Energy Generation and Electrical Machine Control Parameters of DFIG in Wind Turbine

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ABSTRACT

In electrical power generation system and electrical machine, wind turbine technology has rapid developments, and wind energy become increasingly competitive. Development in turbine machine technology raises a number of challenges to be dealt with now and in the future. Study of control parameter of DFIG in Wind Turbine Energy Converter Systems (WTEC) and factors affecting its performance is important to recognize problems in new design. In this work a model has been used to study these parameters and factors.

Keyword: Energy generation, Wind turbine, wind energy, wind aerodynamics, inverters, Double Feed Induction Generator (DFIG), Rotor Side Convertor (RSC), Grid Side Convertor (GSC), Pitch Angle.

I.INTRODUCTION

With the growing demand for electric energy associated with the acute shortage of conventional energy sources, it has become an urgent need to look and search for cheap, clean energy sources. Wind power has become one of the main solutions, establishing itself as one of the renewable energy sources of the most reliable and affordable, with a significant impact on energy production. Statistics show that the power generated from wind energy is the highest among all renewable energy sources [1,2,3,4], as shown in Fig. 1. It increased by 17% in 2015 compared with the previous year (from 369.553MW to 432.883MW) [3]. Wind turbines capable to operate these days at different sites and climates, in hot desert to frozen arctic climates, at wide range of wind speed from 3 m/s up to about 25m/s.

Although the technology of wind turbines is one of the lowest rates of renewable energy is available, but development and progress in wind turbine technology industry requires overcoming the different types of problems that lead to new challenges. One of these challenges facing the exploitation of wind energy is difficult to predict the behavior of the wind.

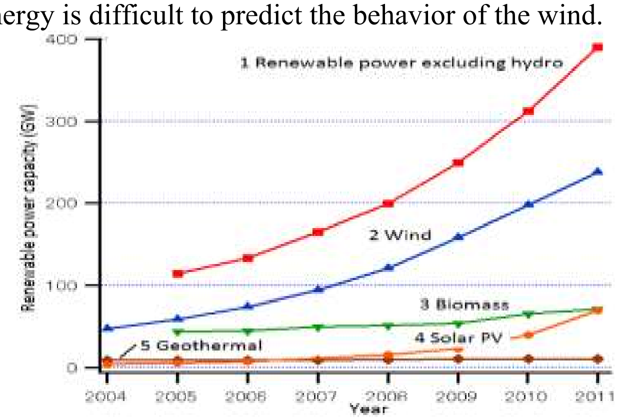

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Figure (1) Global renewable power capacity excluding hydropower generation

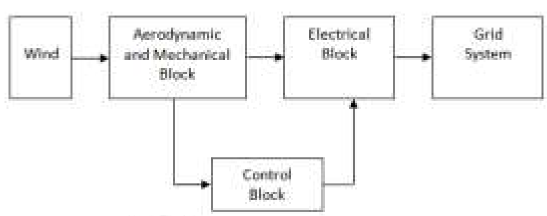
Wind Turbine Classification

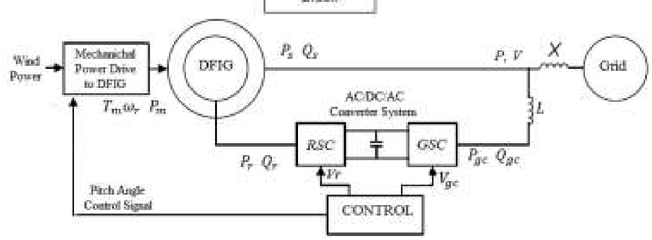
Wind turbine classification categories have different approaches; some are according to historical evolutions of use, other according to methods of its use and/or according to its connection methods with the grid and its operation. Wind turbine with fixed speed and directly connected to the grid is the oldest, the simplest and the cheapest in use. Wind turbine of variable speed which is connected directly or indirectly to the grid are the more modern in usage these days. Wind turbines are equipped with induction machines such as Active-Stall Induction Generator (ASIG), Doubly Fed Induction Generator (DFIG) or Permanent Magnet Synchronous Generator (PMSG) of different method of rotor winding connection (short circuit, through variable resistors, or two rotor windings are also used [5,6,7,8]. All are either connected to the grid directly or via converter or with fully rated convertor. In all categories there are some advantages and some disadvantages, to choose the appropriate method, it is depend on the needs and the time of installation.

Modelling Wind Turbine System

Wind power captured by the blades converted to mechanical power as rotational movement to drive a generator producing electrical power that delivered to the grid system. Wind turbine energy system (WTES) can be represented by a block diagram to show how the system works. The block diagram consist of three major blocks, (the aerodynamic and mechanical block), (the electrical block) and (the control block). This model is to obtain or derive the appropriate parameter values, taking into account that some parameters depend on operating conditions and can be determined from measurements at the site using parameter estimation methodologies.

Since wind turbines are moving toward the use of a generator with full converter system, especially with the drive generator directly connected as (DFIG), thereby eliminating the need for a transmission gearbox, which is a function of the mechanical block, which forms the connection between the aerodynamic and electric blocks [9]. Fig. 2A shows the major parts of (WTES) and Fig. 2B shows the System Diagram of a (DFIG) Based Wind Turbine System. Many other various models representing wind turbine system are established [10,11].





