Approach Control of DFIG Rotor Side Converter- Based on Grid Frequency Coordinated Control

**Zakieldeen M. E. Elhassan, Abusabah I. A. Ahmed &
Othman Hassen Abdalla**

Article history:

Received August 10, 2021

Received in revised form September 25, 2021

Accepted October 07, 2021

Available online October 20, 2021

**Journal of Karary University for
Engineering and Science (JKUES)**

Online ISSN: 1858-8000

Print ISSN: 1858-800X

Approach Control of DFIG Rotor Side Converter Based on Grid Frequency Coordinated Control

Zakideen M. E. Elhassan*, Abusabah I. A. Ahmed * and Othman Hassen Abdalla*

*Department of Electrical and Computer Engineering, Karary University, Khartoum, 12304, Sudan,

Email: zakideenzain@yahoo.com

Abstract

This paper presents an approach frequency coordinated control of Doubly Fed Induction Generator (DFIG) applying in the Rotor Side Converter (RSC) using an order reference active power (P_{ref}). P_{ref} is obtained from the frequency deviation, speed regulation and kinetic energy stored in the DFIG. The P_{ref} is employed as a main controller parameter of the dq-axis currents in the RSC under two case studies. In case1 study, the P_{ref} is used to regulate the q-axis reference current and the grid reactive power controlled d- axis reference current. Whilst in case2 study, the d- axis reference current is produced by P_{ref} , and the rotor mechanical speed responsible to generate the q-axis reference current. The modified vector control method is used to control the Grid Side Converter (GSC) in two case studies. The transient performance of two case studies is simulated by PSCAD/EMTDC program under constant, step and variable wind speeds. A comparative result between two case studies shown that the frequency coordinated control has an ability to control both rotor dq-axis currents, and it enhancing the system frequency as well as improved DFIG voltage stability. However, case2 study has a better response than case1 study during system operated under random wind speed.

Key-terms-grid side converter GSC, rotor side converter RSC, frequency coordinated control, Frequency regulation, doubly fed induction generator DFIG

I. INTRODUCTION

The wind energy is the fastest growing and got more attention and support from the governments and technical institutions, because it is friendly to the environment and cheap power generation. Furthermore, the developments of wind energy technologies are extremely sophisticated, which led it to compete with the fossil-fuel power generation in flexibility and reliability operation. Different generator types have been used in wind energy systems such as Squirrel Cage Induction Generator (SCIG), DFIG and Synchronous Generator (SG) see [1]. Recently, the DFIG has been widely used as a generator in the wind energy power stations. Therefore, it has got many advantages such as, variable-speed operation, optimal power tracking at low wind speed, fast control of real and reactive powers and provides wide rotor speed varied within $\pm 30\%$ of rated speed. However, the main advantage of DFIG is that it provides the reactive power control without adding additional compensator devices [2]. Nowadays, with increasing integration of large-scale wind power in modern power systems, the frequency control becomes a serious problem for a stable and secure operation of the power grid. The main goal of frequency control in the conventional power system is to keep the dynamic balance of frequency between power generation and consumer within the specified limits [3], [4]. However, with the large DFIG wind power penetration into power systems, the power grid frequency has faced instability problems, because the DFIG did not provide any contributions to frequency changes. The main reason behind this is that the DFIG rotor is connected to the grid through back-to-back converters, which decouples the output power from the grid frequency. The other reason is that the DFIG normally operates at Maximum Power Point Tracking (MPPT), so there are no ways to increase the output power more than the

greatest power level [5]. More over, active and reactive powers decoupling control for the DFIG do not play a positive role in the frequency response ability of the power grid because it performs as the hidden inertia for the power grid. For instant, if the RSC operates with a constant frequency, it is easy to track the grid voltage [6]. In some of the literature, auxiliary frequency controllers are proposed to fit into the DFIG wind generation system. For example, the inertial control supports the frequency control by releasing energy from the wind turbines rotating mass. The researchers in this field sometimes are focused their researches to present the DFIG frequency contribution and regulation with the power grid system as in [5], [7], [8]. As it was shown in [9], the kinetic energy stored in the wind turbine generator is used to provide frequency of the conventional generators. The impact of the grid voltage and frequency variations on the wind generators output power has been studied with more details as in [10]. A comparison study of frequency response between DFIG and fixed speed induction generator when the network frequency changing is presented in [11]. Furthermore, a new method control of frequency and voltage together in a wind-energy system based on DFIG are made and discussed in [12], [13]. The most interesting study is to utilize the DFIG to participate in the system frequency regulation, thus by applying a suitable control in the RSC depending on frequency regulation [12].

