LVRT Capability Enhancement of DFIG Wind Turbines

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By

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CERTIFICATE

This is to certify that the Major Project Report entitled **"LVRT Capability Enhancement of DFIG Wind Turbines"** submitted by **Mr. Parashar Thaker (15MEEE27)** 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.
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With immense pleasure, I would like to present this report on "LVRT Capability Enhancement of DFIG Wind Turbines". I am very thankful to all those who helped me for providing valuable guidance throughout the project work. It is a pleasant aspect that I have now the opportunity to express my gratitude towards them.

I would like to express my immense gratitude to Prof. C. R. Mehta (Assistant Professor, Department of Electrical Engineering, Institute of Technology, Nirma University, Ahmedabad) for his valuable guidance, motivation and encouragement throughout my preface of project. His constant support and interest equipped me with a great understanding of different aspects. His supervision and direction right from beginning motivate me to complete this period of project.

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Abstract

In an electrical power systems, low-voltage ride through (LVRT) is the ability of electric generators to stay connected in short periods of voltage dip under any abnormal situation. The usage of renewable sources are increasing with the advancement in technology and depletion of fossil fuels. So, because of that interest in wind energy sources are increased in which Doubly-fed Induction Generator (DFIG) is gaining prime importance. DFIG has mainly Low Voltage Ride-Through problem. The literature survey proposes various LVRT techniques like additional protection circuits installation to limit generated rotor over-current and undesirable dc-link over-voltage during grid disturbances. It also utilizes reactive power injecting-devices installation to surpass any deficiency of reactive power so as to improve the transient performance of DFIG.

The standard test system of WSSC 9-bus is studied by replacing one of the synchronous machine by Type-III wind turbine and the results for the LVRT capability of wind turbine have been analyzed. Various techniques to improvise the LVRT capability have been suggested based on the results obtained.

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Chapter 1

Introduction

1.1 General

As conventional energy source consumption is increasing, environmental issues are also increasing. So because of that interest in technology for generating electricity from renewable sources such as wind energy, solar energy, geothermal energy, etc are increased. As wind energy is considered to be non-polluting and economically viable, it is one of the most important renewable energy sources all over the world.

An increasing number of power system operators have implemented technical standards known as grid codes that wind turbines must meet when connecting to the grid. On the basis of technical specifications, the grid code requirements are two types: static and dynamic requirements. The static requirements discuss the steady state behavior and power flow at the point of common coupling, while the dynamic requirements discuss desired wind turbine generator behavior during fault periods. These requirements cover many topics such as voltage operating range, power factor regulation, and frequency operating range, grid support capability, and low-voltage ride-through (LVRT) capability. The biggest problem in WT design and manufacturing technology is to enhance LVRT capability. LVRT requires WTs to remain connected to the grid also in voltage dip condition.

1.2 Problem Identification

Nowadays high power WTs can run at any speed with adjustment. WTs use either single-fed induction generator (SFIG) or doubly-fed induction generator (DFIG) systems. DFIG based WTs are mostly used in wind power industry as its capability of maximizing energy capture during variable wind condition. They are also controlling active and reactive power for better grid operation. But DFIG still faces problems related to voltage sag and try to enhance an ability of LVRT.

1.3 Objective

The objective of this project is to provide a comprehensive study and analysis of LVRT capability enhancement of DFIG wind turbines. SMIB system and WSSC 9-bus system considered for the case study. Different techniques like crowbar protection and reactive power injecting device STATCOM to enhance LVRT are compare with each other in WSSC 9-bus system.

1.4 Methodology

Various LVRT enhancement techniques :

- Additional protection circuits placement.
- Reactive power injecting-devices installation.

Chapter 2

Literature Survey

(1) Yazan M. Alsmadi, Longya Xu, Frede Blaabjerg, Alejandro Pina Ortega, Aimeng Wang, "Comprehensive analysis of the Dynamic Behavior of Grid-connected DFIG-based Wind turbines under LVRT conditions," IEEE 2015 [3].

- In this paper, the study of LVRT is taken on grid-connected DFIG based WTs. During symmetrical and asymmetrical grid voltage sags, the dynamic behavior of DFIGs and transient characteristics are investigated.
- In the area of power and energy, two basic issues are of special concern: (i) control of active and reactive power in normal conditions and (ii) enhancement of LVRT during voltage dip conditions.

(2) Omar Abdel-Baqi, Adel Nasiri, "A Dynamic LVRT Solution for Doubly Fed Induction Generators," IEEE Transactions on Power Electronics, Vol. 25 (2010) [4].

- The rotor current of generator raises in short circuit or voltage dip condition at grid side which may cause damage to rotor converter. This paper presents design and installation of the series converter on the stator side to limit a current rise in rotor.
- An active ac/dc inverter, three series transformers, and dc-bus capacitor are included in this system. An exponential decaying sinusoidal voltage instead of pure sinusoidal voltage is applied by converter during short circuit or voltage dip condition to lower rating of the components and make system viable for practical solutions.

(3) Amirhasan Moghadasi, Arif Sarwat, Josep M. Guerrero, "A comprehensive review of low voltage ride through methods for fixed-speed wind power generators," Renewable and Sustainable Energy Reviews 55 (2016) 823-839 [1].

- A review of different techniques employed to enhance LVRT capability of fixed-speed induction generators (FSIG) based WTs are represented in this paper.
- Mainly three different approaches or structures depending on power electronic device connection configuration to enhance LVRT capability are categorize in this paper which are series, shunt and series-shunt (hybrid) connections.
- The responses of the FSIG under steady-state and transient-state condition is discussed in the paper.

(4) Jackson John Justo, Francis Mwasilu, Jin-Woo Jung, "Doubly-fed induction generator based wind turbines: A comprehensive review of fault ride-through strategies," Renewable and Sustainable Energy Reviews 45 (2015) 447-467 [5].

- A review of different types of strategies applied to enhance the LVRT capability of doubly-fed induction generators (DFIGs) based WTs during transient-state are present in this paper.
- Various LVRT techniques based on: (1) Additional protection circuit placement and installation, (2) Reactive power injecting-devices installation and (3) Decided control ways or structures have been proposed in the literature.
- The responses of the DFIG under steady-state and transient-state were extensively discussed.

(5) M. Kenan Dsoglu, "A new approach for low voltage ride through capability in DFIG based wind farm," Electrical Power and Energy systems 83 (2016) 251-258 [6].

- This paper represents the protection of DFIGs against voltage sag could be done using conventional crowbar circuits. They may be insufficient in some transient conditions. Demagnetization Current Controller (DCC) for transient analysis used for enhancement of LVRT capability.
- In addition, both stator and rotor circuit electromotive forces were modeled in a DFIG. With and without the DCC, the performances of the DFIG models were compared in paper. A comparison of system behaviors was made between three-phase faults with and without a stator-rotor dynamic.

(6) Lihui Yang, Zhao Xu, Jacob stergaard, Zhao Yang Dong, Kit Po Wong, "Advanced Control Strategy of DFIG Wind Turbines for Power System Fault Ride Through," IEEE Transactions on Power Systems, Vol. 27 (2012) [7].

- According to the grid connection requirement, this paper proposed an advanced control strategy for the rotor and grid side converters of DFIG based WTs to enhance LVRT capability.

- The proposed control strategy can absorb the additional kinetic energy during the fault conditions and significantly reduce the oscillations in the stator-rotor currents and the DC bus voltage which is the major difference from other methods.
- This method can maintain continuous active and reactive power control of DFIG during voltage dip or fault condition which differs from conventional crowbar protection.

(7) Marta Molinas, Jon Are Suul, Tore Undeland, "Low Voltage Ride Through of Wind Farms With Cage Generators: STATCOM Versus SVC," IEEE Transactions on Power Electronics, Vol. 23 (2008) [8].

- Compared to the thyristor controlled SVC, this paper analyses LVRT capability of wind farms using squirrel cage generators can be enhanced by use of an STATCOM.
- Based on torque-slip characteristics, a simplified analytical approach is proposed to quantify the effect of the STATCOM and SVC on the transient stability margin.
- STATCOM gives a large amount of contribution to the transient margin as indicated by both calculations and simulations compared to the SVC. The control strategy implemented in the STATCOM is based on the vector control principle while in SVC is based on PI controller.

(8) Luis M. Fernandez, Francisco Jurado, Jose Ramon Saenz, "Aggregated dynamic model for wind farms with doubly fed induction generator wind turbines," Renewable Energy 33 (2008) 129-140 [9].

- As wind farms penetration increasing in power systems, the wind farms start rises to impact on power system and thus modeling of wind farms has become an interesting research topic.
- A new similar model of wind farms with DFIG WTs is implicit to represent the response of the wind farm by one single similar WT, while all WTs are operated at various wind speeds.
- To represent the effectiveness of the similar model of wind farm, comparing the simulation results of equivalent and complete models during both normal condition and grid disturbances.

Chapter 3

Wind Generator Technologies

3.1 General

The wind turbine generates electrical power from winds kinetic energy [10]. There are two types of wind turbines manufactured in wide range: vertical and horizontal axis types. Arrays of large wind turbines are known as wind farms. They reduced the use of conventional energy sources and also important source of renewable energy. A quantitative measure of wind energy available at any location is called as Wind Power Density (WPD). It calculates mean annual power available per square meter of swept area of a turbine and is tabulated for different heights above ground.

3.2 Wind Turbine Types

Types: Wind turbines can rotate about either a horizontal or a vertical axis. They can also include blades (transparent or not) or be blade-less.

3.2.1 Horizontal axis

Figure 3.1: Horizontal-axis Wind Turbine

Horizontal axis WT (HAWT) has main rotor shaft and electrical generator at top of tower and should be pointed into the wind. Large turbines use wind sensor coupled with servo motor and small turbines are pointed by simple wind wane. Mostly large turbines have a gearbox which turns slow rotation of blades into quicker rotation.

As tower generates turbulence behind it, the WT is positioned upwind of its supporting tower. As high winds are being pushed into tower by blades, so the blades are made to be stiff. The blades are put at remarkable distance in front of tower.

3.2.2 Vertical axis

Vertical axis WT (VAWT) has main rotor shaft adjusted vertically. This type of WT does not require to be pointed into the wind to be effective. The generator and gearbox can be placed near ground, using a direct drive from rotor assembly to the ground-based gearbox, improving accessibility for maintenance.

Figure 3.2: Vertical-axis Wind Turbine

3.3 Wind Generator Technologies

The generator converts mechanical power of turbine into electric power whether it is AC or DC. AC generator can be either synchronous machine or induction machine. The electrical machine works on the principle of action and reaction of electromagnetic induction. The same machine can be used as motor for converting electric power into mechanical power.

3.3.1 Induction Generator (IG)

Induction generator uses the principle of induction motor to produce power. It produces electrical power when its rotor is turned faster than synchronous speed. Rugged brush less construction of induction machine does not need separate DC field power. Induction machine eliminated the disadvantages of both DC machines and synchronous machine which results in low capital cost, low maintenance and better transient performance. Therefore, induction generators are mostly used in wind farms and hydroelectric plants. Many wind power plants use induction machines for economy and reliability.

Fixed Speed Induction Generator (FSIG)

Fixed speed WTs employ squirrel-cage induction machine directly connected to power grid, so they named as fixed-speed induction generator (FSIG). They operate with less than 2% variation in turbine rotor speed. The rotor blades attached to hub at a fixed pitch and air flow over the blades changes from streamline flow to turbulent flow at high wind speeds. This limits the kinetic power extracted from high wind speeds in order to protect the induction machine and drive train from overheating and over speeding. This type of design used in turbines known as stall-regulated. The problem with this type of turbine is that energy capture from the wind is optimal for one wind speed only and suboptimal for other wind speeds.