Figure(2) A) Block diagram of (WTES) Figure (2) B) System Diagram of a (DFIG)

Analytical Discussion of Dfig Wind Turbine System

Aerodynamic and Mechanical Block

The aerodynamic part simulates the rotor blade of the wind turbine system by which the wind kinetic energy is converted to a rotational mechanical energy. This mechanical energy is either fed directly or indirectly through the mechanical block and the transmission gearbox to the electrical block.

The kinetic energy (U) in *Joule* of wind mass (m) in kg flowing at speed (u) in m/sec in the direction(x) in m, which is captured by the wind turbine blades, can be transformed to a power (P_{Wind}) in Watt driving the wind turbine. The aerodynamic theory shows that the wind turbine blades, for a given wind speed; there is a certain rotational speed, in which wind turbine captures the largest amount of energy passing through the swept area, even though not all of this power can be captured by the wind turbine blade.

$$U = \frac{1}{2}mu^2 = \frac{1}{2}(\rho\pi r^2 x)u^2 = \frac{1}{2}(\rho A x)u^2 \quad \text{Joule} \quad \ldots\ldots\ldots\ldots\ldots\ldots.. \quad (1)$$

where (r) is the area radius (blade-length in m), (A) is the cross section area in (m^2), (ρ) is the particle or air density in (kg/m3), and (x) is the thickness of the particle in (m), then the power in the wind, (P_{Wind}), is the time derivative of the kinetic energy:

$$P_{Wind} = \frac{dU}{dt} = \frac{1}{2}\rho A u^2 \frac{dx}{dt} = \frac{1}{2}\rho A u^3 \quad \text{Watt} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

If the air density is given by$\rho = 3.485\frac{P_{rs}}{T} = 1.2254$ kg/m3, where (P_{rs}) is the atmospheric pressure at sea level=101.325 kPa, (T) is the temperature = 288.16 Kelvin, then the power excreted by the wind is;

$$P_{Wind} = \frac{1}{2}\rho A u^3 = \frac{1.742 P A u^3}{T} = 0.6125u^3 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

The overall ratio of the total P_{mech} to the extracted mechanical power $P_{extr.mech}$ is known as a power coefficient (Cp). The power coefficient is a parameter of the rotor blade which is a function of the blade pitch (β), angular velocity of the blade or the Hub Speed (ω_{tur}), wind speed (u) and air density (ρ) as stated earlier and shown in Fig. 3. The extracted mechanical power (P_{ext}) is:

$$P_{ext} = 0.6125u^3 C_p = P_{Wind} C_p \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

$$C_p = \frac{\text{Extracted Power}}{\text{Total Power in Wind}} = \frac{P_{ext}}{P_w} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots... \quad (5)$$

The power coefficient (C_p), can be obtained from the manufacturers or by experimental measurements.

Tip Speed Ratio (TSR) is

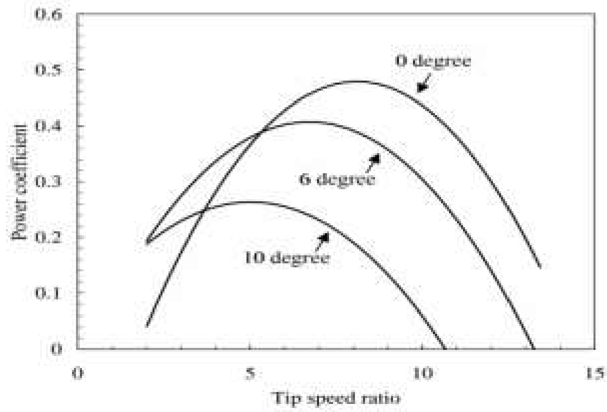
$$\lambda = \frac{r.\omega_{tur}}{u} \quad (6)$$

The angular velocity can be calculated from $\omega_{tur} = \frac{2\pi n}{60}$ where (n) is the rotational speed of the blade in (rev/min), and the equation of torque (T) is

$$T = \frac{0.5\ \rho A u^3 C_p}{\omega_{tur}} = 0.5\ \rho\pi r^3 u^2 C_q \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

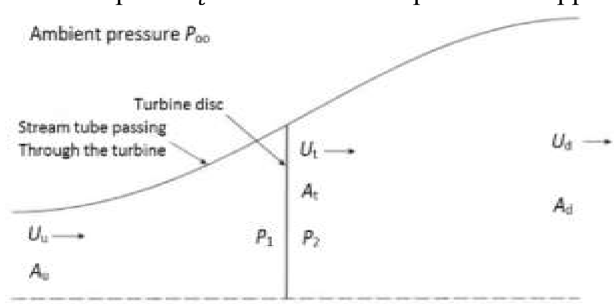
Where (C_q) is the torque coefficient $= \frac{C_p}{\lambda}$ and (r) is the blade length.

Fig. 3 shows the typical relationship between (C_p) and Tip Speed Ratio (TSR) (λ) for various blade pitch angle [7,8,12]:



Figure(3) Power coefficient versus Tip Speed Ratio (TSR) for typical three-blade wind turbine [10].

The power extracted and exerted by wind on the turbine blade, can be derived using a simple model represented by actuator disc, where the turbine is replaced by a circular disc through which the flows of the air stream is at a speed U_t and across it the pressure dropped from P_1 to P_2, Fig. 4.



Figure(4) A sketch of a wind turbine represented by actuator disc

Some of the air kinetic energy is converted to potential energy in order to produce the increased pressure. More kinetic energy is converted into potential energy after the turbine to increase the pressure of air back on atmospheres. This causes the wind speed to continue falling until the pressure is balanced. Once the lowest wind speed point is reached, the air velocity increases again to its value, receiving the kinetic energy of the surrounding air [13].