In this paper, a control scheme of coordinated frequency regulation is used to control DFIG RSC. The frequency-coordinated control of DFIG is tested under steady state and dynamic modes during constant and variable wind velocities. The simulations on an electromagnetic transient package EMTDC/PSCAD was carried out to show the DFIG frequency coordinated control on RSC considering two case studies. Case1 adopts the frequency deviation to generate P_{ref} which

used to control the $I_{qr.ref}$ while the $I_{dr.ref}$ is controlled by grid reactive power. Case2 implements the P_{ref} to control $I_{dr.ref}$ whereas the $I_{qr.ref}$ controlled by using rotor speed. This paper is organized as follows: Firstly, a simulation system case study is explained, and the frequency principle controls of the power system and DFIG is presented. Secondly, the DFIG equations and converters model control using frequency coordinated control strategy are designed to implementation the control characteristics of DFIG. Thirdly, wind power expression and their parameter specification are discussed. Finally, the simulation results are analyzed and discussed.

II. SYSTEM MODEL DIAGRAM

The system model diagram consists of transformer, transmission line, power grid and DFIG based on wind turbine. The DFIG data are listed in the Table. I as in [13]. The stator of DFIG is directly connected to the grid and the rotor is connected through back-to- back converters. The DFIG is controlled in the rotating dq- axis reference frame, with the modified vector control in the GSC and frequency coordinated control in RSC. The DFIG active and reactive powers are controlled by regulating the rotor current and stator voltage. Therefore, the stator voltage needs to be decomposed into decoupling components related to the voltage source converter and its parameters connected. The system schematic model diagram is shown in Fig. 1.

III. FREQUENCY CONTROL

According to the electricity supply regulations and hence the National Grid Company's (NGC) transmission license, the frequency delivered to the consumer must not vary from the declared value by more than 1% [7], [14]. Therefore, the system frequency must maintain under limits certain values around nominal frequency $\pm 0.5Hz$. The frequency droop events indicate three factors, i.e. frequency change rate, frequency nadir and steady-state frequency deviation [15], [16]. Namely the last one is deeply used throughout this paper for controlling DFIG converter. Generally, the energy stored of the rotating mass for a frequency change from nominal frequency f_s to the $f = f_s + \Delta f$, is derived according to [17], [18] as

$$\begin{aligned} \frac{dw}{dt} &= \Delta P_{sys} = \frac{2H}{f_s} \frac{d\Delta f}{dt} \\ \Delta f &= \frac{1}{2\pi} \frac{d\Delta\delta}{dt} = 1 - R\Delta P_g \end{aligned} \quad (1)$$

Where ΔP is the generator angle change, $\hat{f}$ is the frequency change, $\hat{P}_g$ is the generator power change, H is the rotor moment inertia and R is the speed regulation factor (droop); all these parameters in per unit. Based on Eq. 1, the kinetic energy of the rotating mass of the DFIG turbine depends on the frequency change so the rate of change of frequency (ROCOF) must be used to generate a necessary active power to provide signal control to the convertor and improve frequency point in the case of frequency event. The strong relationship between frequency and active power can be employed through the inertia rotating mass energy to achieve the DFIG RSC control.

Fig. 1. The System Model Diagram

IV. DFIG MATHEMATICAL EQUATIONS

Referring to the DFIG equivalent circuit in dq-axis frame, the stator and rotor voltages could be written as in [13]:

$$V_{ds} = R_s i_{ds} - \omega_s \lambda_{qs} + p \lambda_{ds} V_{qs} = R_s i_{qs} + \omega_s \lambda_{ds} + p \lambda_{qs} \quad (2)$$

$$\begin{aligned} V_{dr} &= R_r i_{dr} - \omega_{sl} \lambda_{qr} + p \lambda_{dr}; \\ V_{qr} &= R_r i_{qr} + \omega_{sl} \lambda_{dr} + p \lambda_{qr} \end{aligned} \quad (3)$$

$$\begin{aligned} \lambda_{ds} &= L_s i_{ds} + L_m i_{dr}; \\ \lambda_{qs} &= L_s i_{qs} + L_m i_{qr}; \\ \lambda_{dr} &= L_r i_{dr} + L_m i_{ds}; \\ \lambda_{qr} &= L_r i_{qr} + L_m i_{qs} \end{aligned} \quad (4)$$

