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Grid Impacts of Wind Power: A Voltage Stability and Power Quality Control in Electric Power System

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Abstract — *This paper demonstrated the study of the voltage stability of 400kV power system connected by wind power plant, village-Navadra, Gujarat, India. The 9.6MW Induction Generator (IG) is installed at Navadra wind power plant and connected to the 400kV. The analysis of the power system connection between grid and wind turbine plant is proposed. The MATLAB/Simulink program with sim power system tool box is used to analyze the proposed system. The simulation results show that effectiveness of different FACTS devices and different types of generator based wind power plant such as induction generator, doubly fed induction generator and synchronous generator with full scale converter.*

Keywords*- voltage stability, power quality, Flexible ac transmission system (FACTS).*

I. INTRODUCTION

Renewable energy generation systems are being connected in increasing numbers to power systems worldwide. Doubly Fed Induction Generators (DFIG) is proving most successful over Fixed Speed Generator & Synchronous Systems due to rapid growth of power electronic control technology. The Variable Speed Wind Turbine-Generators (DFIG) improves the stability and power quality of system.

A 9.6-MW wind farm consisting of twelve 800 kW wind turbines connected to a 33-kV distribution system exports power to a 400-kV grid through a 46-km, 33-kV feeder at Village: Navagam, Dist: Rajkot, Gujarat. A 2300V, 2-MVA plant consisting of a motor load (1.68 MW induction motor at 0.93 PF) and of a 200-kW resistive load is connected on the same feeder at bus B33. Both the wind turbine and the motor load have a protection system monitoring voltage, current and machine speed.

This paper demonstrated the analysis of voltage stability of 400kV system which is connected to wind turbines and study the grid impact of wind power on voltage stability and power quality control in electric power system. The proposed system is simulated with different FACTS device such as SVC, STATCOM, SSSC, TCSC and UPFC and different wind turbines such as induction generator, doubly fed induction generator and synchronous generator with full scale converter and observed the effectiveness of different FACTS devices with different generator based wind power plant.

II. FACTS DEVICES FOR WIND POWER SYSTEM

Recent development of power electronics introduces the use of FACTS devices in power systems. FACTS devices are capable of controlling the network condition in a very fast manner and this unique feature of FACTS devices can be exploited to improve the transient stability of a system. Reactive power compensation is an important issue in electrical power systems and shunt FACTS devices play an important role in controlling the reactive power flow to the power network and hence the system voltage fluctuations and transient stability [1]. SVC and STATCOM are members of FACTS family that are connected in shunt with the system. Even though the primary purpose of shunt FACTS devices is to support bus voltage by injecting (or absorbing) reactive power, they are also capable of improving the transient stability by increasing (decreasing) the power transfer capability when machine angle increases (decreases), which is achieved by operating the shunt FACTS devices in capacitive (inductive) mode [2]. Shunt FACTS devices give maximum benefit from their stabilized voltage support when sited at the mid-point of the transmission line [3]. Among the available FACTS devices, the Unified Power Flow Controller (UPFC) is the most versatile one that can be used to improve steady state stability, dynamic stability and transient stability [4].

In general, FACTS Controllers can be divided into four categories: Series Controllers, Shunt Controllers, and Combined series-series Controllers, Combined series-shunt Controllers. FACTS controllers are used for the dynamic control of voltage, impedance and phase angle of high voltage AC transmission lines.

III. HARDWARE OF GRID CONNECTED DFIG

A major emphasis of the present work is to develop an improved system and method to build a hardware platform for high-performance ac drives. The system consist a basic configuration of a DFIG based wind turbine. The stator is normally directly connected to the power system, and the rotor is interfaced through a variable frequency power converter, which decouples the speed of the rotor from the frequency of the power network. The converter system comprises two AC/DC Insulated-Gate Bipolar Transistors (IGBTs) based Voltage Source Converters (VSCs) linked by a DC bus voltage supply. The VSC system allows variable speed operation of the wind turbine by injecting an adjustable voltage into the rotor at slip frequency. In order to cover a wide operating range from sub-synchronous to super-synchronous speeds, the VSC system must operate in all four quadrants, as rotor power will flow bi-directionally. In order to demonstrate the application of such a system to wind power generation the experimental setup is developed which has ability to control rotor current allows for reactive power control and variable speed operation, so it can operate at maximum efficiency over a wide range of wind speeds and improved the quality of power. The software implementation of conventional rotor side converter control and, control of the front end converter is used.