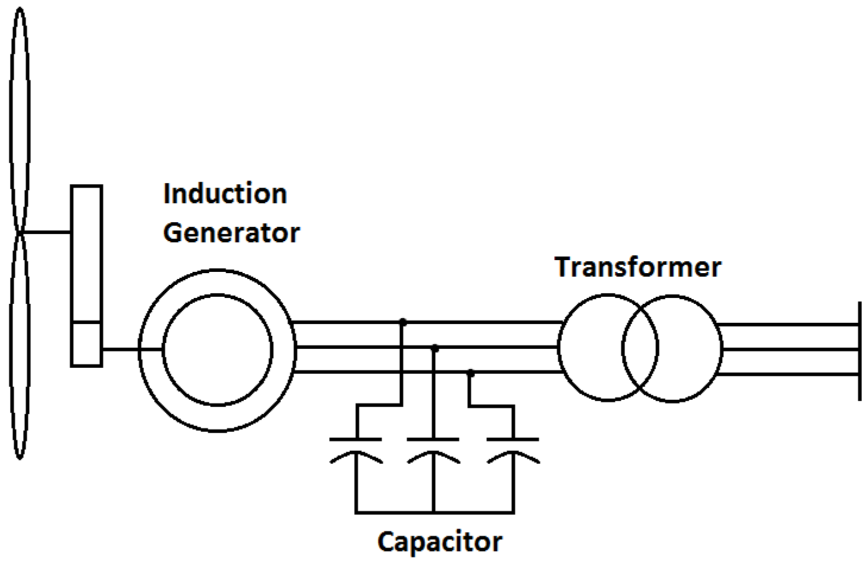


Figure 3.3: Fixed Speed Induction Generator

FSIG wind turbines are robust, low-cost, simple and reliable. As variable-speed wind turbines (DFIGs) form the bulk of new installed capacity, FSIG will expect to continue to play a role in power system of future. As variable speed is generally needed in industrial and domestic area, focus is largely on DFIG. They simplify the mechanical drive train and aerodynamics, which are evaluating power and rotor speed control mechanisms.

Doubly Fed Induction Generator (DFIG)

Doubly-fed induction generator (DFIG) is primary technology used in some large WTs with variable-speed operation. DFIG consists of wound rotor with stator winding connected directly to grid. The rotor windings interfaced through a back-to-back bidirectional voltage source converter which converts power at varying rotor frequencies to DC and then back to fixed grid frequency. The decoupling of active and reactive power is achieved through the use of power electronic converter in a DFIG wind turbine.

Modern variable-speed WTs operated by power converter in order to achieve high efficiency. The most captivating specialty of the DFIG is that only 20 to 30% of the power needs to pass through frequency conversion as compared with 100% in the variable-speed synchronous generator which gives a considerable cost advantage in the power electronics cost. Cyclo converter or voltage source converter is used as AC-AC frequency converter. Nowadays doubly-fed induction generator (DFIG) has become very popular in the field of WTs. WTs remain connected to the grid in case of a voltage sag or short circuit condition which requires in new regulation and the built-in potential of WT actively endorses the grid.

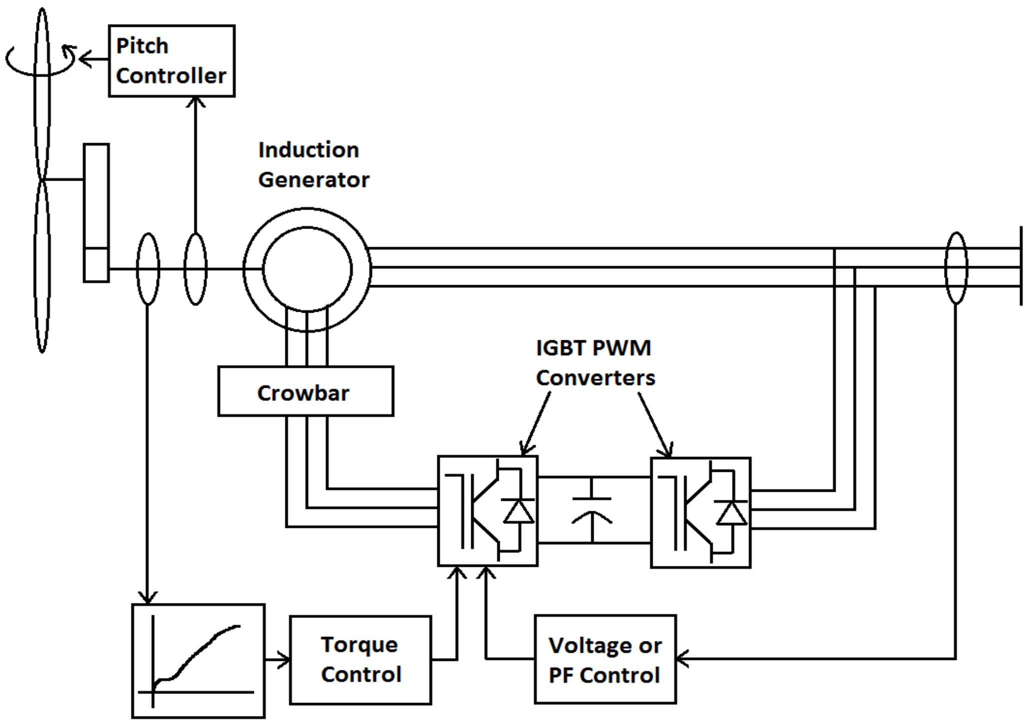


Figure 3.4: Doubly Fed Induction Generator

3.3.2 Synchronous Generator (SG)

Synchronous generator (SG) works on the principle of rotating magnetic field which induces AC voltage in stator windings. With fixed supply frequency, machine works at constant speed. These types of generators are not suited for variable-speed without power electronic converters. They are suited to generally small wind generators and constant-speed systems.

The synchronous machine has some advantages over induction machine. When SG is connected to the grid, it does not require power from grid. But nowadays wind plants use induction generator and connect to large grids. They are rarely used in gear-driven systems. The Low-speed design of SG has some advantages in direct-drive variable-speed WTs.

Permanent Magnet Synchronous Generator (PMSG)

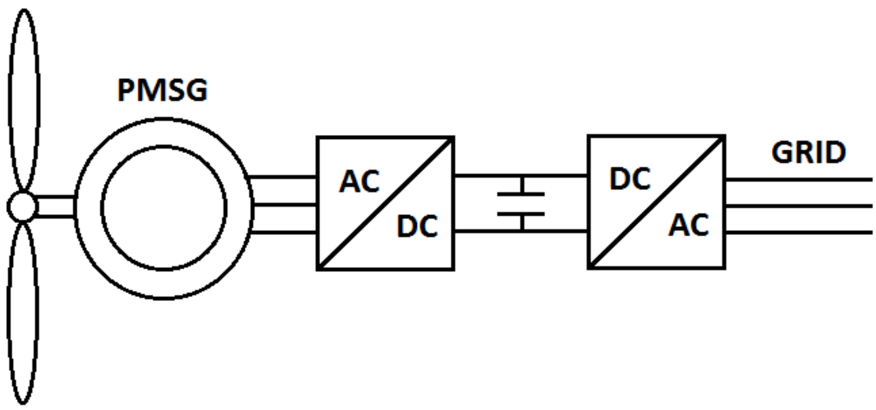


Figure 3.5: Permanent Magnet Synchronous Generator

A permanent magnet is used in permanent magnet synchronous generator (PMSG) instead of coil which works with excitation field. In this machine, synchronous word refers to fact that rotor and magnetic field rotate with same speed. The magnetic field is generated through shaft mounted permanent magnet mechanism and current is induced into stationary armature. These generators are major source of commercial electrical energy. They are generally used with steam turbines, gas turbines, reciprocating engines and hydro turbines to convert mechanical power into electrical power for grid. Some WTs are also using this type of generator.

Chapter 4

LVRT

In the electric power system, Low Voltage Ride Through (LVRT) or Fault Ride Through (FRT), is the ability of electric generators to stay connected in short periods of voltage dip for any abnormal situation [11]. Induction generators constitute 30 percent of todays installed wind power. Induction generators are very sensitive to grid voltage disturbances and need to enhance their low voltage ride through (LVRT) capability.

4.1 LVRT Characteristics

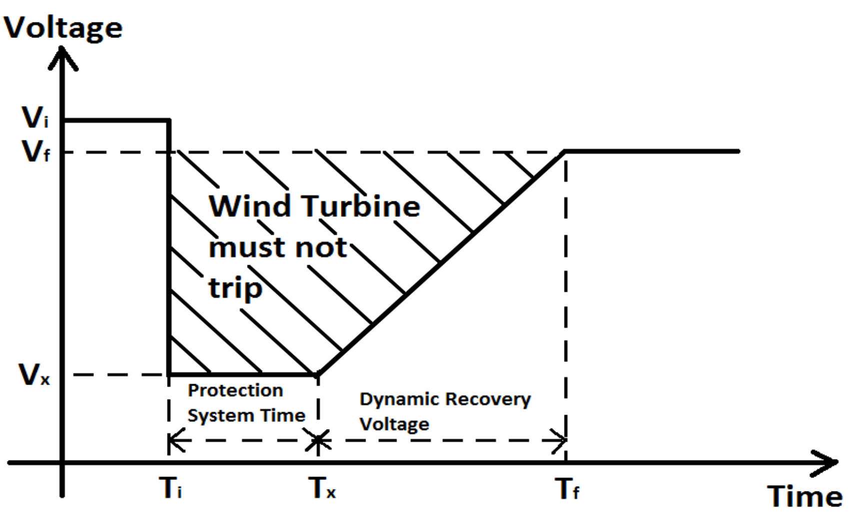


Figure 4.1: Typical LVRT Characteristic of a wind turbine

A typical LVRT characteristic is shown in Fig. 4.1[3]. According to the LVRT specification, wind turbines are required to stay connected to the grid and supply reactive power, when the PCC voltage drops and falls in the shaded area, as shown in Fig. 5.1. Wind turbines must be able to operate continuously at Vf % of the rated PCC line voltage Vi. The level of the voltage sag (Vx) and fault clearance time (Tx) are decided by the turbine protection system based on the location and type of fault. The slope of the recovery depends on the reactive power support and the strength of the interconnection. So much steeper and stronger systems could minimize ride-through requirements of the generators.

Table 4.1: Fault clearing time and Voltage limits

Nominal System Voltage (kV)	Fault Clearing Time, T(ms)	Vf (kV)	Vx (kV)
400	100	360.00	60.00
220	160	200.00	33.00
132	160	120.00	19.80
110	160	96.25	16.50
66	300	60.00	9.90

Table 4.1 shows fault clearing time for various system nominal voltage levels [12]. Higher fault clearance times for the wind farms may be agreed to with the SEB (State Electricity Board)/ STU (State Transmission Utility). In such case, the SEB/ STU shall specify to the wind farm operators the required opening times for circuit breakers at various locations.

4.2 FSIG LVRT categories

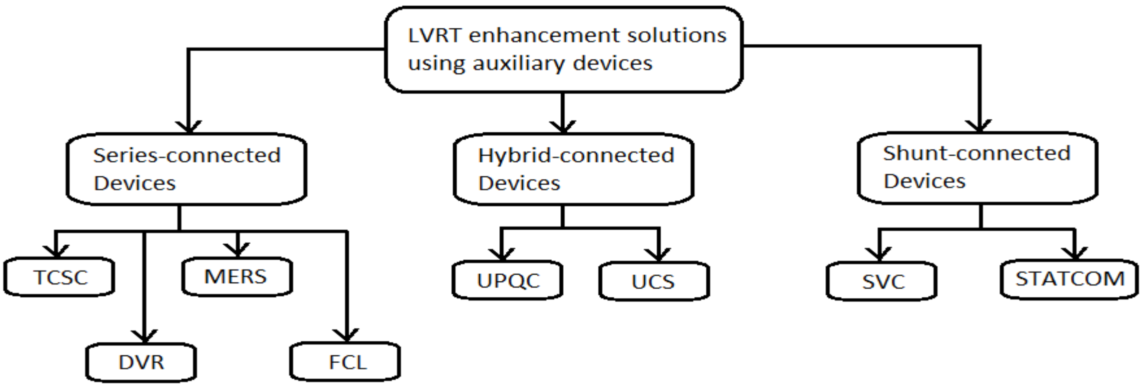


Figure 4.2: Classified LVRT capability enhancement methods [1]

4.3 DFIG LVRT Strategies

Various LVRT techniques based on : (1) Additional protection circuits placement and installation, (2) Reactive power injecting-devices installation and (3) Decided control ways or structures have been proposed in the literature [5]. To limit generated rotor over-current and undesirable dc-link over-voltage during grid disturbance, protection circuits are used. To surpass any deficiency of reactive power so as to improve the transient performance of DFIG, reactive power injecting-devices are used. To limit the inrush rotor currents, some control ways are used which are based on linear and nonlinear control strategies like vector control, use of rotor side and grid side power controllers.