Where these notations denoted to V_{ds} , i_{ds} , λ_{ds} , V_{qs} , i_{qs} and λ_{qs} are the dq-axis stator voltages, currents and flux linkages, respectively. Similarly, V_{dr} , i_{dr} , λ_{dr} , V_{qr} , i_{qr} and λ_{qr} are the dq-axis rotor voltages, currents and fluxes linkage, R_s , L_s , R_r , L_r and L_m are the stator resistance, stator self-inductance, rotor resistance, rotor self-inductance, magnetising inductance, respectively, ω_s is the synchronous reference frame speed, ω_{sl} is the slip speed ($\omega_s - \omega_r$), ω_r is the rotor frequency speed and p denoted to derivative operator d/dt . The stator active power (P_s) and reactive power (Q_s) are given as,

$$P_s = 1.5(V_{ds} i_{ds} + V_{qs} i_{qs}); Q_s = 1.5(V_{qs} i_{ds} - V_{ds} i_{qs}) \quad (5)$$

$$P_s = 1.5V_{ds} i_{ds}; Q_s = -1.5V_{ds} i_{qs} \text{ for } V_{qs} = 0.0 \quad (6)$$

Similarly, the grid active and reactive powers could be written as,

$$P_g = 1.5V_{dg} i_{dg}; Q_g = -1.5V_{dg} i_{qg} \quad (7)$$

The DFIG mechanical motion and electromagnetic torque equations are given by:

$$P\omega_r = \frac{P}{f}; T_e = 1.5PL_m(i_{qs} i_{dr} - i_{ds} i_{qr}) \quad (8)$$

TABLE I
DFIG AND SYSTEM PARAMETERS (1.5 MVA DFIG).

Rated power 1.5 MW	Transformer ratio 0.69/20 kV
Rated voltage 0.69 kV	Rated power 5 MVA
Rated frequency 50 Hz	Line voltage 20 kV
Number of pole pairs, P 2.0	Line length 30 km
stator winding resistance, R_s 0.0084 pu	Transmission line parameters were adopted from PSCAD library
Rotor winding resistance, R_r 0.0083 pu	DC link capacitance 9800 μ F
Stator leakage inductance, L_{Ls} 0.167 pu	DC link reference voltage 1200 V
Rotor leakage inductance, L_{Lr} 0.1323 pu	Shaft stiffness, K_{tg} 1.5 pu/rad
Magnetizing inductance, L_m 5.419 pu	Turbine inertia constant, H_t 3.5 s
Inertia constant, H_g 1.1 s	Shaft damping factor D_{tg} 0.3 pu/ rad/sec

V. RSC APPROACH CONTROL

The main objective of the RSC is to keep the power flow between the converter and grid constant irrespective to any change in the GSC. In normal operation, the RSC regulates the reactive power injection by controlling q-axis current and active power by using d-axis current see [19]. The RSC equation can be written through the rotor dq-axis voltage as in Eq.3 and Eq. 4 as in [20],

$$\begin{aligned} V_{dr} &= R_r i_{dr} + L_d i_{qr} + e_{d1} + e_{d2} + L_{\sigma r} p i_{dr} \\ L_d &= -\omega_{sl} L_{\sigma r}; \\ e_{d1} &= -\omega_{sl} \frac{L_m}{L_s} \lambda_{qs}; \\ e_{d2} &= \frac{L_m}{L_s} p \lambda_{ds}; \\ L_{\sigma r} &= \frac{L_r L_s - L_m^2}{L_s} \end{aligned} \quad (9)$$

$$\begin{aligned} V_{qr} &= R_r i_{qr} + L_q i_{dr} + e_{q1} + e_{q2} + L_{\sigma r} p i_{qr} \\ L_q &= \omega_{sl} L_{\sigma r}; \\ e_{q1} &= \omega_{sl} \frac{L_m}{L_s} \lambda_{ds}; \\ e_{q2} &= \frac{L_m}{L_s} p \lambda_{qs} \end{aligned} \quad (10)$$