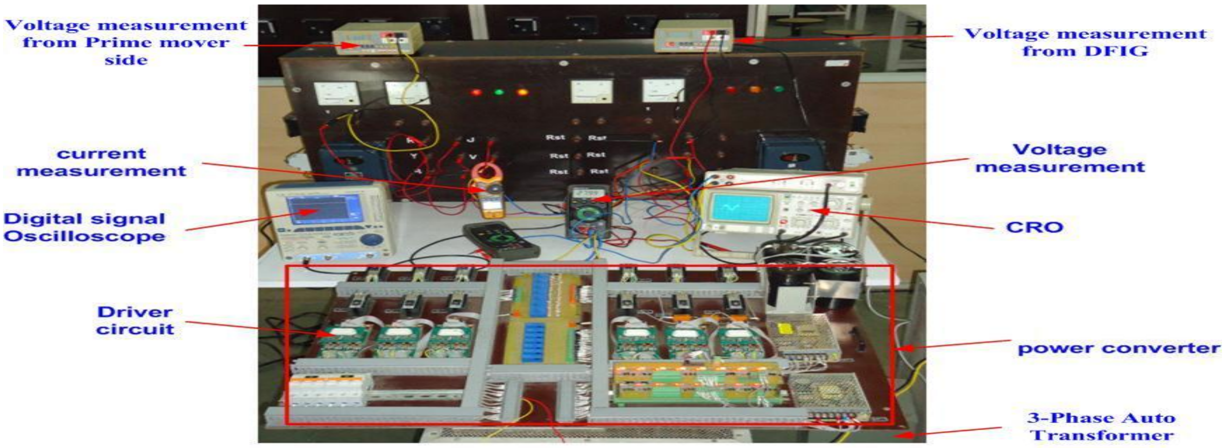

Fig.1. Complete Hardware Setup

IV. WIND POWER PLANT

The model is based on the steady- state power characteristics of the turbine. The stiffness of the drive train is infinite and the friction factor and the inertia of the turbine must be combined with those of the generator coupled to the turbine. The output power of the turbine is given by the following equation:

$$P_m = C_p(\lambda, \beta)\rho A/2V^3 wind \tag{1}$$

Where P_m is mechanical output power of the turbine (W), C_p is performance coefficient of the turbine, ρ is the air density (kg/m3), A is turbine swept area (m2), Vwind is wind speed (m/s), λ is tip speed ratio of the rotor blade tip speed to wind speed and β is Blade pitch angle (deg).

