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Comparative analysis of induction generators for wind power system

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Abstract —This paper describes the performance comparison of a wind power systems based on two different induction generators as well as the experimental demonstration of a wind turbine simulator for the maximum power extraction. The two induction machines studied for the comparison are the squirrel-cage induction generator (SCIG) and the doubly fed induction generator (DFIG). The techniques of direct grid integration, independent power control, and the droop phenomenon of distribution line are studied and compared between the SCIG and DFIG systems. Both systems are modeled in Matlab/Simulink environment, and the operation is tested for the wind turbine maximum power extraction algorithm results. Based on the simulated wind turbine parameters, a commercial induction motor drive was programmed to emulate the wind turbine and is coupled to the experimental generator systems. The turbine experimental results matched well with the theoretical turbine operation.

Keywords- Doubly Fed Induction Machines, Field-Oriented Control, Maximum Power Tracking, Wind Power System.

I. INTRODUCTION

The increasing emphasis on renewable wind energy has given rise to augmented attention on more reliable and advantageous electrical generator systems. Induction generator systems have been widely used and studied in wind power system because of their advantages over synchronous generators, such as smaller size, lower cost, and lower requirement of maintenance. The straightforward power conversion technique using squirrel-cage induction generator (SCIG) is widely accepted in fixed-speed applications with less emphasis on the high efficiency and control of power flow. However, such direct connection with grid would allow the speed to vary in a very narrow range and thus limit the wind turbine utilization and power output. Another major problem with SCIG power system is the source of reactive power; that is, an external reactive power compensator is required to hold the distribution line voltage and prevent the whole system from overload. On the other hand, the doubly fed induction generator (DFIG) with variable-speed ability has higher energy capture efficiency and improved power quality and thus has attracted more attentions. With the advent of power electronic techniques, a back-to-back converter, which consists of two bidirectional converters and a dc link, acts as an optimal operation tracking interface between generator and grid . Field-oriented control (FOC) is applied to both rotor- and stator-side converters to achieve desirable control on voltage and power. Generally, the FOC has been presented based on DFIG mathematical equations only. However, a three-phase choke is commonly used to couple the stator-side converter into the grid.

Therefore, this project proposes the FOC schemes of stator-side converter involving the choke, and it turns out that both stator- and rotor side converter voltages consist of a current regulation part and a cross-coupling part. First, this paper presents an experimental setup to emulate the wind turbine operation in torque control mode and thus to obtain a power operation curve for optimal power control. Second, the modeling and simulation of SCIG and DFIG wind systems are studied. Comparison between SCIG without static var compensator (STATCOM) and SCIG with STATCOM as well as DFIG system clearly indicates difference in resulted distribution line voltage. This project is organized as follows. The wind turbine is modeled and simulated using the turbine emulator, and an expression of optimal output power versus rotor speed is proposed, the SCIG wind power system is established based on wind turbine system. The DFIG is introduced by mathematical model, indicating the relationship of voltage, flux, and torque. At last, steady-state and dynamic experiment/simulation results are presented and discussed.

1.1 Motivation

Renewable energy application as an integral part of the “big” energy picture has gained a tremendous amount of interest in recent years due to their environmental friendly characteristics and finite resources of fossil fuel. Nowadays, wind farms are being planned and/or utilized around the world in large numbers, and the power ratings of wind turbines both, individually and on farms, are increasing. DFIG are invariably the choice when it comes to multi-megawatt variable-speed variable-pitch wind turbine. DFIG- based wind turbine provides power conversion at lower cost and reduced mechanical stress due to its unique feature which is partial size rate rotor power converter needed to achieve the full control of the machine at variable wind speed.

Typically, DFIG - based wind turbines are installed far away (hundreds of miles are very common) from the load centers where the electric power grid is weak and characterized by low short-circuit ratios and voltage regulation problems. Limited reactive power capability is a major drawback of DFIG-based wind turbine when it is connected to a weak power grid.
Hence, in order to integrate DFIG into the modern power system, it is important to assess wind turbines dynamic behavior, steady state performance, and impacts on the interconnected power network with regard to its active and reactive power capability and voltage control.
Therefore, integration of energy storage systems (ESS) into DFIG-based wind turbine is an attractive approach for reducing the fluctuation of the output power of DFIG-based wind turbine due to wind speed variation. This dissertation is motivated for a better understanding of the DFIG-based turbine in terms of modeling, vector control and its interaction to the power grids.

II. LITERATURE REVIEW

M.Orabi, T.Ahmed and M. Nakaoka proposed this paper highlights the induction generator emciency as a basic lector for operating the wind turbine connected to utility grid, through AC/DC/AC converter, at its maximum power trackha To have maximum power extracted from the wind turbine through the induction generator, the loading parameters have to be controlled in the direction of maximum efficiency of the induction generator. To anatine the effect of the generator efficiency, a simple equivalent circuit is proposed to represent the AC/DC/AC converter-grid combination as rein by the induction generator to simplify the analysis. The steady state performance of the induction generator is invested An accurate range of operation for the load parameter is developed. This analysis is based on the condition of operating the system not only on the m-um power extracted of the wind turbine but also on the maximum induction generator efficiency[1].