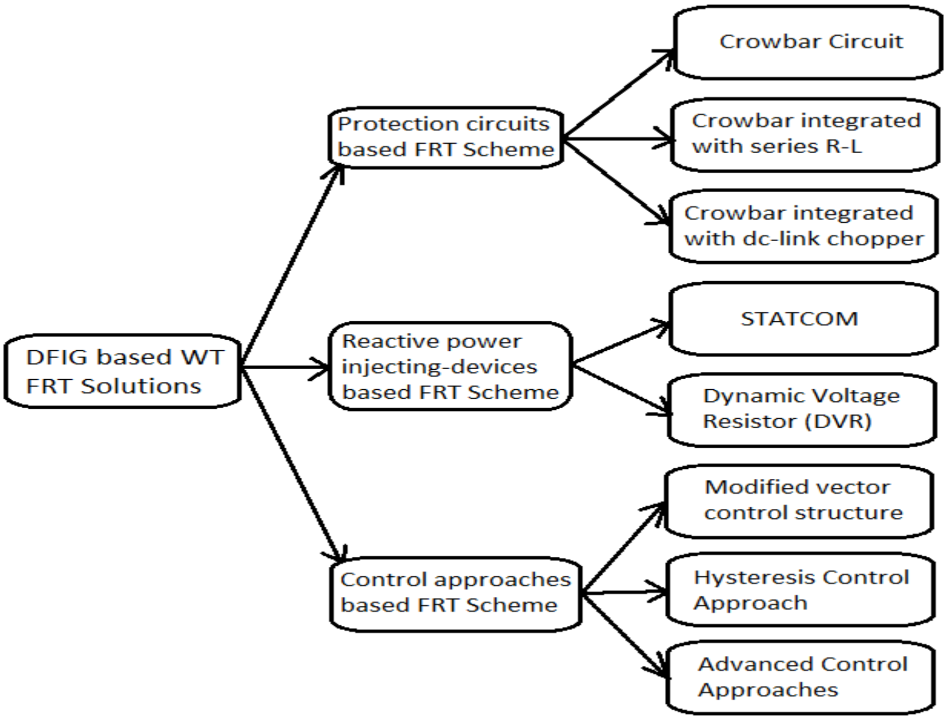


Figure 4.3: Categories of LVRT strategies for DFIG based WTs

Chapter 5

Load Flow Studies

5.1 Introduction

In power system, load flow study is steady state solution of power system network [2]. Power system basically contains an electric network and solved for steady-state powers and voltages at different buses. As the loads are given in terms of complex powers and generators are mostly behave like power sources rather than voltage sources, direct analysis of circuit is not possible. The main information obtained from load flow study comprises of magnitudes and phase angles of load bus voltages, reactive powers and voltage phase angles at generator buses, real and reactive power flow on transmission lines together with power at reference bus.

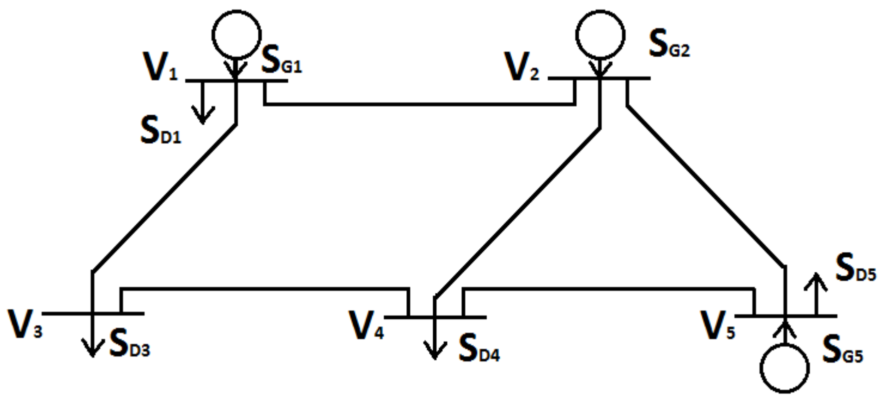


Figure 5.1: One-line diagram of a five bus system

In load flow analysis, main focus is on voltages at various buses and power injection into the transmission system. Here, S_{GS} and S_{DS} represent complex powers injected by generators and complex powers drawn by loads; while V_s represent complex voltages at various buses.

5.2 Load flow buses

In load flow studies, three types of buses used :
(1) Slack bus/ Swing bus/ Reference bus
(2) PQ bus/ Load bus
(3) PV bus/ Generator bus

Various types of buses use different terms and give output on the basis of it which is shown in table. Generally, there is only one slack bus used in power system. Almost 80% of all buses in power system are PQ buses while 10% of all buses in power system are PV buses.

Table 5.1: Buses and their solution

No.	Bus Type	Known	Unknown
1	Slack Bus	$\|Vi\|$, δi	Pi, Qi
2	PQ Bus	Pi, Qi	$\|Vi\|$, δi
3	PV Bus	Pi, $\|Vi\|$	Qi, δi

5.3 Load Flow Methods & Comparison

In load flow studies, mainly three methods are used for load flow which are :
(1) Gauss Seidel Method
(2) Newton Raphson Method
(3) Fast Decoupled Method
Comparison of Load flow methods are here :

Table 5.2: Comparison of Load flow Methods [2]

Parameters of Comparison	**GS method**	**NR method**	**FD method**
Coordinates	Rectangular Coordinates	Polar Coordinates	Polar Coordinates
Mathematical oprations	Minimum Requirement of calculation to completes one iteration	jacobian matrix calculated in each iteration	Less no of operation compare to NR
Time	Less time consuming	Time/iteration is 7 times of GS	Less time compare to both methods
Convergence	Linear	Quadratic	Geometric
Total numbers of iterations	Large number	3 to 5 only for large systems	Only 2 to 5 iteration
Selection of slack bus	Slack bus selection affects the convergence	Sensitivity to this minimum	Average
Accuracy	Less accurate	More accurate	Average
Memory	Less memory	Large memory	Only 60% of memory compare to NR method
Programming level	Easy	Hard	Medium
Reliability	More reliable for small system	Reliable for any system	Reliability compare to NR method is more

Chapter 6

Case Study

In this project, two systems are taken for a case study in PSCAD simulation software: (1) Single Machine Infinite Bus (SMIB) System and (2) Western System Coordinating Council (WSSC) 9-bus system. Mainly Doubly fed induction generator (DFIG) used instead of one standard generator in the system.

6.1 Case Study of SMIB System

The system of study is the one induction machine connected to infinite bus system through a transformer and transmission line [13]. Fig.6.1 shows single line diagram of SMIB system. SMIB system model implemented in PSCAD simulation software depicted in fig. 6.2.

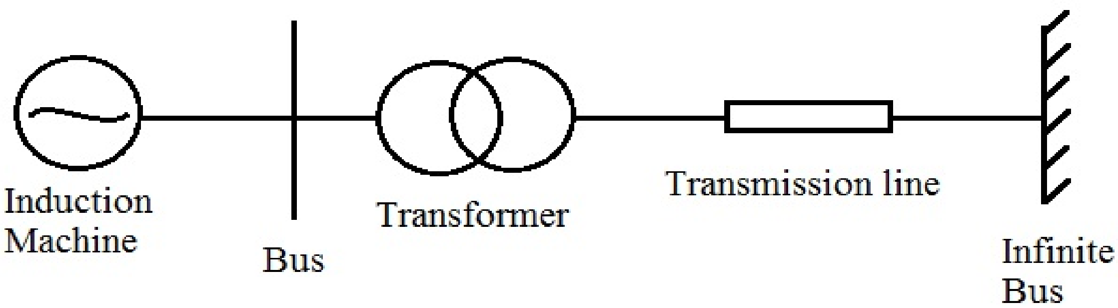


Figure 6.1: Single line diagram of SMIB system

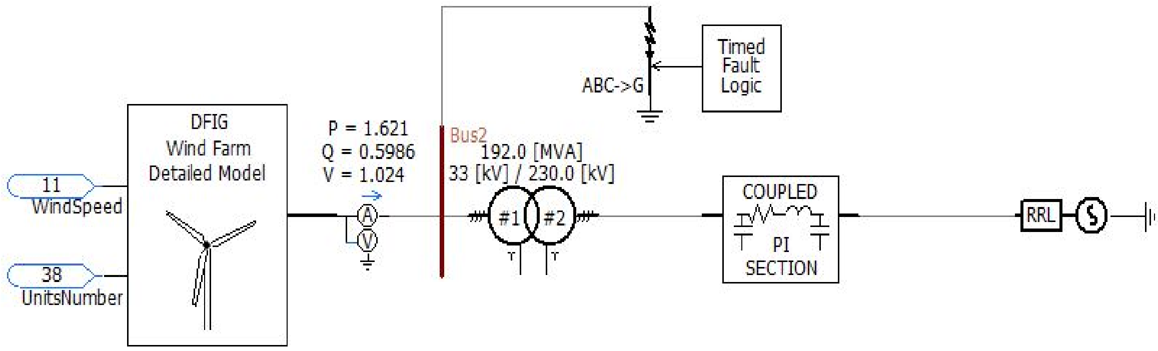


Figure 6.2: SMIB system implemented in PSCAD software

Graphical responses of voltage, active power and reactive power at Gen in steady state condition are shown in figs. 6.3 and 6.4. Base voltage is taken as 33kV and base MVA is taken as 100MVA. Simulation runs for 18s and system takes some time to stable, so fault created after that much time.

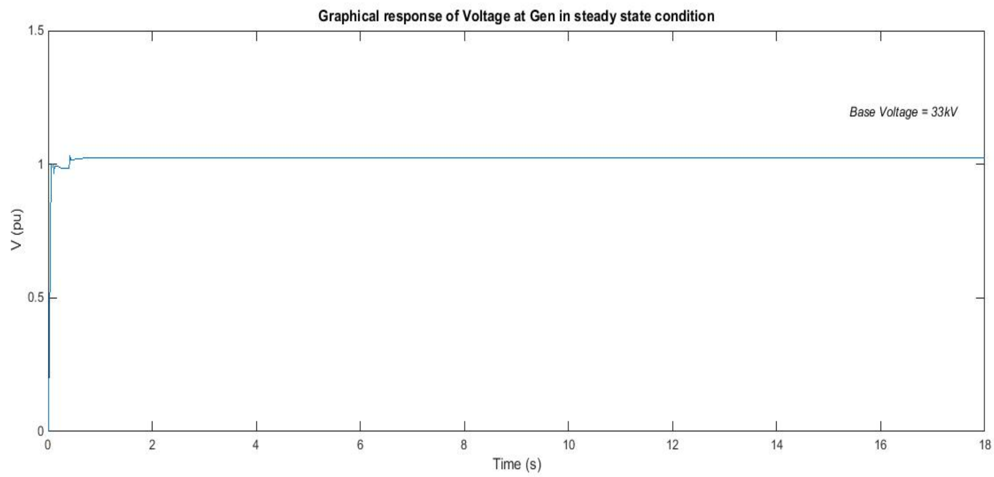


Figure 6.3: Graphical response of Voltage at Gen bus in steady state condition

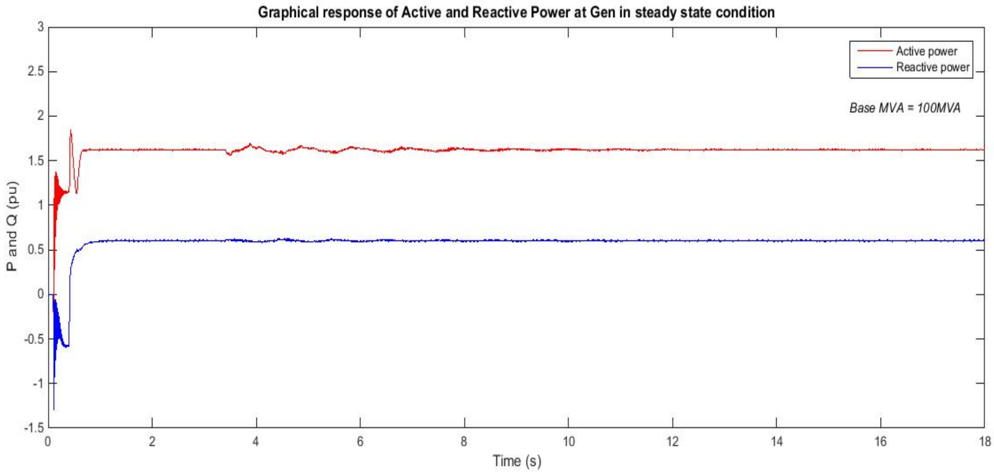


Figure 6.4: Graphical response of Active and Reactive power at Gen bus in steady state condition

Graphical responses of voltage, active power and reactive power at Gen in fault condition are shown in figs. 6.5 and 6.6. The fault is created at 12s and duration of fault is 0.1s. Voltage dropped during this fault from 1pu to 0.028pu. Active and reactive power dropped during fault from 1.65pu to 0.0581pu and 0.601pu to -0.0514pu respectively.