Here it should be mentioned that the actuator disc theory is useful to discuss the overall efficiency of turbines, but not for designing the turbine blades to achieve the desired performance.

The power developed by the turbine is

$$P_{mech} = (P_1 - P_2) \quad (8)$$

Where: P_1 and P_2 are the pressure before and after the circular disc in the actuator, as shown in Fig. 4, A_t is the disc turbine area, the volume flow continuity gives:

$$A_u U_u = A_d U_d = A_t U_t \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

therefore momentum exerted on the turbine equals the change of momentum between the upstream and downstream flows at the disc sides, thus

$$Mass\ flow \text{ x } Velocity\ difference = (P_1 - P_2)A_t \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (10)$$

$$Mass\ flow \text{ x } Velocity\ difference = \rho A_u U_u (U_u - U_d) \quad \ldots\ldots\ldots \quad (11)$$

This gives Bernoulli's equation at the upstream and downstream of the actuator disc

$$P_\infty + \tfrac{1}{2}\rho U_u^2 = P_1 + \tfrac{1}{2}\rho U_t^2 \quad \ldots \quad (12)$$
$$P_\infty + \tfrac{1}{2}\rho U_d^2 = P_2 + \tfrac{1}{2}\rho U_t^2 \quad \ldots \quad (13)$$

Where (P_∞) is the ambient pressure in the two flows of upstream and downstream of the actuator disc.

From equations (9, 10, 11, 12 and 13), the mechanical power extracted is then the difference between input and output power in the wind

$$(P_1 - P_2) = \frac{1}{2}\rho\left(U_u^2 - U_d^2\right) = \rho \frac{A_u}{A_t} U_u (U_u - U_d) = \rho U_t (U_u - U_d) \quad (14)$$

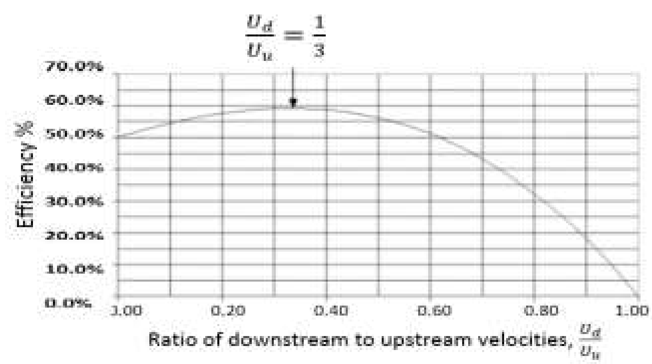
Where

$$U_t = \frac{1}{2}(U_u + U_d) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (15)$$

From equations (8, 10, 11 and 14) the efficiency of the system is given by

$$\eta = \frac{Power}{\frac{1}{2}\rho A_t U_u^3} = \frac{1}{2}\left[1 - \frac{U_d}{U_u}\right]\left[1 + \frac{U_d}{U_u}\right]^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (16)$$

Differentiating equation 8, shows that the maximum efficiency occurs when ($U_u = 3U_d$) and ($A_u = \frac{2}{3}A_t$), which means that the downstream area (A_d) is 3 times the upstream area (A_u). Fig. 5 shows the variation of efficiency (or the power coefficient, C_p) with the ratio of downstream to upstream velocity.



Figure(5) Variation of efficiency with the ratio of downstream to upstream velocity

or

$$P_{mech} = \frac{1}{2}\rho\left(A_u U_u^3 - A_d U_d^3\right) = \frac{1}{2}\rho\left(\frac{8}{9}A_u U_u^3\right) \quad \text{W} \ldots\ldots\ldots\ldots\ldots\ldots \quad (17a)$$

This shows that 8/9 of the original power is extracted ideally, and from equation (15), using ($A_u = \frac{2}{3}A_t$), this yields to

$$P_{mech} = \frac{1}{2}\rho\left[\frac{8}{9}\left(\frac{2}{3}A_t U_u^3\right)\right] = \frac{1}{2}\rho\left(\frac{16}{27}A_t U_u^3\right) \quad \text{W} \ldots\ldots\ldots\ldots\ldots\ldots \quad (17b)$$

Theoretically, the maximum efficiency could be achieved of a wind turbine according to this relation is about 16/27. The factor 16/27=0.593 is called the Betz coefficient or the power coefficient, which shows that an actual turbine cannot extract more than 59.3% of non-disturbed air. But practical power coefficient values range from 20-50% [14].

Mechanical Results

From above mathematical analysis and according to the empirical equation suggested by Anderson and Boss [15],

$$C_p = \frac{1}{2}(\lambda - 0.022\beta^2 - 5.6)e^{-0.17\lambda} \quad \text{……………………………………} \quad (18)$$

Using equations (4), (5), (6) and (18) we get the results in Table (1), which shows that Blade Pitch angle is playing a major rule on the performance of the wind turbine and its efficiency as it has affect on the Power Coefficient C_p and the Tip speed ratio (TSR)

Table (1) Tip speed Ratio TSR versus The power Coefficient C_p at different Pitch Angle.

