# Fault Analysis and Control of Grid Connected Wind Turbine Driving Squirrel Cage Induction Generator

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**Abstract -** *This paper aims to simulate a wind turbine model with three-phase squirrel-cage induction generator, the system is connected to the utility grid. It describes the simulation of a common fault (three phase fault) that occurs along the transmission line of the power system. The response of the wind turbine and the three-phase squirrel-cage induction generator are analyzed and discussed at different fault periods. Finally A transient fault ride through controller is designed to control and improve the system performance during and after fault occurrence, the controller is a simply PID controller tuned by genetic algorithm and is used to control the turbine blade pitch angle.*

***Key Words***: Transient fault, Wind turbine, Induction generator, Pitch angle controller.

## 1. INTRODUCTION

Wind energy plays an important role in the world energy system nowadays and this role is going to be expanded due to the several benefits of the wind energy [1]. Before the accomplishment of a wind power project many pre-studies are required in order to verify the possibility of integrating of the wind power plant in the electrical network. In many countries the renewable energy plants especially the wind ones are going to be the alternative for the conventional power plants so they have to take over many of the control tasks to keep the power system stable [2]. One of these control tasks is to ride through the transient faults in the power system. This means that the generation mustn't be lost due to the voltage excursions caused by transient faults. This paper introduces a survey of one of the most common line faults (three phase to ground fault) that may occur in the power system and the effect of the three phase to ground fault on the grid voltage and frequency.

## 2. WIND TURBINE MODELING

Fig -1, Fig -2, and Fig -3 show schematic diagram of the system, the wind turbine model, and the three-phase squirrel-cage induction generator respectively [3]. The system is connected to the utility grid [4]. The model is created using MATLAB software that enables the dynamic and static simulations of electromagnetic and electromechanical systems where the three-phase squirrel-cage induction generator is a standard model in MATLAB library. Table -1 and Table -2 show the main parameters of the proposed wind turbine and the three-phase squirrel-cage induction generator in this work respectively. The used gear box in this work was selected to extract the maximum power from the wind so all the results and analysis are taken at the rated wind speed 13 meter/sec.

