SIMULATION OF GRID CONNECTED INDUCTION GENERATORS FOR POWER QUALITY IMPROVEMENT

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ABSTRACT-***This paper distinguishes the performance of wind power systems for two types of induction generators to have better performance and maximum extraction of power using FACTS devices. Doubly fed induction generator (DFIG) and squirrel- cage induction generator (SCIG) are the two types of generators classified. The FACTS devices used are STATCOM and UPFC. Direct grid integration, independent power control and droop phenomena of distribution line are the techniques used for two types of induction generators. All these systems are modeled and simulated in MATLAB/Simulink software.***

INDEX TERMS-*Doubly fed induction machines, hybrid power system, maximum power tracking, reactive power compensation, field oriented control, unified power flow control, SSSC, STATCOM.*

INTRODUCTION

Today's alarming feature is managing energy demand using renewable energy sources like wind, PV, diesel system, micro turbine etc. The major energy source used for wind power grid is wind. Wind is the lucrative source of power with many advantages. Generators play vital role in wind power generation. Among them the induction generators are more advantageous when compared with the synchronous generators in size, efficiency, cost, maintenance[2][3]. In wind power systems the straight forward power conversion technique, direct grid integration methods are used for squirrel cage induction type generators which is of fixed speed application with low efficiency, control of power flow and requires reactive power compensator externally to prevent system from over load. Doubly fed induction type of generator of improved power quality, high energy capturing efficiency is used for variable speed applications. DFIG has back to back converter with two bidirectional converters and DC link in between them for optimal operation tracking interface between grid and the generator. Here the field oriented control(vector control method) technique, independent power control methods are used[4]-[6]. In DFIG FOC method is applied to both stator and rotor for the maximum control of power and voltage.The coupling choke is used to connect grid with stator side converter . As the wind power system is always fluctuating harmonics will be present in transmission line this can be overcome by using various power electronic devices like STATCOM, UPFC, DPFC. This paper deals with UPFC to have minimum harmonic distortion with maximum power extraction. First, this paper explains the complete experimental setup for wind power system and its controlling methods. Second is simulation of SCIG, DFIG with wind power system. Third is simulation of the Induction generators using STATCOM,UPFC in grid. Finally, comparison of both induction generators in power grid with and without UPFC is analyzed.

WIND TURBINE

A wind turbine by using the power of wind, drives an electrical generator and produce electrical energy. Wind by passing over the blades generate lift and exert turning forces. These rotating blades turns the shaft present in nacelle and goes into gearbox. Gear box adjust the rotational speed which is suitable for generator to convert rotational energy to electrical energy with the use of magnetic fields. Kinetic energy is extracted by wind turbine from the swept area of blades. The power contained in the wind is given by kinetic energy of flowing air mass per unit time.

$$P_{air} = 0.5\rho A V_\infty^3 \quad (1a)$$

P_{air} is power contained in wind (watts), ρ is air density(1.225kg/m^3at 15^o c and normal pressure), A is swept area (square meters) and is wind velocity without rotor reference[3],[8].C_p (Power coefficient) reduces the power transmitted to the rotor of wind turbine

$$C_p = \frac{P_{Wind\ turbine}}{P_{Air}} \quad (1b)$$

$$P_{Wind\ turbine} = \rho C_p(\lambda,\beta) A V_\infty^3 \quad (1c)$$

C_p value depends on tip speed ratio λ, and pitch angle β as shown in Fig.1. A non linear model describes $C_p(\lambda,\beta)$ as[8]

$$C_p(\lambda,\beta) = c_1(c_2 - c_3\beta - c_4\beta^2 - c_5)e^{-c_6} \quad (2)$$