From Eq.9 and E. 10, the dq-axis rotor voltages are depending on induced voltage associated to dq-axis stator flux linkages in steady state and dynamic, induced voltage related to the inductance $L_{\sigma r}$ with dq-axis current at steady state and dynamic. Through the vector control unit with generalized law the reference values of dq-axis voltages based on Eq.9 and E. 10 are written as :

$$\begin{aligned} V_{dr}^* &= V_{dr}' + V_{drop} + V_{ind}; \\ V_{qr}^* &= V_{qr}' + V_{drop} + V_{ind} \end{aligned} \quad (11)$$

Where V_{dr}' and V_{qr}' are the voltages obtained through PI controller, V_{drop} is the voltage dissipated in the rotor resistance and V_{ind} is the induced voltage related to stator and rotor inductances. Form Eq.11, if we considered the V_{dr}' and V_{qr}' are effective predominant elements in the equation and the other parameters are neglected. The dq-axis voltage V_{dr}^* and V_{qr}^* can be controlled by the dq-axis current through PI controllers. This voltage must be transformed to the three phases synchronous frame to compare with measured rotor voltage and the error is used as input to the PWM. Due to this point and simplicity, these voltages are used to control the RSC and its determined mainly from the PI controller with an input of the control error as below,

$$\begin{aligned} V_{dr}' &= (i_{dr}^{ref} - i_{dr})(K_{dp} + \frac{K_{di}}{s}) \\ V_{qr}' &= (i_{qr}^{ref} - i_{qr})(K_{qp} + \frac{K_{qi}}{s}) \end{aligned} \quad (12)$$

Where the i_{dr}^{ref} and i_{qr}^{ref} are the variable dq-axis rotor reference currents, K_{dp} , K_{qp} , K_{di} and K_{qi} are the dq-axis rotor currents proportional and integral gains respectively. The values of these parameters are designed to achieve full system parameter optimizing and prevent oscillation current occurred during transient operation. The dq-axis currents transfer functions are used to check the proposed method steady state stability. Furthermore, the root locus method was also used to confirm the stability under ignoring the drop voltage and induced voltage. Based on this an assumption the control of the RSC is considered only through PI controller and the DFIG parameters using rotor dq-axis reference currents, which are mainly issued of the approach control method in this study.

A. RSC reference parameters

The i_{dr}^{ref} and i_{qr}^{ref} are obtained from reference active power P_{ref} , reference rotor speed ω_{ref} and reference grid reactive power Q_g^{ref} . The main important factor of these parameters is the P_{ref} , which is a significant topic in this paper study. The P_{ref} is calculated as a function of power response of frequency deviation, inertial control response power and auxiliary power signal. The P_{ref} equation basic on the [5], [7], [21] could be written as:

$$\begin{aligned} \Delta P_{sys} &= 2H f_{sys} \frac{df_{sys}}{dt}; \\ \Delta P &= -\frac{1}{R}(f_0 - f_{sys}); \\ P_{ref} &= \Delta P + P_0 - \Delta P_{sys} \end{aligned} \quad (13)$$

Here ΔP_{sys} is the system power response of inertial control, H is the DFIG inertia constant, f_{sys} is the system frequency measured from the grid side using frequency/phase measurement device, f_0 is the nominal frequency (50Hz), R is the speed regulation drop (set as i.e.0.04), is the system active power response of frequency deviation and P_0 is the nominal power which sets to a suitable value according to the DFIG rated power (i.e. 90%of P). However, in reference [21], the P_0 is calculated from the MPPT which let the P_{ref} stability with margin risk. To get the active power from MPPT is very complicated, and it needs synchronizing between turbine time response and the DFIG time constant which is too difficult to apply it. The droop controller can regulate the active power output in proportion to the frequency deviation

TABLE II
PI CONTROLLER PARAMETERS.

$K_{p1} = 0.05$	$K_{i1} = 0.2$	$K_{p2} = 0.005$	$K_{i2} = 12$
$K_{p3} = 0.007$	$K_{i3} = 12$	$K_{p4} = 0.005$	$K_{i4} = 10$

with the droop ratio $1/R$. Using inertial controller, the kinetic energy from the rotating mass of DFIG is quickly released through power electronic converter, so that the additional active power can be provided to reduce the rate of change of frequency (ROCOF) and minimized frequency point in the case of frequency change. The proposed control method of RSC uses the frequency coordinated control is depended on the relationship of voltage oriented control method, which in this case the active and reactive can be controlled by the dq-axis rotor currents as in [13]. The approach control method of RSC is adopted in two case studies as below.

