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Control of Double Fed Induction Generator for Wind Conversion System

Driss Saidani, Othman Hasnaoui and Rachid Dhifaoui

Research Unit: Electrical Machines and Power Systems (RME), INSAT Tunisia

Abstract: This paper deals with a variable speed device to produce electrical energy on a power network, based on double fed induction generator (DFIG). This device is assigned to equip nacelles of wind turbines. The objective of the proposed control strategy is to maximize energy captured from the wind turbine. The developed maximum wind power extraction algorithm has the capability of searching the maximum wind turbine power at variable wind speed, constructing an intelligent system to control the inverter for maximum power extraction. We develop here three parts, the first relates to the formulation of a model of the power coefficient. The coefficients of sensitivity are literally established. Second, the control of the proposed structure is achieved by using proportional integrator controllers which are based on the linear model and tested under variation of wind speed. The third part shutter of the study develops the mathematical model of the DFIG and a structure of control with unit power factor. The system has been validated by numerical simulation using data from a wind turbine borrowed from library of PSAT, [8]. The simulation results have shown good performances of the system and a better grid integration of the wind energy with the proposed control strategy.

Key Words: Variable Speed Wind Energy Conversion System (VSWECS), Direct Fed Induction Generator (DFIG), Wind Power, Power Coefficient, pitch control.

1. Introduction

Renewable energy systems are becoming a topic of great interest and investment in the world. Tunisia is one of the interested countries in the world in using wind power. Prospects for 2010 year point to $300MW$ installed power wind energy, which will represent a significant percentage (10%) of the total capacity in the Tunisian electrical system.

Wind energy has been the subject of much recent research and development. The development arises from the technological maturity. In order to overcome the problems associated with fixed speed wind turbine system and to maximize the wind energy capture, many new wind farms will employ variable speed wind turbine. They are based on Direct Drive Synchronous Generator (DDSG) or Double Fed Induction Generator (DFIG), [2, 3]. DFIG offers several advantages when compared with fixed speed generators including speed control, reduced flicker. These merits are primarily achieved via control of the rotor side converter, [4, 5, 6]. Many works have been proposed for studying the behaviour of DFIG based wind turbine system connected to the grid. Most existing models widely use vector control [8, 9, 13].

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Double Fed Induction Generator can be used as shown on Fig.1. The stator is directly connected to the grid and the rotor is fed to magnetize the machine.

This paper suggests a control of Double Fed Induction Generator for Wind Conversion System. The control designs stator voltage is ideal, the frequency and amplitude of the stator or grid voltage are constant. It is structured as follows. We start this study with an introduction to the wind energy conversion and a power coefficient model. Second, the study aims to illustrate power and pitch angle control strategies, which are a key operation in wind energy conversion. This strategy ensures perfect tracking of maximum captured power. Finally, we study a control scheme for DFIG during the grid connection. The control of electrical power between the stator of DFIG and the power network by controlling independently the active and reactive power is presented. Several investigations have been developed using frequency converter and classical PI regulators.

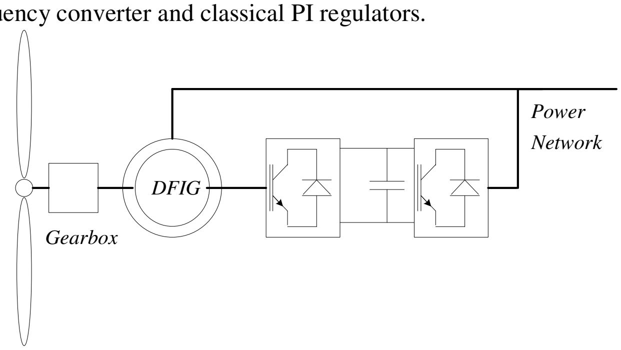


Fig.1. Double Fed Induction Generator

2. Theoretical fundamentals of wind energy conversion systems

The power in the wind is proportional to the cube of the wind speed. However, only part of the wind is extractable. At a climatic condition characterized by a wind speed v_w and air density ρ, the energy produced by a wind turbine blades with radius R, is governed by:

$$P_w = K_P {v_w}^3 \qquad K_P = \frac{1}{2}\rho\pi R^2 \tag{1}$$

The extracted power P_m is given by equation (2) where C_p is called power coefficient. This coefficient characterizes turbine efficiency and is dependent on the pitch angle θ_p, the wind speed v_w and the mechanical speed ω_m. Maximum value of C_p is fixed by Betz constant, $C_{p\max} = 0.59$.