Where c_1=0.5, c_2=116/λ_i, c_3=0.4, c_5=5, $c_6 = 21/\lambda_i$, and

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

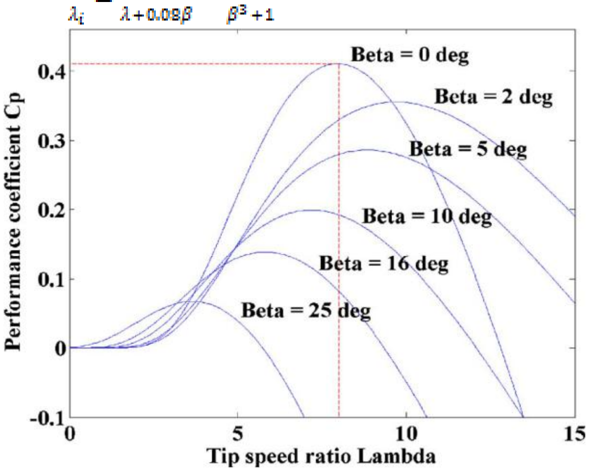

Fig-1: C_p-λ curve for the turbine model

$$\lambda = \frac{\omega R}{V_\infty}$$

R is radious of swept area(meters), ω is rotational speed of rotor(rpm) .

we obtain maximum value of $c_p$from graph in Fig.2. for power coefficient and tip speed ratio. The torque for wind turbine in torque control mode operation is as follows

$$T = \frac{P}{W_r} = 0.5\rho\pi R_{blade}^3 v_W^2 \frac{c_p}{\lambda} \quad (4)$$

$$= 0.5\rho\pi R_{blade}^3 v_W^2 C_m$$

where C_m is torque performance coefficient depends on pitch angle, wind speed and angular frequency. At any particular wind speed we can obtain torque and output

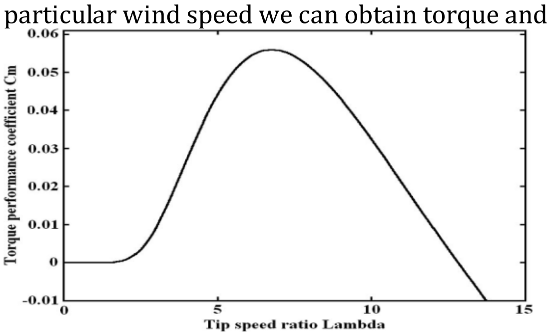

Fig-2: C_m-λ curve for the turbine emulator

power by changing speed of rotor. In configuration of wind turbine emulator system c_m , torque commands are calculated by giving the angular frequency as feedback to the controller.

SCIG WIND POWER SYSTEM

SCIG wind power system consists of mainly three stages for delivering the energy from turbine to grid. All the three stages are having different voltage levels and regarded on these voltage the stages are classified as wind farm stage(low voltage V_{wt}), distribution stage(medium voltage V_{dis}) and grid transmission stage (high voltage V_{grid})[10]. Three phase transformers interface all these three stages. Regulation of pitch angle is based on nominal power P_{nSCIG} , this is considered as reference active power. V_{dis}, I_{dis} are line-to-line voltage and phase current, which are required for reactive power compensation of distributed line. Firstly the straight forward technique is used in SCIG is simple, reliable, less cost with rugged construction and limitations of potential voltage instability, fixed wind speed requirement limited its performance[2],[4]. For a particular speed of wind the output active power is constant in fixed speed generator of SCIG. So the wind speed is proportional to active power until nominal power is reached. At nominal power the wind speed is called nominal wind speed. After this nominal wind speed the pitch angle controlling action takes place and prevent the active power not exceeding nominal value. In this way the output power is controlled when the wind speed is above nominal range. The pitch angle will be determined by using open loop control of regulated active power shown in Fig .4. Pitch angle control is done mechanically so exact result will not be obtained due to some loss. As the turbine blades are large, inertia and pitch angle changes should be in slow range and reasonable which lead to voltage droop in the distribution line resulting in overload problem without reactive power compensator. So to avoid this problem static compensator is used in SCIG. The schematic diagram of SCIG is given in Fig.3.