M.Molinas , J.A.Suul and T.Undeland proposed this paper analyzes the extent to which the low voltage ride through (LVRT) capability of wind farms using squirrel cage generators can be enhanced by the use of a STATCOM, compared to the thyristor controlled staticvar compensator (SVC). The transient stability margin is proposed as the indicator of LVRT capability. A simplified analytical approach based on torque-slip characteristics is first proposed to quantify the effect of the STATCOM and the SVC on the transient stability margin. Results from experiments with a STATCOM and a 7.5 kW induction machine emulating a wind turbine are used to validate the suggested analytical approach. Further verifications based on detailed time-domain simulations are also provided. Calculations, simulations and measurements confirm how the increased STATCOM rating can provide an increased transient stability margin and thus enhanced LVRT capability. Compared to the SVC, the STATCOM gives a larger contribution to the transient margin as indicated by both calculations and simulations. The inaccuracies introduced by neglecting the flux transients in the suggested approach are discussed and found reasonable for an estimation method when considering the simplicity compared to detailed time-domain simulation studies. A method for estimating the required rating of different compensation devices to ensure stability after a fault is suggested based on the same approach[2].

Z.Chen,J.M.Guerrero and F.Blaabjerg proposed this paper reviews the power electronic applications for wind energy systems. Various wind turbine systems with different generators and power electronic converters are described, and different technical features are compared. The electrical topologies of wind farms with different wind turbines are summarized and the possible uses of power electronic converters with wind farms are shown. Finally, the possible methods of using the power electronic technology for Improving wind turbine performance in power systems to meet the main grid connection requirements are discussed[3].

Y.Lei.A.Mullane, and Lightbody proposed Due to its many advantages such as the improved power quality, high energy efficiency and controllability, etc. the variable speed wind turbine using a doubly fed induction generator (DFIG) is becoming a popular concept and thus the modeling of the DFIG based wind turbine becomes an interesting research topic. Fundamental frequency models have been presented but these models are often complex with significant numerical overhead as the power converter block consisting of power control, rotor side and grid side converter control and DC link are often simulated in detail. This paper develops a simple DFIG wind turbine model in which the power converter is simulated as a controlled voltage source, regulating the rotor current to meet the command of real and reactive power production. This model has the form of traditional generator model and hence is easy to integrate into the power system simulation tool such as PSS/E. As an example, the interaction between the Arklow Bank Wind Farm and the Irish National Grid was simulated using the proposed model. The model performance and accuracy was also compared with the detailed model developed by DIgSILENT. Considering the simplification adopted for the model development, the limitation and applicability of the model were also discussed in this paper[4].

R. Ganon. G. Sybille, and S. Bernard proposed this paper presents the modeling and real-time simulation of a doubly-fed induction generator driven by a wind turbine in large power systems. The Matlab/Simulink/Sim Power Systems software is used to develop the model for simulation of electromagnetic transients in power systems. The code generated by the

Real-Time Workshop of Simulink is linked to the Hypersim digital real-time simulator. A case study example of real-time simulation of wind turbines in a generic series compensated power system is presented [5].

III. METHODOLOGY

3.1 Wind Energy

Wind power is the conversion of wind energy into a suitable form of energy, such as using wind turbines to generate electricity, windmills for mechanical power, wind pumps for water pumping, or sails to propel ships. The total amount of economically extractable power available from the wind is considerably more than present human power use from all sources. Wind power, as an alternative to fossil fuels, is abundant, renewable, widely spread, clean, and produces no greenhouse gas emissions during operation. Wind power is the world's rapid growing source of energy.
The majority of electricity is generated by burning coal, rather than more eco-friendly methods like hydroelectric power. This use of coal causes untold environmental damage through CO2 and other toxic emissions. The energy sector is by far the biggest source of these emissions, both in the India and globally, and if we are to tackle climate change it is clear we need to move away from burning limited fossil fuel reserves to more sustainable and renewable sources of energy.

3.2 Wind Turbine

A wind turbine is a machine for converting the kinetic energy in the wind into mechanical energy. If the mechanical energy is used directly by machinery, such as a pump or grinding stones, the machine is called a windmill. If the mechanical energy is then converted to electricity, the machine is called a wind generator.
Wind energy is extracted through wind turbine blades and then transferred by the gearbox and rotor hub to the mechanical energy in the shaft, which drives the generator to convert the mechanical energy to electrical energy. Several models for power production capability of wind turbines have been developed. The mechanical power captured Pmech by a wind turbine, depends on its power coefficient Cp given for a wind velocity and can be represented by

$$P_m = C_p(\lambda, \beta) \cdot \frac{1}{2}\rho A v_w^3 \quad (1)$$

Where ρ and R correspond to the air density and the radius of the turbine propeller, respectively. The power coefficient can be described as the portion of mechanical power extracted from the total power available from the wind, and it is unique for each turbine. This power coefficient Cp is generally defined as a function of the tip speed-ratio which,in turn, is given by λ.