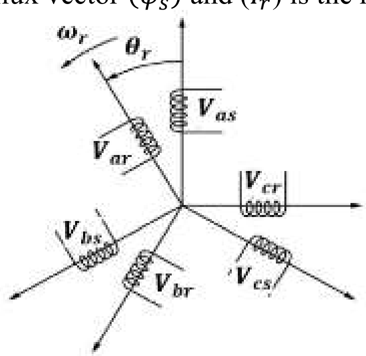
	TSR λ							Pitch
	0	2	4	6	8	10	12	Angle β
Power Coefficient C_p	0	0.05	0.45	0.45	0.37	0.33	0.25	0^o
	0	0.06	0.33	0.33	0.32	0.28	0.20	5^o
	0	0.07	0.28	0.28	0.22	012	0.00	10^o
	0	0.10	0.30	0.30	0.10	0.00	0.00	15^o

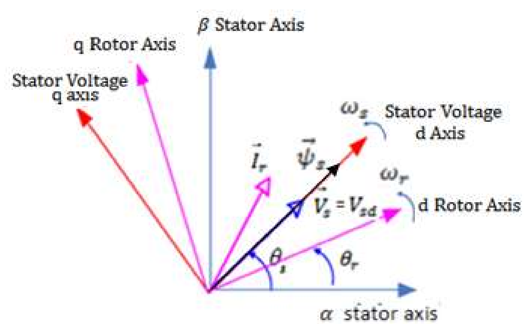
Electrical Block

The electrical block is the part of wind turbine energy system (WTES) which is responsible to convert the mechanical power to electrical power to be fed into the power grid.

The electrical block may consist of a) fixed speed induction generator, b) a generator of fully rated converter or c) a Double-Fed Induction Generator (DFIG). Because of the change in wind speed, the wind energy would be volatile so that generators which use permanent magnets and fixed windings would deliver unregulated voltage and frequency. Consequently a generator of variable speed with constant frequency such as (DFIM) is needed; in addition DFIG offers efficient and reliable performance with moderate cost over the other types of generators. Thus DFIG will be studied in this work to investigate its performance as well as its control system parameters

Fig. 6A shows a simple diagram of induction generator, with the stator and rotor voltages remarks by a, b and c referring to the phases, with (θ_r) represent the rotor position (displacement angel) in radians and (ω_r) the electrical rotational speed of the rotor in (rad/sec). Fig. 6B shows the vector diagram of rotor and stator voltage V, current I and the flux Ψ in d-q frame axis, where (θ_s) and (θ_r) are the stator and rotor displacement angle in radians, (ω_s) is the stator synchronous speed, (ω_r) is the rotor rotational speed both in rad/sc, (V_s) and (V_{sd}) are the stator voltage vector both aligned in phase with flux vector (ψ_s) and (I_r) is the rotor current.





Figure(6) A) Three-phase machine diagram

Figure(6) B) Vector diagram of rotor and stator V, I and Ψ in d-q frame axis

The basic equation for the terminal voltages, neglecting saturation and losses in the core for a sinusoidal magnetomotive force in matrix form [16,17] :

$$\mathrm{V} = \mathrm{RI} + \frac{d\mathrm{L}}{dt}\mathrm{I} + \mathrm{L}\frac{d\mathrm{I}}{dt} \qquad \text{……………………………..} \qquad (19)$$

From Fig 6A it is clear that the self and mutual inductances in matrix (L) are a function of electrical rotor position (θ_r). Appling the chain rule to the time derivative of the induction matrix in equation (19) gives

$$\frac{dL}{dt} = \frac{dL}{d\theta_r}\frac{d\theta_r}{dt} = \frac{dL}{dt}\omega_r \qquad \text{……………………………………………} \qquad (20)$$

Substituting equation (19) in (20) gives

$$\mathrm{V} = \mathrm{RI} + \frac{d\mathrm{L}}{d\theta_r}\omega_r\mathrm{I} + \mathrm{L}\frac{d\mathrm{I}}{dt} \qquad \text{………………………………..} \qquad (21)$$

Here it should be notice where ever it used in the matrices that: (R_s) and (R_r) are the stator and rotor resistance respectively in ohms, (L_s) and (L_r) are the stator and rotor inductance respectively in henrys, (L_m) is the magnetizing inductance in henrys, (ω_s, ω_r) are the synchronous angular speed at the stator and the angular speed of the rotor respectively both in red/sec, and (P_n) are number of poles in machine.

The stator/rotor voltages (v) and the flux (ψ) equations from the above equations and according to Park reference frame can be rewritten as follow:

$$v_{ds} = R_s i_{ds} + \frac{d\psi_{ds}}{dt} - \omega_s\psi_{qs} \qquad \text{…………………………..} \qquad (22)$$

$$v_{qs} = R_s i_{qs} + \frac{d\psi_{qs}}{dt} + \omega_s\psi_{ds} \qquad \text{………………………………...} \qquad (23)$$

$$v_{dr} = R_r i_{dr} + \frac{d\psi_{dr}}{dt} - (\omega_s - \omega_r)\,\psi_{qr} \qquad \text{…………………………} \qquad (24)$$

$$v_{qr} = R_r i_{qr} + \frac{d\psi_{qr}}{dt} + (\omega_s - \omega_r)\,\psi_{dr} \qquad \text{………………………...} \qquad (25)$$

