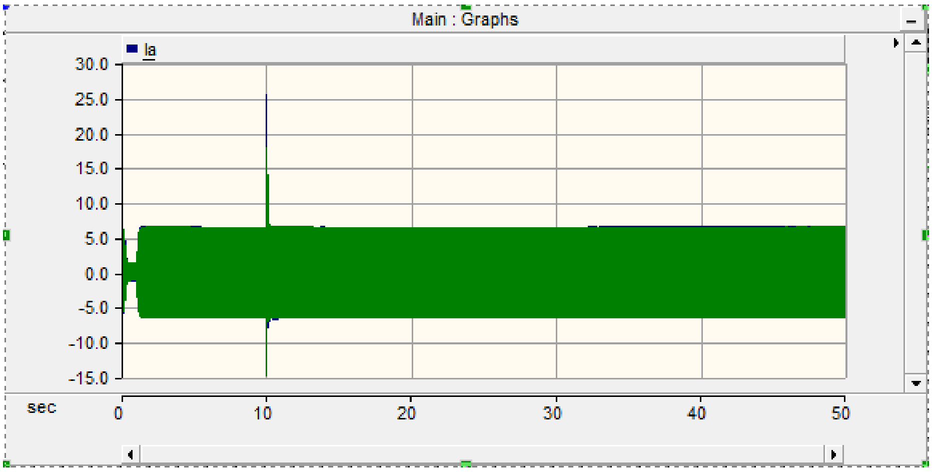


Figure 5.10: Three phase to ground fault(LLL-G) at bus-3

Figure 5.10 shows the three phase to ground (LLL-G) fault near wind farm. Fault current is 25.3445 kA as shown in the figure. Three phase to ground fault is more severe compare to two phase to ground fault. Thus a stable value is achieved depending on the system dynamics based on generation and load connected.

Table 5.5: Fault current at bus-3

Types of faults	Fault current(kA) in WSCC system	Fault current with wind
L-G	45.76387	22.3351
LL-G	62.7946	23.2895
LLL-G	71.0924	25.3445
LL	35.5921	22.57035
LLL	47.6911	26.3237

Fault Created near Synchronous Generator at Bus-2

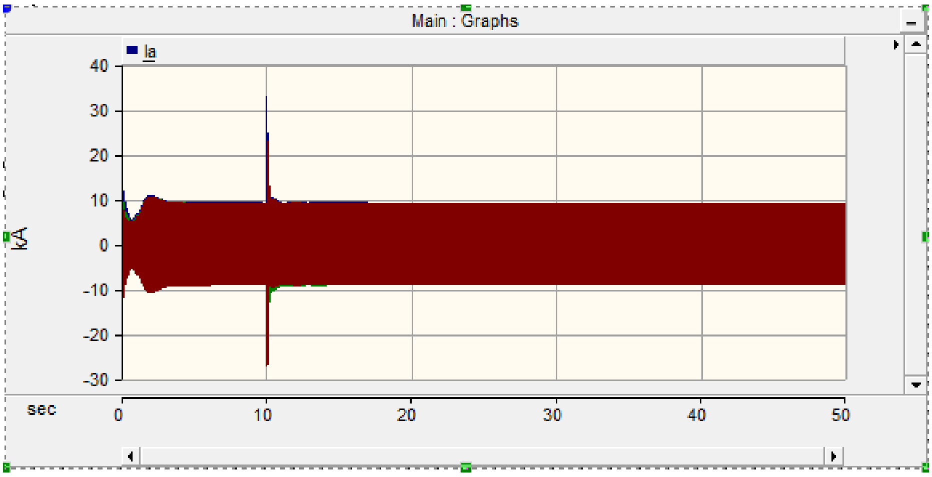


Figure 5.11: Three phase to ground fault(L-G) at bus-2

Figure 5.11 show the phase to ground (L-G) fault near machine-2. Fault current is 32.7979 kA as shown in the graph. System became stable after 16 sec. Thus the stable value of current is achieved.