2.1 Wind turbine Squirrel Cage Induction Generator:

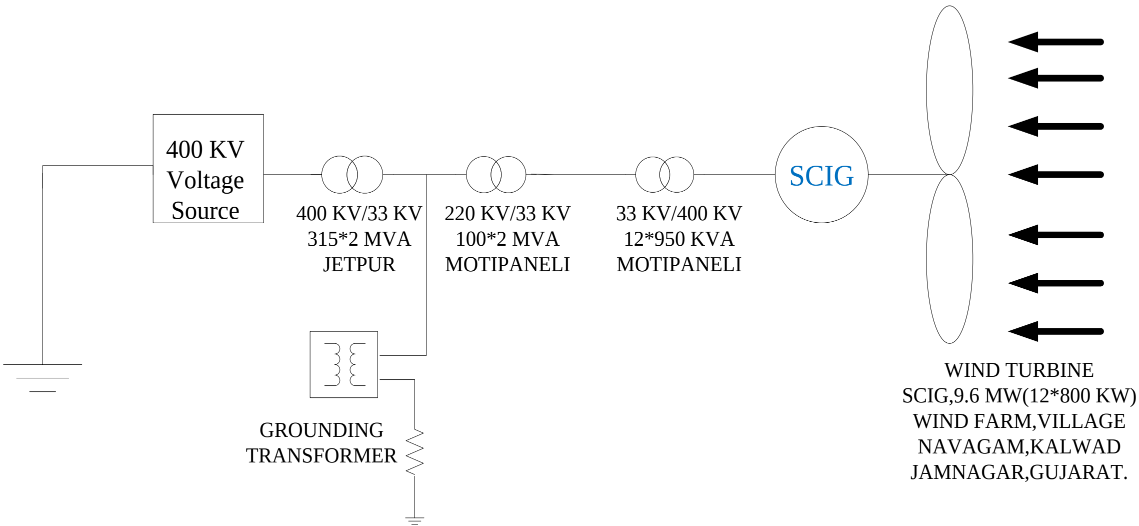

Fig.2. Single Line Diagram of a 9.6 Mw wind farm system

A wind farm consisting of twelve 800-kW wind turbines is connected to a 33-kV distribution system exports power to a 400-kV grid through a 30-km 33-kV feeder. The 9.6-MW wind farm is simulated by three pairs of 800-kW wind-turbines. Wind turbines use squirrel-cage induction generators (SCIG). The stator winding is connected directly to grid and the rotor is driven by a variable-pitch wind turbine. The pitch angle is controlled in order to limit the generator output power at its nominal value for winds exceeding the nominal speed (9 m/s). In order to generate power the IG speed must be slightly above the synchronous speed. Speed varies approximately between 1 pu at no load and 1.005 pu at full load. Each wind turbine has a protection system monitoring voltage, current and machine speed.

Reactive power absorbed by the IGs is partly compensated by capacitor banks connected at each wind turbine low voltage bus (400 kvar for each pair of 800- kW turbine). Open the "Wind Farm" block and look at "Wind Turbine 1". Open the turbine menu and look at the two sets of parameters specified for the turbine and the generator. Each wind turbine block represents four 800-kW turbines. The turbine mechanical power as function of turbine speed is displayed for wind speeds ranging from 4 m/s to 10 m/s. The nominal wind speed yielding the nominal mechanical power (1pu=3 MW) is 9 m/s. In this simulation, the system is observed during 20 s.

The wind speed applied to each turbine is controlled by the "Wind 1" to "Wind 3" blocks . Initially, wind speed is set at 8 m/s, then starting at t=2s for "Wind turbine 1", wind speed is rammed to 11 m/s in 3 seconds. The same gust of wind is applied to Turbine 2 and Turbine 3, respectively with 2 seconds and 4 seconds delays. Then, at t=15 s a temporary fault is applied at the low voltage terminals (400 V) of "Wind Turbine 2".

2.2 Wind turbine Doubly Fed Induction Generator

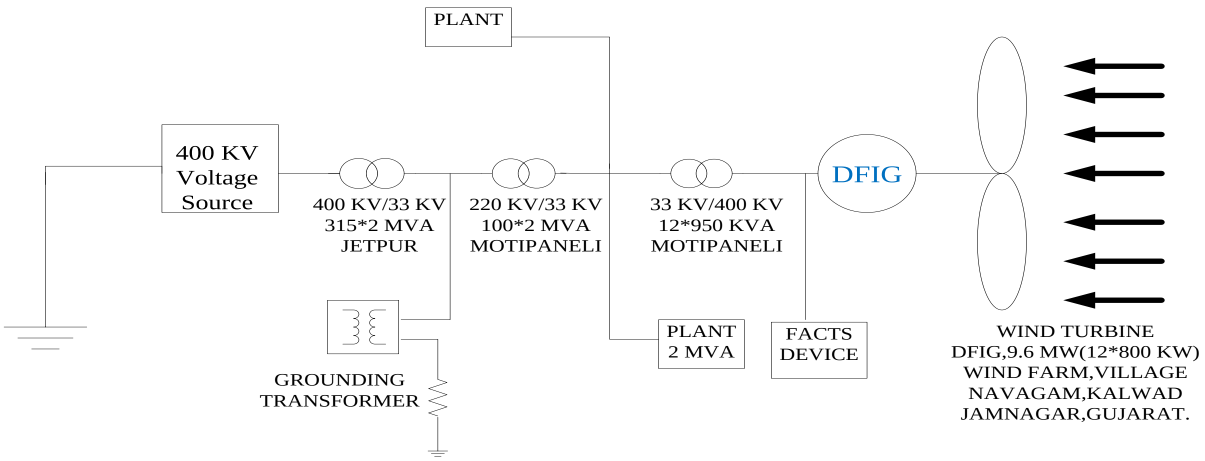

Fig.3. Single Line Diagram of a 9.6 MW Doubly Fed Induction Generator based Wind Farm System