3.3 Induction Machine Analysis

The following figure shows the torque vs speed characteristic of typical squirrel cage induction machine. In the figure, it can be seen that when the induction machine is running at Synchronous speed at the point where the slip is zero i.e. the rotor is spinning at the same speed as the rotating magnetic field of the stator, the torque of the machine is zero. If the induction machine is to be operated as a motor, the machine is to operated just below its synchronous speed.

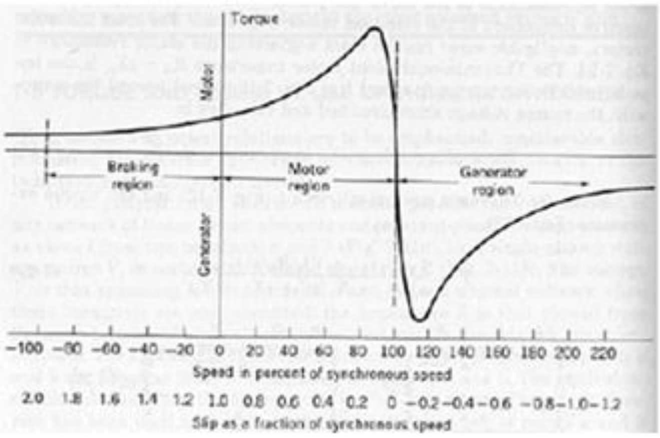

Fig. 1: Torque vs. Speed Characteristics of Squirrel-cage Induction Generator

The other hand, if the induction machine is to be operated as a generator, its stator terminals should be connected to a constant-frequency voltage source and its rotor is driven above synchronous speed (s<0) by a prime mover such as the wind turbine shaft. The source fixes the synchronous speed and supplies the reactive power input required exciting the air magnetic field and hence the slip is negative.

3.4 Induction Generator

Induction generators and motors produce electrical power when their rotor is rotated faster than the synchronous frequency. For a typical four-pole motor (two pairs of poles on stator) operating on a 60 Hz electrical grid, synchronous speed is 1800 rotations per minute. Similar four-pole motor operating on a 50 Hz grid will have synchronous speed equal to 1500 rpm. In normal motor operation, stator flux rotation is faster than the rotor rotation. This is initiating stator flux to induce rotor currents, which create rotor flux with magnetic polarity opposite to stator. In this way, rotor is dragged along behind stator flux, by value equal to slip. In generator operation, a prime mover (turbine, engine) drives the rotor above the synchronous speed. Stator flux still induces currents in the rotor, but since the opposing rotor flux is now cutting the stator coils, active current is produced in stator coils, and motor is now operating as a generator, and sending power back to the electrical grid.

3.5Grid Connected Induction Generator

Grid connected induction generators develop their excitation from the Utility grid. The generated power is fed to the supply system when the IG is run above synchronous speed. Machines with cage type rotor feed only through the stator and generally operate at low negative slip. But wound rotor machines can feed power through the stator as well as rotor to the bus over a wide range known as Doubly Fed Induction Machines .

3.5.1 Fixed Speed Grid Connected Wind Turbine Generator:

The structure and performance of fixed-speed wind turbines as shown in Fig.4.5 depends on the features of mechanical sub-circuits, e.g., pitch control time constants etc.

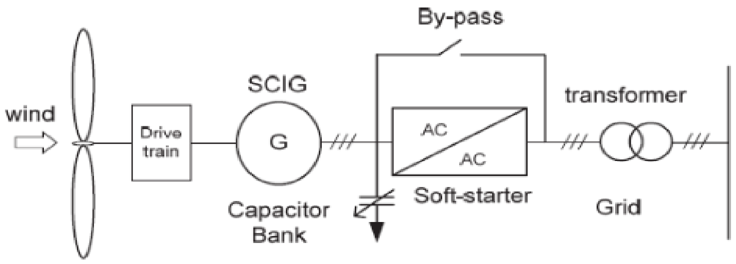

Fig 2 : fixed speed wind turbine with directly grid connected squirrel-cage induction generator.

The reaction time of these mechanical circuits may lie in the range of tens of milliseconds. As a result, each time a burst of wind hits the turbine, a rapid variation of electrical output power can be observed. These variations in electric power generated not only require a firm power grid to enable stable operation, but also require a well-built mechanical design to absorb high mechanical stress, which leads to expensive mechanical structure, especially at high-rated power.