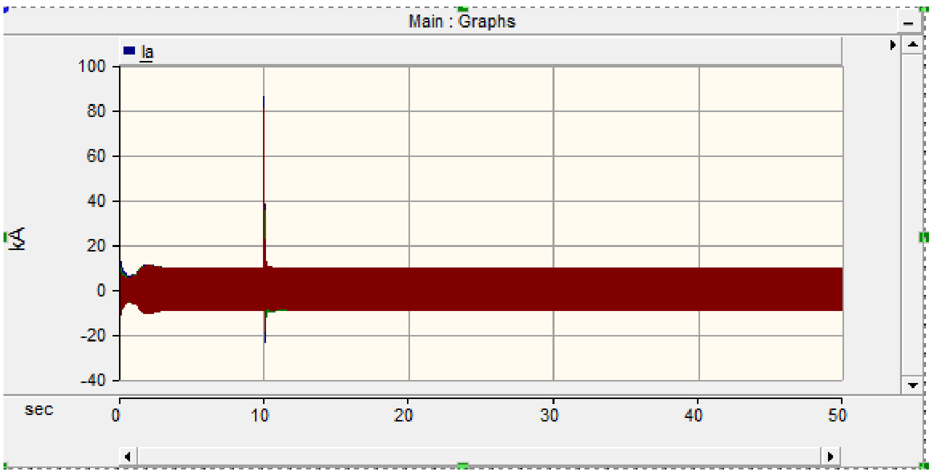


Figure 5.12: Three phase to ground fault(LLL-G) at bus-2

Figure 5.12 shows the three phase to ground (LLL-G) fault near machine-2. Fault current is 85.852248 kA as shown in the figure. Three phase to ground fault is more severe compare to two phase to ground fault. Thus a stable value is achieved depending on the system dynamics based on generation and load connected.

Table 5.6: Fault current at Synchronous generator-2

Types of faults	Fault current(kA) in WSCC system	Fault current with wind
L-G	34.35706	32.7979
LL-G	85.40431	83.3952
LLL-G	88.99880	85.852248
LL	43.41779	33.9340
LLL	46.7723	37.27566

Fault Created near Synchronous Generator at Bus-1

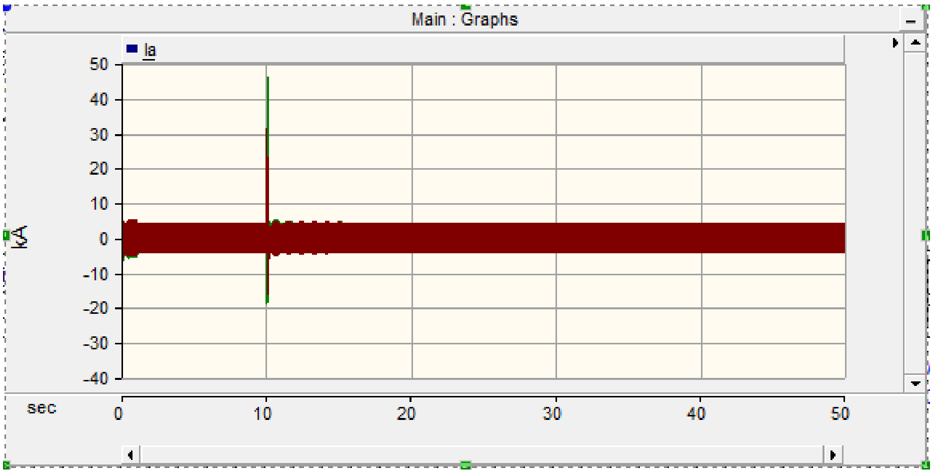


Figure 5.13: Phase to ground fault(L-G) at bus-1

Figure 5.13 shows the phase to ground (L-G) fault near machine-1 which creates 45.98733 kA fault current.