A 9.6-MW wind farm consisting of twelve 800 kw wind turbines connected to a 33-kV distribution system exports power to a 400-kV grid through a 46-km, 33-kV feeder at Village: Navagam, Dist: Rajkot, Gujarat. A 2300V, 2-MVA plant consisting of a motor load (1.68 MW induction motor at 0.93 PF) and of a 200-kW resistive load is connected on the same feeder at bus B33. Both the wind turbine and the motor load have a protection system monitoring voltage, current and machine speed. The DC link voltage of the DFIG is also monitored.

Wind turbines use a doubly-fed induction generator (DFIG) consisting of a wound rotor induction generator and an AC/DC/AC IGBT-based PWM converter. The stator winding is connected directly grid while the rotor is fed at variable frequency through the AC/DC/AC converter. The DFIG technology allows extracting maximum energy from the wind for low wind speeds by optimizing the turbine speed, while minimizing mechanical stresses on the turbine during gusts of wind. The optimum turbine speed producing maximum mechanical energy for a given wind speed is proportional to the wind speed. For wind speeds lower than 10 m/s the rotor is running at sub synchronous speed. At high wind speed it is running at hyper synchronous speed The turbine mechanical power as function of turbine speed is displayed for wind speeds ranging from 5 m/s to 16.2 m/s. The DFIG is controlled in order to follow the red curve. Another advantage of the DFIG technology is the ability for power electronic converters to generate or absorb reactive power, thus eliminating the need for installing capacitor banks as in the case of squirrel-cage induction generators.

The simulation mode allows transient stability type studies with long simulation times. In this simulation, the system is observed during 50 s.

2.3 Wind turbine Synchronous Generator

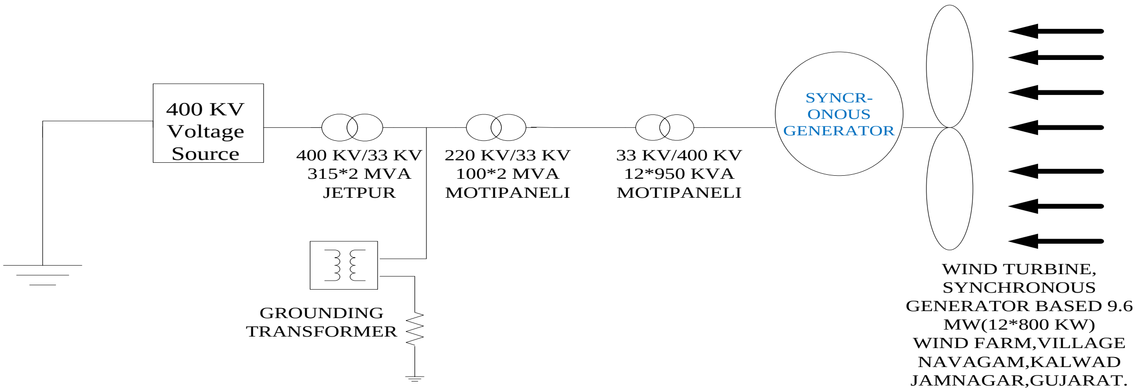

Fig.4. Single Line Diagram of Synchronous Generator Based Wind Farm system

The wind turbine presented in this simulation model consists of a synchronous generator connected to a diode rectifier, a DC-DC IGBT-based PWM boost converter and a DC/AC IGBT-based PWM converter. The Type of technology allows extracting maximum energy from the wind for low wind speeds by optimizing the turbine speed, while minimizing mechanical stresses on the turbine during gusts of wind. The simulation is performed using Matlab/Simulink software.In this simulation model the wind speed is maintained constant at 15 m/s. The control system of the DC-DC converter is used to maintain the speed at 1 pu. The reactive power produced by the wind turbine is regulated at 0 Mvar. The sample time used to discretize the model (Ts= 2 microseconds) is specified in the Initialization function of the Model Properties.