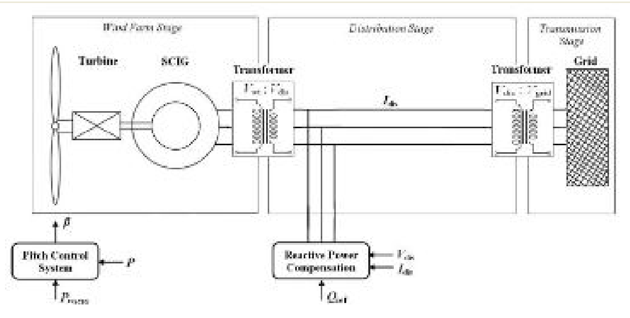

Fig-3: SCIG wind power system topology

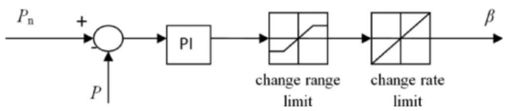

Fig-4: Pitch angle control

DFIG WIND POWER SYSTEM

Primarily dynamic slip control method is used to fulfill the variable speed operation for wind turbine. In this rotor winding is connected to variable resistor and slip is controlled by varying resistance[4],[11]. Achieving limited variations of generated speed and necessity of external reactive power compensator are disadvantages of this method. For complete generation of power without reactive power compensator and control of both active, reactive powers independently DFIG is used in wind power systems[2],[4],[8]. In this DFIG the need of statcom is absent due to presence of back to back converter. This paper produces DFIG model first and then controlling methods of power converters regulating the active and reactive power independently. The stator side converter control involves an RL series choke. Controlling of both rotor side and stator side converter voltages end with cross coupling part and current regulation part.

The DFIG wind power system consists of wound rotor induction and ac/dc/ac IGBT based PWM converter as shown in Fig.6. The back to back converter has two parts, the stator grid side converter and rotor side converter. The voltage source converters using IGBT's and capacitor present between the two converters act as DC voltage source. The stator windings of generator, grid are connected to each other on one side where as rotor side converter, turbine are connected to each other by using slip rings and brushes at variable frequency.

The equivalent circuit of DFIG is shown in Fig 5 and equations[4],[11],[12] related to it are as follows:

$$V_{ds} = R_s \text{Ids} - \omega_s \Psi_{qs} + d\Psi_{ds}\, dt$$

$$V_{qs} = R_s \text{Iqs} + \omega_s \Psi_{qs} + d\Psi_{qs}\, dt \qquad (5)$$

$$V_{dr} = R_r \text{Idr} - s\omega_s \Psi_{qr} + d\Psi_{dr}\, dt$$

$$V_{qr} = R_r \text{Iqr} + s\omega_s \Psi_{dr} + d\Psi_{qr}\, dt \qquad (6)$$

$$\Psi_{ds} = L_s \text{Ids} + L_m \text{Idr}$$

$$\Psi_{qs} = L_s \text{Iqs} + L_m \text{Iqr} \qquad (7)$$

$$\Psi_{dr} = L_r \text{Idr} + L_m \text{Ids}$$

$$\Psi_{qr} = L_r \text{Iqr} + L_m \text{Iqs} \qquad (8)$$

$$\text{Te} = \frac{3}{2} \text{np}(\Psi_{ds} \text{Iqs} - \Psi_{qs} \text{Ids}) \qquad (9)$$

where $L_s = L_{ls} + L_m$; $\text{Lr} = L_{lr} + L_m$;

$$s\omega_s = \omega_s - \omega_r$$

The above equations represents voltage V, current I, flux Ψ, electromagnetic torque T_e for the equivalent circuit of DFIG. As DFIG uses vector control method all the equations are given with respect to d-axis, q-axis, rotor(r) and stator(s). Here n_p means number of pole pairs L_m is the mutual inductance of generator and J is the coefficient of inertia.

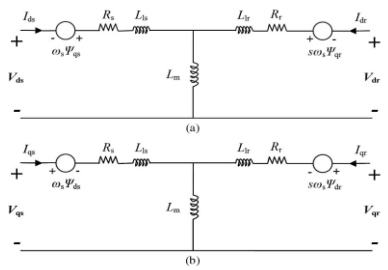

Fig-5: Equivalent circuit of DFIG .(a)d-axis model. (b) q-axis model.