Where

$$\psi_{ds} = L_s i_{ds} + L_m i_{dr} \qquad \text{…………………………………...} \qquad (26)$$

$$\psi_{qs} = L_s i_{qs} + L_m i_{qr} \qquad \text{…………………………………...} \qquad (27)$$

$$\psi_{dr} = L_r i_{dr} + L_m i_{ds} \qquad \text{…………………………………...} \qquad (28)$$

$$\psi_{dr} = L_r i_{qr} + L_m i_{qs} \qquad \text{……………………………………} \qquad (29)$$

Assuming the rotor and stator are electrically and magnetically symmetrical, so the resistance matrix and inductance matrix can be simplified [17], and by rearranging equation (21) into state-variable form with current as the state variable gives

$$\frac{d\mathrm{I}}{dt} = \mathrm{L}^{-1}\left\{-\mathrm{R} - \omega_r\frac{d\mathrm{I}}{d\theta_r}\right\}\mathrm{I} + \mathrm{L}^{-1}\mathrm{V} \qquad \text{………………………} \qquad (30)$$

From which the current of the IG can be calculated. By multiplying equation (21) by the transpose of the current vector, the equation for the power P is obtained [18]. This gives

$$P_{ins} = \mathrm{I}^T V = \mathrm{I}^T\mathrm{RI} + \mathrm{I}^T\frac{d\mathrm{L}}{d\theta_r}\omega_r\mathrm{I} + \mathrm{I}^T\mathrm{L}\frac{d\mathrm{I}}{dt} \qquad \text{………………………} \qquad (31)$$

where ($\mathrm{I}^T\mathrm{R}\,\mathrm{I}$) is the copper losses in the generator windings (P_{copper}), and ($\mathrm{I}^T\mathrm{L}\frac{d\mathrm{I}}{dt}$) is the magnetic power stored in the generator ($P_{magnetic}$) , and ($\omega_r\mathrm{I}^T\frac{d\mathrm{L}}{d\theta_r}\mathrm{I}$) is the mechanical power (P_{mech}).

The mechanical torque (T_{gen}) in (Nm) is obtained by dividing the mechanical power by the mechanical rotational speed of the rotor (Ω_{gen}):

$$T_{gen} = \frac{P_{mech}}{\Omega_{gen}} \qquad \text{……………………………………..} \qquad (32)$$

where ($\Omega_r = \frac{2\omega_r}{P_n}$) and P_n is the total number of poles of the generator, by substituting the mechanical rotational speed and the mechanical torque in eq. (32) gives

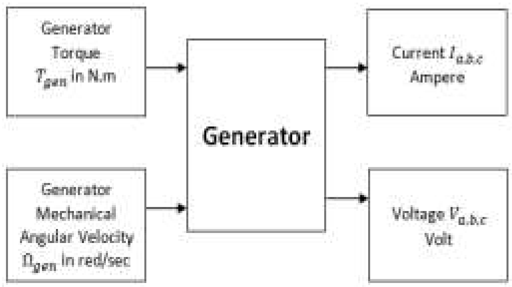
$T_{gen} = \frac{P_n}{2} \mathrm{I}^T \frac{d\mathrm{L}}{d\theta_r} \mathrm{I}$ ……………………………. (33)

If ($\mathbb{d}$) is the total mechanical damping and (J) is the total inertia, then the electromagnetic torque (T_{em}) is

$T_{em} = \frac{3}{2} p \frac{L_m}{L_s} (i_{dr} i_{qs} - i_{qr} i_{ds})$ ……………………….. (34)

$T_{em} = J \frac{d\Omega_{gen}}{dt} + \mathbb{d}\Omega_{gen} + T_r$ ………………………… (35)

The state space equations (30) and (33), both represent the block diagram of the induction generators, as in fig. 7.



Figure(7) Block diagram of input/output variables of electrical model

Electrical Results

In the case of using electrical convertor, both the real power and the reactive power that are extracted can be controlled by the converters.

If the stator flux is set aligned with the d axis and the grid is strong and stable, then the flux (ψ) would be constant, and the stator resistance is neglected then $\psi_{ds} = \psi_s$ and $\psi_{qs} = 0$, then equations 30, 31, 34 and 35 yield

$v_{ds} = 0$ …………………………………………………….. (36)

$v_s = v_{qs} \simeq \omega_s \psi_s$ ………………………………………… (37)

Where the stator voltage (v_s) is constant and

$\psi_s = L_s i_{ds} + L_m i_{dr}$ ………………………………………… (38)

$0 = L_s i_{qs} + L_m i_{qr}$ ………………………………………… (39)

$T_{em} = -\frac{3}{2} p \frac{L_m}{L_s} \psi_s i_{qr}$ ………………………………………… (40)

Equation (40) shows that the electromagnetic torque can be controlled directly by (i_{qr}) current when the current reference is

$i_{qr,ref} = -\frac{2L_s\omega_s}{3pu_sL_m} T_{em,ref}$ ………………………………….. (41)

The stator reactive power is

$Q_s = \frac{3}{2}\left(u_{qs} i_{ds} - u_{ds} i_{qs}\right)$ …………………………………... (42)

Substituting eq. 36 and eq. 38, then the stator reactive power becomes;

$Q_s = \frac{3}{2} \frac{u_s}{L_s\omega_s} (u_s - L_m \omega_s i_{dr})$ …………………………………… (43)