$$P_m = P_w C_p(v_w, \theta_p, \omega_m) \tag{2}$$

Wind speed and mechanical speeds are usually gathered in a unique variable noted λ designing the tip-speed ratio expressed as follows where η corresponds to the gearbox speed coefficient:

$$\lambda = 2\eta \frac{R\omega_m}{v_w} \tag{3}$$

As it is necessary to consider mechanical speed in per unit with respect to the base pulsation ω_b of the power system, we rewrite equation (3) as follows where p stands for the number of poles of electric generator:

$$\lambda = K_\lambda \frac{\omega_m}{v_w} \qquad K_\lambda = 2\eta \frac{R\omega_b}{p} \tag{4}$$

Throughout this paper, we will therefore express extracted mechanical energy by:

$$P_m = K_P {v_w}^3 C_p(\lambda, \theta_p) \tag{5}$$

General shape of power coefficient C_p versus λ is indicated in Fig.2 giving a generic diagram of wind turbine conversion process.

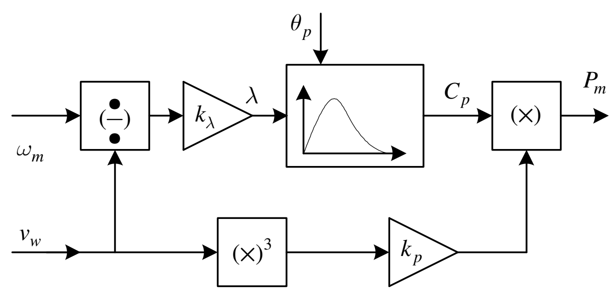


Fig.2: Generic diagram of wind energy extraction

Dynamic stability of wind turbines can be highly improved with adequate blade angle control. This control is usually activated at high wind speed to maintain a suitable mechanical speed ω_m and power P_m. It realises transient reduction of mechanical power by acting on the power coefficient. Once the rated power of the generator is reached the turbine goes into pitch control mode. The pitch angle of the blade is mechanically adjusted to limit the turbine power transfer. Fig.3 shows a common pitch control angle scheme.

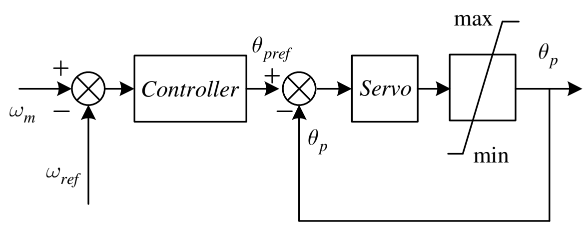


Fig.3: General block diagram of pitch angle control

3. Power coefficient modelling

Power coefficient of wind turbines is a crucial factor in energy optimisation and control. Unfortunately, this coefficient is in general unknown because it is a know how industrial practises and is not therefore given in technical documentation. Available modelling approaches [7, 13] are numerical functions build by scientific researchers to describe in a general way what is observed in practice. Sensitivity factors of the coefficient are helpful to evaluate the variation of the power with respect to wind speed, pitch angle and mechanical speed. For variable speed, we formulate the most popular representation as follows:

$$C_p(\lambda, \theta_p) = K_C f_1(y) f_2(y) \tag{6}$$

Where:

$$f_1 = K_4 y - K_5 \theta_p - K_6 \quad , \quad f_2 = e^{-K_7 y} \quad \text{and}$$

$$y = y(\lambda, \theta_p) = \frac{1}{\lambda + K_1 \theta_p} - \frac{K_2}{1 + K_3 \theta_p^{\ 3}}$$

Well setting parameters K_i of the previous model is a key operation to obtain good description of the wind energy conversion process and a reliable pitch control. In fact, if these parameters are not well selected, one can be faced to serious numerical problems. In practice, pitch control is activated only if mechanical speed goes below the nominal value. In addition pitch angle should be saturated by an upper bound. Therefore, parameters K_i should check the following conditions over the pitch angle permitted interval:

$$\begin{cases} y(\lambda, \theta_p) \geq 0 & \forall \lambda \leq \lambda_{\max} \\ f_1(y, \theta_p) \geq 0 & \forall \theta_p \leq \theta_{p\max} \end{cases} \tag{7}$$