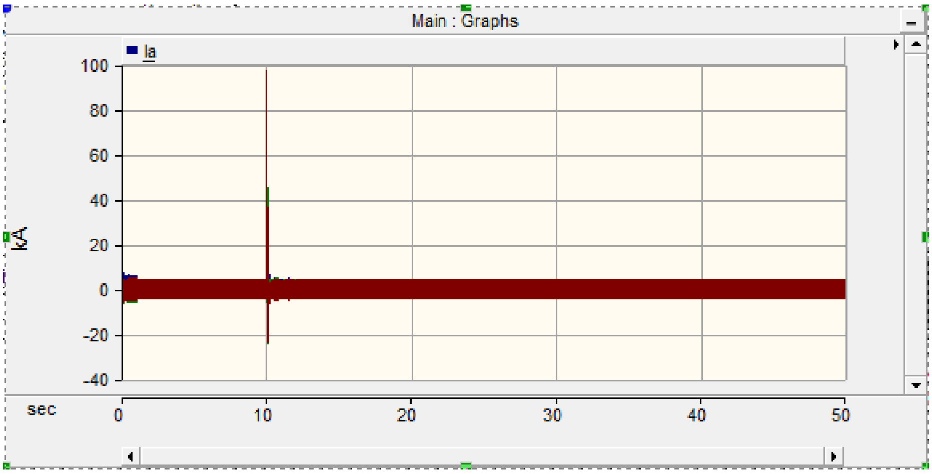


Figure 5.14: Three phase to ground fault(LLL-G) at bus-1

Figure 5.14 shows the three phase to ground (LLL-G) fault near machine-1. Fault current is 97.34455 kA as shown in the figure. Three phase to ground fault is more severe compare to two phase to ground fault. Thus a stable value is achieved depending on the system dynamics based on generation and load connected.

Table 5.7: Fault current at Synchronous generator-1

Types of faults	Fault current(kA) in WSCC system	Fault current with wind
L-G	47.67856	45.98733
LL-G	85.25911	80.83139
LLL-G	90.47033	97.34455
LL	31.14049	18.97533
LLL	38.550799	26.9696

Fault Created at Bus-4

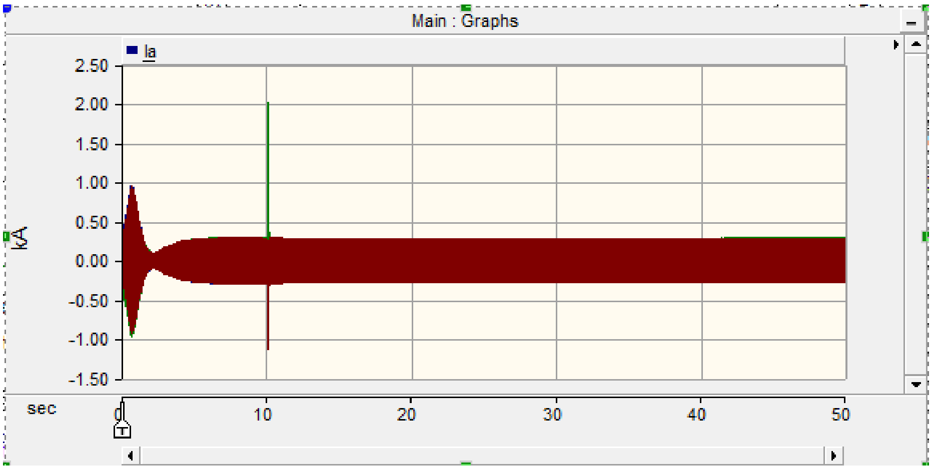


Figure 5.15: Phase to ground fault(L-G) at bus-4

Figure 5.15 shows the phase to ground (L-G) fault at bus-4 which creates 2.01906 kA fault current.