3.5.2 Variable Speed Wind Turbine Generators:

A way to make more convenient turbines is variable speed turbines. Variable speed turbines have become the most dominating type of the yearly installed wind turbines as they can store. some of the power fluctuations due to turbulence by increasing the rotor speed, pitching the rotor blades, these turbines can control the power output at any given wind speed.

Fig.4.6 shows a variable speed turbine connected to a Squirrel- Cage Induction Generator SCIG. Although these direct online systems have been built up to 1.5 MW, but presence of power inverter causes lots of disadvantages such as:

a) This power converter, which has to be rated at 1 p.u. of total system power, is expensive.

b) Converter efficiency plays an important role in total system efficiency over the entire operating range.

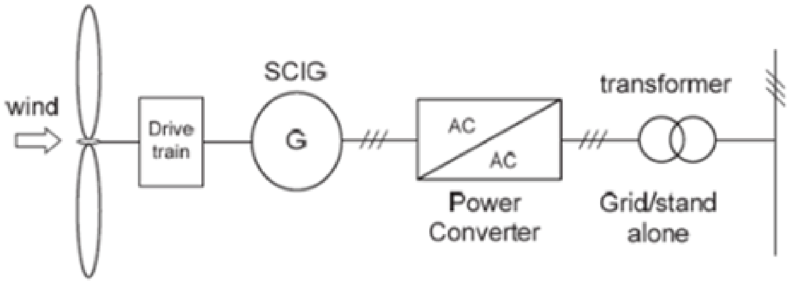

Fig 3: variable speed wind turbine with squirrel-cage induction generator

Another way is using Doubly Fed Induction Generator DFIG, as shown in Fig.3.3 It consists of a stator connected directly to grid and a rotor – via slip rings – is connected to grid through four-quadrant ac-to-ac converter based on insulated gate bipolar transistors (IGBTs). This system offers the following advantages:

1. Reduced inverter cost, because inverter rating is typically 30% of total system power.
2. Improved system efficiency.
3. Power-factor control can be implemented at lower cost.
4. It has a complete control of active and reactive power.

The doubly fed induction generator with a power converter shown in above fig. is a simple and highly controllable way to transform the mechanical energy from the variable speed rotor to a constant frequency electrical utility grid.

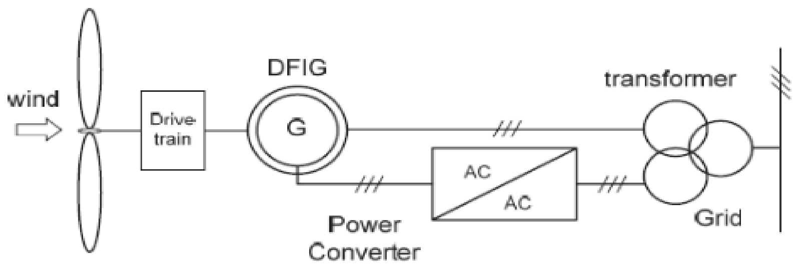

Fig 4: Variable speed wind turbine with doubly-fed induction generator

The main reason for the popularity of the doubly fed wind induction generators connected to the national networks is their ability to supply power at constant voltage and frequency while the rotor speed varies.

3.6 Doubly Fed Induction Generator (DFIG)

Traditionally, the dynamic slip control is employed to fulfill the variable-speed operation in wind turbine system, in which the rotor windings are connected to variable resistor and control the slip by the varied resistance. This type of system can achieve limited variations of generator speed, but external reactive power source is still necessary. Consequently, to completely remove the reactive power compensation and to control both active and reactive power independently, DFIG wind power system is one of most popular methods in wind energy applications.
This paper reproduces DFIG model first of all and then concentrates on the controlling schemes of power converters, in which the active and reactive power are controlled independently. In particular, the stator-side converter control involving an RL series choke is proposed. Both controlling of rotor- and stator-side converter voltages end up with a current regulation part and a cross-coupling part. The wind turbine driving DFIG wind power system consists of a wound-rotor induction generator and an ac/dc/ac insulated gate bipolar transistor (IGBT)-based pulse width-modulated (PWM) converter (back-to-back converter with capacitor dc link). In this configuration, the back-to-back converter consists of two parts: the stator-/grid-side converter and the rotor-side converter. Both are voltage source converters using IGBTs, while a capacitor between two converters acts as adc voltage source. The generator stator windings are connected directly to grid (with fixed voltage and frequency of grid) while the rotor winding is fed by rotor-side converter through slip rings and brushes, at variable frequency.