1) *Case1 study*: This case study is commonly used in the RSC of DFIG based on wind energy. However, in this study is modified from the work as in [12] which described the distribution of DFIG in power system frequency regulation. Moreover, this method study was clearly implemented and discussed as in [21], [22]. In this case study, the active power (P_{ref} and P_g) is used to control I_{qr}^{ref} and the grid reactive power (Q_{ref} and Q_g) employed for controlling I_{dr}^{ref} . The expressions of rotor dq- axis reference currents through PI controllers can be written as,

$$\begin{aligned} I_{dr}^{ref} &= (Q_{ref} - Q_g)(K_{p1} + \frac{K_{i1}}{s}); \\ I_{qr}^{ref} &= (P_{ref} - P_g)(K_{p2} + \frac{K_{i2}}{s}) \end{aligned} \quad (14)$$

2) *Case 2 study*: In this case study, the authors present a new approach method to use frequency regulation for controlling the rotor d-axis current. This control is implemented by generating reference active power (P_{ref}) then compared with the DFIG active power (P_g) and the error is used as input of the PI controller to produce I_{dr}^{ref} instead of I_{qr}^{ref} . The I_{dr}^{ref} is produced from the rotor mechanical speed and rotor reference speed. Similarly the dq-axis current equations can be given as,

$$\begin{aligned} I_{dr}^{ref} &= (P_{ref} - P_g)(K_{p3} + \frac{K_{i3}}{s}); \\ I_{qr}^{ref} &= (\omega_m - \omega_{ref})(K_{p4} + \frac{K_{i4}}{s}) \end{aligned} \quad (15)$$

In two case studies, both dq-axis reference currents are compared with dq-axis currents measured from the rotor side to get reference rotor values for enabling insulated gate bipolar transistor (IGBT) gates. The values of different stage of PI controllers are listed in Table. II. Moreover, the P_{ref} and ω_{ref} are also employed to provide qualify and adequate control loop for pitch angle control which discussed in the below section. The overall block diagram control of the RSC is shown in Fig. 2. Case 2 study was compared with case 1 study to show the ability of frequency coordinated control to control both direct and quadrature currents.

B. GSC model

The GSC is in charge of controlling part of the power flow in the DFIG. This power is incompletely delivered through RSC, DC link and finally is transmitted by the GSC to the grid. The

Fig. 2. The DFIG converters control Model

GSC can operate in different power factor control depending on the DFIG requirements [24]. The dynamic equations of GSC depending on the voltage oriented control in the dq-axis frame could be written as in [13], [25], [26], [27]:

$$\begin{aligned} P i_{ds} &= \frac{1}{L_g}(v_{ds} - v_{di}) + \omega_s i_{qs}; \\ P i_{qs} &= -\frac{1}{L_g}v_{qi} - \omega_s i_{ds} \end{aligned} \quad (16)$$

Where v_{ds} is the stator d-axis voltage and it represented the voltage of the AC grid (stator q-axis voltage is by definition, $v_{qs} = 0$, v_{di} and v_{qi} are the dq-axis components of the generated VSC voltage. Eq. 16 clearly showed that attempting to change i_{ds} using v_{ds} will also cause a transient change in i_{qs} . So a modification has to be made to the control loop by adding a PI controller. Therefore, the GSC needs a decoupled response to possible a request change of i_d without change i_q and vice-versa. Considering the PI controller, the output of decoupled controller can be expressed as in [13],

$$\begin{aligned} v_{di} &= -(K_p + \frac{K_s}{s})(i_{ds}^{ref} - i_{ds}) + \omega_s L_g i_{qs} + v_{ds}; \\ v_{qi} &= -(K_p + \frac{K_s}{s})(i_{qs}^{ref} - i_{qs}) - \omega_s L_g i_{ds} \end{aligned} \quad (17)$$

Where $K_p + \frac{K_s}{s}$ is the transfer function of PI controller, substituting Eq. 17 into Eq. 16 yields:

$$\begin{aligned} p i_{ds} &= \frac{1}{L_g}(K_p + \frac{K_s}{s})(i_{ds}^{ref} - i_{ds}); \\ p i_{qs} &= \frac{1}{L_g}(K_p + \frac{K_s}{s})(i_{qs}^{ref} - i_{qs}) \end{aligned} \quad (18)$$