V. SIMULATION MODEL AND RESULTS

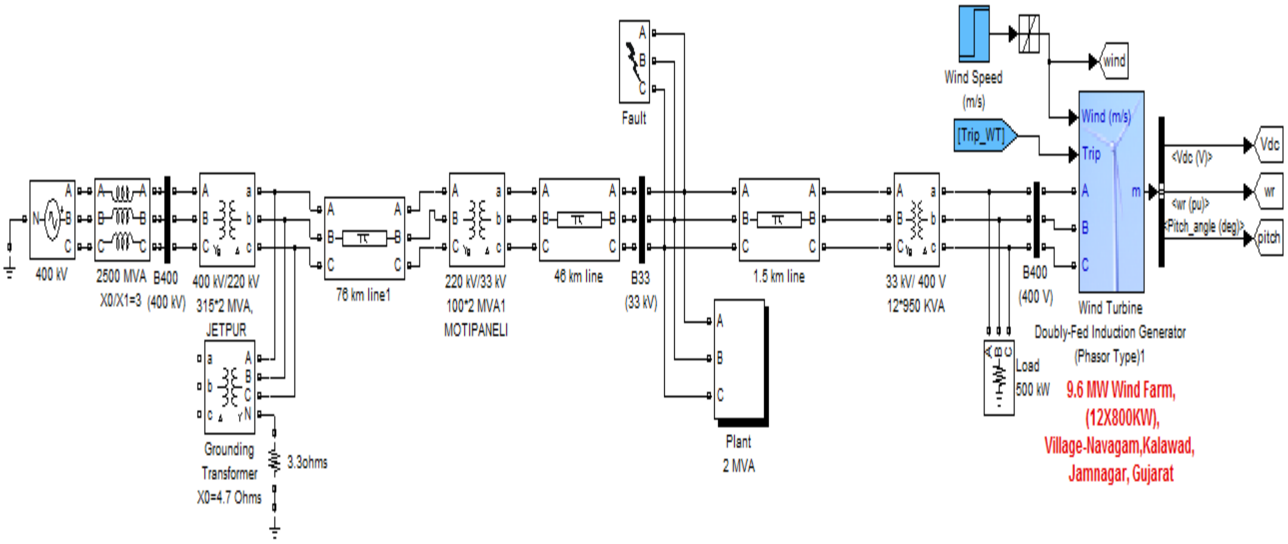

Fig. 5 A 9.6 MW DFIG Based Wind Farm without Fault and without FACT Device

Now the above figure shows the simulation model of a 9.6 MW Doubly Fed Induction Generator based Wind Farm. Here the simulation model run without any fault in the system and without any FACT device and observed the simulation results of Grid and Wind Turbine Generator without Fault and Without FACT Device. With the help of above model, we simulated with different FACTS devices and different types of generator based wind power plant such as induction generator, doubly fed induction generator and synchronous generator with full scale converters.