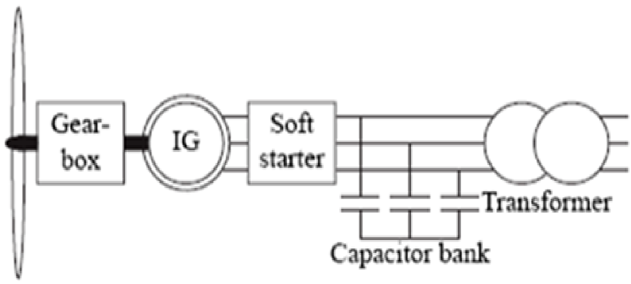



**Fig -1**: Schematic Diagram of the System

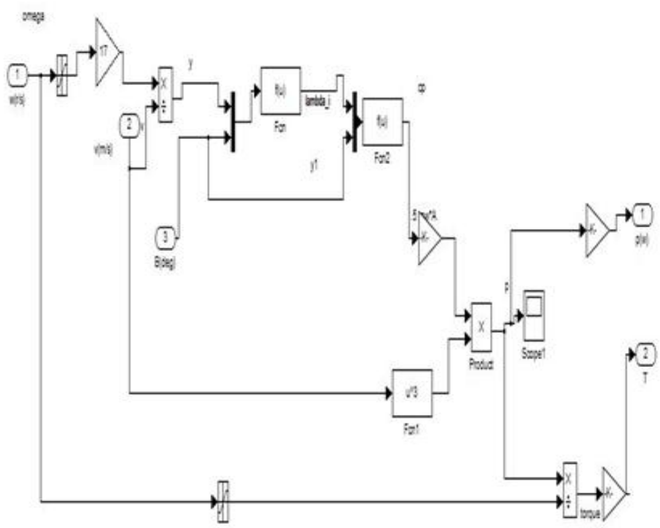


**Fig -2**: Matlab simulink model for the proposed wind turbine.

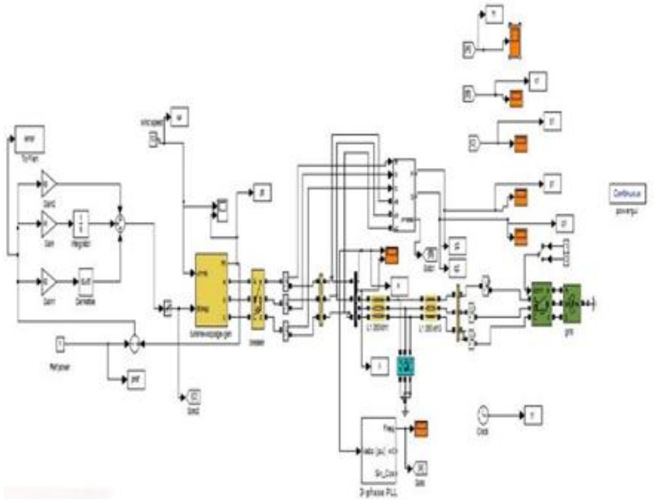


**Fig -3**: Matlab Simulink model for the proposed wind turbine with SCIG Connected to the grid [3].

| | |
|---|---|
| The rotor mechanical power [MW] | 0.5 |
| The rotor blade radius [m] | 17 |
| The rotor angular speed [rad/sec] | 4.5 |
| The air density [kg/m3] | 1.225 |
| Gear box ratio | 37 |
| The rated wind speed [m/sec] | 13 |
| Cut-off wind speed [m/sec] | 5 |
| Number of rotor blades | 3 |

**Table -1:** Wind turbine parameters [5].

| | |
|---|---|
| rated power [VA] | 550000 |
| Rated frequency (Hz) | 50 |
| Pole pairs | 2 |
| Rated voltage (v) | 690 |
| Stator resistance (ohm) | 0.01818 |
| Stator inductance (h) | 0.00019 |
| rotor resistance (ohm) | 0.00995 |
| Rotor inductance (h) | 0.00019 |
| Mutual inductance (h) | 0.00945 |
| Inertia (kg.m2) | 600 |

**Table -2:** Induction generator parameters [5].

## 2.1 Wind Turbine Equations

The rotor mechanical power (W) of the wind turbine is expressed as:

$$P_w = \frac{1}{2}\rho C_p(\beta, \lambda_i) A V_w^3 \quad (1)$$

Where, Vw is the wind speed at the center of the rotor (m/s), A=πR2 is the rotor surface area (m2), and R is the rotor radius (m), ρ is the air density (kg/m3) and, and $C_p$ is the rotor aerodynamic power coefficient.

The rotor mechanical torque can be calculated from Pw by

$$T_w = \frac{P_w}{\omega_R} \quad (2)$$

Where ωR is the rotor angular velocity, in rad/sec, and the rotor aerodynamic power coefficient $C_p$ is the percentage of the kinetic energy of the incident air mass that is converted to mechanical energy by the rotor, and it is expressed as follow:

$$C_p = C_p(\beta, \lambda_i) \quad (3)$$

Where:

$$\lambda_i = \frac{1}{\frac{1}{(\lambda + 0.08\beta)} - \frac{0.035}{(\beta^3 + 1)}} \quad (4)$$

Where λ is the tip speed ratio of the blade if the pitch angle of the blade is constant and defined as:

$$\lambda = \frac{R\omega_R}{V_w} \quad (5)$$

The Performance Curves of the used wind turbine has two indicators, namely power and torque, which are varying with the wind speed.

The power determines the amount of energy captured by the rotor, while the torque developed determines the size of the gearbox and must be matched to the electrical generator which is driven by the rotor. In order to characterize the actual performance of a wind turbine regardless of how it operates, e.g. at constant or variable speed these indicators are expressed in non-dimensional terms as functions of tip speed ratio [5].