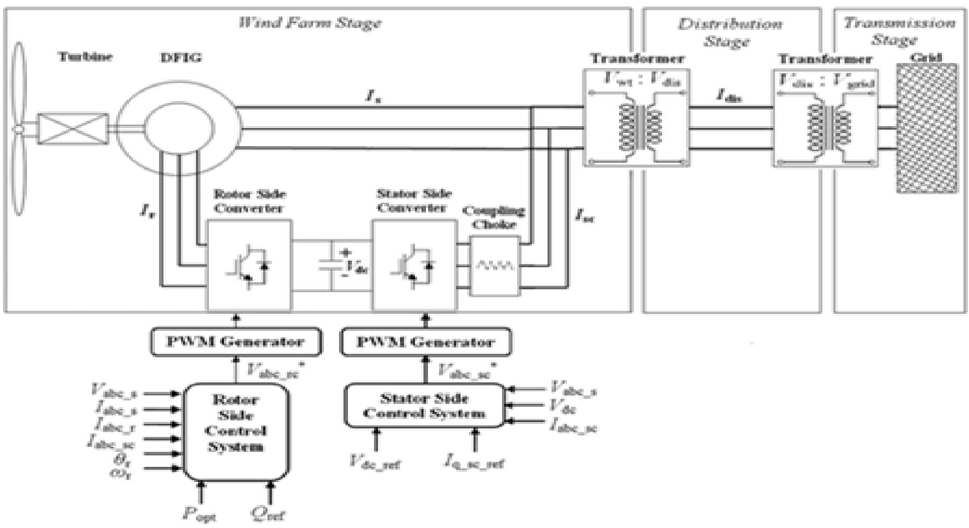

Fig. 5 DFIG wind power system

The control system is divided into two parts-stator-side converter control system and rotor-side converter control system. An equivalent circuit of DFIG is depicted, and the relation equations for voltage V, current I, flux Ψ, and torque Te.

3.7 SCIG Wind Power System

Shows the schematics of the SCIG system including the wind turbine, pitch control, and reactive power compensator. The entire system includes three stages for delivering the energy from wind turbine to the power grid. The first one is wind farm stage which handles with low voltage Vwt, the second is distribution stage which has medium voltage Vdis, and the third is grid transmission stage which has high voltage Vgrid. The three-phase transformers take care of the interface between stages [9]. As mentioned, nominal power PnSCIG is considered as active power reference to regulate the pitch angle while Vdis and Id is denote the distribution line-to-line voltage and phase current, and they are monitored to favor the reactive power compensation for distribution line. This fairly straightforward technique was first used since it is simple and has rugged construction, reliable operation, and low cost. However, the fixed-speed essential and potential voltage instability problems severely limit the operations of wind turbine [1], [3]. Since SCIG is of fixed-speed generator, for a particular wind speed, the output active power is fixed as well. Thus, with the increase of wind speed, so does the output power until the nominal power is reached.

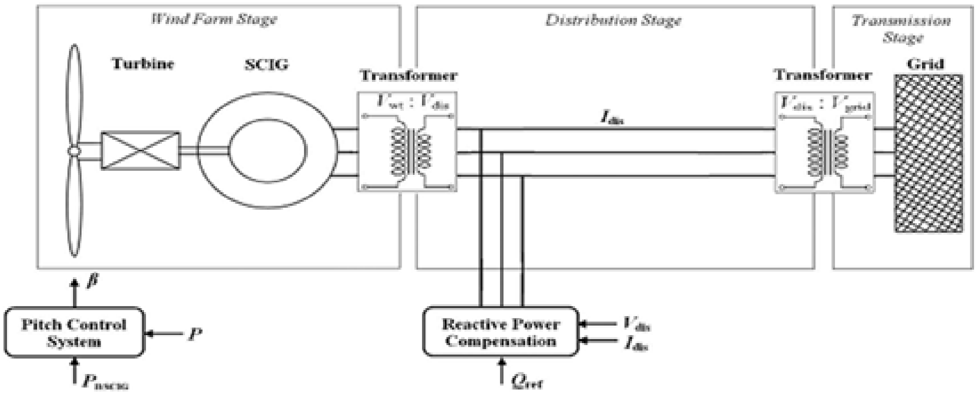

Fig. 6 SCIG winds power system topology.

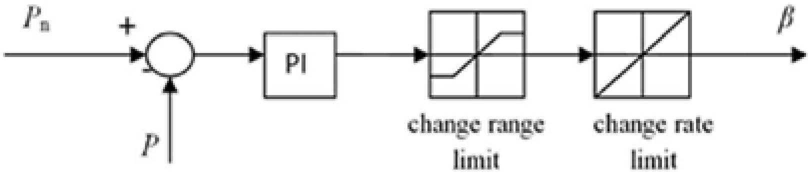

Fig.7. Pitch angle control

The wind speed at this moment is called nominal wind speed. Beyond this speed, the pitch angle system will prevent the output power from exceeding the nominal value. That is, when the wind speed is below nominal value, the power capture can vary with the change of wind speed; and when the wind speed is above nominal value, the pitch angle control system will limit the generated power by changing the pitch angle. In such way, the output power will be stabilized at nominal value where the wind speed is always above nominal speed. The pitch angle is determined by an open loop control of regulated output active power and by that shown .Due to the huge size of blade and, thus, inertia, pitch angle has to change in a slow rate and a reasonable range. It is also worthy to notice that, without reactive power source, the SCIG system tends to lead to a voltage droop in distribution line which will cause overload problem. In the simulation section, the comparison between SCIG system with and without STATCOM is conducted.

