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RESEARCH ARTICLE

Efficient Control of Doubly Fed Induction Generator Wind Turbine Implementation in Matlab Simulink

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ABSTRACT
This paper presents an efficient control of Doubly Fed Induction Generator in variable speed wind power generation. The DFIGs are widely used in variable speed wind energy conversion system (WECS) because their voltage source converters only handle a fraction of the total output power under steady-state conditions. A back-to-back power electronic converter (AC-DC-AC) is used in the rotor circuit of the DFIG, allowing the generator to work in both sub-synchronous and super-synchronous mode. In this work the control and implementation of the rotor, grid side and pitch angle controller is detailed. The aim of the grid side converter is to keep the dc-link voltage constant and also compensate the reactive power rather than providing an additional compensating device such as SVC or capacitors banks in parallel to the machine which leads to many problems such as over voltage. The rotor-side converter controls the rotor speed and allows decoupled control between the active reactive powers by using vector control technique. The pitch angle and rotor side controller will be control in coordination to prevent system failure during wind gust. The performance of the control system is demonstrate using Matlab Simulink.

Key-Words: - Wind turbine, DFIG, reactive power, PI controller, WECS,

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I. INTRODUCTION

In recent years, environmental pollution has become a major concern in people's daily lives and a possible energy crisis has led researchers to develop new technologies for generating clean and renewable energy. Wind power along with solar energy, hydropower and tidal energy are possible solutions for an environmentally-friendly energy production. Among these tapping wind energy appears to be the most promising source of renewable energy and has the fastest growing trend (approximately 20% annually) in the power industry [1]. Over the last years, there has been a strong penetration of renewable energy resources into the power supply network. Wind energy generation has played a very important role in this area. Doubly fed induction generator (DFIG) based wind turbines have undoubtedly become one of the leading technologies for wind turbine manufacturers, demonstrating that it is a cost effective, efficient, and reliable solution [1]. The DFIG is the most commonly used generator wind energy conversion system, accounting for around 50% of the installed wind turbines nominal capacity worldwide [2]. DFIGs have several characteristics that make them one of the preferred alternatives for variable speed wind energy conversion systems [3]. Since it has the advantage of using fraction power converter a fraction [4] [3]. With this configuration it is possible to control the generator speed system within ±30% the synchronous speed by a rotor connected power converter [2]. Despite the reduced power rating of the converter, the generator can be fully controlled by field oriented control (FOC), achieving good decoupling of the generator active and reactive power [4]. Operation above and below synchronous speed is feasible [2]. Due to their wide use in wind turbine system, the development of advanced and reliable control techniques for DFIGs has received significant attention during the last years. Vector control is the most popular application used in wind energy conversion [10]. This method allows for a decoupled control of the active and reactive power of WTS via regulating the quadrature components of the rotor current vector independently.The increase penetration of wind turbines in electrical power systems has begun to influence overall power system behavior and it will no longer be possible to run a power system by only controlling large scale power plants. It is therefore important to study the behavior of wind turbines in to the power system and their interaction with other generation equipment and with loads. Most of the control strategies for DFIG wind turbines referred in literature [8][15] are based on producing the maximum power for the best conditions of economic exploitation, when all the produced energy can be delivered to the grid. In this case, the wind turbine operates with optimum power efficiency for a wide range of wind speeds, without exceeding the rated power and with the desired power factor or generation voltage. However, the wind turbines are today demanded to regulate both active and reactive powers according to the power set points ordered by the wind turbine control system, which are defined considering the generation capability and the power needs. Therefore, the present article focuses on the study of the control of DFIG wind turbine.

II. DESCRIPTION AND MODELING OF THE WIND ENERGY CONVERSION SYSTEM

2.1 DESCRIPTION OF THE SYSTEM

A wind energy conversion system is a complex system in which knowledge from a wide array of fields comprising of aerodynamics, mechanical, civil and electrical engineering come together. The principle components of a modern wind turbine are the tower, the rotor and the nacelle, which accommodates the transmission mechanisms and the generator. The wind turbine transforms wind kinetic energy to mechanical energy by using rotor blades. This energy is then transformed into electric energy by a generator [9]. The main component of the mechanical assembly is the gearbox, which transforms the slower rotational speeds of the wind turbine to higher rotational speeds on the generator side [10]. The system is made up of several components, participating directly in the energy conversion process. There are also other components that assist the system to achieve this task in a controlled, reliable, and efficient way. In order to better understand the process of wind energy conversion, descriptions of the major parts of a wind turbine are given in the in figure 1.Since the energy source for a WECS is wind kinetic energy, wind speed plays a key role in several aspects of the conversion process, especially in relation to the maximum power output. Therefore, the equation (1) introduces the relation between wind speed and power captured by the blades. This provides the necessary insight to explain how the power output of a wind turbine can be regulated by adjusting the blade pitch angle or by controlling the generator's torque or speed. These power control methods are essential to ensure a maximum power output over a wide range of wind speeds. They also enable reliable and safe operation, protecting the mechanical and structural parts of the wind turbine from damage during strong wind gusts.