The power coefficient $C_p$ for a wind turbine is defined based on the extracted power as:

$$C_p(\beta,\lambda_i) = \frac{power}{0.5\rho V_w^{\ 3} A} \quad (6)$$

The theoretical maximum value of the power coefficient is $C_p$ =0.593 and it is called the Betz limit. The turbine power coefficient [6] is represented by various approximation expressions .In this work, $C_p(\beta,\lambda_i)$ is given by the following equation.

$$C_p(\beta,\lambda_i) = 0.73\left(\frac{151}{\lambda_i} - 0.002\,\beta - 13.2\right)e^{\frac{-18.4}{\lambda_i}} \quad (7)$$

To obtain the maximum power coefficient a differentiation of equation (7) is done at zero pitch angle yields the next equation:

$$C_p(0,\lambda_i)_{\max} = \max[\ 110.23\left(\frac{1}{\lambda} - 0.1197\right)e^{-18.4(\frac{1}{(\lambda-.003)})}\ ]$$

The maximum power coefficient is 0.44 where the optimum tip speed ratio is 5.8. It can be observed that the maximum value of $C_p$ is much less than the Betz limit due to the imperfect blade design. Fig.2 shows the MATLAB Simulink model for the proposed wind turbine.

Fig -4 shows the relation between the power coefficient $C_p$ and the tip speed ratio based on MATLAB Simulink results, it can be seen from the figure that the maximum power coefficient is 0.44 and the optimum tip speed ratio is 5.8 as derived from the mathematical equations, these values depend on the wind speed and the turbine design.

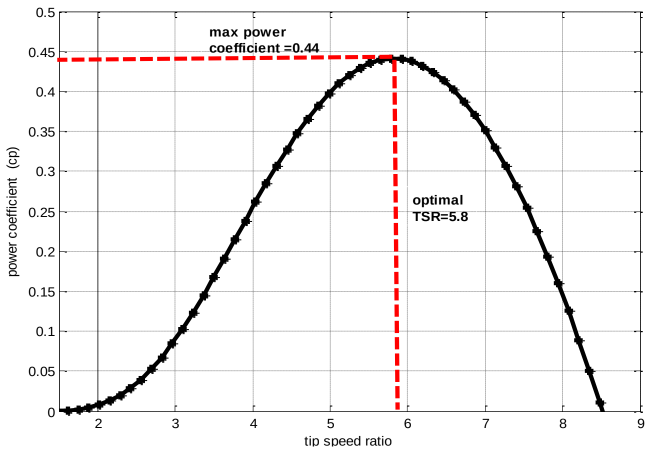



**Fig -4** $C_p$ -λ performance curve for a modern three blade wind turbine.

Fig -5 shows the relation between the tip speed ratio and the turbine output power at different wind speeds and fixed pitch angle at zero degree, it can be noticed that as the wind speed increases the output power increases.

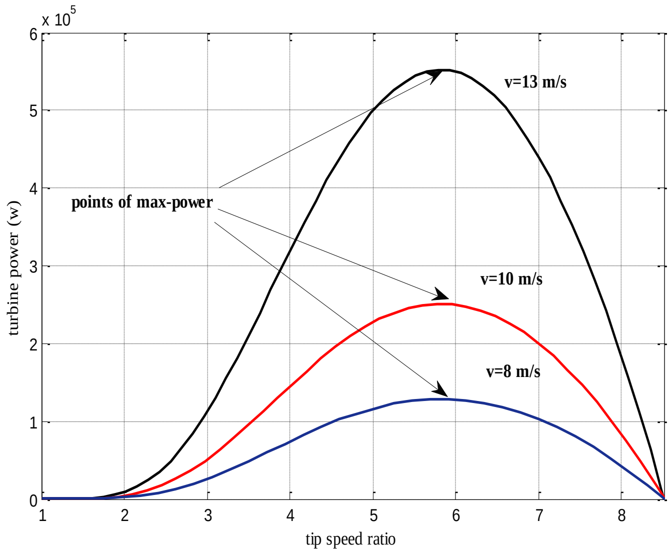



**Fig -5** Rotor aerodynamic power vs. rotor speed tip speed ratio at B=0 degree

Fig -6 shows the relation between the tip speed ratio and the turbine output power at different wind speeds and fixed pitch angle at 8 degrees. It can be noticed that as the wind speed increases the output power increases but the output power decreases with increasing the pitch angle.