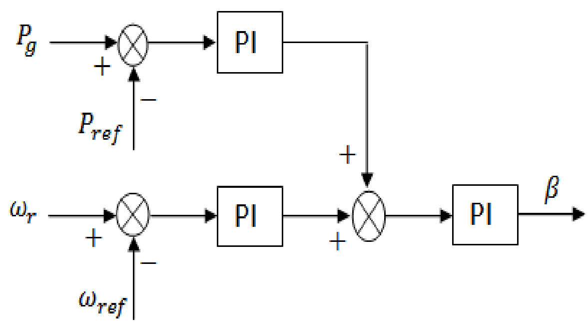
Controlling the stator reactive power to get unity power factor is achieved by acting on i_{dr} and the reactive power command ($Q_{s.ref} = 0$). The direct current reference ($i_{dr.ref}$) is:

$i_{dr.ref} = \frac{u_s}{L_m\omega_s}$ ……………………………………………… (44)

Control Block

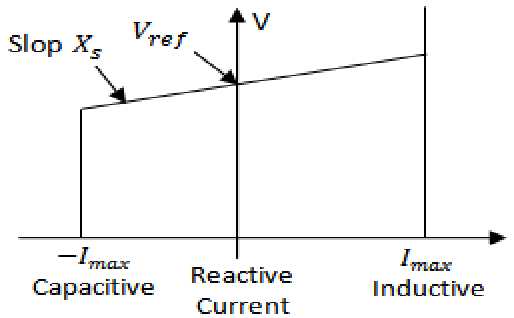
Advanced control system is usually used in wind turbine systems to extract maximum power from wind at all time. The proposed control strategy is to maintain the voltage constant at the terminals of WTES as at (PV) bus bar, such as a conventional generator bus with excitation control, as well as to ensure reliable operation of power systems in various operating conditions and prevent a worse performance under certain extreme conditions. If there is a change in the terminal voltage of the DFIG duo to any change in the load / disturbance or a change in wind speed, here there is a need without delay to restore the basic values. The desired response of the controller is based on the initial voltage value V_0 and the final steady-state voltage value (V_{final}).

Practically with DFIG the controller consists of two parts. The first is the Master Controllers (MC) (variable pitch angle method) which regulate the pitch angle to limit the wind power utilization by adjusting the system rotation speed to the optimal tip speed ratio so that the output power of the generator regulated to the optimum value. Fig. 8 shows the control block diagram to regulate the pitch angle (β).



Figure(8) Block diagram to regulate the pitch angle (β).

The second is the generator controller which regulates the DFIG field current to adjust the voltage. The stator of the DFIG is connected to the grid directly while the rotor side is connected to the grid through a back-to-back converter system (AC/DC/AC converter). This converter system is divided into two components: rotor side converter RSC to feed the wound rotor which is used to control the wind turbine output power and the voltage (or reactive power) measured at the grid terminals, and grid side converter GSC which is usually connected through an a coupling inductor (L) to feed the grid. A capacitor is connected between these two converters at the DC side acting as a source of DC voltage. Thus, DFIG offers flexible control and stability property because of their ability to control these converters [19]. In fact the power generated by the rotor (P_r) is small compared with the power generated by the stator (P_s) where (P_r) is a function of the slip sign (s) and it is positive if (s) is negative. Moreover (GSC) and (RSC) have the capability of generating or absorbing reactive power and could be used to control the reactive power or the voltage at the grid terminals by the reactive current flowing in the (RSC) converter. The V-I characteristic of WTES at voltage regulation mode, is shown in Fig. 9. If the reactive current imposed by the converter rating is between ($-I_{max}$, $+I_{max}$) then the voltage regulated at (V_{ref}).



Figure,(9) V-I characteristic of wind turbine energy system

The generator controller is responsible of controlling the active power of the system. The stator flux is adopted by converting the current and voltage into a reference frame which rotates at the synchronous speed. The power and the current relationship become linear in this rotating frame and the power set point converted to the current set point which makes the control less difficult. In the following the d-axis of the rotating reference frame used for d-q transformation is to be aligned with the flux which is in phase with the positive sequence of the grid voltage, Fig. 6B.

The control procedure is to compare an ideal value (voltage or current) as a reference with an actual one and the difference (error) is set to zero. In the DFIG control system, (PI) controller with dynamic adaptation is applied to reduce the error between the actual output power (P) or the terminal voltage (V) with the ideal (desired) (P_{ref}) or (V_{ref}) value to zero.

The RSC control is used to control the output power and the voltage at the grid terminal to keep a constant value such that the DFIG terminals modeled as a (PV) bus as stated before. The power control system compare the total net power (which is the generator output power (P_g) plus the total power losses (P_{loss}) where the (P_{loss}) is sum of the mechanical ($P_{m.loss}$) and the electrical ($P_{e.loss}$)), with reference power signal (P_{ref}), the error is reduced to zero using a power regulator and the output of the regulator is ($I_{qr.ref}$) current, then this ($I_{qr.ref}$) is in turn added to (I_{qr}) and the sum of them processed in other (IP) to reduce the error to zero and the output of this (IP) is (V_{qr}).

The voltage control system compare the terminal voltage ($V = V_s$) with reference voltage (V_{ref}) and the error is reduced to zero by voltage regulator (PI), the output of (PI) is the reference rotor direct axis current ($I_{dr.ref}$). This ($I_{dr.ref}$) is compared with direct axis rotor current (I_{dr}) and the error set to zero by another (PI), the output is the direct axis voltage of the rotor (V_{dr}). These voltages (V_{dr} and V_{qr}) is fed back into the system as a control signal voltage.