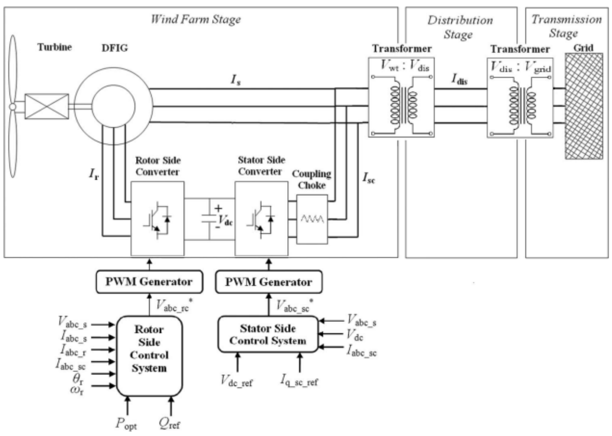

Fig-6: Wind turbine-doubly fed induction generator system

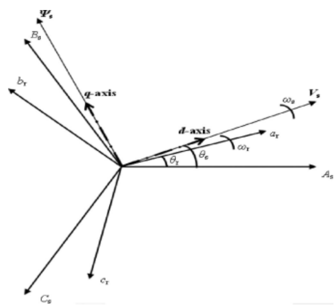

Fig-7: Stator voltage FOC reference frame

Rotor side converter control

If the voltage equations with respect to stator in equation (5) are considered without derivative parts we can have stator flux.

$$\Psi\text{ds} = (\text{Vqs} - \text{RsIqs})/\omega\text{s}$$

$$\Psi\text{qs} = (\text{Vds} - \text{RsIds})/(-\omega\text{s})$$

$$\Psi_s = \sqrt{\Psi_{ds}^2 + \Psi_{qs}^2} \qquad (10)$$

As the stator is directly connected with grid, it will have same magnitude and frequency as that of grid so if we align D-axis with stator voltage vector then $V_{ds} = V_{ds}$, $V_{qs} = 0$, $\Psi_s = \Psi_{ds}$, $\Psi_{ds} = 0$ that means the stator voltage based vector control scheme as shown in Fig.7., similarly from equation(7) to(9) the rotor side converter reference currents are also derived as

$$I_{dr\_ref} = -\frac{2L_sT_e}{3n_pL_m\Psi_s} \quad (11)$$

$$P_{e\_ref} = P_{opt} - P_{loss} = T_e w_r$$
$$P_{loss} = R_sI_s^2 + R_rI_r^2 + R_cI_{sc}^2 + Fw_r^2 \quad (12)$$

In the above equations, F is the friction factor, $I_{sc}$is current on stator side, R_c is the resistance of choke, P_{opt}, P_{e_ref} and P_{loss} are required active power , reference active power, system power loss. From the equations(10)-(12) in which active power is used as command inputs for determining I_{dr_ref} (current reference). As the stator side converters reactive power is zero the output reactive power is the stator reactive output power. Voltage signals V_{dr}^1, V_{qr}^1 are derived by the regulation of currents and coupling parts of voltage V_{dr}^2, V_{dr}^2 are derived from the voltages and flux equations depicted in equations (6)-(8).The control scheme for rotor side is shown in Fig.8.

$$= Q_s + Q_{sc} = Q_s = Im[(V_{ds} + jV_{qs})(I_{ds} + jI_{qs})*]$$
$$= -VdsIqs = -Vds(1/Ls)(\Psi s - LmIqr) \quad (13)$$

$$V_{dr}^2 = R_rI_{dr} - s\omega_s(L_rI_{qr} + L_mI_{qs}) \quad (14)$$
$$V_{qr}^2 = R_rI_{qr} + s\omega_s(L_rI_{dr} + L_mI_{ds})$$

Finally rotor side converter voltage signals in dq-axis is given as

$$V_{drc} = V_{dr} = V_{dr}^1 + V_{dr}^2 \quad (15)$$
$$V_{qrc} = V_{qr} = V_{qr}^1 + V_{qr}^2$$

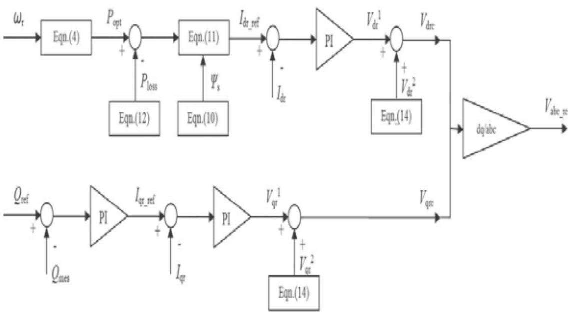

Fig-8: Rotor-side converter control scheme

Stator side converter control

The three phase series RL choke is used between stator and stator side converter. In order to derive the voltage signal for stator side we use cross coupling model. The equations related to voltage with respect to choke (ch) and stator side converter (sc) are given in Fig. 9

$$V_{dsc} = V_{ds} - V_{dch}$$
$$V_{qsc} = V_{qs} - V_{qch} \quad (16)$$

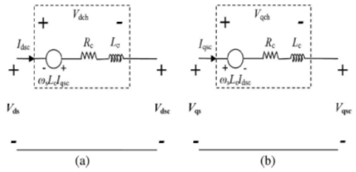

Fig-9: Equivalent circuit of stator side converter choke.(a)d-axis model.(b)q-axis model