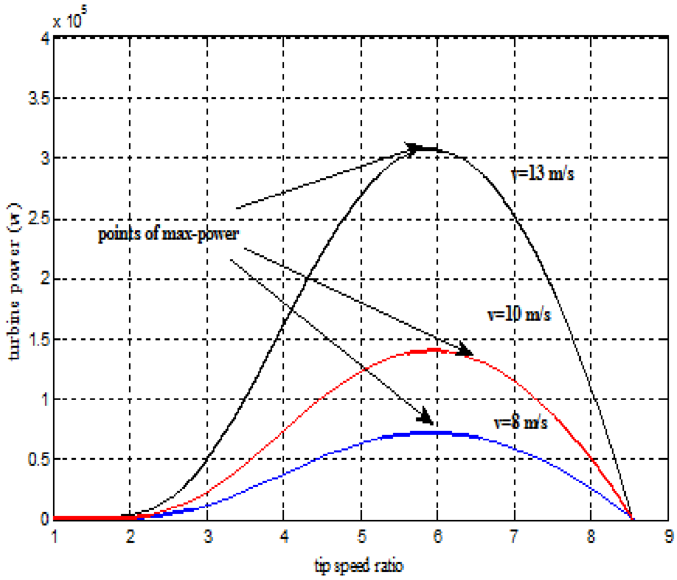
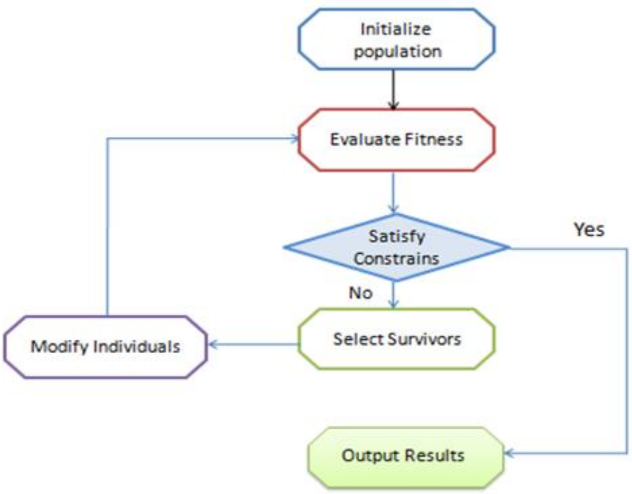



**Fig -6** Rotor aerodynamic power vs. rotor tip Speed ratio at B=8 degree

## 3. GENETIC ALGORITHM TECHNIQUE

Genetic algorithm optimization technique can be used in control systems to search the optimal gains of the PID controller and its derivatives, this search saves a lot of time, effort, and very accurate than trial and error method or Ziegler optimization method.

### 3.1 Genetic Algorithmic Steps




Genetic algorithm flowchart

## 4. FAULT ANALYSIS

The frequency in an AC power system is stable when the electrical demand plus the electrical losses equal the electrical generation in the system. An imbalance between generation and demand leads to grid frequency rising if the generation exceeds demand, and the grid frequency dropping if the demand exceeds the generation. The grid frequency finds a new equilibrium if there is either sufficient frequency sensitive load in the system, or if the generators are equipped with governors that adjust the prime mover power so the generators pull the frequency back to its rated value. Governor controllers which control the mechanical power of the prime mover, are used to control the steady state frequency of the system in all modern power systems.

### 4.1 Three Lines to Ground Fault

This case represents a three-lines to ground short circuit fault occurred at time 4 sec to 4.5 sec for half second fault duration and the same fault occurred in another study case at time 12 sec to 14 sec for two second fault duration to check the system and controller performance at different operation times.