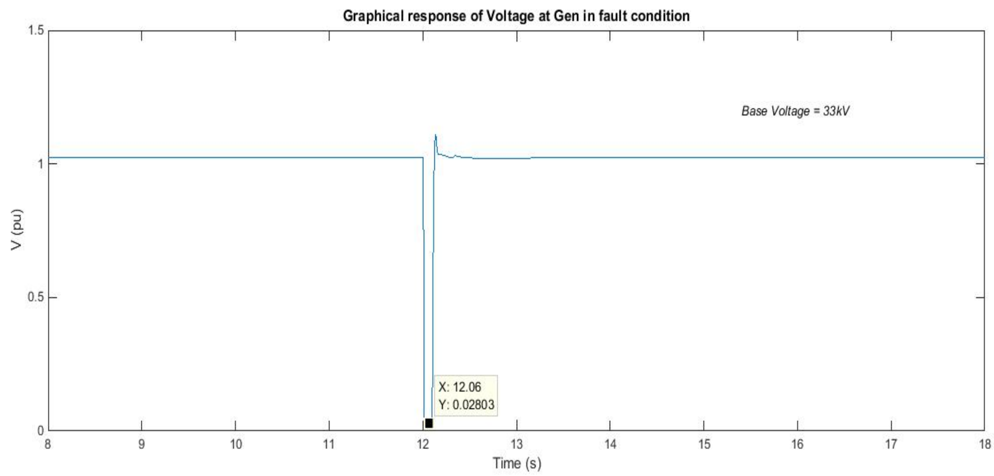


Figure 6.5: Graphical response of Voltage at Gen bus in fault condition

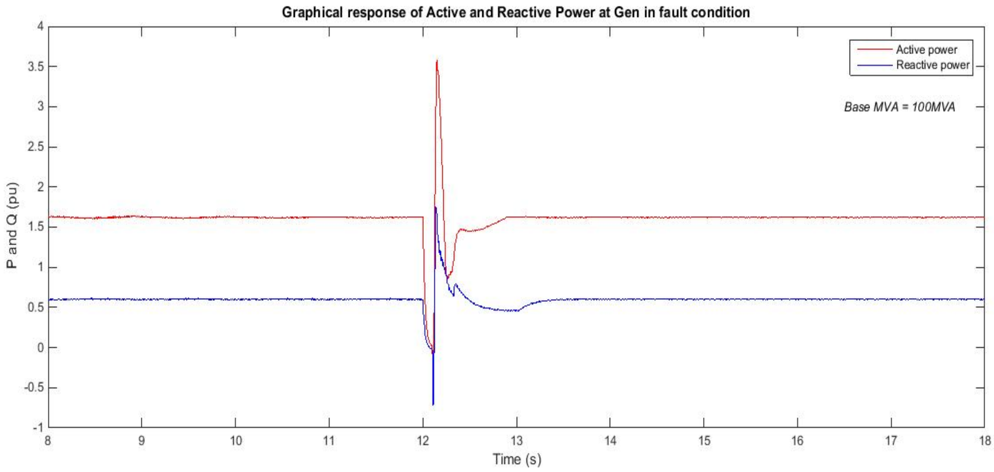


Figure 6.6: Graphical response of Active and Reactive power at Gen bus in fault condition

6.2 Case Study of 9-bus System

In this case study, mainly Doubly fed induction generator (DFIG) used with WSSC 9-bus system. Fig. 6.7 shows single line diagram of the 9-bus system.

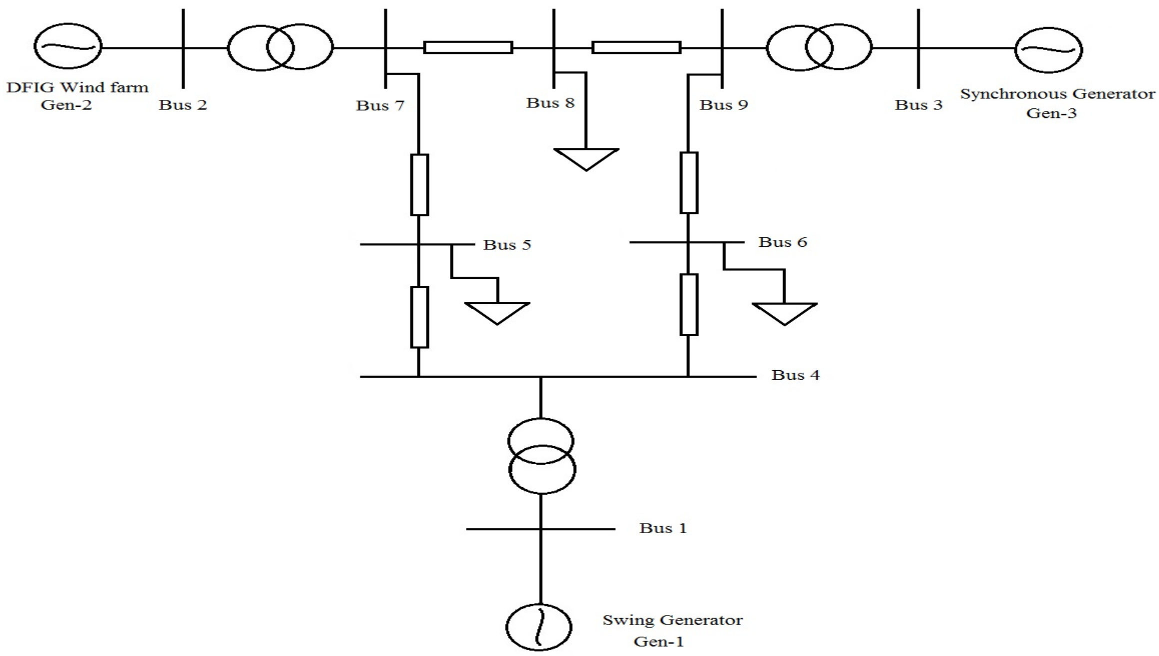
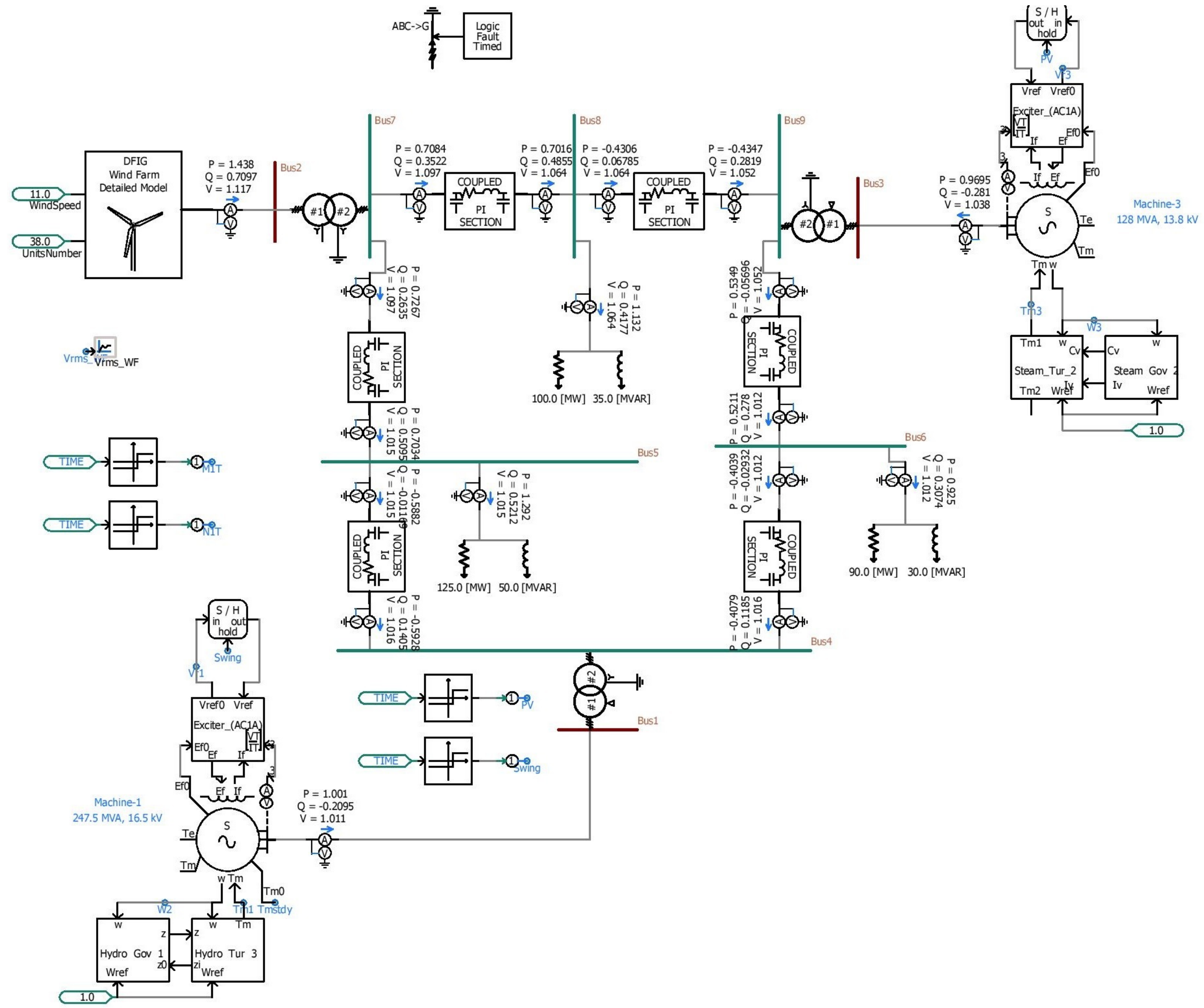


Figure 6.7: Single line diagram of WSSC 9-bus system



ABC->G
Logic Fault Timed
DFIG Wind Farm Detailed Model
11.0 WindSpeed
38.0 UnitsNumber
P = 1.438
Q = 0.7097
V = 1.117
Bus2
Bus7
Bus8
Bus9
Bus3
Bus5
Bus6
Bus4
Bus1
P = 0.7084
Q = 0.3522
V = 1.097
P = 0.7016
Q = 0.4855
V = 1.064
P = -0.4306
Q = 0.06785
V = 1.064
P = -0.4347
Q = 0.2819
V = 1.052
COUPLED PI SECTION
P = 0.9695
Q = -0.281
V = 1.038
Machine-3
128 MVA, 13.8 kV
Exciter_(AC1A)
Steam_Tur_2
Steam Gov 2
1.0
P = 0.7267
Q = 0.2635
V = 1.097
P = 1.132
Q = 0.4177
V = 1.064
100.0 [MW] 35.0 [MVAR]
P = 0.5349
Q = -0.05696
V = 1.052
P = 0.5211
Q = 0.278
V = 1.012
Vrms_WF
TIME
M1T
N1T
P = 0.7034
Q = 0.5095
V = 1.015
P = -0.5882
Q = -0.0116
V = 1.015
P = 1.292
Q = 0.5212
V = 1.015
125.0 [MW] 50.0 [MVAR]
P = -0.4039
Q = -0.02932
V = 1.012
P = 0.925
Q = 0.3074
V = 1.012
90.0 [MW] 30.0 [MVAR]
P = -0.5928
Q = 0.1405
V = 1.016
P = -0.4079
Q = 0.1185
V = 1.016
S / H in out hold
Swing
PV
Machine-1
247.5 MVA, 16.5 kV
P = 1.001
Q = -0.2095
V = 1.011
Hydro Gov 1
Hydro Tur 3
Tm0
Tmstdy
1.0

WSSC 9-bus system model implemented in PSCAD simulation software depicted in above figure. In PSCAD simulation software, DFIG connected to bus-2 in WSSC 9-bus system with the use of crowbar and STATCOM for LVRT enhancement. The 9-bus system test case consists of 9 buses, 3 generators, 3 two-winding power transformers, 6 lines and 3 loads. The base kV levels are 13.8 kV, 16.5 kV, 33 kV and 230 kV. The base MVA is 100MVA [14]. The line complex powers are around hundreds of MVA each. As a test case, this 9-bus case is easy to control as it has few voltage control devices.