After arrangements, coefficients sensitivities, to respect wind speed, pitch angle and mechanical speed, are expressed as fellows where parameters K_i and function f_i are given in appendix-1:

$$\begin{cases} K_{vw} = \dfrac{\partial P_w}{\partial v_w} = K_{12} v_w^2 f_2 (3f_1 + \lambda f_5 f_6) \\ K_\beta = \dfrac{\partial P_w}{\partial \theta_p} = K_{12} v_w^3 f_2 \left(f_7 f_6 - K_{11} \right) \\ K_\omega = \dfrac{\partial P_w}{\partial \omega} = K_{12} v_w^2 f_2 f_6 f_8 \end{cases} \tag{8}$$

4. Power and pitch angle control strategies

Power control strategy is a key operation in wind energy conversion systems. It is in direct relation with economics in the sense that optimizes extracted power. Reliability and secure regimes are also highly dependent on the installed control schemes. Pitch control also affects dynamic behaviour of wind turbines when it's faced to severe perturbations. Generally speaking, available control approaches aim to run wind turbines along the so-called maximum power point tracking (MPPT) curve. Fig.4 establishes how extracted power evolves versus generator speed at different increasing wind speed values and shows general non linear form of MPPT curve. In practice, a linear model is adopted. This model is indicated in Fig.4 by the blanc-dotted curve. Energy production begins at 50% of the rated mechanical speed that corresponds to wind speed cut-in. Then, extracted power increases linearly with the generated speed until admissible limit is reached. This limit is assigned to rated values of the generated speed and wind speed. This control model will be considered in the remaining part of the paper. To take into account some limits that guarantee stability of control structure; let us consider curve (REF) bringing out the breaking points. Associated pitch angle control is illustrated in Fig.5 and described by the differential equation:

$$\frac{d\theta_p}{dt} = \frac{K_p \phi(\omega_m - \omega_{ref}) - \theta_p}{\tau_p} \tag{9}$$

Variable ϕ is a function which allows varying the pitch angle set point only when the difference $(\omega_m - \omega_{ref})$ exceeds a predefined value $\pm\Delta\omega$. The pitch control works only for the super synchronous speeds. An anti-wind up limiter locks the pitch angle to $\theta_p = 0$ for sub-synchronous speeds.

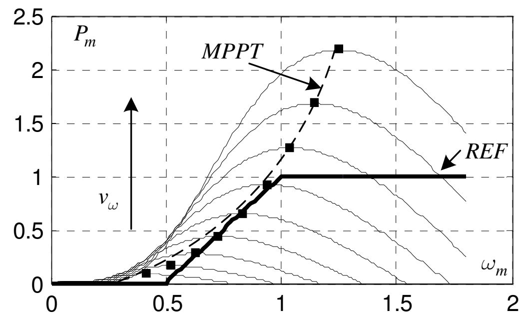


Fig.4: Power speed control characteristic and Reference characteristic

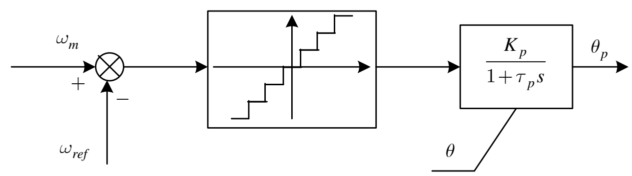


Fig.5: Bloc diagram of pitch angle control

5. Double fed induction generator-based wind energy system (DFIG)

5-1. Generator Model in the reference frame

According to the adopted framework, electrical model of induction generator is described by the following equations established with the conventional notations: (s) for the stator variables and (r) for the rotor ones. Equations are all noted in the per unit system.

$$\begin{cases} \overline{V}_s = -R_s \overline{I}_s + \dfrac{1}{\omega_b}\dfrac{d\overline{\Phi}_s}{dt} + j\overline{\Phi}_s \\ \overline{V}_r = -R_r \overline{I}_r + \dfrac{1}{\omega_b}\dfrac{d\overline{\Phi}_r}{dt} + j\,g\,\overline{\Phi}_r \end{cases} \quad , \; g = 1-\omega_m \qquad (10)$$

Where $\overline{V}_s$ and $\overline{V}_r$ are the stator and rotor vector voltage, R_s and R_r are the stator and rotor resistance, $\overline{I}_s$ and $\overline{I}_r$ are the stator and rotor vector current. The stator and rotor vectors flux $\overline{\Phi}_s$ and $\overline{\Phi}_r$ are linked to the vectors current by:

$$\begin{cases} \overline{\Phi}_s = -X_s \overline{I}_s - X_m \overline{I}_r \\ \overline{\Phi}_r = -X_m \overline{I}_s - X_r \overline{I}_r \end{cases} \qquad (11)$$