The GSC control is used to regulate the voltage of the DC bus capacitor. A (PI) controller is used to reduce the error between (V_{dc}) and ($V_{dc.ref}$), the current regulator output is ($I_{dgc.ref}$). The current (I_{dgc}) is in phase with grid line voltage that controls the flow of active power. In addition internal loop current regulator is used to control the magnitude and phase angle of the generators voltage (V_{gc}) generated by the GSR, which has two parts the first is (V_{dgc}) which is depending on the difference between (I_{dgc}) and ($I_{gc.ref}$) that is produced by the DC voltage regulator, while the second part is (V_{qgc}) depends on the difference between (I_{qgc}) and the specified reference ($I_{q.ref}$). To study a DFIG control parameters, block diagram modeling the above procedures is shown in Fig. 10.

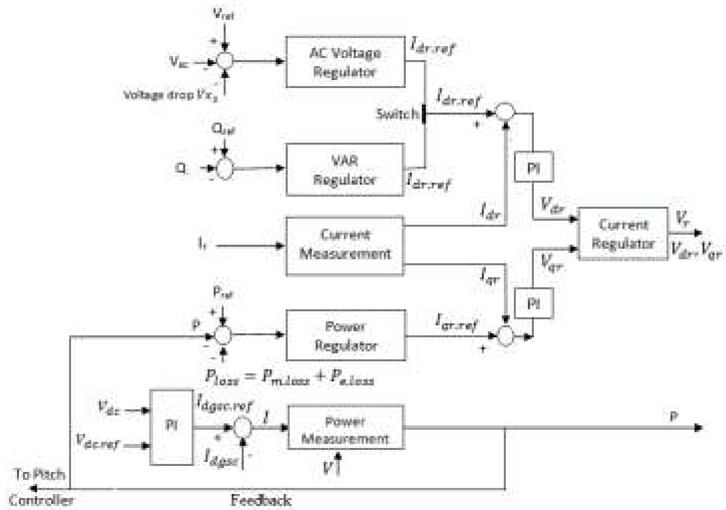


Figure (10) : Voltage and power controller

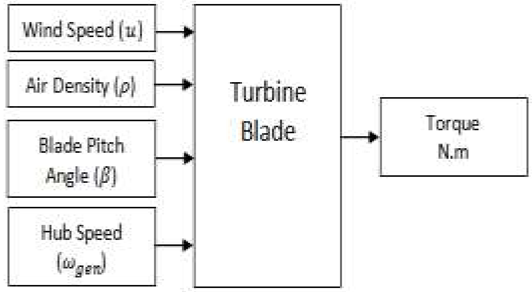
Discussion

Regarding the mechanical part of the wind turbine system, the aerodynamic plays a key role in converting the necessary energy obtained from wind power, to rotate the turbine blade. The amount of wind energy, which can be extracted, is depending on the aerodynamics of the rotor blades so that a wind turbine must be provided with a pitch control system to adjust the speed which has influence on the generator output from the rotor.

Four main parameters affect the motion of turbine blades; wind speed (u), air density (ρ), the blade pitch angle (β) and the hub speed (ω_{turb}) Fig. 11. Despite the fact that wind speed and air density are both playing a major rule on the amount of energy that can be captured from wind, but they are uncontrollable. While the other two parameters the blade pitch angle and the hub speed, can be controlled to extract energy from the wind by changing the blade angle pitch, but it should not be too large so that turbulence develops and increases drag, which may lead to loss of lift, the hub speed is directly proportional to the Tip Speed Ratio (λ) which is varied with the power coefficient (Cp), (equation 5).

Wind turbines operate in a three range of wind speed; the first at normal wind speed which is called (the power optimization region) in which energy is extracted from the wind efficiently. At low speed the wind direction varies but the turbine will not follow the direction instantly, it will have a small Yaw angle on average, follow cosine wave.

The second part is the power limitation region when the wind speed is greater than normal; therefore the pitch control system is activated to control the amount of power that exerted on the turbine according to the wind speed without overload the generator and/or the converter system. The third part is the cut out region in which the wind speed exceed the allowable speed, hence the generator switch out protecting it from damages due to high torque.



Figure(11) Parameters affect the torque of the turbine blade

With respect to the electric part many control approaches are used previously to control induction machine [12,16,20,21,22]. In this work a DFIG is used; in which the change in wind speeds influence the generator output from the rotor that to be converted into stable AC current with a constant frequency. Modern wind power systems are nowadays operated with variable rotor speed. A frequency converter adapts the variable frequencies and voltages of the generator to the required network frequency, phase angle and voltage.

From the analytical discussion, DFIG can be represented by a block diagram using the state space equation (30, 32 and 33), as in Fig. 7.

DFIG have four parameters that affect its performance, (V_{abc}), (I_{abc}), (Ω_{gen}), and (T_{gen}) as shown Fig. 7. The first two are electrical quantity while the other two are mechanical. Terminal voltage (V_{abc}) of DFIG has a direct impact on their performance and efficiency, but increase the voltage to increase energy production would cause problems for the insulators. Increase the current (I_{abc}) to feed the network, will cause an increase in copper losses which cannot be avoided and must be determined by the design value.

Equation 32, ($T_{gen} = \frac{P_{mech}}{\Omega_{gen}}$), shows a relationship between the Torque (T_{gen}) and the speed (Ω_{gen}) of the generator. Increasing any of them would lead to increase the mechanical power (P_{mech}) which increases the total production of electrical power. But there is a certain limited amount of torque at which the maximum output power would be gained, as well the speed which is limited and depends on the turbine design and the system frequency.