Parameters of one DFIG generator is shown in table 6.1 which is used in WSSC 9-bus system instead of Gen-2 [15].

Table 6.1: Parameters of one DFIG generator

Parameters	**Value**
Rated power	5.0MW
Rated stator voltage	690V
Rated frequency	60Hz
Nominal wind speed	11m/s
Stator resistance	0.0054pu
Rotor resistance	0.0060pu
Stator leakage inductance	0.1016pu
Rotor leakage inductance	0.1100pu
Magnetizing inductance	4.5pu
Pole pairs	3
Stator/rotor turns ratio	0.3
Rotational inertia	3.0s
Nominal dc-link rated voltage	1200V
dc bus capacitor	7800uF

6.2.1 Steady State Condition

Firstly steady state condition is considered in the WSSC 9-bus system. In general, the simulation time is 18s and step time is 50us but this is changing for different cases. The base voltages are 16.5kV, 33kV and 13.8kV for Gen-1, Gen-2 and Gen-3 respectively. The base MVA is 100MVA for all generators. The generators take minimum 7s to 10s to come in normal condition. So any fault in the system is created after 10s. After the system is stable, voltages are around 1pu.

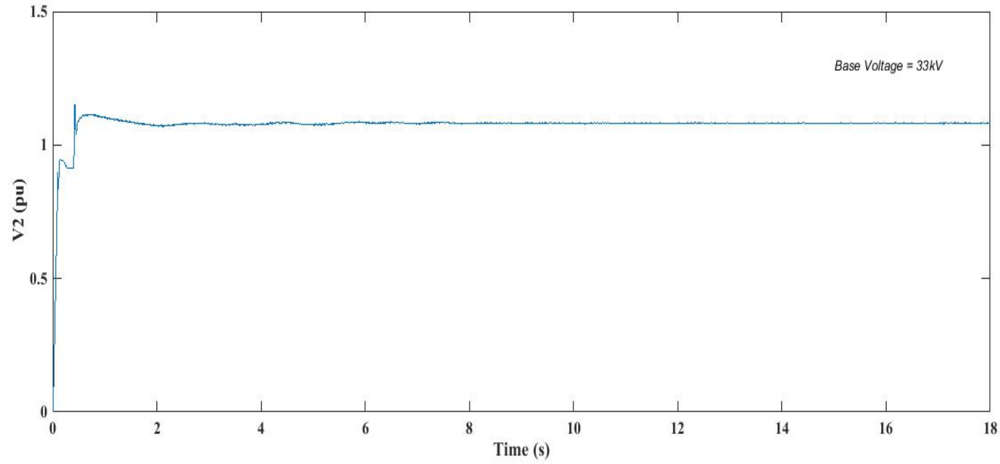


Figure 6.8: Graphical response of Voltage at Gen bus 2 in steady state condition

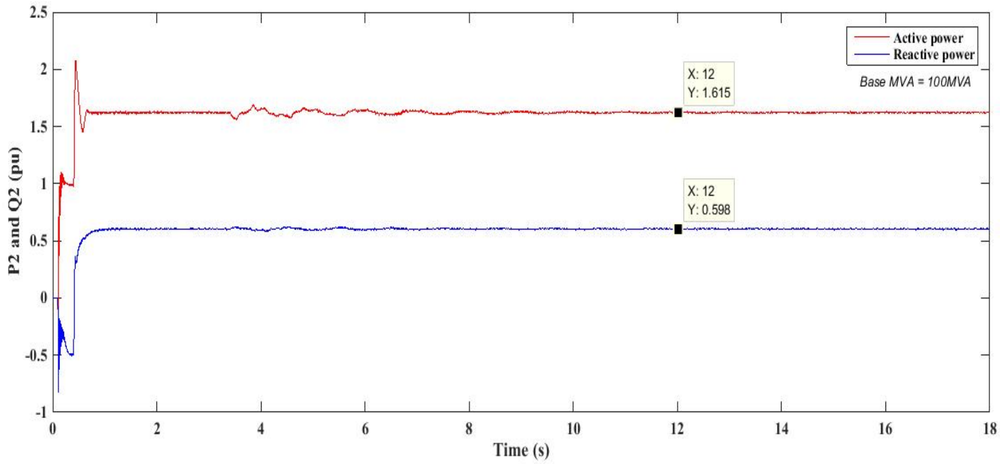


Figure 6.9: Graphical response of active power and reactive power at Gen bus 2 in steady state condition

Figs. 6.8 and 6.9 show graphical responses of voltage and power near Gen bus 2 respectively. Voltage is around 1.1pu, active power is 1.6120pu (165MW) and reactive power is 0.6010pu (60MVar).

Figs. 6.10 and 6.11 depict graphical responses of voltage and power near Gen bus 1 respectively. Voltage is around 1.0pu, active power is 0.7640pu (76MW) and reactive power is -0.0347pu (-3MVar).

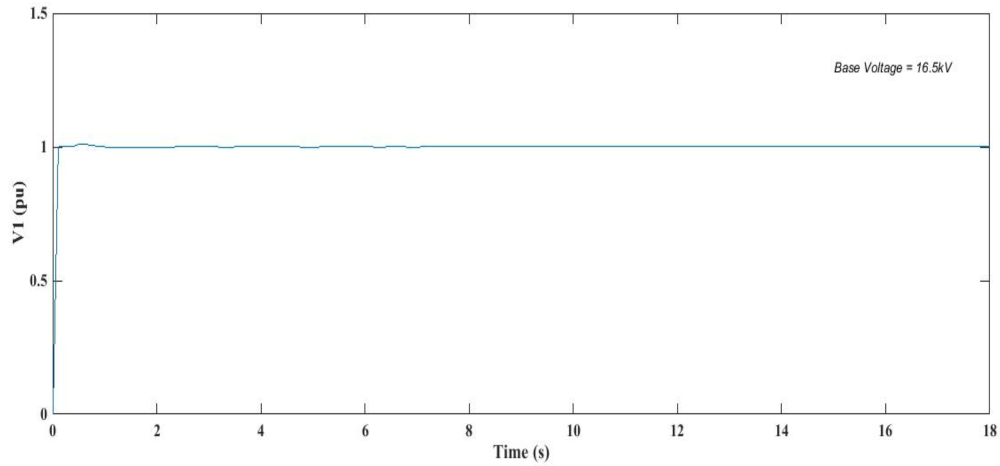


Figure 6.10: Graphical response of Voltage at Gen bus 1 in steady state condition

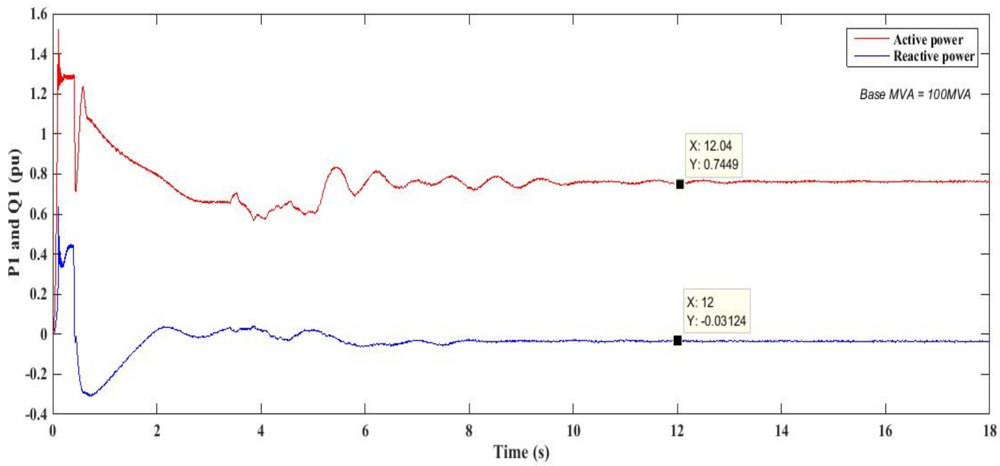


Figure 6.11: Graphical response of active power and reactive power at Gen bus 1 in steady state condition

Figs. 6.12 and 6.13 show graphical responses of voltage and power near Gen bus 3 respectively. Voltage is around 1.0pu, active power is 0.8565pu (85MW) and reactive power is -0.3533pu (35MVar).

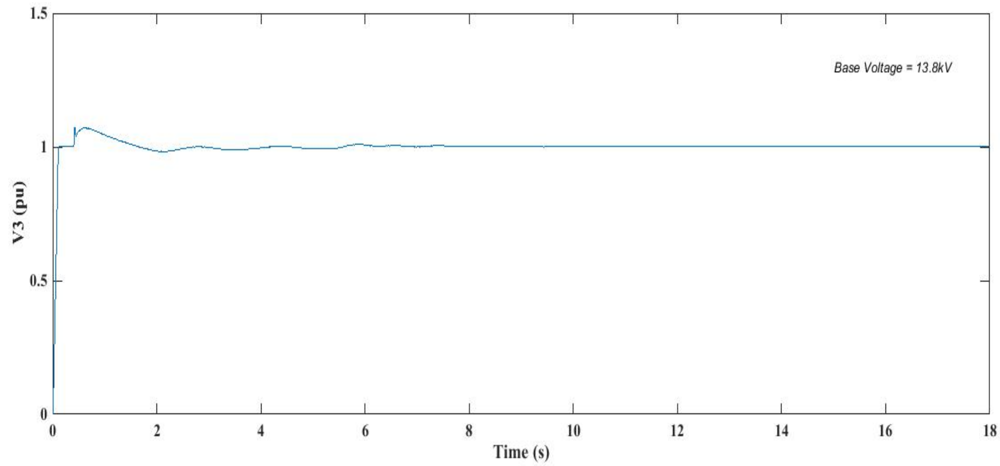


Figure 6.12: Graphical response of Voltage at Gen bus 3 in steady state condition

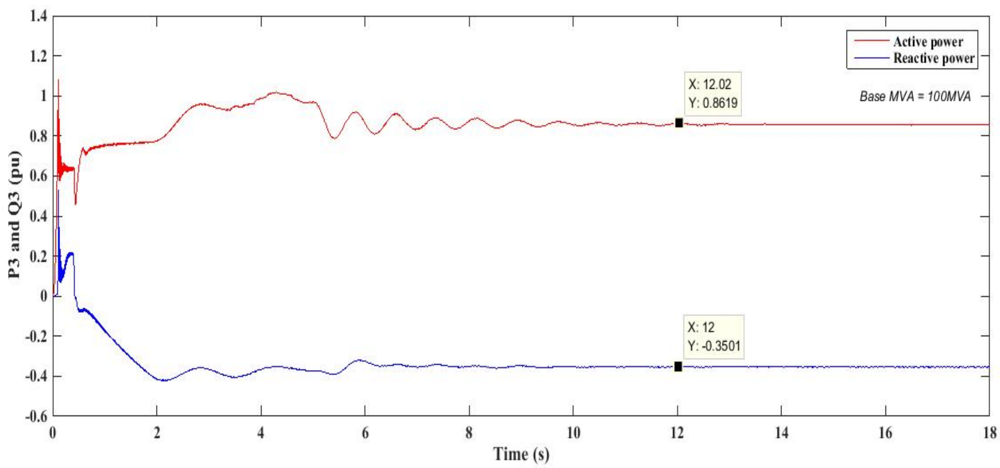


Figure 6.13: Graphical response of active power and reactive power at Gen bus 3 in steady state condition

6.2.2 Fault Condition

Secondly fault condition is considered in the WSSC 9-bus system. The base voltages are 16.5kV, 33kV and 13.8kV for Gen-1, Gen-2 and Gen-3 respectively. The base MVA is 100MVA for all generators. The fault is created at 12s on bus-5 and duration of fault is 0.1s.