By replacing the components of stator and rotor flux by their equations in terms of the direct and quadrature components, we obtain:

$$\begin{cases} \dfrac{d\,I_{ds}}{dt} = \dfrac{\omega_b}{D}[-R_s X_r\, I_{ds} + (X_s X_m - gX_m^2) I_{qs} + R_r X_m\, I_{dr} + (1-g) X_r X_m\, I_{qr} - X_r V_{ds} + X_m V_{dr}] \\ \dfrac{d\,I_{qs}}{dt} = \dfrac{\omega_b}{D}[-(X_s X_r - gX_m^2) I_{ds} - R_s X_r I_{qs} - (1-g) X_r X_m\, I_{dr} + R_r X_m I_{qr} - X_r V_{qs} + X_m V_{qr}] \\ \dfrac{d\,I_{dr}}{dt} = \dfrac{\omega_b}{D}[R_s X_m\, I_{sd} - (1-g) X_s X_m\, I_{qs} - R_r X_s\, I_{dr} - (X_m^2 - gX_s X_r) I_{qr} + X_m V_{ds} - X_s V_{dr}] \\ \dfrac{d\,I_{qr}}{dt} = \dfrac{\omega_b}{D}[(1-g) X_s X_m\, I_{ds} + R_s X_m\, I_{qs} + (X_m^2 - gX_s X_r) I_{dr} - R_r X_s I_{qr} + X_m V_{qs} - X_s V_{qr}] \end{cases} \quad (12)$$

Where $D = X_s X_r - X_m^2$. The standard model is given by (12) where matrix *A* and *B* are furnished in appendix-2.

$$\frac{d\bar{x}}{dt} = A\bar{x} + B\bar{u} \quad , \quad \bar{x} = \begin{bmatrix} I_{ds} & I_{qs} & I_{dr} & I_{qr} \end{bmatrix}^T \; , \; \bar{u} = \begin{bmatrix} V_{ds} & V_{qs} & V_{dr} & V_{qr} \end{bmatrix}^T \quad (13)$$

5-2. Inverter model and control strategy

The dynamics of stator flux is controlled only by the stator voltage. Stator voltage is imposed by the network; stator flux is established very quickly. We can thus admit the following simplifying relation and consider that the flow of the stator evolves in a static way according to the relation:

$$\frac{d\bar{\Phi}_s}{dt} \cong \bar{0} \quad (14)$$

Thus, according to the reference frame carried by the stator vector voltage and neglecting the effect of stator resistance, we have the following condition where V holds for voltage magnitude on a grid $(V = V_s)$: $\Phi_{qs} = 0$, $\Phi_{ds} = V_s = V_{qs}$, $V_{ds} = 0$. We deduce the following relations:

$$\begin{cases} I_{ds} = -\dfrac{V_s + X_m I_{dr}}{X_s} \\ I_{qs} = -\dfrac{X_m}{X_s} I_{dr} \end{cases} \quad (15)$$

Active and reactive powers of stator on the shaft are governed by the following equations:

$$\begin{cases} P_s = \Phi_{ds} I_{qs} = V_s I_{qs} = -\dfrac{X_m}{X_s} V_s I_{qr} \\ Q_s = \Phi_{ds} I_{ds} = V_s I_{ds} = -\dfrac{V_s^2}{X_s} - \dfrac{X_m}{X_s} V_s I_{dr} \end{cases} \tag{16}$$

On the other hand, working at null reactive power is generally desirable. That option forces the current components to check:

$$\begin{cases} I_{ds} = 0 \\ I_{dr} = -\dfrac{V_s}{X_m} \end{cases} \tag{17}$$

The expression of the electromagnetic torque is then reduced to:

$$T_e = P_s = -X_m I_{qs} I_{qr} = -\frac{X_m}{X_s} V_s I_{qr} \tag{18}$$

Generally, the wind turbine is directly connected to the generator with a gearbox. The rotational system may therefore be modelled by a simple equation of motion:

$$\frac{d\omega_m}{dt} = \frac{T_m - T_e}{2H} = \frac{P_m - T_e \omega_m}{2H\omega_m} \tag{19}$$

Where H is the turbine rotor inertia (s) and T_e is the mechanical torque.
In steady state, time derivative of mechanical speed vanish.