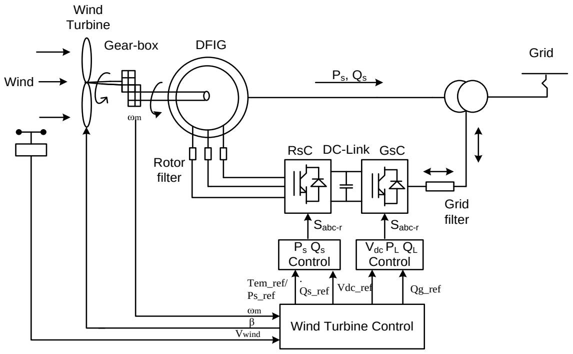


Fig.1: Schematic diagram of wind turbine based DFIG

The fig.1 presents WECS, which uses DFIG. From the system viewpoint, the conversion chain can be divided into three interacting main components which will be separately modeled: wind turbine, gearbox, DFIG.

2.2. AERODYNAMIC MODELING

The relation between the wind speed and mechanic power, delivered by the wind turbine, can be described by the following equation:

$$P_m = 0.5\rho\pi R^2 V^3 C_p(\lambda, \beta) \qquad (1)$$

$$\lambda = \frac{\Omega_r R}{V} \qquad (2)$$

For VSWT, the approximate expression of the power coefficient can be described by the following expression:

$$C_p = f(\lambda,\beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)exp\left(\frac{C_5}{\lambda_i} - C_6\lambda\right) \quad (3)$$

Where:

C1 = 0.5176; C2 = 116; C3 = 0:4; C4 = 5; C5 = 21; C6 = 0:0068

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \qquad (4)$$

Fig.2 shows the characteristic of the power coefficient, with a fixed pitch angle for the 1.5MW turbine used in this work.

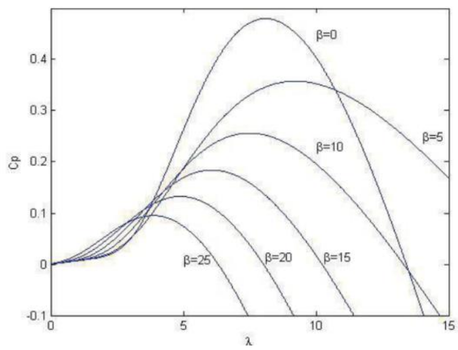


Fig.2: Power coefficients versus tip speed ratio

2.3. DFIG MODELLING

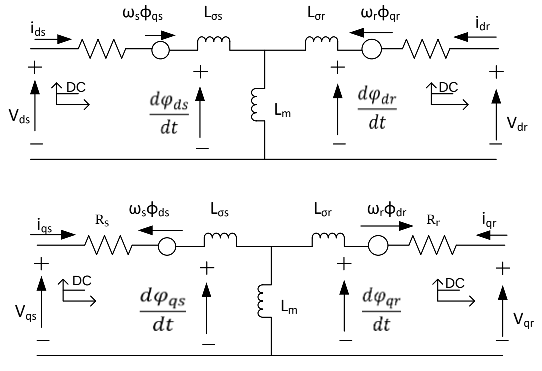


Fig.3: DFIG electrical model

The classical equations of the DFIG model in the d-q reference frame rotating at w_s speed are written as follows:
Stator voltage components:

$$\begin{cases} V_{ds} = R_s . I_{ds} + \frac{d\phi_{ds}}{dt} - w_s \phi_{qs} \\ V_{qs} = R_s . I_{qs} + \frac{d\phi_{qs}}{dt} + w_s \phi_{ds} \end{cases} \quad (5)$$

Rotor voltage components:

$$\begin{cases} V_{dr} = R_r . I_{dr} + \frac{d\phi_{dr}}{dt} - (w_s - w_r).\phi_{qr} \\ V_{qr} = r . I_{qr} + \frac{d\phi_{qr}}{dt} + (w_s - w_r).\phi_{dr} \end{cases} \quad (6)$$