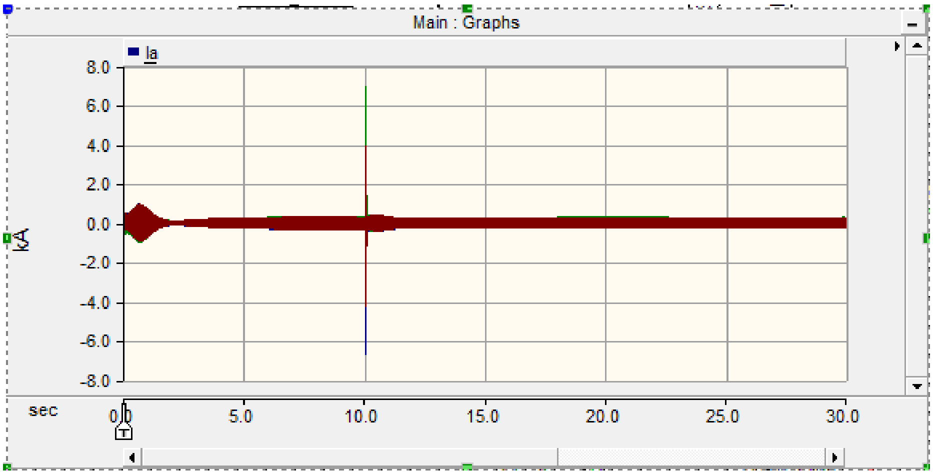


Figure 5.16: Three phase to ground fault(LLL-G) at bus-4

Figure 5.16 shows the three phase to ground (LLL-G) fault at bus-4. Fault current is 6.88998 kA as shown in the figure. Three phase to ground fault is more severe compare to two phase to ground fault. Thus a stable value is achieved depending on the system dynamics based on generation and load connected.

Table 5.8: Fault current at bus-4

Types of faults	Fault current(kA) in WSCC system	Fault current with wind
L-G	1.5390	2.01906
LL-G	4.15171	5.46264
LLL-G	7.10136	6.88998
LL	3.4171	6.21515
LLL	3.7821	7.19330

Fault Created at Load-1

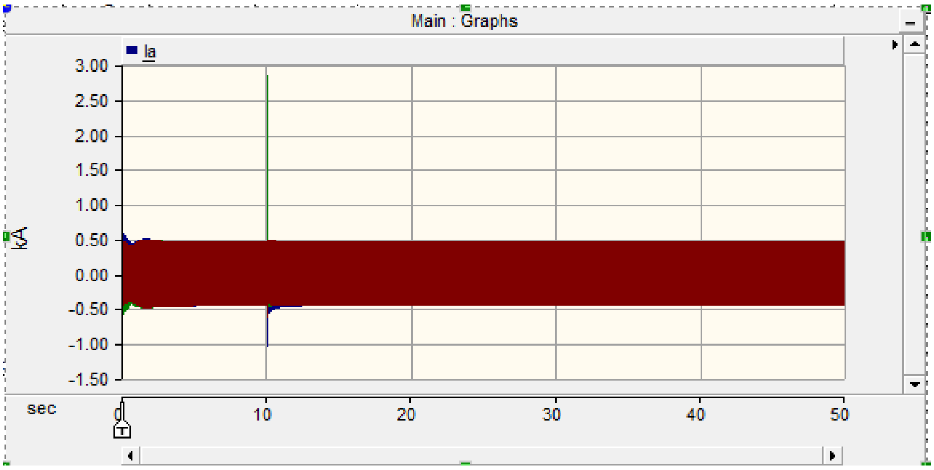


Figure 5.17: Phase to ground fault(L-G) at load-1

Figure 5.17 shows the phase to ground (L-G) fault at load-1 side which creates 2.83452 kA fault current. When fault is clear from the system it will try to regain equilibrium position. System became stable at 11.2 sec.