The stator of the generator is connected directly to the grid, so the frequency is the same as the grid system, while the rotor connected to the grid via two back to back converters with a capacitor is connected between these two converters on the DC side acts as a DC voltage source; one converter connected to the rotor RSC and the other to the grid GSC through a coupling inductor. With nonlinear load, a low pass filter is used, to reduce the harmonic affect on the DC side. Thus, DFIG offers flexible control and stability property of their ability to control these converters.

Conclusion

Wind turbine system of DFIG generator with two back-to-back PWM converters has been presented. The controlled system has been described and the significance of various parameters in the controller structure is investigated. (dq) vector-control techniques have been applied to both converters. The vector control has been embedded to gain maximum power energy from the wind

Simple back-to-back DFIG scheme employed with the system grid connected. The scheme can also be used for supplying an isolated AC load, especially better to be used with a controlled dump load. The wind energy converting system participates in improving power quality by controlling the GSC for filtering the harmonic currents. PI controllers are usually used for voltage regulation of

DFIG. Problems facing wind energy system is the randomness of wind which may lead to fluctuations in output power.

At low wind speeds the rotor speed is controlled using the electrodynamics torque of the generator and at high wind speeds the rotor speed is controlled using the pitch angle.

It can thus be concluded, that the DFIG wind turbine can operate in the same manner as a conventional power plant does. Variable speed wind turbines DFIG can respond immediately to changes in active as well as reactive power demands.

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APPENDICES

Appendix 1: ACRONYM

WTECS	Wind Turbine Energy Conversion System
WT	Wind Turbine
PCC	Point of Common Coupling
RSC	Rotor Side Convertor
DFIG	Double Feed Induction Generator
HSF	High Selectivity Filter
GSC	Grid side Convertor
PMSG	Permanent Magnet Synchronous Generator
LPF	Low Pass Filter
MPPT	Maximum Power Point Tracking
ASIG	Active-Stall Induction Generator
PMSG	Permanent Magnet Synchronous Generator
WTES	Wind turbine energy system
FSIG	Fix speed induction generator
MC	Master Controller
PI	Proportional Integral controller
PWM	Pulse Width Modulation converters

Appendix 2: SYMBOLS and ABBREVIATIONS

U	The kinetic energy	Joule
m	mass	Kg
u	Speed	m/sec
x	distance, thickness	m
P_{Wind}	Wind Power	Watt
R	Radius, blade length	m
A	Cross section area	m^2
ρ	particle or air density=1.2254	Kg/m^3
P_{rs}	atmospheric pressure at sea level =101.325 kPa	kPa
T	temperature = 288.16	Kelvin
P_{mech}	Mechanical power	Watt
$P_{extr.mech}$	extracted mechanical power	Watt
Cp	power coefficient	
β	blade pitch angle	Rad
λ	Tip speed ratio (TSR)	
ω_{tur}	Wind turbine angular velocity	rad/sec
N	Rotational speed of blade	rev/sec

T	Torque	N.m
C_q	Torque coefficient= $\frac{C_p}{\lambda}$	
$U_{u,}$ U_d	Speed of air stream at the actuator circular disc	m/sec
U_t	Average speed at the actuator disc	
$A_{u,}$ $A_t A_d$	Areas at air stream chanel	m^2
P_1, P_2	pressure before and after the circular disc of actuator	Pascal or N/m^2
M	Momentum	N.sec or kg m/sec
P_∞	Ambient pressure at air stream actuator disc	Pascal or N/m^2
η	Efficiency	
V_s, V_r	Stator rotor voltages remarks by a b and c referring to phases	volt or in p.u.
θ_r	rotor position or displacement angel	radians
ω_r	Electrical rotational speed of the rotor	rad/sec
V, I, Ψ	vector diagram of rotor and stator voltage, current and the flux in d-q frame axis	
θ_s and θ_r	(θ_s) and (θ_r) are the stator and rotor displacement angle in radians,	rad
ω_s , ω_r	stator synchronous speed, and rotor rotational speed	rad/sec
V_s , V_{sd}	stator voltage vectors both aligned in phase with flux vector (ψ_s) and	volt
I_r	rotor current.	Amp
R_s ,R_r	stator and rotor resistance respectively	ohm
L_s . L_r	stator and rotor inductance respectively	Henry
L_m	magnetizing inductance	Henry
ω_s	synchronous angular speed at the stator	rad/sec
ω_r	angular speed of the rotor	rad/sec
P_n	Number of poles	
T	Time	sec
P_{copper}	copper losses in the generator windings	Watt
$P_{magnetic}$	magnetic power stored in the generator	Watt
P_{loss}	total power losses	Watt
T_{gen}	mechanical torque	Nm
Ω_{gen}, Ω_r	mechanical rotational speed of the rotor	rad/sec
$\mathbb{d}$	total mechanical damping	N.s/m
J	total inertia	$Kg.m^2$
T_{em}	electromagnetic torque	Nm
i_{dr}, i_{qr}	Current direct & quadrature axis respectively	amp
Q_s	Stator reactive power	VA
V_{final}	Final steady state voltage value	volt
V_{ref}	Reference voltage	volt
P_r	Rotor generated power	Watt
S	Slip sign	
$P_{m.loss}$	mechanical power loss	Watt
$P_{e.loss}$	electrical power loss	Watt