For the voltage signals V_{dch}^2, V_{qch}^2 the coupling part is given by

$$V_{dch}^2 = R_cI_{dsc} - w_sL_cI_{qsc} \quad (17)$$
$$V_{qch}^2 = R_cI_{qsc} + w_sL_cI_{dsc}$$

By regulating the currents I_{ds} and I_{qsc}(in which I_{qsc_ref} current reference is given directly and I_{dsc_ref} is determined by regulating dc link voltage) we determine V_{dch}^1, V_{qch}^1 .

Thus we can obtain the voltage signals as

$$V_{dsc} = V_{ds} - V_{dch}^1 - V_{dch}^2 \quad (18)$$
$$V_{qsc} = V_{qs} - V_{qch}^1 - V_{qch}^2$$

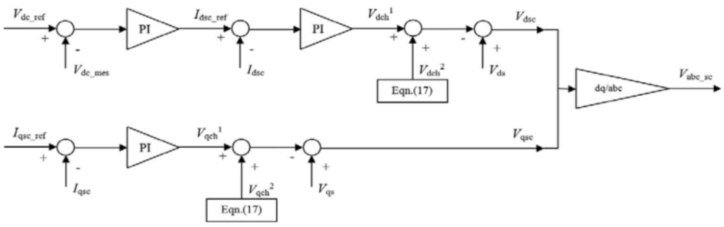

Fig-10: Stator –side converter control scheme

Unified power flow controller

The generation of power using wind energy is enormously increasing now a days because of its advantages. In order to provide more generation with increased system performance and high quality power many of the power electronic devices are used in the system due to this there are some disadvantages that is generation of harmonics resulting in disruptions, disturbances, power quality reduction[15]. To avoid these FACTS controllers are ultimate tools, which provides advantages in both static and dynamic operation by controlling the impedance, phase angle and voltage magnitude. These are having capability of controlling transmission line flows directly. UPFC is one of the new facts controllers that provide quick sensation for high voltage transmission network. It is combination of two devices STATCOM and SSSC with dc link capacitor between them as shown in Fig.11. UPFC is connected in shunt with transmission line by shunt transformer and series with transmission line by series transformer.

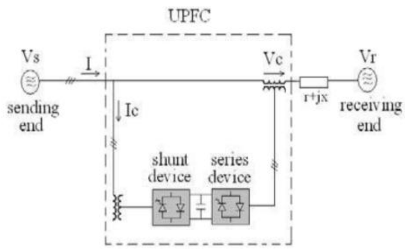

Fig-11: UPFC connected to a transmission line

The series inverter controls both active and reactive power by injecting the three phase voltage of required magnitude and phase angle in series with the line and these voltage injection can be done in many ways like direct voltage injection mode, line impedance emulation mode etc. The shunt inverter operates to inject controllable current to transmission line ,there are also various modes in controlling the shunt inverter like VAR control mode in this feedback signal (dc voltage) is required, this can be overcome by using automatic voltage control mode[16]. The mathematical model of UPFC along with related equations of both powers obtained by using real and imaginary powers of power equation are given in Fig .12 and equations respectively

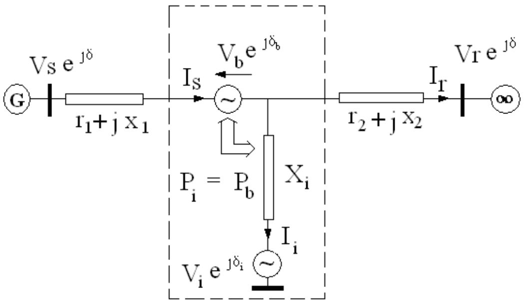

Fig-12: Mathematical model of UPFC

$$P_s = R[V_s\angle\delta \times I_s^*]$$

$$= 0.138 + 0.25 \times \sin(\delta_b - \delta) - 0.138 \times \cos\delta + 1.56\sin\delta + 0.02\cos(\delta_b - \delta)$$

$$Q_s = I_m[V_s\angle\delta \times I_s^*]$$

$$= 1.56 - 1.56 \times \cos\delta + 0.25 \times \cos(\delta - \delta_b) + 0.02\sin(\delta - \delta_b) - 0.138\sin\delta$$