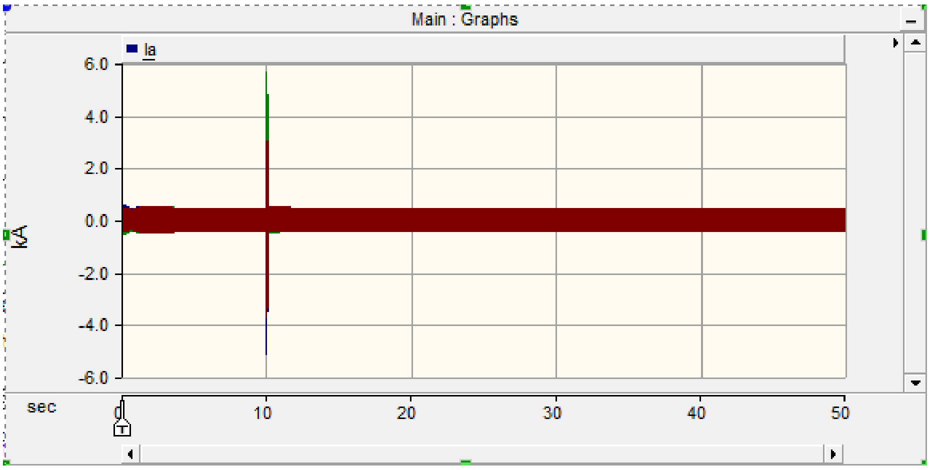


Figure 5.18: Three phase to ground fault(LLL-G) at load-1

Figure 5.18 shows the three phase to ground (LLL-G) fault at load-1 side. Fault current is 5.65186 kA as shown in the figure. Three phase to ground fault is more severe compare to two phase to ground fault. Thus a stable value is achieved depending on the system dynamics based on generation and load connected.

Table 5.9: Fault current at load-1 side

Types of faults	Fault current(kA) in WSCC system	Fault current with wind
L-G	2.79283	2.83452
LL-G	5.72577	5.05534
LLL-G	6.06036	5.65186
LL	2.00209	4.5321
LLL	2.27964	5.652737

5.2.1 Effect of Line Length in Fault Current

In WSCC 9-bus system line connected between bus 7-8 is increased by 10 km. Impedance is increased due to increase in line length so, the Fault current is reduced. That comparison is shown in table.

Table 5.10: Comparison of fault current with line length of 10km at machine-1

Types of faults	Fault current(kA) with 1km line	Fault current(kA) with 10km line
L-G	45.98733	33.2589
LL-G	80.83139	70.2985
LLL-G	97.34455	82.5679
LL	18.97533	11.0127
LLL	26.9696	18.9825

Table 5.11: Comparison of fault current with line length of 10km at machine-2

Types of faults	Fault current(kA) with 1km line	Fault current(kA) with 10km line
L-G	32.7979	21.5723
LL-G	83.3952	71.2389
LLL-G	85.852248	73.9822
LL	33.9340	22.0125
LLL	37.27566	25.3245

Table 5.12: Comparison of fault current with line length of 10km at machine-3

Types of faults	Fault current(kA) with 1km line	Fault current(kA) with 10km line
L-G	22.3351	10.9852
LL-G	23.2895	11.8547
LLL-G	25.3445	13.5629
LL	22.57035	11.0215
LLL	26.3237	14.4921

Table 5.13: Comparison of fault current with line length of 10km at bus-4

Types of faults	Fault current(kA) with 1km line	Fault current(kA) with 10km line
L-G	2.01906	1.5224
LL-G	5.46264	2.5462
LLL-G	6.88998	3.9572
LL	6.21515	3.4398
LLL	7.19330	4.3524

Table 5.14: Comparison of fault current with line length of 10km at load-1 side

Types of faults	Fault current(kA) with 1km line	Fault current(kA) with 10km line
L-G	2.83452	1.9542
LL-G	5.05534	2.2019
LLL-G	5.65186	2.7207
LL	4.53212	2.0231
LLL	5.65274	2.7295

As shown in above tables fault current is reducing by increasing the line length. At different locations the effects of a change in current magnitude is different. As the line length increases the reactance of a line will increase that will reduce the fault current.