The stator and rotor flux can be express as follows:
Stator flux components:

$$\begin{cases} \phi_{ds} = L_s . I_{ds} + L_m . I_{dr} \\ \phi_{qs} = L_s . I_{qs} + L_m . I_{qr} \end{cases} \quad (7)$$

Rotor flux components:

$$\begin{cases} \phi_{dr} = L_r . I_{dr} + L_m . I_{ds} \\ \phi_{qr} = L_r . I_{qr} + L_m . I_{qs} \end{cases} \quad (8)$$

DFIG electromagnetic torque

$$T_{em} = -\frac{3p}{2} \frac{L_m}{L_r} (\phi_{ds} . I_{qr} + \phi_{qs} I_{dr}) \quad (9)$$

The active and reactive powers at the stator, as well as those provide for the grid are defined as follows:

$$\begin{cases} P_s = \frac{3}{2} (V_{ds} . I_{ds} + V_{qs} . I_{qs}) \\ Q_s = \frac{3}{2} (V_{qs} . I_{ds} - V_{ds} . I_{qs}) \end{cases} \quad (10)$$

III. CONTROL STRATEGY OF THE DFIG

When the DFIG is connected to an existing grid, this connection must be established by the synchronization of the stator voltages with the grid voltages, which is used as a reference [11].In order to obtain a decoupled control of active-reactive powers the DFIG model requires all quantities to b expressed in the stator flux reference frame where the flux leakage is oriented along the d axis fig.4

3.1. FIELD ORIENTED CONTROL STRATEGY

The rotor-side converter is controlled in a synchronously rotating d-q axis frame, with the d-axis oriented along the stator flux vector positionfig.4. In this approach, decoupled control between the stator active and reactive powers is obtained. The influence of the stator resistance can be neglected [12] and the stator flux can be held constant as the stator is connected to the grid. Since the stator is directly connected to the grid and the stator flux can be considered constant, and if the voltage dropped in the stator resistance has been neglected [13] [12], the voltage equations, flux equations currents equations and stator active and reactive powers equations can be simplified in study state as :

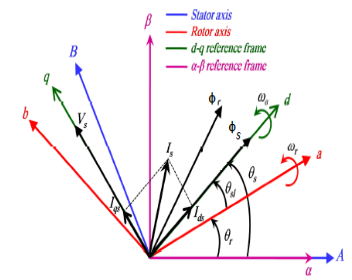


Fig.4: Stator Field oriented control technique

$$\begin{cases} \phi_{ds} = \phi_s \\ \phi_{qs} = 0 \\ V_{ds} = 0 \\ V_{qs} = w_s \phi_s = V_g \end{cases} \quad (11)$$

$$\begin{cases} \phi_s = L_s . I_{ds} + L_m . I_{dr} \\ 0 = L_s . I_{qs} + L_m . I_{qr} \end{cases} \quad (13)$$

$$\begin{cases} I_{ds} = \frac{\phi_s}{L_s} - \frac{L_m}{L_s} . I_{dr} \\ I_{qs} = -\frac{L_m}{L_s} . I_{qr} \end{cases} \quad (14)$$

$$\begin{cases} P_s = \frac{3}{2} V_g . I_{qs} \\ Q_s = \frac{3}{2} V_g . I_{ds} \end{cases} \quad (15)$$

Replacing the stator currents by their expressions given in the system (12), the equations below are expressed:

$$\begin{cases} P_s = -\frac{3}{2} V_g \frac{L_m}{L_S} . I_{qr}) \\ Q_s = \frac{3}{2} V_g (\frac{\phi_s}{L_s} - \frac{L_m}{L_s} . I_{dr}) \end{cases} \quad (16)$$

The electromagnetic torque is as follows

$$T_{em} = -\frac{3P}{2}\frac{L_m}{L_s}\phi_s . I_{qr} \quad (17)$$

Due to the constant stator voltage, the stator active and reactive powers are controlled by means of I_{qr} and I_{dr} respectively. We could express the rotor voltages according to the rotor currents, thus we obtain

$$\begin{cases} V_{dr} = (R_r + s\sigma L_r) I_{dr} - w_{sl}\sigma L_r I_{qr} \\ V_{qr} = (R_r + s\sigma L_r) I_{qr} + w_{sl}(\sigma L_r I_{dr} + \frac{L_m^2}{L_s} I_{ms}) \end{cases} \quad (18)$$

Where:

$$\sigma = 1 - \frac{L_m^2}{L_S L_r} \quad , \quad w_{sl} = w_s - w_r$$

3.2. ROTOR SIDE CONVERTER

The aim of the rotor side converter is to independently control the active power (rotor speed) and reactive power at the stator terminal. The generic control scheme of the rotor side converter is illustrated in Fig. 2. In order to decouple the electromagnetic torque and the rotor excitation current, the induction generator is controlled in the stator-flux oriented reference frame, which is a synchronously rotating reference frame, with its d-axis oriented along the stator-flux vector position [14]. The typical proportional-integral (PI) controllers are used for regulation in both rotor speed (outer) control loop and rotor current (inner) control loop.