3.7.1 STATCOM

A STATCOM or Static Synchronous Compensator is a regulating device used on alternating current electricity transmission networks. It is based on a power electronics voltage-source converter and can act as either a source or sink of reactive AC power to an electricity network. If connected to a source of power it can also provide active AC power. A STATCOM works by rebuilding the incoming voltage waveform by switching back and forth from reactive to capacitive load. If it is reactive, it will supply reactive AC power. If it is capacitive, it will absorb reactive AC power. This is how it acts as a source/sink.

IV. EXPERIMENTAL RESULT

The below fig shows that if the wind speed is change turbine speed is fluctuate that why voltage is fluctuate up to the final simulation value of 5. The GSC in DFIG maintain the DC link voltage to almost constant value at 1200 V during normal operation .In that case initial value is 1.1 at the point of 0.1 the rotor speed constant .Vdc is constant hence Wr is also constant . Active power to maintain the fluctuation is in Vdc. Initial value is 9 then the voltage is at dc link 1200v and the reactive power is also constant.

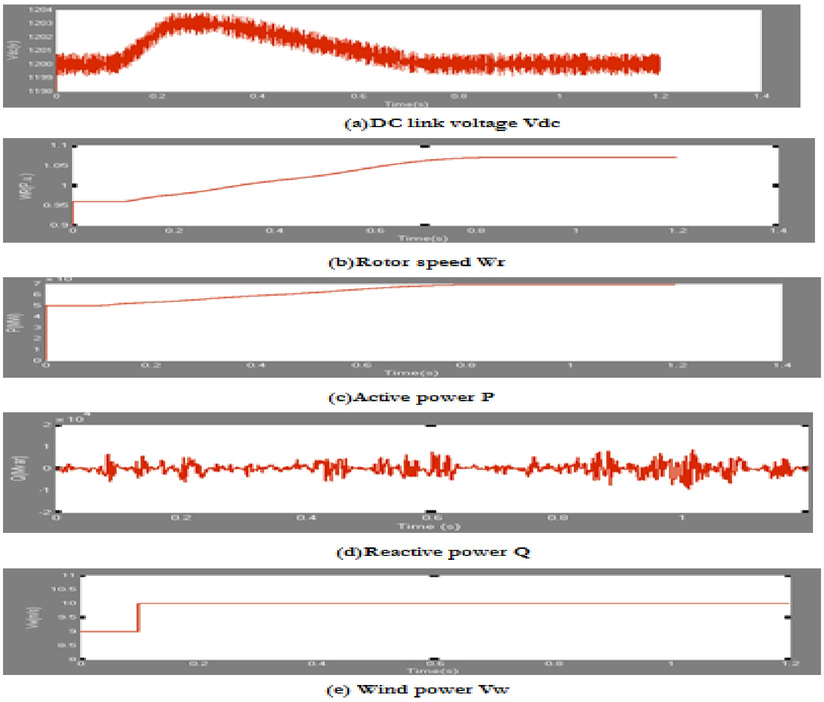

Fig 8 Wind step response (a) DC link voltage Vdc (b) Rotor speed Wr (c) active power P (d) Reactive power Q (e) wind speed Vw

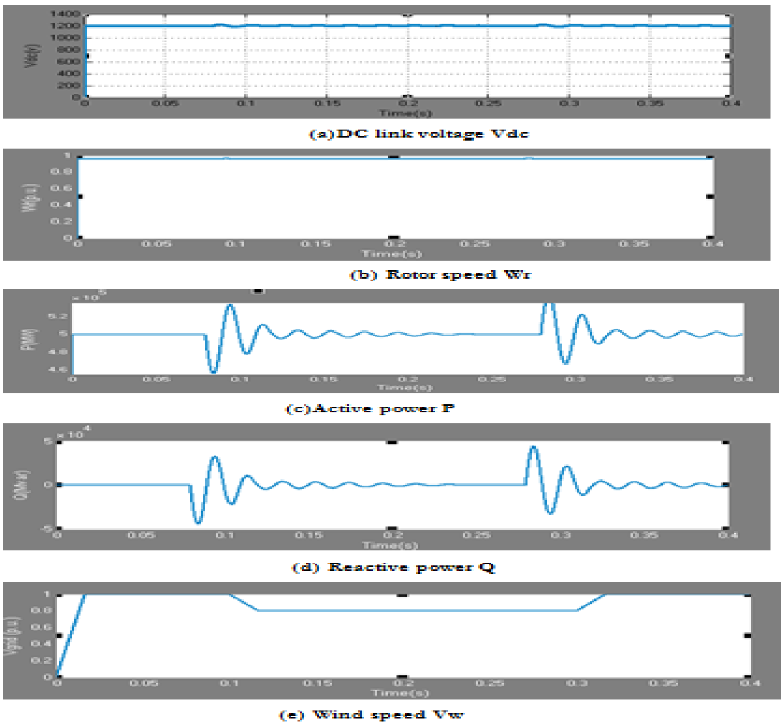

Fig 9. Dynamic response to grid voltage droop (a) DC link voltage Vdc (b)Rotor speed Wr (c)Active power P(d) Reactive power Q(e) Grid voltage Vgrid