If the short circuit happens close to a generator, the voltage at the generator terminals will be suppressed so the generator cannot export active power, hence a step change in generation occurs. In any case, a short circuit upsets the balance between load and generation in a step change. If, as described above, generators cannot export electrical power during a short circuit fault they have to accumulate the mechanical energy, with which the prime mover drives the generator. A rotating machine can only accumulate energy by accelerating. Hence the generators accelerate during the fault, and, after the fault is cleared, it tries to export as much electrical power as possible to decelerate again. As a result, the rotor speed of the generators oscillates.

If wind turbines are to take over such damping tasks they have to have a very effective means of controlling their electrical output power. A common wind turbine type is the fixed speed active-stall wind turbine, which has a pitch control system that allows the turbine to vary the pitch angle of the blades, If an active-stall turbine is to limit its power, it pitches its blades to an angle where the airflow around the blades gets detached from the surface of the blades and becomes turbulent, i.e. the blade stalls [7].

The next simulation shows the effect of this fault on the grid frequency Fig -7, the wind system pitch angle Fig -8, reactive and active power of the SCIG Fig -9 & Fig -10 and the rms voltage Fig -11 pre- and after the fault clearance when using pitch controller (Genetic Algorithm PID) and in case of not using controller in two separated study cases.

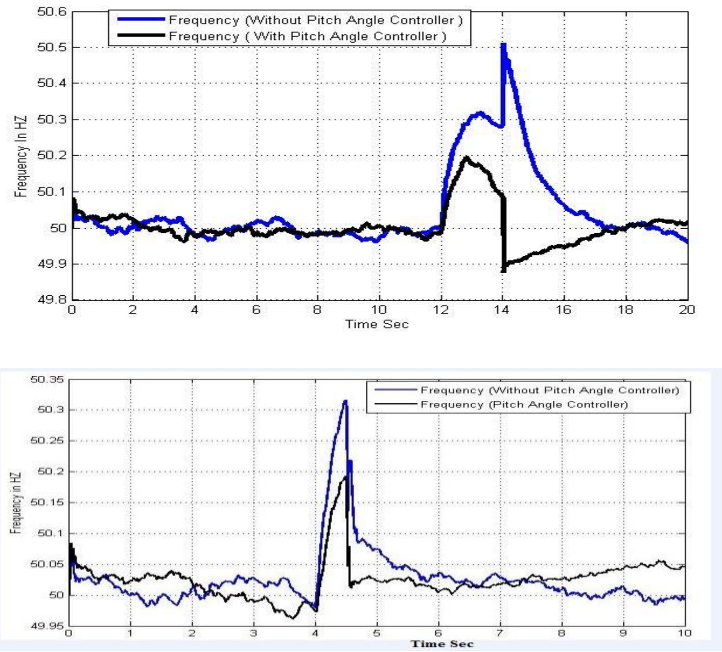



**Fig -7** System frequency in HZ with using pitch angle controller (Genetic Algorithm PID) and without, for both study cases as explained.