$$T_m = T_e = \frac{P_m}{\omega_m} = -\frac{X_m}{X_s} V_s I_{qr} \tag{20}$$

The reference variables of the rotor current are given by (21) and the components of the rotor voltage are expressed by (22).

$$\begin{cases} I_{dr\_ref} = -\dfrac{V_s}{X_m} \\ I_{qr\_ref} = -\dfrac{X_s}{X_m} \dfrac{P_{m\_ref}}{\omega_m V_s} \end{cases} \tag{21}$$

$$\begin{cases} V_{dr} = -R_r I_{dr} + g\sigma X_r I_{qr} + \dfrac{X_r}{w_b} \dfrac{dI_{dr}}{dt} \\ V_{qr} = -R_r I_{qr} - g\sigma X_r I_{dr} - \dfrac{X_r}{w_b} \dfrac{dI_{qr}}{dt} \end{cases} \tag{22}$$

Differential equations for the inverter currents are as follows:

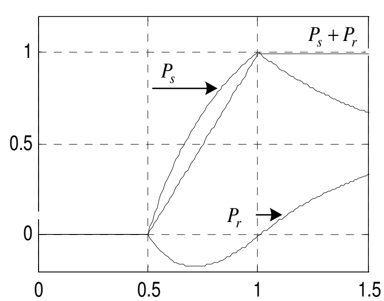
$$\begin{cases} \dfrac{dI_{dr}}{dt} = \dfrac{i_{dr-ref} - i_{dr}}{\tau} \\ \dfrac{dI_{qr}}{dt} = \dfrac{i_{qr-ref} - i_{qr}}{\tau} \end{cases} \quad (23)$$

The rotor voltage given by the inverter is expressed by:

$$\begin{cases} V_{dr} = -R_r I_{dr} + g\sigma X_r I_{qr} + \dfrac{X_r}{w_b} \dfrac{i_{dr-ref-i_{dr}}}{\tau} \\ V_{qr} = -R_r I_{qr} - g\sigma X_r I_{dr} - \dfrac{X_r}{w_b} \dfrac{i_{qr-ref} - i_{qr}}{\tau} \end{cases} \quad (24)$$

6- Simulation results

The proposed control scheme is simulated in MATLAB/Simulink environment for three phases $2\,MVA$ DFIG having the parameters summarised in table 1 reported in appendix-3. All variables are normalised and treated in p.u. systems.
As indicated, the first step of the proposed evolution of stator and rotor powers is compared to the wind power. Fig.6 and Fig.7 depict the evolution of the stator and rotor active and reactive powers and the active power transferred to the grid. Curves of reference power (Fig.4) and transferred power to the grid are practically confused; the light difference observed around one p.u. corresponds to the rotor losses.



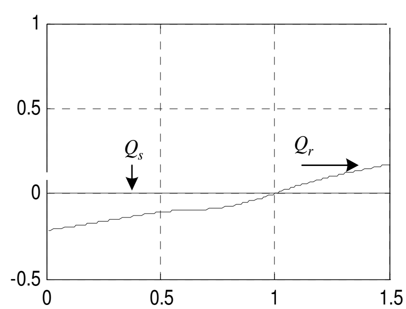


Fig.6. Stator, rotor and transferred active powers Fig.7. Stator, rotor and transferred active powers

The second step is to initialize the wind speed to $0.9\,pu$. At $t = 20\,s$, we apply a step of wind speed ($0.5\,pu$), Fig.8 . This involves an increase of the power wind. The active power delivered by the DFIG must fellow the characteristic of reference. Fig.8 depicts the reference active power and the active power transferred by the

DFIG to the grid. We note here the active power is limited by the upper limit. Fig.8 gives the evolution of the mechanical speed. It exceeds its rated value and return to the nominal value. This phenomenon results by the variation of the power coefficient, fig.9 and more precisely in the variation of the pitch angle, Fig.10.