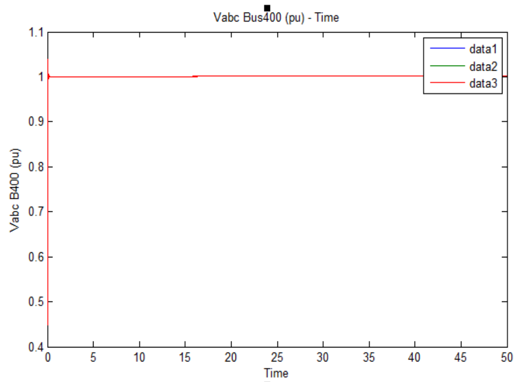

Fig.6 Vabc at Bus400(pu) V/s Time of Grid

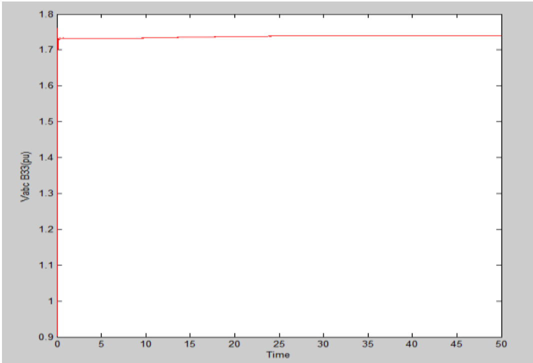

Fig.7 Vabc at Bus33 (pu) V/s Time of Grid

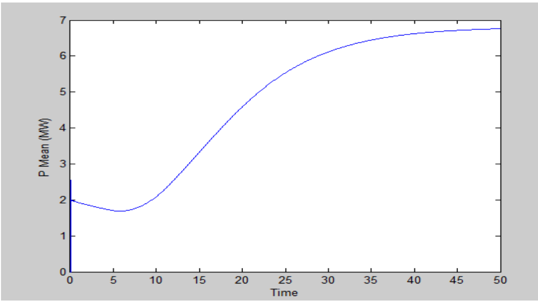

Fig.8 P_ mean (MW) V/s Time of WTG

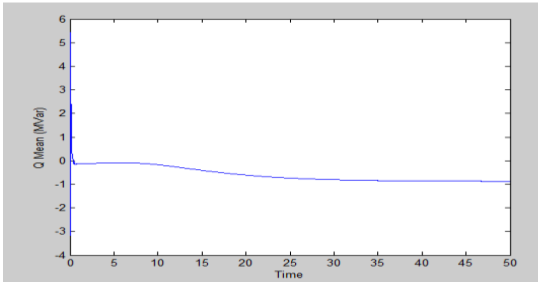

Fig.9 Q _ mean (MVar) V/s Time of WTG

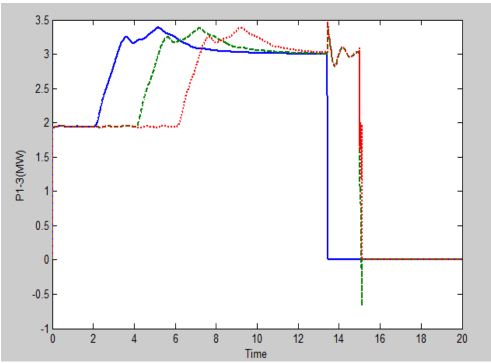

Fig.10 P1-3 V/s Time of Wind Turbine Generator

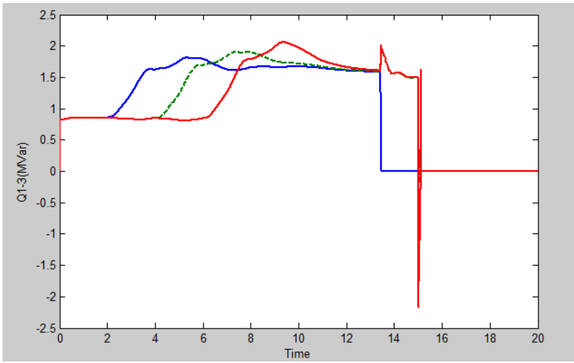

Fig.11 Q1-3 V/s Time of Wind Turbine Generator

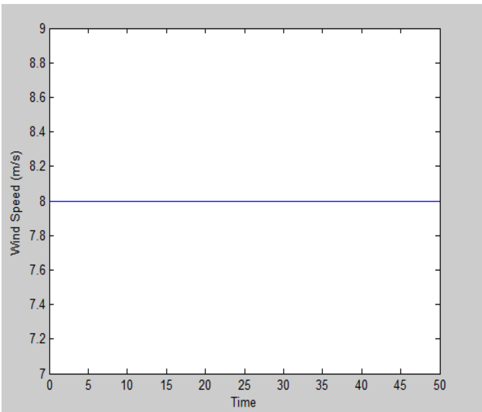

Fig.12 Wind Speed (m/s) V/s Time of WTG

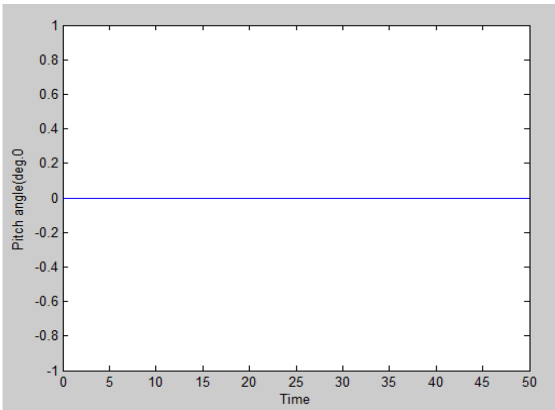

Fig.13 Pitch Angle (deg.) V/s Time of WTG

Simulations and Simulation results are aimed to present the grid impact of wind power in voltage stability and power quality control in electrical power system. Here we demonstrated the transient analysis of a wind-driven squirrel cage induction generator (SCIG), Doubly Fed Induction Generator (DFIG) and Synchronous generator with full-scale converter. For comparison purpose, wind-driven squirrel cage induction generator (SCIG), Doubly Fed Induction