5.2.2 Effect of Speed Variation of Wind in Fault Current

Wind speed is the variable parameter with respect to time. It depends on the location of the farm. Moreover wind power is proportional to the cubic wind speed. Here for the comparison two different wind speed is chosen. Wind speed variation should be considered for accurate short-circuit study.

Table 5.15: Comparison of fault current at bus-2 with variation of wind speed

Types of faults	Fault current(kA) with 10m/s	Fault current(kA) with 4m/s	Fault current(kA) with 20m/s
L-G	22.3351	21.2548	25.3648
LL-G	23.2895	22.0125	26.5811
LLL-G	25.3445	24.5689	28.2571
LL	22.5704	21.6028	25.8722
LLL	26.3237	25.2145	29.2570

The fault current is changing by changing the wind speed as shown in table. It will increase if speed will be more and vice-versa.

Table 5.16: Comparison of fault current at bus-2 with variation of wind speed

Types of faults	Fault current(kA) with 10m/s	Fault current(kA) with 4m/s	Fault current(kA) with 20m/s
L-G	32.7979	31.3582	34.5278
LL-G	83.3952	82.5641	85.4791
LLL-G	85.852248	84.6218	87.2149
LL	33.9340	32.4413	35.9214
LLL	37.27566	36.2713	39.5472

Table 5.17: Comparison of fault current at bus-1 with variation of wind speed

Types of faults	Fault current(kA) with 10m/s	Fault current(kA) with 4m/s	Fault current(kA) with 20m/s
L-G	45.98733	45.4248	46.2105
LL-G	80.83139	80.3547	81.0254
LLL-G	97.34455	96.8245	97.9981
LL	18.97533	18.5288	20.1299
LLL	26.9696	26.6326	27.9845

Table 5.18: Comparison of fault current at bus-4 with variation of wind speed

Types of faults	Fault current(kA) with 10m/s	Fault current(kA) with 4m/s	Fault current(kA) with 20m/s
L-G	2.01906	1.82325	2.4214
LL-G	5.46264	5.21348	5.8246
LLL-G	6.88998	6.62115	7.2164
LL	6.21515	6.01234	6.6282
LLL	7.19330	6.90127	7.5210

Table 5.19: Comparison of fault current at load side-1 with variation of wind speed

Types of faults	Fault current(kA) with 10m/s	Fault current(kA) with 4m/s	Fault current(kA) with 20m/s
L-G	2.83452	2.73214	2.89921
LL-G	5.05534	4.92375	5.12482
LLL-G	5.65186	5.51472	5.75814
LL	4.5321	4.48674	4.62178
LLL	5.652737	5.45278	5.70213

As shown in table the fault current magnitude is increased as the wind speed is increased and vice-versa. The variation in magnitude of the fault current with respect to wind speed is less compare fault current at bus-3.

5.3 Summary

This chapter includes the simulation results of the 9 bus system when one of the synchronous generator is replaced by a wind source. It also includes the results of fault analysis at different locations in the same system. Effect of line length in fault current and speed variation in wind generation has been discussed. If the speed of the wind farm increases the fault current will increase and vice-versa.

Chapter 6

Conclusion And Future Scope

6.1 Conclusion

For the understanding of dynamic and transient behaviour of a system, the WSCC 3-machine 9-bus system has been used as the standard test bus model. The steady state analysis of the system has been carried out in PSCAD/EMTDC and the results are compared with the load flow results mentioned in reference [15] which indicates that results obtained are satisfactory. Fault analysis is carried out on the system which shows the severity of the different types of fault indicating that LLL-G fault has the highest effect on the system which may damage the different equipments in the line.

The above analysis is also carried out on a system where the 85 MW synchronous generator is replaced by a renewable energy source(wind) and the results are compare with the conventional WSCC 3-machine 9-bus system. Finally, from the work done, it can be concluded that variation of line length has a direct impact on the fault current i.e. if the line length is increased, fault current is decreased and vice-versa. Also, variation in wind speed has the significant effect on the fault current but this is reverse to the effect of the variation of line length.