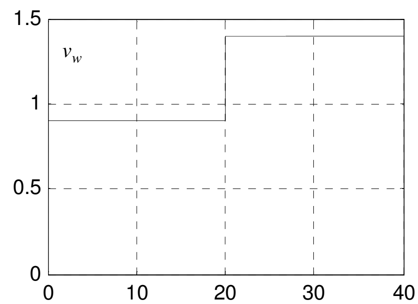


Fig.8. Reference and transferred powers

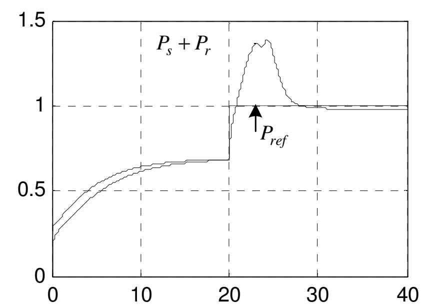


Fig.9. Reference and transferred powers

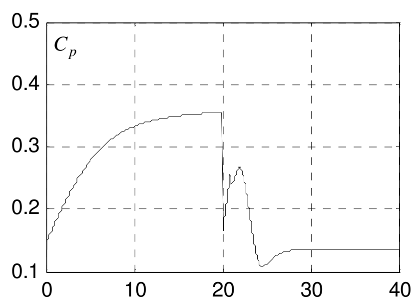


Fig.9. Power coefficient C_p

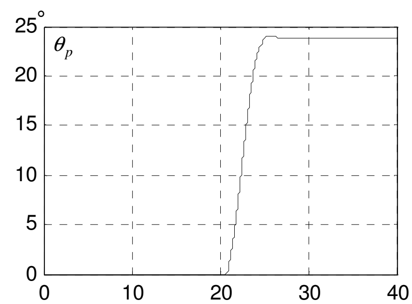


Fig.10. Pitch angle θ_p

6 – Conclusion

In this paper, we studied a control algorithm dealing with variable wind speed energy conversion systems (VSWECS) connected to the public grid. The considered algorithm is based on the use of static converters structure. The proposed scheme ensures perfect tracking of maximum captured power and improves good dynamics of four control loops. It has been shown by simulations that the proposed algorithm gives a good performance for the maximum power tracking. The simulation results obtained by using the Matlab/simulik tool show the effectiveness of the studied model. As a future work, we plan to use these results to regulate the output voltage of the induction generator.

7 – References

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8- Appendix

Appendix-1

$$f_5 = \frac{1}{(\lambda + K_9\theta_p)^2 v_w}\ , \qquad f_6 = K_2 - K_4 f_3\ , \qquad f_7 = \frac{-K_9}{(\lambda + K_9\theta_p)^2} + \frac{3K_8K_{10}\theta_p^2}{(1+K_8\theta_p^3)^2}\ ,$$

$$f_8 = \frac{-Rv_w}{(R\omega + v_w K_9\theta_p)^2}$$

$$K_{12} = \frac{1}{2}\rho S K_1\ ,\quad K_9 = K_7K_8\ ,\quad K_{10} = (2K_8 - 1)K_5\ ,\quad K_{11} = K_6K_8$$

$K_1 = 0.008$, $K_2 = 0.035$, $K_3 = 1$, $K_4 = 116$, $K_5 = 0.4$, $K_6 = 5$, $K_7 = 12.5$, ($K_8 = 1$ for variable speed)

Appendix-2

$$A = \frac{\omega_b}{D}\begin{bmatrix} -R_sX_r & X_sX_r - gX_m^2 & R_rX_m & (1-g)X_rX_m \\ -(X_sX_r - gX_m^2) & -R_sX_r & -(1-g)X_rX_m & R_rX_m \\ R_sX_m & -(1-g)X_sX_m & -R_rX_m & -(X_m^2 - gX_sX_r) \\ (1-g)X_sX_m & R_sX_m & X_m^2 - gX_sX_r & -R_rX_s \end{bmatrix}$$

$$B = \frac{\omega_b}{D}\begin{bmatrix} -Xr & 0 & X_m & 0 \\ 0 & -Xr & 0 & X_m \\ X_m & 0 & -X_s & 0 \\ 0 & X_m & 0 & -X_s \end{bmatrix}$$

Appendix-3

Table 1: Double Fed Induction Generator Data, [7]

Nominal wind speed	$12.5\, m/s$	Pitch control gain integral K_p	10
Rated power P	$2\, MVA$	Pitch control time constant τ_p	$3s$
Rated voltage V	$25\, kV$	Inertia constant H	$3s$
Stator resistance R_s	$0\, pu$	Inverter time constant τ_i	$0.01s$
Rotor resistance R_r	$0.01 pu$	Number of poles p	4
Stator reactance X_s	$3.1 pu$	Gear box ratio η	$1/89$
Rotor reactance X_r	$3.08\, pu$	Blade length	$75\, m$
Magnetisation reactance X_m	$3\, pu$	Number of blade	3