Generator (DFIG) and Synchronous generator with full-scale converter at fixed and variable speeds are studied using MATLAB/SIMULINK software package. First we simulated the wind-driven doubly fed induction generator without fault and with fault condition. Then we apply the different FACTS devices such as SVC,STATCOM ,SSSC,TCSC and UPFC in point of common coupling at various bus systems of a 9.6 MW Doubly Fed Induction Generator (DFIG) based wind farm system, observed the simulated system and made the comparison of DFIG with different FACTS devices. Finally we concluded the DFIG with FACTS device named Unified Power Flow Controller (UPFC) system is good as compared to DFIG with other FACTS devices. Second we simulated the wind-driven Squirrel Cage Induction Generator without fault and with fault condition. Then we apply the different FACTS devices such as SVC,STATCOM,SSSC,TCSC and UPFC in point of common coupling at various bus systems of a 9.6 MW Squirrel Cage Induction Generator (SCIG) based wind farm system, observed the simulated system and made the comparison of SCIG with different FACTS devices. Finally we concluded the SCIG with FACTS device named Unified Power Flow Controller (UPFC) system is good as compared to SCIG with other FACTS devices.

At last, we simulated the 9.6 MW Synchronous Generators (SG) with Full Scale Converter based wind farm system. We applied the fault of a six-cycle 0.25 pu voltage drop programmed at t=0.03s and observed the simulated system as well as data of results. The system recovers after fault elimination. Then we made a comparison table WPP challenges performed by different wind turbine generators such as DFIG, SCIG and SG with full scale converter. We divided the performances of different wind turbines into four parts like Excellent, Good, Limited and Dependent.

	TYPES OF WIND TURBINE GENERATORS			
	WPP CHALLANGES	**DFIG**	**SCIG**	**SYN.GEN.**
1.	Voltage Stability	**E**	**L**	**G**
2.	Active Power Generation/Absorption	**E**	**G**	**G**
3.	Reactive Power Generation/Absorption	**E**		**D**
4.	Voltage Level	**G**	**L**	**G**
5.	Current Level	**G**	**L**	**G**
6.	Generator Speed Stability	**E**	**D**	**G**
7.	DC Voltage Level	**E**		**G**
8.	Rotor Speed	**D**	**D**	**D**
9.	Pitch Angle	**D**	**D**	**D**
10.	Wind Speed	**D**	**D**	**D**

Table: 1. Comparison of WPP Challenges Performed by different Wind Turbine Generators
DFIG-Doubly Fed Induction Generator
SCIG-Squirrel Cage Induction Generator
Syn.Gen.- Synchronous Generator with Full Scale Converter

Performance	**Excellent**	**Good**	**Limited**	**Dependent**
Indicator	E	G	L	D

Table: 2. Performance Indicator Table For Services Performed by different Wind Turbine Generators

VI. CONCLUSION

From the above simulations, Simulation results and comparison tables, we concluded the following points for grid impact of wind power in voltage stability and power quality control in Electrical Power System. Different from SCIG, the Synchronous generator and DFIG are not in need for a fixed capacitor to generate the active power, and grid can easily feed the reactive losses of transmission lines and transformer at any value of SCR. This increases the dynamic stability of DFIG and SG when compared with SCIG. During fault, the SCIG draws higher reactive power against the reactive power of DFIG and reactive power of Synchronous Generator with Full Scale Converter. For the phase-to-ground fault, the time required to recover stability is higher than as compared to DFIG and SG with full scale converter. DFIG and Synchronous Generator with Full Scale converter are more stable than SCIG Wind Farms. The performance of DFIG is better than SCIG and Synchronous Generator with Full Scale Converter. Among all the FACTS devices such as SVC, STATCOM, SSSC, UPFC and TCSC the performance of Unified Power Flow Controller is better as compared to other FACTS devices.

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