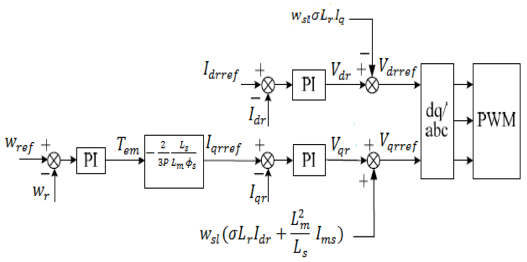


Fig. 5: Control scheme of the rotor side converter

3.3. GRID SIDE CONVERTER

The aim of the control of the grid side converter is to maintain the DC-link capacitor voltage at a set value as well as to guarantee converter operation with unity power factor. Fig. 6 shows the control scheme of the grid side converter. In order to obtain the independent control of active and reactive power flowing between the grid and the grid side converter, the converter control operates in the grid-voltage oriented reference frame, which is asynchronously rotating reference frame, with its d-axis oriented along the grid-voltage vector position [14]. Similarly, the typical PI controllers are used for regulation in both DC-link voltage (outer) control loop and grid side inductor current (inner) control loop.

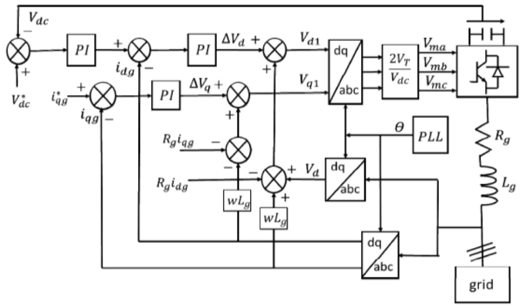


Fig.6: Control scheme of the grid side converter

3.4. PITCH ANGLE CONTROLLER

The pitch angle controller comes into operation only in event that the input wind power exceeds the rated machine power, since under such conditions the rotor speed cannot be controlled by increasing the generator power without causing damage [15]. The pitch controller varies the angle of attack of wind onto the turbine blades and by doing so limits the maximum power extracted from the aero generator to the machine rated power. The fig.3 represents the turbine versus wind speed

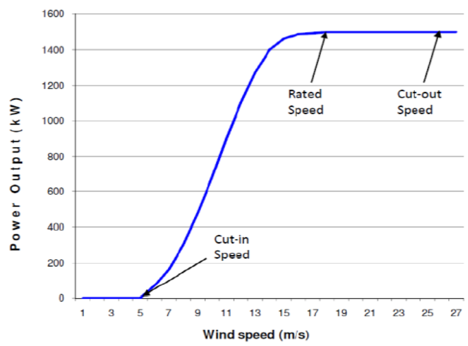


Fig.7: DFIG operation under different wind speeds

IV. SIMULATION RESULTS

The DFIG wind turbine considered in this work presents a rated power of 1.5 MV and 575 V. To evaluate the control systems, the wind turbine controlled by the proposed control systems have been simulated in MATLAB/Simulink environment. The wind turbines have been simulated operating with the unity power factor (zero reactive power). The pitch angle control device implemented limits the mechanical power delivered by the aerodynamic so that, the system can operate regardless the weather conditions (wind variations) without any risk of damage to the DFIG. In wind below rated wind speed, the generator operates below rated power (Fig 8d), and the pitch angle is kept at a minimum degree. In winds above rated wind speed, the control systems adjusts the output power to the rated power, limits the rotational speed to the rated speed and acts on the pitch angle (Fig. 8b) limiting the power extracted from the wind. Active and reactive powers are controlled according to grid requirements. The negative sign of the active power (Fig.8d) means the grid receives energy provided by DFIG. (Fig 2c) shows that the reactive power is regulated to zero showing that the expected power factor is well implemented. The DC bus voltage is regulated to its reference value with low ripples (Fig.8g). In general, reactive power compensation is a major problem for this type of system, and that was resolved by the network side converter. No additional device is implemented to ensure the compensation of reactive power.