Figs. 6.14 and 6.15 show graphical responses of voltage and power near Gen bus 2 respectively. At the time of fault, voltage is dipped from 1.1pu to 0.1708pu, active power is dipped from 1.6120pu to 0.0581pu and reactive power is change from 0.6010pu to -0.0514pu at Gen bus 2.

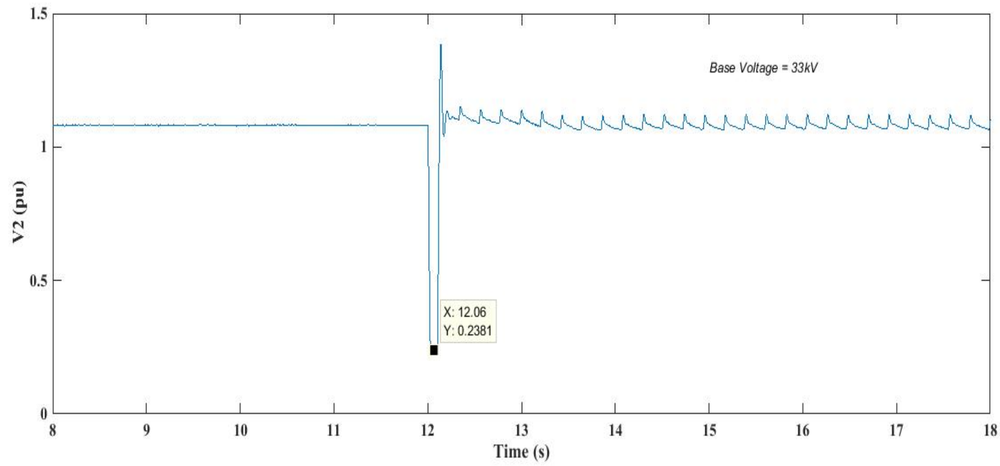


Figure 6.14: Graphical response of Voltage at Gen bus 2 in fault condition

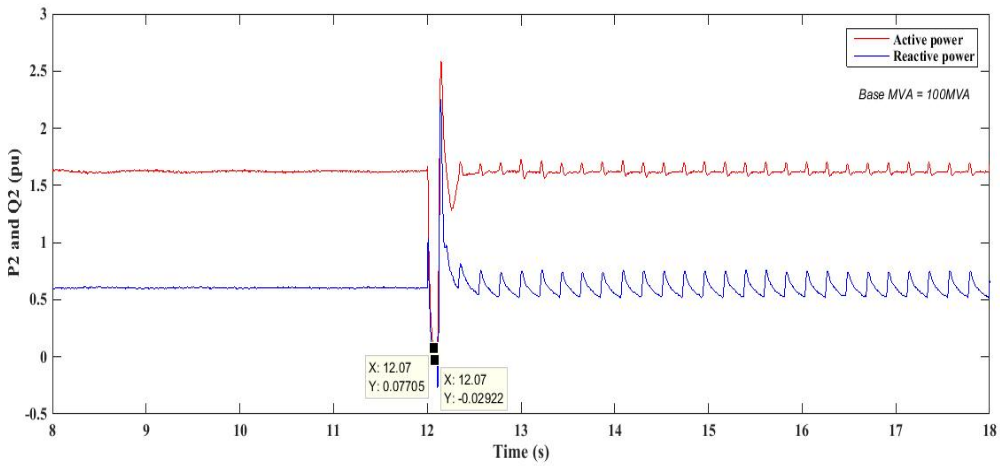


Figure 6.15: Graphical response of active power and reactive power at Gen bus 2 in fault condition

Figs. 6.16 and 6.17 depict graphical responses of voltage and power near Gen bus 1 respectively. At the time of fault, voltage is dipped from 1.0pu to 0.8868pu, active power is dipped from 0.7640pu to 0.6656pu and reactive power is change from -0.0347pu to 7.726pu at Gen bus 1.

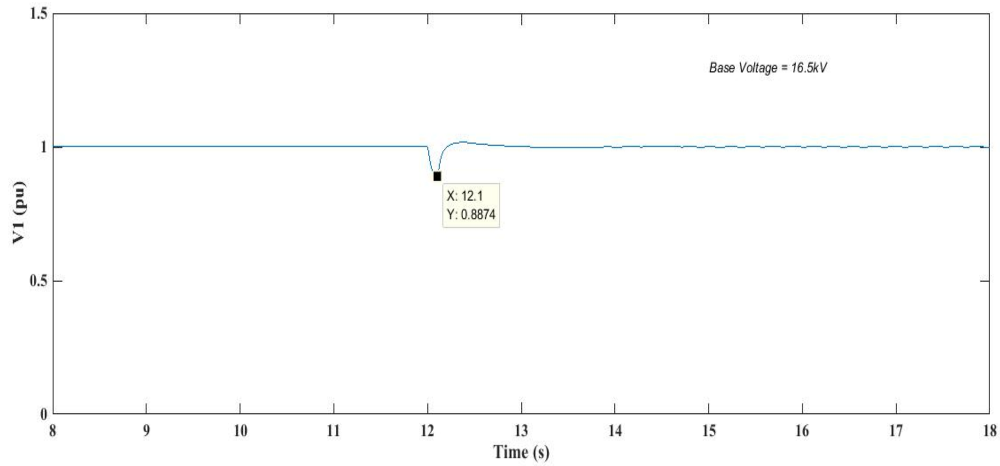


Figure 6.16: Graphical response of Voltage at Gen bus 1 in fault condition

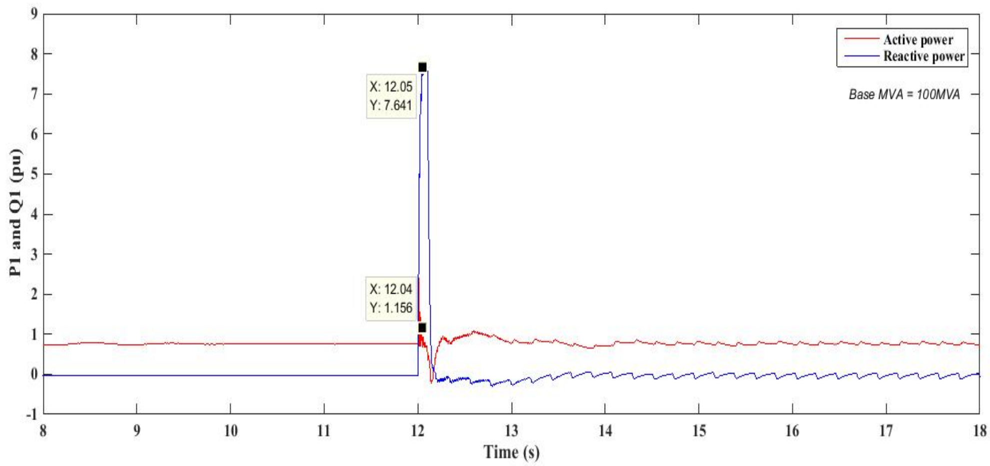


Figure 6.17: Graphical response of active power and reactive power at Gen bus 1 in fault condition

Figs. 6.18 and 6.19 show graphical responses of voltage and power near Gen bus 3 respectively. At the time of fault, voltage is dipped from 1.0pu to 0.5886pu, active power is dipped from 0.8565pu to 0.6364pu and reactive power is change from -0.3533pu to 0.7428pu at Gen bus 3.

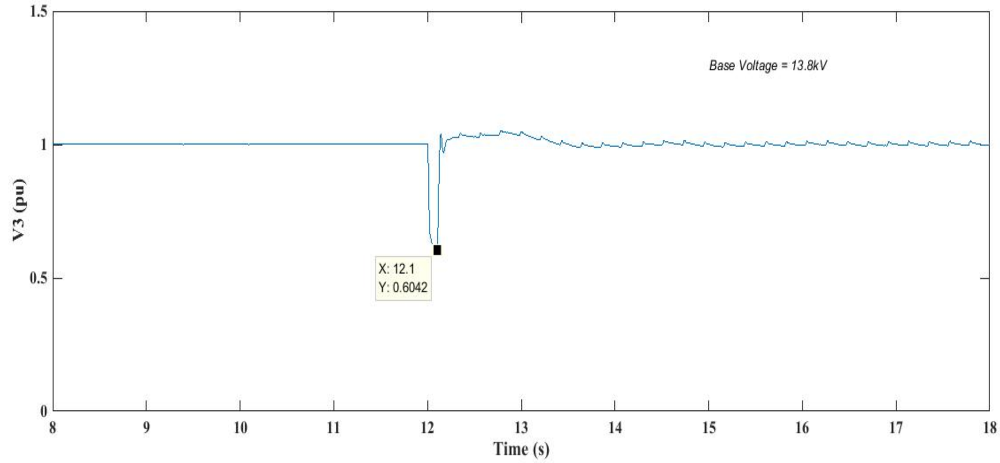


Figure 6.18: Graphical response of Voltage at Gen bus 3 in fault condition

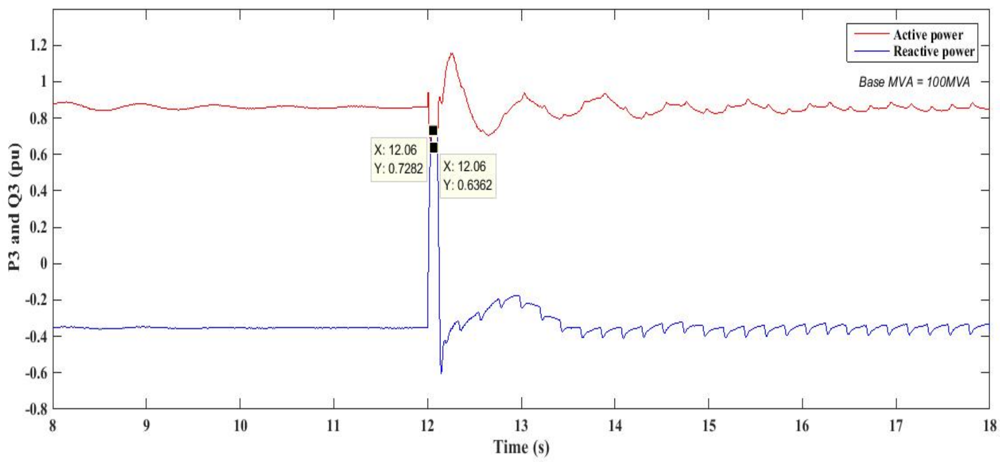


Figure 6.19: Graphical response of active power and reactive power at Gen bus 3 in fault condition

6.2.3 Fault Condition using Crowbar

Thirdly fault condition using crowbar protection is considered in the WSSC 9-bus system. The base voltages are 16.5kV, 33kV and 13.8kV for Gen-1, Gen-2 and Gen-3 respectively. The base MVA is 100MVA for all generators. The fault is created at 12s and duration of fault is 0.1s. Voltage results during fault using crowbar is better than simple fault condition (second condition).