The above fig . shows that Second, the system dynamic response to varied wind speeds is investigated. Due to the large H of the system, dynamic variation can last and be observed in a long time period before converging to the steady-state values. To shorten such period, H = 0.1 s is used in this part of simulation. With stable steady-state initial values, three regular types of wind speeds are examined for dynamic responses, including step, ramp, and gusty winds. The varied winds and corresponding results for Vdc Q are shown in Figs, where the system can always reach a new optimal steady state after a few seconds. In the aforementioned results, the reduced inertia constants can only decrease the converging time, making the system reach a new steady state quicker, and it has no effects on steady-state values. At last, the system dynamic response to a grid disturbance is Vw=9m/s, a remote voltage droop in grid is programmed from t =0.09 to 0.29s. The dynamic responses are presented in Fig. During this process, since the wind speed remains the same, control system effectively makes the system recovers in approximate 0.1 s.

Simulation Result Of Squirrel Cage Induction Generator

A traditionally SCIG wind power system is developed in matlab / Simulink . in order to investigate the system performance . fig 6.7 shows the dyanamic variation and steady state of pitch angle β, generator speed Wr, produced active power P and consumed reactive power Q.

- A ramp wind speed Vw the wind speed increase slovely 8m/s and reach final constant from t=10s to t= 16s and it remains constant to the end of simulation t=40s after system reach steady state.

- The flxtuation in result during t=0 to t=2.5s due to initial condition . In simulation the initial speed of generator is set as slip = -0.01p.u. with respect to the synchronous speed and then response to the wind speed input disturbance other initial value for power and voltage are zero

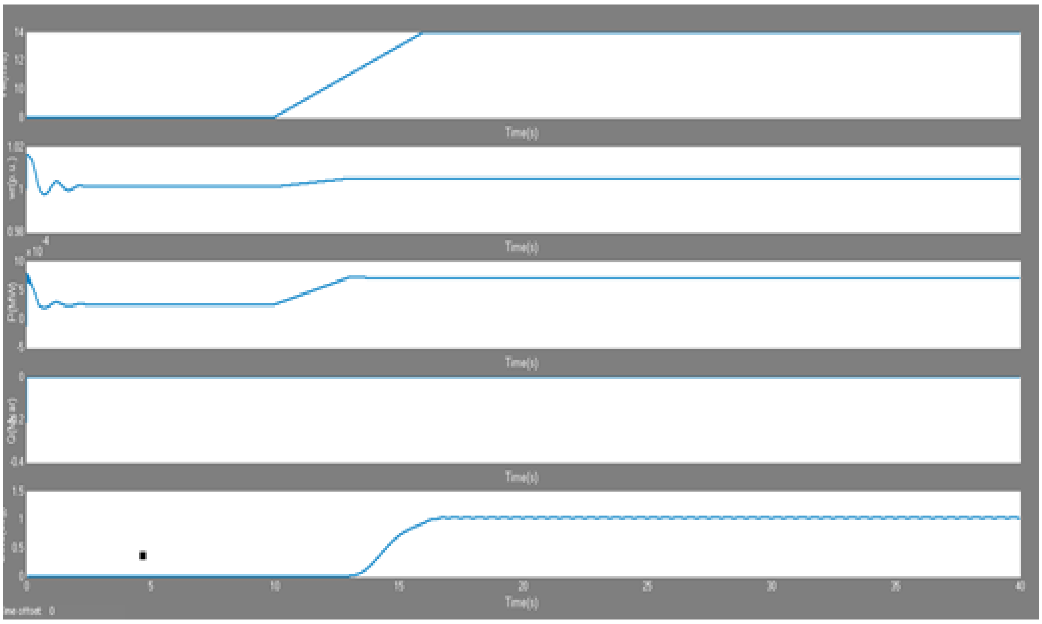

Fig.10 simulation result for SCIG system (a) wind speed Vw (b) generator speed Wr (c)active power P (d) reactive power Q (e) pitch angle β

- The steady state result for Vw = 8 m/s indication operation of p= 0.29 Mw (fig.4.1) if the value is lower than the nominal value of 0.855 MW . after t=10 sec with increase of Vw p until t=13 s when Vw exceed nominal value (11m/s).