The limits of δ, δ_b are given based on the relations $0 \le \delta_b \le 2\Pi$, $0 \le \delta \le 0.71$ radians. The maximum limit of δ depends on the stability margin. As the parameters δ, δ_b are varied, the changes in the sending end active and reactive powers in shown in Fig.13.

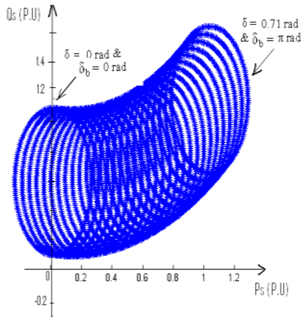

Fig-13: Real power versus Reactive power with UPFC

SIMULATION RESULTS

SCIG

The SCIG wind power system is designed in Matlab/Simulink and the data related to it is given in the table I. The performance of the system can be studied by using ramp signal as wind speed (V_w). Fig .18., shows the dynamic and steady state variations of active power (P), reactive power (Q), generator speed (w_r) and pitch angle (β). Here the pitch angle control takes place only when the wind speed exceeds 11 m/s which is considered as nominal wind speed. After 11 m/s the pitch angle effectively controls active and reactive powers this is clearly explained in the Fig .15. As SCIG is of independent control with narrow rotor speed change we cannot obtain the optimal active power output for this purpose we use Statcom to provide the required reactive power for improving the voltage stability, decreasing the overload problem etc,. The variation in SCIG operation with and without statcom is shown in Fig 16. and obtained that compensated reactive power which is obtained from the statcom is 0.3 MVAR of steady state power[16]. Since the statcom is shunt compensated device it has controlling effect on voltage only and the internal harmonics present due to various indirect loads cannot be rectified .To overcome this problem UPFC is used between generator and grid as shown in Fig 14.

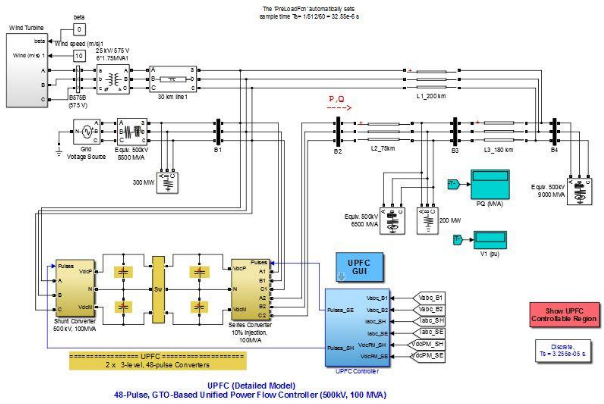

Fig-14: SCIG Wind power system with upfc

TABLE -I

SCIG-BASED WIND POWER SYSTEM PARAMETERS

Parameter	Value
Nominal Wind Speed v_w	11 m/s
Nominal Active Power P_{nSCIG}	0.855 MW
Grid Voltage V_{grid}	120 kV
Grid Frequency f_{grid}	60 Hz
Distribution Line Voltage V_{dis}	12.5 kV
Wind Turbine Bus Voltage V_{wt}	575 V
Stator Resistance R_s	0.0048 p.u.
Stator Leakage Inductance L_s	0.1248 p.u.
Rotor Resistance R_r	0.0044 p.u.
Rotor Leakage Inductance L_r	0.1791 p.u.
Mutual Inductance L_m	6.77 p.u.
STACOM Constant Voltage V_{dc}	4 kV
STACOM Equivalent Capacitance C	625 µF

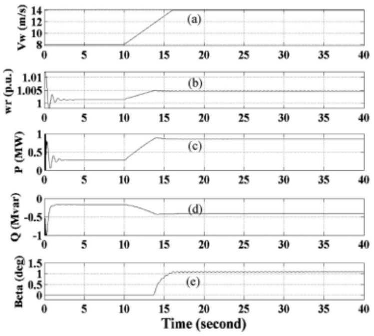

Fig.15. Simulation results of SCIG system:(a)Wind speedV_w;(b)generatorspeedω_r;(c)activepowerP;(d)reactive power Q; (e)pitch angle β