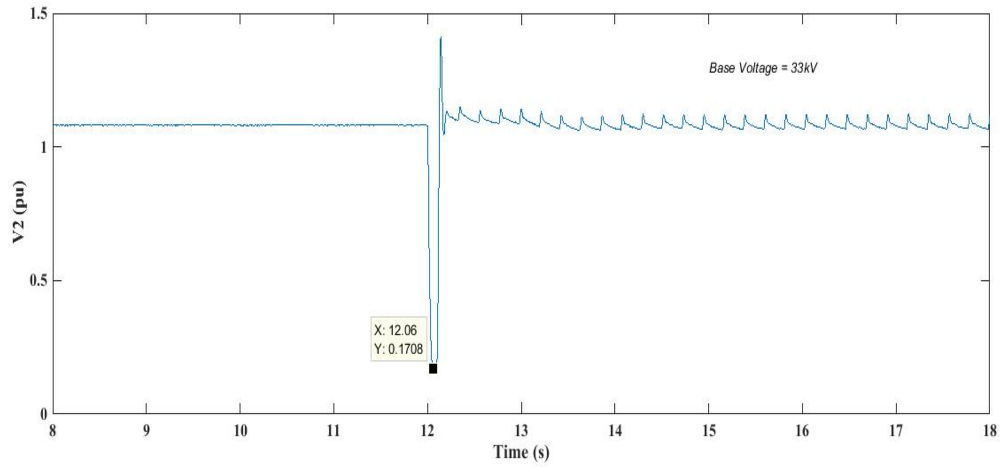


Figure 6.20: Graphical response of Voltage at Gen bus 2 in fault condition using crowbar

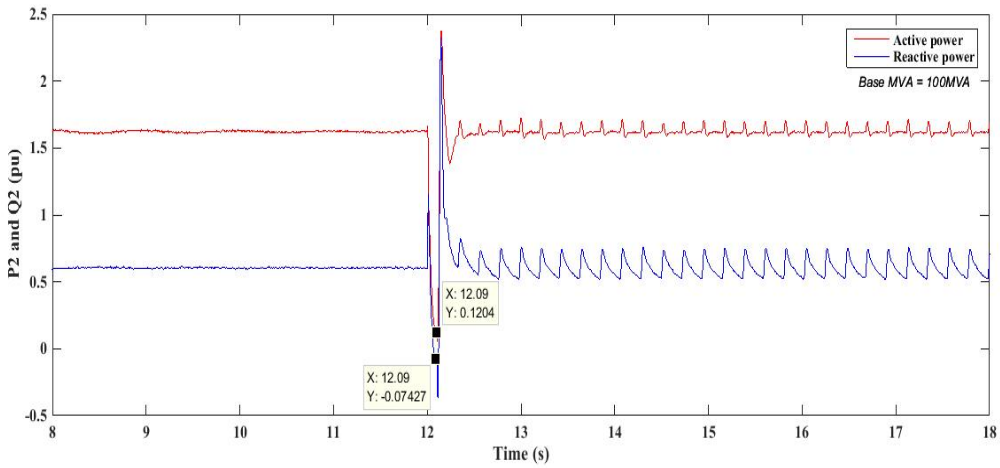


Figure 6.21: Graphical response of active power and reactive power at Gen bus 2 in fault condition using crowbar

Figs. 6.20 and 6.21 show graphical responses of voltage and power near Gen bus 2 respectively. The voltage is dipped from 1.1pu to 0.2378pu, active power is dipped from 1.6120pu to 0.1168pu and reactive power is change from 0.6010pu to -0.0854pu at Gen bus 2.

Figs. 6.22 and 6.23 depict graphical responses of voltage and power near Gen bus 1 respectively. The voltage is dipped from 1pu to 0.8874pu, active power is dipped from 0.7640pu to 0.6585pu and reactive power is change from -0.0347pu to 7.745pu at Gen bus 1.

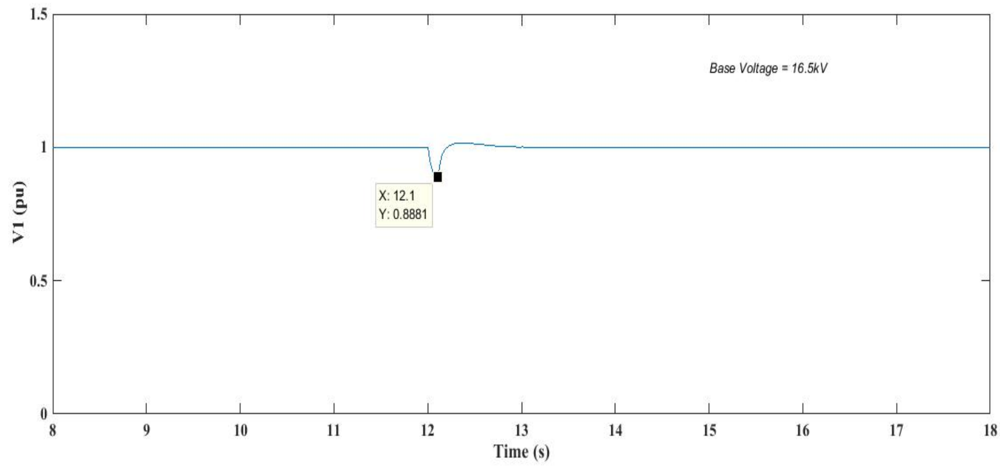


Figure 6.22: Graphical response of Voltage at Gen bus 1 in fault condition using crowbar

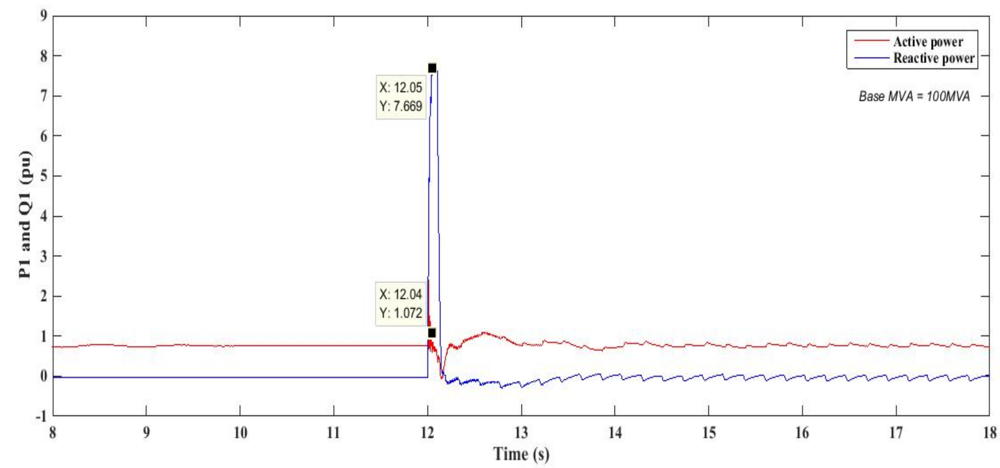


Figure 6.23: Graphical response of active power and reactive power at Gen bus 1 in fault condition using crowbar

Figs. 6.24 and 6.25 show graphical responses of voltage and power near Gen bus 3 respectively. The voltage is dipped from 1pu to 0.6042pu, active power is dipped from 0.8565pu to 0.5574pu and reactive power is change from -0.3533pu to 0.7605pu at Gen bus 3.

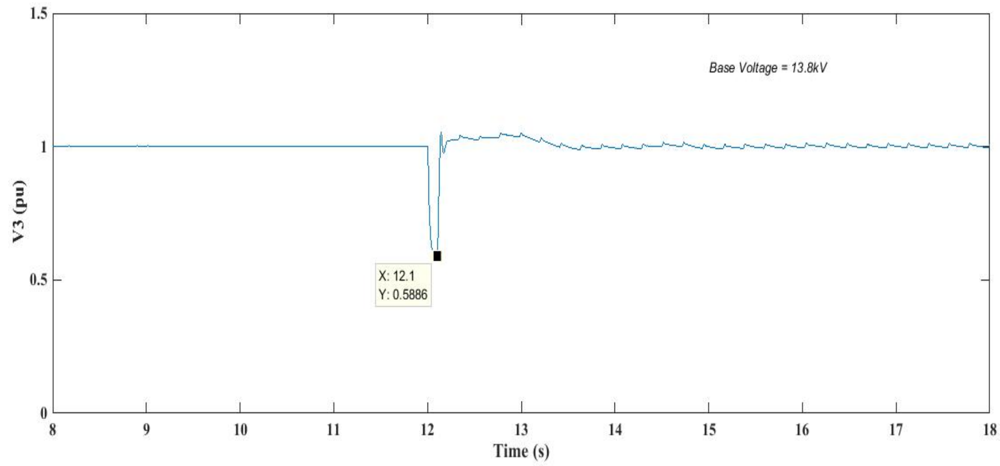


Figure 6.24: Graphical response of Voltage at Gen bus 3 in fault condition using crowbar

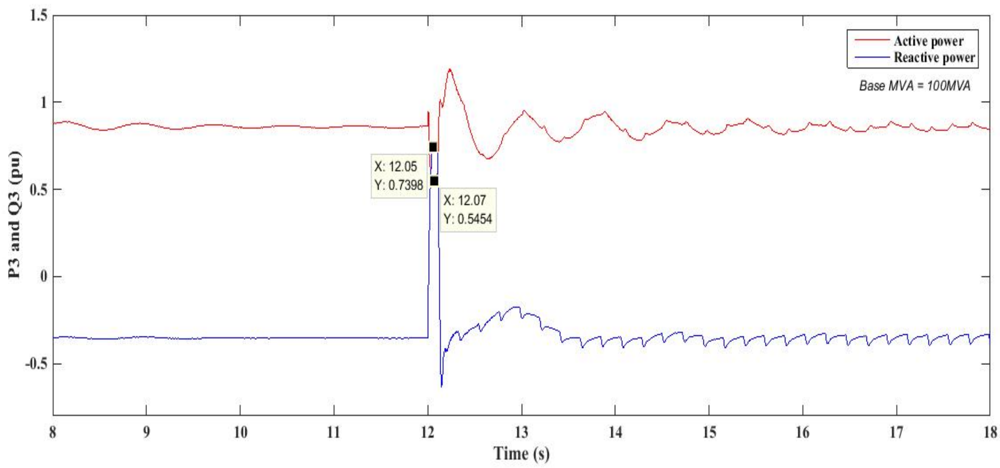


Figure 6.25: Graphical response of active power and reactive power at Gen bus 3 in fault condition using crowbar

6.2.4 Fault Condition using STATCOM

Lastly fault condition using reactive power injecting device - STATCOM is considered in the WSSC 9-bus system. The base voltages are 16.5kV, 33kV and 13.8kV for Gen-1, Gen-2 and Gen-3 respectively. The base MVA is 100MVA for all generators. The fault is created at 12s and duration of fault is 0.1s. Voltage results during fault using STATCOM is better than all other condition (second and third condition).