6.2 Future Scope of Work

The results obtained are closely matching the desired one but extra efforts are needed to bring the exact one. Improvement options can be suggested to reduce the effect of fault current with the use of SFCL and STATCOM. Short-circuit ratio of the system can be calculated.

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Appendix A

System Data

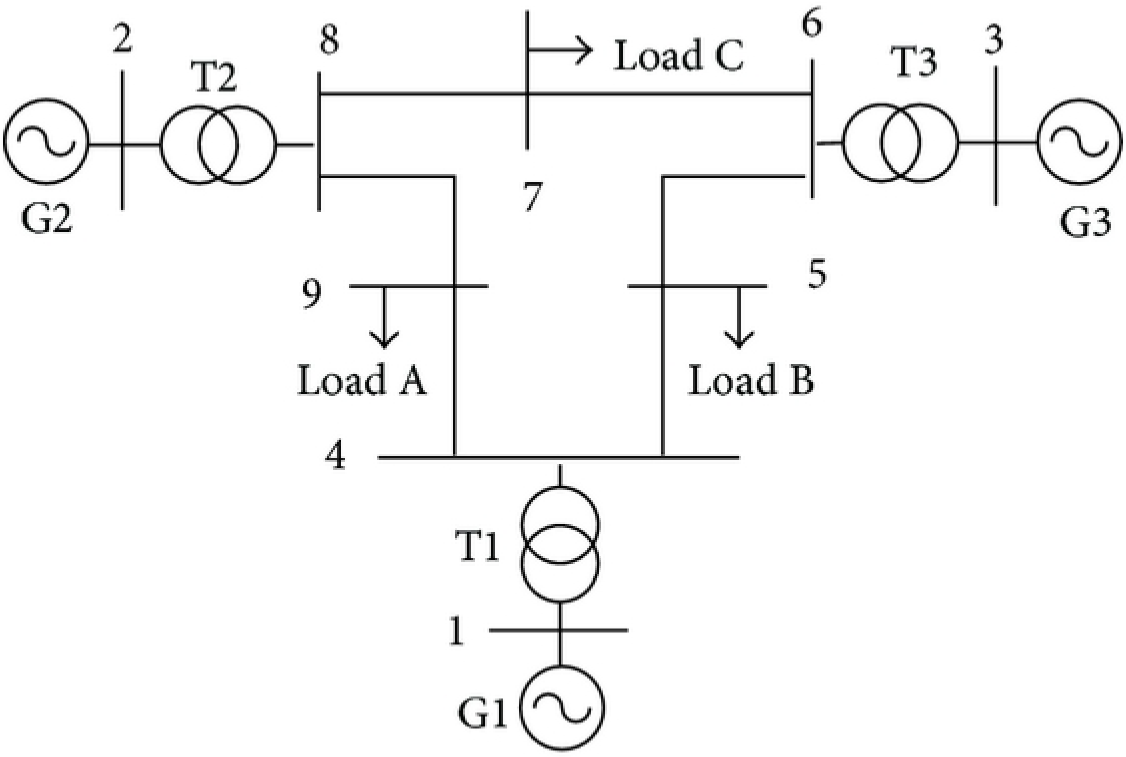

Figure A.1: WSCC 3-generators 9-bus system

Table A.1: Generator Data

Generator	1	2	3
Rated MVA	247.5	192.0	128.0
kV	16.5	18.0	13.8
Power Factor	1.0	0.85	0.85
Type	hydro	steam	steam
Speed	180r/min	3600r/min	3600r/min
x_d	0.1460	0.8958	1.3125
x'_d	0.0608	0.1198	0.1813
x_q	0.0969	0.8645	1.2578
x'_q	0.0969	0.1969	0.25
x_l(leakage)	0.0336	0.0521	0.0742
T'_{do}	8.96	6.00	5.89
T'_{qo}	0	0.535	0.600

Table A.2: Load Data

Load connected to bus	P(MW)	Q(MW)
5	125	50
6	90	30
8	100	35