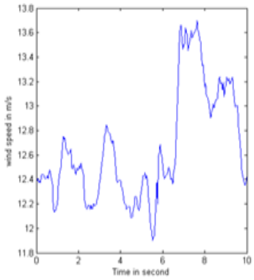


Fig 8a Wind speed in m/s

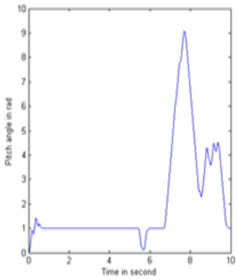


fig 8b Pitch angle control

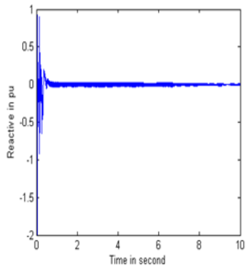


Fig 8c Reactive power in pu

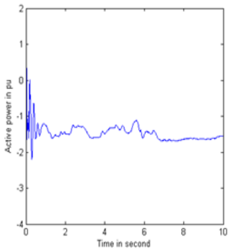
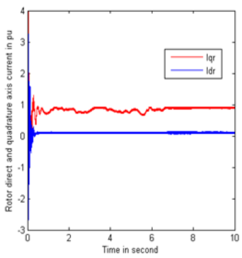


Fig 8d Active power in pu



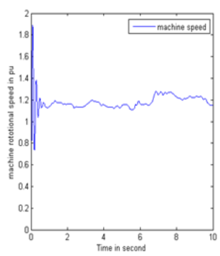


Fig 8e dq rotor current in puFig.8f machine rotational speed

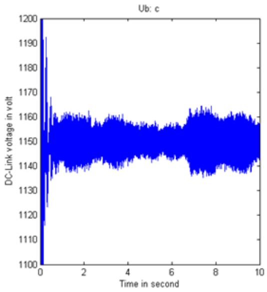


Fig.8g DC-Link voltage in V

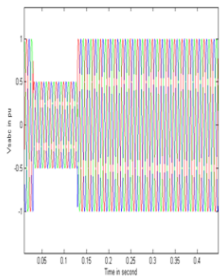


Fig.8h Grid voltage in V

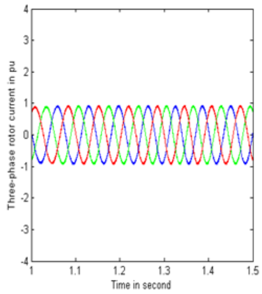


Fig 8i Three-phase current

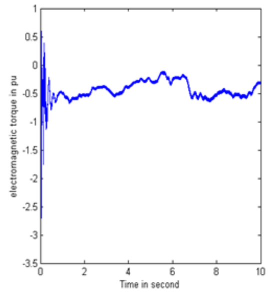


Fig 8j machine torque

When the available wind power is less than rated, the blades are set at minimum pitch to maximize the mechanical power. The dynamics of the pitch control are moderately fast, and can have significant impact on dynamic system behavior. Since a unity power factor is expected in this system, the reactive power should stay at zero, and from the reactive power curve shown in fig 8c, it can be seen that no matter what the wind speed is, the reactive power tries to be kept at zero. The role of the pitch angle controller is to regulate the pitch angle when the wind speed exceeds its rated value of 12.5 m/s. The pitch angle profile is shown in Fig 8b. The turbine control model sends a power order to the electrical control, requesting that the converter deliver this power to the grid. From the fig 8g it can be seen that the grid-side controller will attempt to keep the DC-link voltage as constant under various wind speed conditions.

Parameters	value	Unit
Rated power	1.5	MW
DC-link capacitor	0.3	mF
Stator resistance	0.023	pu
Rotor resistance	0.016	pu
Base power	1.65	pu
Grid nominal voltage	575	V
Frequency	50	Hz
Wind turbine rotor Radius	91.2	m
Number of pole pair	3	
Rotor inductance	0.16	pu
Stator inductance	0.18	pu
Magnetizing inductance	2.9	pu

V. CONCLUSION

This work presents vector control of DFIG integrated in a wind energy conversion system by applying the field oriented control technic (FOC). The field orientated control scheme has been developed to control both rotor side and grid side converters for a wind driven DFIG system. First of all, the wind turbine and generator modelling as well as the synthesis of a proportional-integral controller (PI) have been developed. Computer simulation has been carried out in order to validate the effectiveness of the proposed system. The results of this study confirm that vector control of DFIG applied to the wind energy conversion system connected to the grid offers good dynamic performance. But its deployment requires the mastery of the DFIG parameters variation.

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We would also like to show our gratitude to my co-worker for sharing their pearls of wisdom with us during the course of this research, and we thank 3 "anonymous" reviewers for their so-called insights. We are also immensely grateful to (List names and positions) for their comments on an earlier version of the manuscript.

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