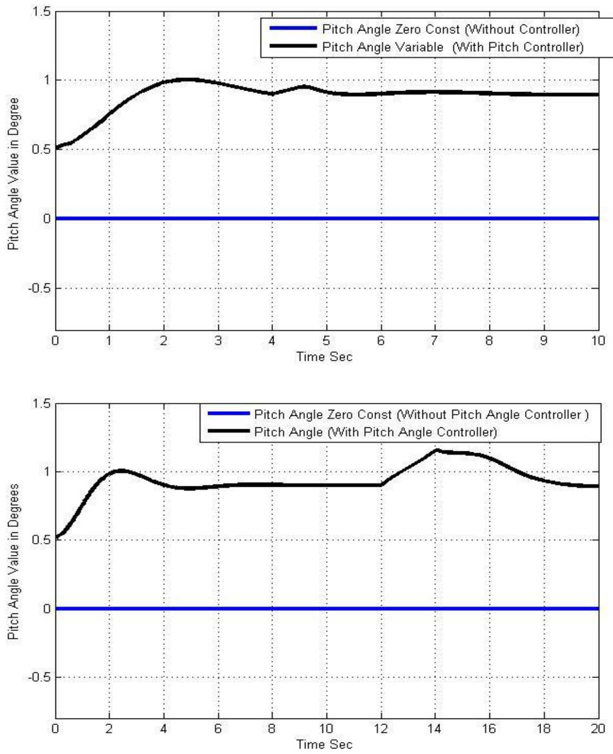



**Fig -8** Wnd turbine pitch angle value (Degree)

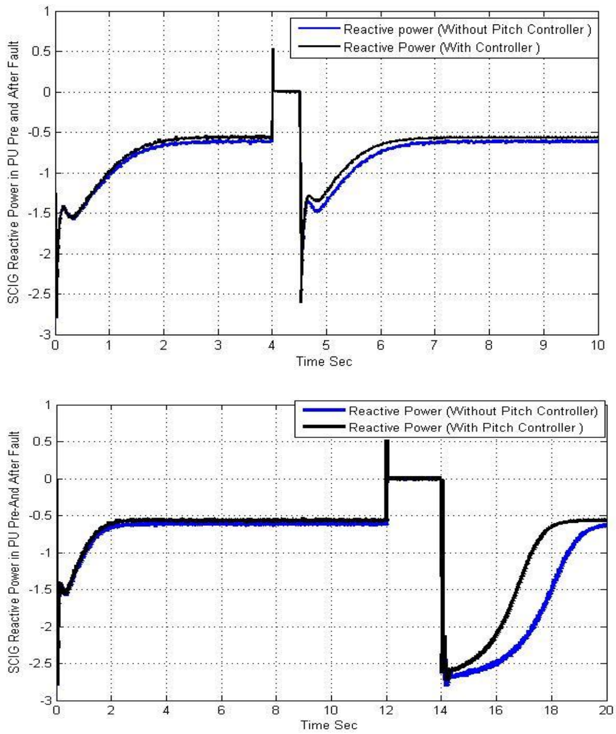



**Fig -9** Reactive power of squirrel cage induction generator with and without pitch controller for both study cases.

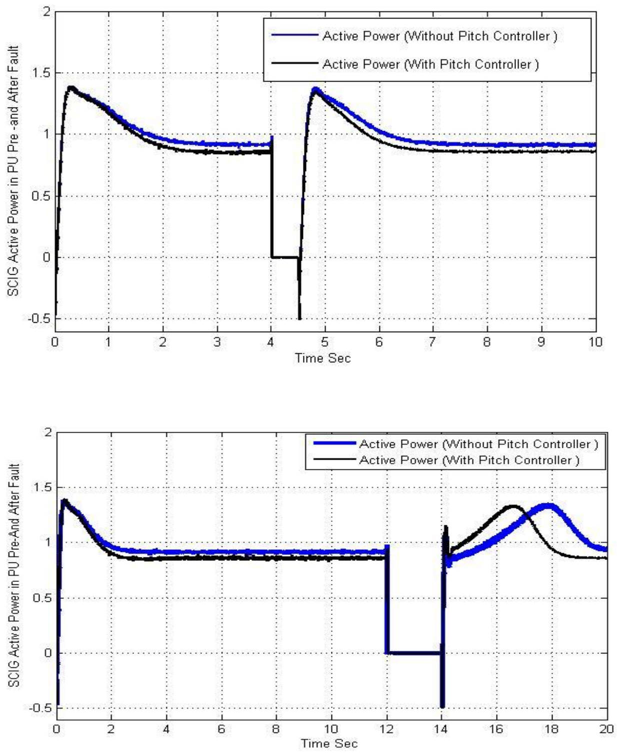



**Fig -10** Active power of squirrel cage induction generator with and without pitch controller for both study cases.

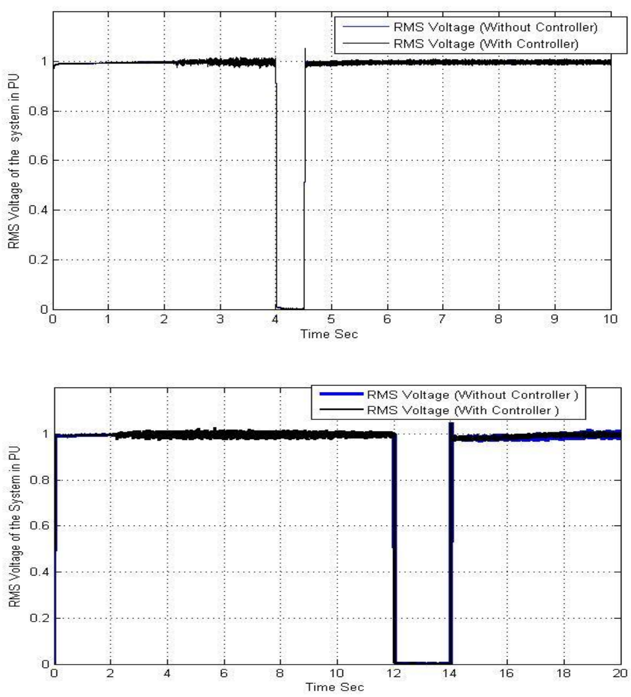



**Fig -11** RMS output voltage per unit in case of using and not using pitch angle controller for both study cases

## 5. CONCLUSIONS

This paper provides an overview about the behavior of a grid connected wind turbine driving squirrel cage induction generator and how the system deals with a severe three phase to ground SC fault, It provides also an overview about the response of the wind turbine pitch angle, the three-phase squirrel-cage induction generator, the grid voltage and frequency before the fault occurrence, during the fault, and after the fault.

In the future work more effective, smart, and fast controller must be designed to dampen the oscillations, or disconnecting the wind turbine system in case of very severe faults.

## REFERENCES

[1] Patel, Mukund R. "Wind and Solar Power Systems." CRC Press, Boca Raton, FL, 1999.
[2] Kling W.L., and Slootweg J.G., Wind Turbines as Power Plants. Proceedings of the IEEE/Cigré Workshop on Wind Powerand the Impacts on Power Systems, p. 7 pp.,(Oslo, Norway), 2002
[3] Chapter 3 - Modeling and Analysis of Induction Machines Power Quality in Power Systems and Electrical Machines (Second Edition), 2015,Mohammad A.S.