- The pitch control effectively limits the output P around the nominal value of 0.855MW and settled new pitch angle at roughly t=17 sec.

- The rotor speed can only vary in fixed speed system and impossible to active power output the active power output at Vw =8m/s and > 11m/s in SCIG are 0.29 and0.855MW. the lower than DFIG system.

Simulation Result Of SCIG with STATCOM And SCIG without STATCOM

To provide necessary reactive power a STATCOM is added on the distribution line investigate the improvement.

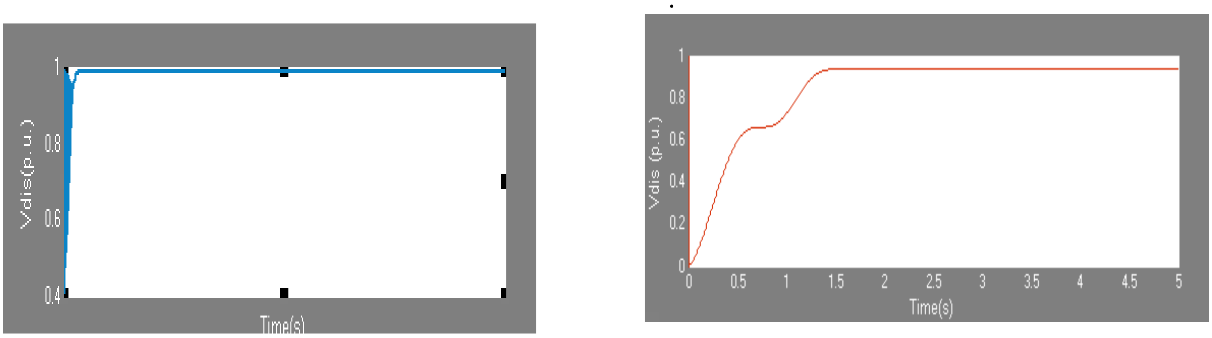

Fig.11. Distribution voltage for SCIG system with/ without STATCOM and DFIG system

The above fig 10 shows the distribution line voltage can drop by approximately 0.055 p.u. in SCIG system without STATCOM will be a potential induction of overload in system.SCIG system with STATCOM can hold distribution voltage to 0.99 p.u. and favorable to grid system stability.

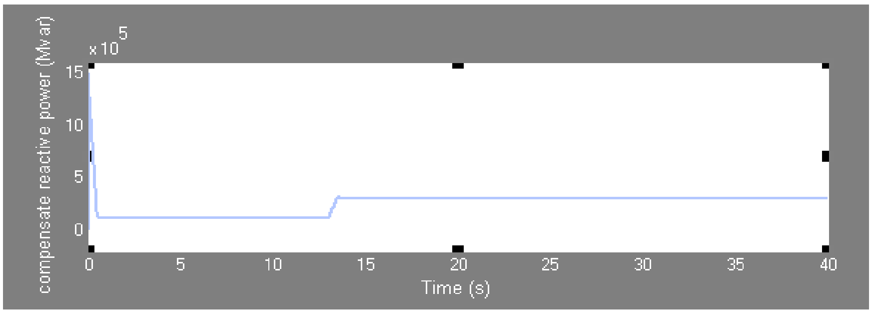

Fig. 12. STATCOM compensated reactive power

The above fig. 11 the compensate reactive power from STATCOM and equal to 0.3 Mvar in the steady state a little bit less than the real consumed as same as reactive power in SCIG. although STATCOM provide impressive help on constant distribution line voltage.

V. CONCLUSION

This dissertation work the comparison of the wind turbine systems using SCIG and DFIG generator systems. With the experimentally investigated wind turbine model, a SCIG and a DFIG wind power systems are modeled and simulated in Matlab/Simulink. An optimal active-power-versus-rotor-speed relationship has been proposed for turbine model first, and it functions as a lookup table for tracking the maximum output active power. The SCIG system presents the need of external reactive power source to support grid voltage, and it can keep the output power at the nominal level by pitch control but cannot accordingly change the rotor speed to achieve maximum wind power capture at different wind speeds. In contrast, the DFIG system does not need reactive power compensator to hold distribution line voltage and achieves optimal active power controlling. Both voltage control schemes for two converters consist of a current regulation part and a cross-coupling part. The turbine emulator system performs well and follows the theoretical and simulated maximum power extraction points in different operating condition.

Table 1 : SCIG and DFIG wind power system

	SCIG	**DFIG**
Speed Operation	fixed or limited variable	variable
Line Voltage	drop by 0.05 p.u.	stable constant
Control Scheme	pitch control	FOC
Active Power	varies with v_w but not optimally	varies with v_w optimally
Reactive Power	uncontrollable; need compensation	controllable
Power Rating	< 1MW	> 1MW
Cost and Complexity	low and simple	high

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