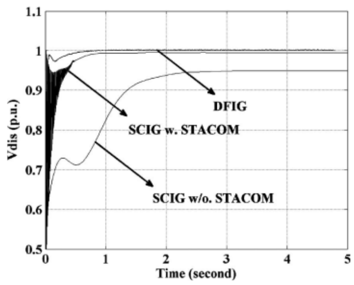

Fig-16: Distribution voltages for SCIG system with/without STATCOM and DFIG system.

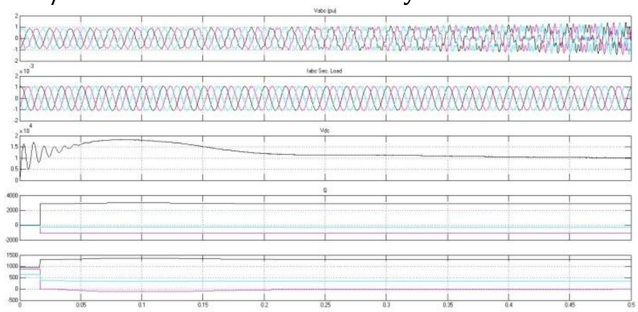

Fig-17: Simulation results of SCIG with UPFC line voltage(V_{abc}),line current(I_{abc}),DC link voltage (V_{dc}), reactive power (Q),active power (p).

DFIG

DFIG wind power systems is simulated by using the parameters listed in table III and proposed optimal power curve. The DFIG in wind power system allows the maximum extraction of power without reactive power compensation and here independent control of both powers takes place. In DFIG simulation model the switch frequency of the converter is 27 times that of grid frequency. Both the power circuit, control circuit models are discretized at different times. The nominal powers are treated as electrical and mechanical powers. The simulation values are listed in table II. The steady state response of the system is verified by using the bus voltage of 1200V_{dc} and reactive power as zero which is taken as input command. Small amount of power is dropped due to power loss in[13] and the rotor speed and optimal tracking of output powers is also achieved for various wind speed cases which conclude the steady state operation. During first cycle the real and reactive powers are vanished due to calculation time cost .For the dynamic response of a system we use the H=0.1s to reduce the converging time and obtain the new steady state within few seconds. The steady state response of the DFIG wind power system is shown in Fig .18.

TABLE- II

DFIG-BASED WIND POWER SYSTEM PARAMETERS

Parameter	Value
Nominal Wind Speed v_w	11 m/s
Nominal Apparent Power S_e	1.67 MVA
Nominal Active Power P_{nDFIG}	1.5 MW
Power Factor pf	0.9
Grid Voltage V_{grid}	120 kV
Grid Frequency f	60 Hz
Distribution Line Voltage V_{dis}	12.5 kV
Wind Turbine Bus Voltage V_{wt}	575 V
Generator Number of Pole Pairs n_p	3
Stator Resistance R_s	0.0071 p.u.
Stator Leakage Inductance L_s	0.171 p.u.
Referred Rotor Resistance R_r	0.005 p.u.
Referred Rotor Leakage Inductance L_r	0.156 p.u.
Stator-to-Grid Coupling Resistance R_c	0.003 p.u.
Stator-to-Grid Coupling Inductance L_c	0.3 p.u.
Mutual Inductance L_m	2.9 p.u.
Nominal DC-link Voltage V_{dc}	1.2 kV
DC-link Capacitance C	10 mF
Maximum C Converter Current I_{conv_max}	0.5 p.u.
System Inertia Coefficient H	5 second
Generator Friction Damping F	0.01 p.u.