[4] Integration of power from offshore wind turbines into onshore grids Offshore Wind Farms, 2016, O.D. Adeuyi, J.
[5] H.M.Elzoghby "Dynamic response and control of a grid connected wind farm with different types of generators" Ph.D theisis, 2011.
[6] HU Jia-bing†, HE Yi-kang," Dynamic modelling and robust current control of wind-turbine driven DFIG during external AC voltage dip research" Received Sept. 12, 2005
[7] A.D., Sørensen P., and Blaabjerg F., Simulation Model of an Active-Stall Fixed-Speed Wind.
[8] ELTRA. Specifications for Connecting Wind Farms to the Transmission Network-Second Edition,2000.
[9] Kling W.L., and Slootweg J.G., Wind Turbines as Power Plants. Proceedings of the IEEE/Cigré Workshop on Wind Powerand the Impacts on Power Systems, p. 7 pp., (Oslo, Norway), 2002.
[10] S. Seman, "Transient Performance Analysis of Wind-Power IG,", Helsinki University of Technology, Espoo, Finland, Nov. 2006.
[11] Hansen A.D., Sørensen P., Blaabjerg F., and Bech J. WIND ENGINEERING , VOL: 26, ISSUE: 4, pp. 191 208, 2002
[12] A survey of fault diagnosis for onshore grid-connected converter in wind energy Volume 66, December 2016,
[13] Experimental enhancement of fuzzy fractional order PI+I controller of grid connected variable speed wind energy Energy Conversion and Management, Volume 123, 1 September 2016,
[14] Analysis of fault current contribution of Doubly-Fed IG Wind Turbines during unbalanced grid faultsOriginal Research Article Renewable Energy, Volume 91, June 2016,
[15] Future research directions for the wind turbine generator systemReview Article Renewable and Sustainable Energy Reviews, Volume 49, September 2015.