The i_{qs}^{ref} could be obtained from Eq. 6. The GSC control model diagram overall can be seen through the DFIG converter schematic diagram as shown in Fig. 3. To investigate this model, the stator voltage angle θ_s is calculated by using a phase lock loop (PLL), then it used to transform GSC variables from abc stationery to dq synchronous frame, and vice versa. The GSC three phase voltages must transform to abc stationary frame to compare with three-phase voltage measured from the stator side, then it used as an input to the PWM. The reference DC link voltage $V_{dc,ref}$ is set to a coordinated value related to the phase voltage and the amplitude index (m_a). The model

Fig. 3. The DFIG converters control Model

diagram of the GSC contains three feedback control loops: two inner current loops for the accurate control of the dq-axis currents and one outer DC voltage feedback loop for the control of DC voltage. There is infinity of different controllers that might be used to control these loops. However, the most widely used is the proportional integral (PI) controller due to its simplicity. To compute the PI regulator parameters, the relationship between the voltage and current must be known.

VI. WIND TURBINE MECHANICAL SYSTEM

The wind turbine conversion system based on two-mass system model which is obtained from the three-mass model reduction by neglecting the moment of inertia for the shafts and the gearbox wheels and adding the gearbox to the generator side. Therefore the resultant model is essentially a two mass model connected by a flexible shaft. The wind system dynamic equations can be written as in [28], [29],

$$\begin{aligned} T_w - T_c &= J_t \frac{d\omega_t}{dt} + D_t \omega_t; \\ T_c - T_e &= J_g \frac{d\omega_g}{dt} + D_g \omega_g; \\ T_c &= D_{tg}(\omega_t - \omega_g)dt + K_{tg}(\theta_t - \theta_g) \end{aligned} \quad (19)$$

Where T_w , T_e , T_c are the turbine resultant torque, generator torque, coupling torque. J , D , K , $\dot{\theta}$ and $\ddot{\theta}$ are the inertia constant, damping coefficient, stiffness coefficient, rotating speed and angular position, respectively. The subscripts letters t, g and tg are referring to the turbine, generator and flexible coupling between generator and turbine. The turbine model parameters are defined in Table. I as in the appendix, and it's referred to the shaft side. These differential equations can be solved as in [30]. The wind turbine torque (T_w) is

TABLE III
WIND TURBINE AND PITCH ANGLE CONTROLLER DATA.

Wind turbine	Pitch controller
Rated power, P_m 2.0MW	Proportional gain, K_p 3.2 Åř/ pu
Rotor radius, R 40 m	Integral gain, K_i 6.2 Åř/ pu
Air density, 1.229 kg/m3	Blade integral gain, K_b 0.4 s
Gearbox ratio 60	Blade actuator rate 10 Åř/s

obtained from the turbine captured power based on [31], [32], [33], [34] as:

$$\begin{aligned} T_w &= \frac{0.5 \rho \pi R^3 V_m C_p(\lambda, \beta)}{\omega_t}; \\ \lambda &= \frac{R \omega_t}{V_w} \end{aligned} \quad (20)$$

Where ρ is the air density (1.225kg/m3), R is the rotor radius, V_w is the wind speed in m/s, λ is the tip speed ratio, β is the blade pitch angle in degree (β is usually set to zero for the maximum value of C_p), C_p is the output power coefficient (function in both β and λ) and ω_t is the turbine speed (rad/sec). The theoretical maximum value of C_p is given by the Betz's limit, (about 0.593) as in [26]. Many numerical equations have been developed to calculate the C_p for identifying values of λ) and β as in [34]:

$$\begin{aligned} C_p(\lambda, \beta) &= 0.73 \left(\frac{151}{\lambda_j} - 0.58\beta^{2.14} - 13.2 \right) e^{\frac{-18.4}{\lambda_j}}; \\ \lambda_j &= \frac{1}{\frac{1}{\lambda - 0.02\beta} - \frac{0.003}{\beta^3 + 1}} \end{aligned} \quad (21)$$

However, in this paper, adequate control of pitch angle was implemented in the PSCAD software program, and the angle β is calculated from the block diagram obtained from the active power and rotor mechanical speed through PI controllers.