TABLE -III

SIMULATION AND CONTROL PARAMETERS

Parameter	Value
Power System Sampling Period T_{s_Power}	5e-6 sec
Control System Sampling Period $T_{s\_Control}$	1e-4 sec
Switch Frequency f_{sw}	1620 Hz
Transmission Distance D_{tran}	30 km
Reactive Power Regulator Coefficients K_p; K_i	0.05; 5
DC-link Voltage Regulator Coefficients K_p; K_i	0.002; 0.1
Rotor-side Current Regulator Coefficients K_p; K_i	0.3; 8
Stator-side Current Regulator Coefficients K_p; K_i	2.5; 500

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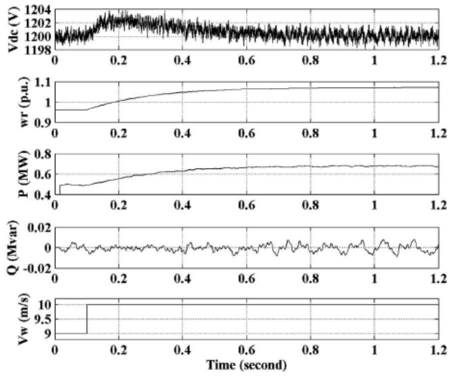

Fig-18: Simulation results for DFIG system. (a)DC-link voltage V_{dc}. (b) rotor speed ω_r.(c) active power P.(d) reactive power Q (e) Wind speed V_ω.

In the above Fig 18. if we closely observe the real and reactive powers are having harmonics for single load. If we consider nonlinear loads then these harmonics will create severe problems a unified power flow controller is used to control power flow in the transmission line connecting three buses for three various loads as shown in Fig 19. The zigzag phase shifting transformer and ideal switches are used to build a GTO-type voltage source inverters, used as shunt and series converters in simulated model. In UPFC 48 pulse PWM is used to send pulses to both SSSC and STATCOM whenever required UPFC can be operated in three different modes . UPFC mode of operation includes the shunt inverter as a STATCOM, which controls the reactive power, and transfers active power to the series converter through DC bus[17]. In UPFC volage control is made by shunt inverter and current control is made by series inverter. As explained in SCIG the UPFC controls all the three power flow parameters and reduce the harmonics it is clearly shown in Fig 20.

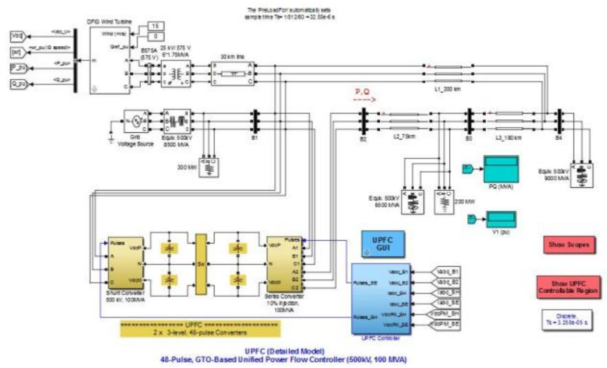

Fig-19: DFIG Wind power system with UPFC

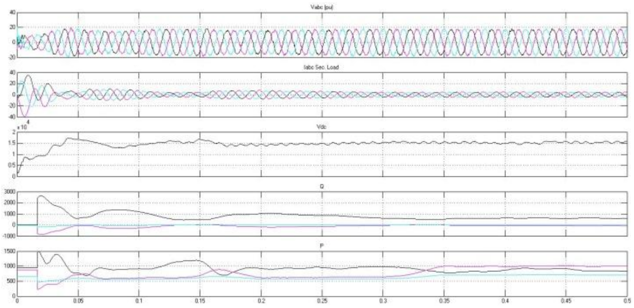

Fig-18: Simulation results of DFIG with UPFC line voltage(V_{abc}),line current(I_{abc}),DC link voltage (V_{dc}), reactive power (Q),active power (p).

CONCLUSION

This paper clearly explained the wind power systems operation with various induction generators and concluded that both schemes consists of current regulation part , cross coupling part .SCIG wind power systems require reactive compensator additionally to compensate reactive power required and this system is suitable for low power ratings. Whereas DFIG controls both the powers independently and achieve optimal active power controlling with any reactive compensator. To reduce harmonics in the system we have used two facts devices statcom, UPFC and concluded that UPFC performs better for both wind power systems. The functioning of wind power systems using DFIG with UPFC facts controller results best in which all transmission line parameters are controlled safely. The summary of SCIG and DFIG wind power systems is shown in the table V.

TABLE-IV

SUMMARY OF SCIG AND DFIG WIND POWER SYSTEMS

	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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