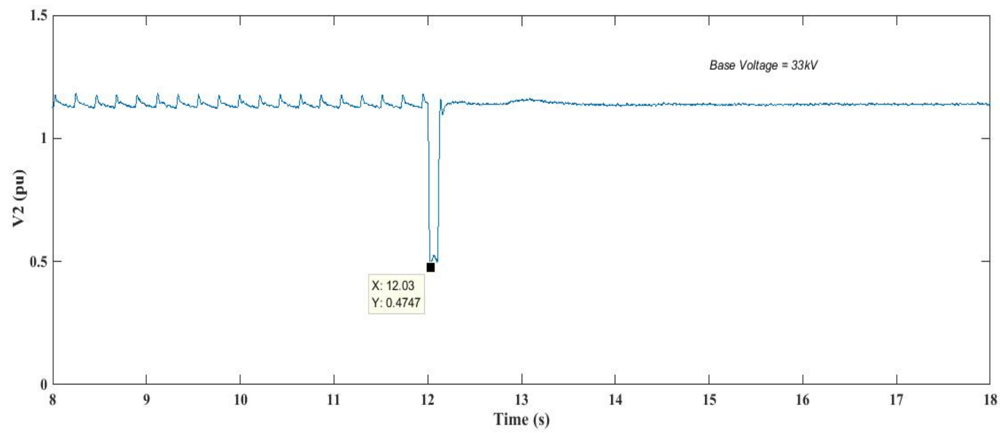


Figure 6.26: Graphical response of Voltage at Gen bus 2 in fault condition using STATCOM

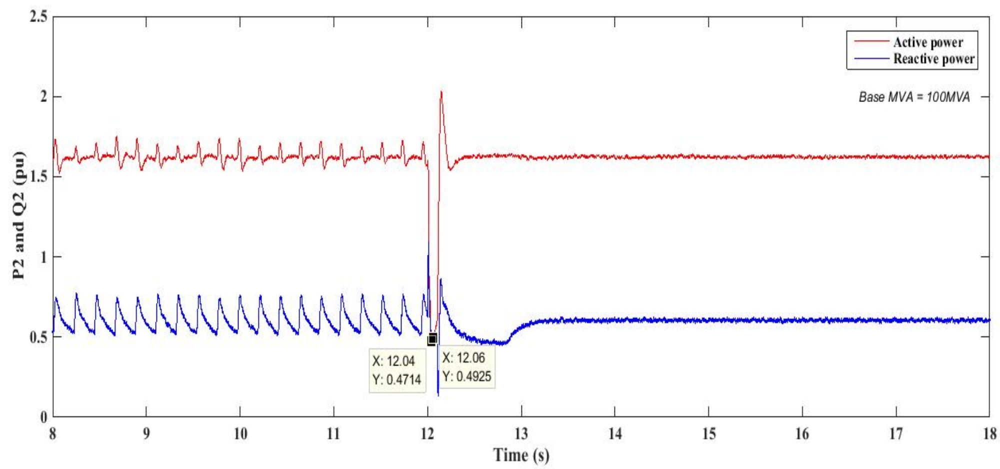


Figure 6.27: Graphical response of active power and reactive power at Gen bus 2 in fault condition using STATCOM

Figs. 6.26 and 6.27 show graphical responses of voltage and power near Gen bus 2 respectively. The voltage is dipped from 1.1pu to 0.4747pu, active power is dipped from 1.6120pu to 0.5329pu, reactive power is change from 0.6010pu to 0.5258pu at

Gen bus 2.
Figs. 6.28 and 6.29 depict graphical responses of voltage and power near Gen bus 1 respectively. The voltage is dipped from 1pu to 0.6633pu, active power is dipped from 0.7640pu to 0.6185pu, reactive power is change from -0.0347pu to 7.538pu at Gen bus 1.

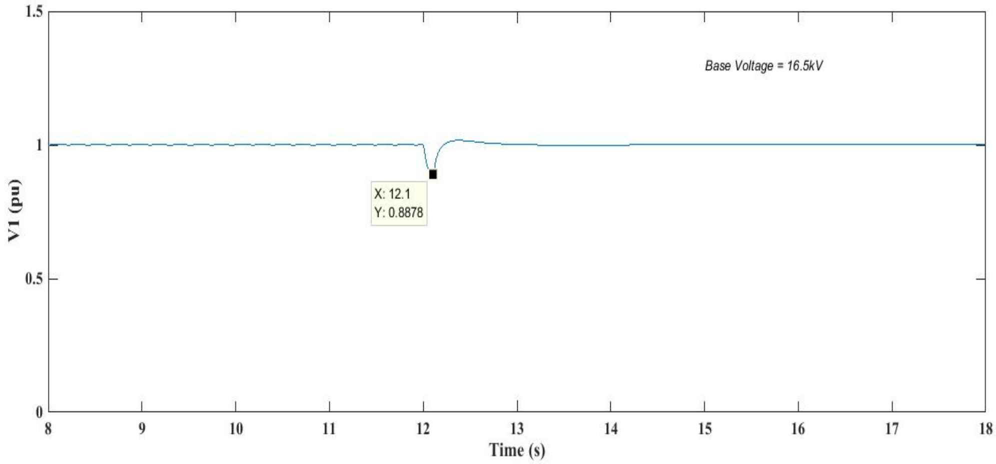


Figure 6.28: Graphical response of Voltage at Gen bus 1 in fault condition using STATCOM

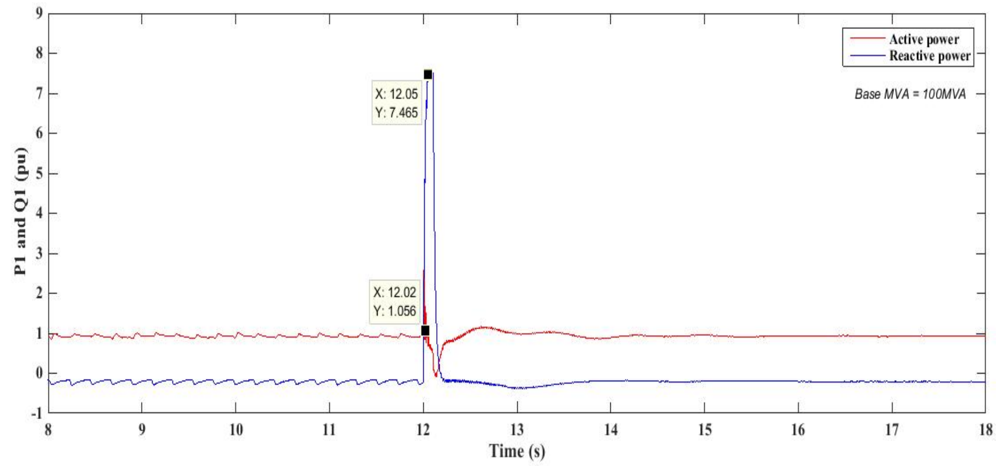


Figure 6.29: Graphical response of active power and reactive power at Gen bus 1 in fault condition using STATCOM

Figs. 6.30 and 6.31 show graphical responses of voltage and power near Gen bus 3 respectively. The voltage is dipped from 1pu to 0.5886pu, active power is dipped from 0.8565pu to 0.5633pu, reactive power is change from -0.3533pu to 0.5618pu at Gen bus 3.

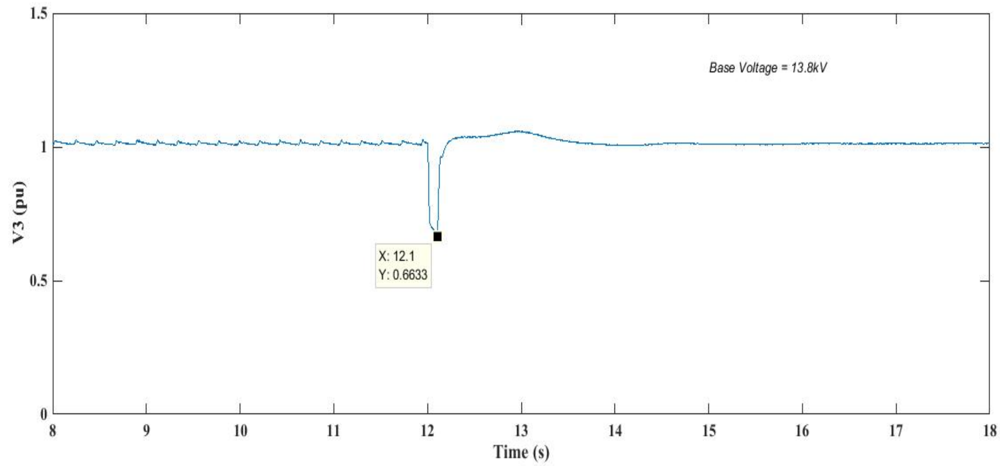


Figure 6.30: Graphical response of Voltage at Gen bus 3 in fault condition using STATCOM

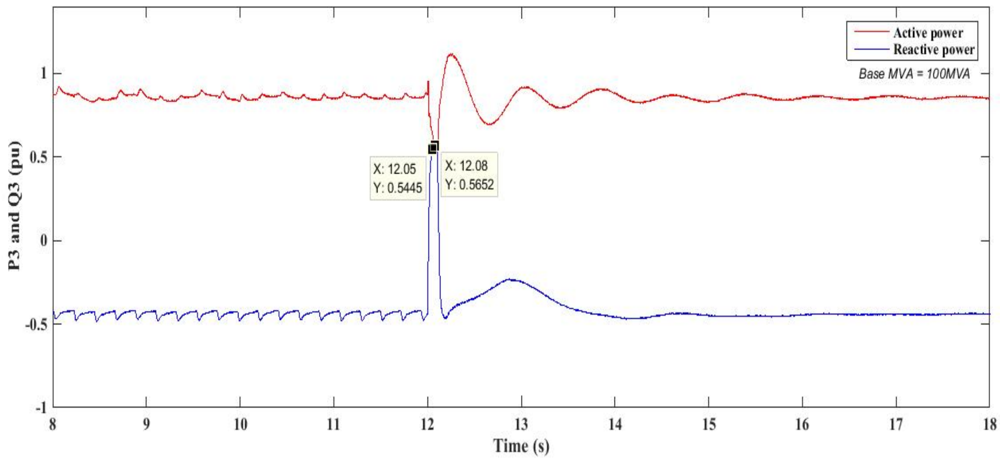


Figure 6.31: Graphical response of active power and reactive power at Gen bus 3 in fault condition using STATCOM

6.3 Load Flow Studies

Load flow study is taken for this above 9-bus case study. In load flow analysis, main focus is on voltages at various buses and power injection into the transmission system. Voltages, active powers and reactive powers are taken at different buses. For steady state condition, voltages are around 1pu and powers are shown in table 6.2.

Table 6.2: Load flow in steady state condition

	V (pu)	P (pu)	Q (pu)
Bus 1 (Hydro)	1.000	0.7640	-0.0347
Bus 2 (Wind)	1.104	1.6120	0.6010
Bus 3 (Steam)	1.005	0.8565	-0.3533

Table 6.3 depicts load flow study in fault condition. The fault is created at 12s near bus-5. Voltage dipped at Gen-2 (wind generator) from 1pu to 0.1708pu. The changes in active and reactive power are shown.

Table 6.3: Load flow in fault condition at 12.0s

	V (pu)	P (pu)	Q (pu)
Bus 1 (Hydro)	0.8868	0.6656	7.7260
Bus 2 (Wind)	0.1708	0.0581	-0.0514
Bus 3 (Steam)	0.5886	0.6364	0.7428

Table 6.4 depicts load flow study in fault condition using crowbar. The fault is created at 12s near bus-5. Voltage dipped at Gen-2 (wind generator) from 1pu to 0.2378pu. Voltage results for this condition is better than normal fault condition. The changes in active and reactive power are shown.

Table 6.4: Load flow in fault condition using Crowbar at 12.0s

	V (pu)	P (pu)	Q (pu)
Bus 1 (Hydro)	0.8874	0.6585	7.7450
Bus 2 (Wind)	0.2378	0.1168	-0.0854
Bus 3 (Steam)	0.6042	0.5574	0.7605

Table 6.5 depicts load flow study in fault condition using STATCOM. The fault is created at 12s near bus-5. Voltage dipped at Gen-2 (wind generator) from 1pu to 0.4747pu. Voltage results for this condition is better than all other fault condition. The changes in active and reactive power are shown.

Table 6.5: Load flow in fault condition using STATCOM at 12.0s

	V (pu)	P (pu)	Q (pu)
Bus 1 (Hydro)	0.6633	0.6185	7.5380
Bus 2 (Wind)	0.4747	0.5329	0.5258
Bus 3 (Steam)	0.5886	0.5633	0.5618

Chapter 7

Conclusion & Future Scope

7.1 Conclusion

From the literature survey and case study, DFIG wind turbine technology is studied and LVRT capability enhancement methods are identified. The first concept is done in PSCAD which is supportive of the theoretical concept and calculation. Preliminary simulation analysis shows that the different LVRT enhancement schemes need to deal with wind turbine technologies in the electrical field. These techniques are applied in the 9-bus system and also check load flow results. For LVRT enhancement, two different techniques using crowbar and STATCOM implemented in the 9-bus system. Simulation results of voltage are improvised using these techniques. Reactive power injecting device technique in which STATCOM used, is better than all other techniques. These techniques are compared with each other through the simulation results.

7.2 Future Scope

- Work on other techniques for LVRT enhancement
- Simulate various LVRT techniques in standard system
- Analyze and compare various techniques of LVRT enhancement

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