VII. PITCH ANGLE CONTROL

The Pitch angle controller of the DFIG is designed to achieve a maximum output mechanical power to produce a high turbine torque. This design considers rotor speed and grid power changing during the system abnormal operation. The controller block diagram of pitch angle is implemented in the PSCAD and the PSCAD wind turbine model is used to generate the torque. Fig. 4 shows the pitch angle control diagram and the controller parameters of the model diagrams are listed in the Table. III. The simulation studied model in Fig. 1 is conducted in the PSCAD/EMTDC program. The system disturbances with a three-phase fault in the grid voltage busbar at 10 sec with duration time 0.13sec. The simulation initial conditions set as: shaft torque enables at 0.5 sec, the pitch angle control adds at 1.5 sec. The simulation results are carried out by using interface between PSCAD and MATLAB programs to plot the results with high quality.

A. Step Wind Speed

The wind velocity started with 9 m/sec and after 5sec it changed to 11m/sec to check wind turbine operation under step input wind speed. Series of results have been obtained to investigate the DFIG behaviour under frequency coordinated control as below. Fig. 5 (a) shows the wind speed waveform

Fig. 6. DFIG simulation results: a) Rotor speed (ω_r), b) Active power (P_g), c) Reactive power (Q_g), d) Terminal voltage (V_t)

Fig. 7. DFIG response: (a) Wind curve; (b) Pitch angle; (c) Electromagnetic torque T_e ; (d) Rotor speed ω_r .

Fig. 8. DFIG power and voltage response: (a) Active power P_g ; (b) Reactive power Q_g ; (c) Terminal voltage V_t ; (d) DC-link voltage V_{dc} .

also are briefly presented to avoid redundancy discussion. Fig. 7 (a-d) shows random wind speed (V_w), pitch angle blade, T_e and ω_r , respectively. Through these figures, we can see that the DFIG did not lose the synchronism operation even during fault and randomly wind speed variation. This result indicates that the two case studies have an ability to control DFIG in different operation conditions. However, case2 showed reliability result essentially in the pitch angle control result. Depending on this method control, the crucial output results of DFIG have strongly gained robust control and smooth dynamic operation. The P_g , Q_g , V_t and V_{dc} simulation results are shown in Fig. 8 (a-d), respectively. The P_g response curve at steady state in two case studies is stable but in dynamic state, case1 has higher negative value reaches to -1.18MW which means that this power is received from grid side, and this may be led to instability of DFIG operation. However, case2 has a good response at transient operation because the PI controller controlled by the active power and rotor mechanical speed. This result scenario can be seen in Fig. 8(a). Fig. 8 (b) shows the Q_g curve which the steady state value (SSV) is 0.09 Mvar in case1 and in case2 is about -0.6Mvar. The two values are in within the allowable rate of the 1.5MW DFIG wind turbine. The DFIG terminal voltage (V_t) profile curve has better steady state stability in case1 study and a good dynamic response in case2, this refers to the parameters control in each method. The voltage profile with significant indicator values of voltage stability are marked in voltage profile curve as in Fig. 8 (c). The DC link voltage in two case studies is clearly presented as in Fig. 8 (d). Consequently, from these results, we concluded that case1 and case2 studies are very convincing to control the RSC of DFIG either in steady state or dynamic state under a different kind of wind speed. However, case2 study which explored by authors is more suitable to apply in the DFIG control during variable wind speeds. Despite the higher values at starting and this can be addressed by adjusting the initial conditions to corresponding values.

VIII. CONCLUSION

In this paper, approach control of DFIG RSC using a frequency coordinated method has been presented. In this approach method, the RSC reference dq-axis currents are controlled by grid reactive power and active power based on system frequency regulation. The frequency coordinated is used to generate active power from the frequency deviation and the DFIG hidden kinetic energy. This active power compares with the generator power to produce signal control, which used to control either Irq-ref current as in case1 study or Ird-ref current as in case2 study. The simulation is conducted using the PSCAD software program, and the studied model is adopted at steady state and dynamic state during step and variable wind speeds. From the simulation outcome, there is no bigger a huge change in the DFIG power in abnormal operation because adequate control is provided to the DFIG converters through frequency coordinated control. The case2 study presented a new control of the RSC in the d-axis current using active power captured from frequency deviation. Using this case study, the DFIG has gotten strongly operation with

stable performance, constant rotor speed and fixed DC link voltage. Furthermore, the output power of DFIG is more linear, stable and safety transient response with smoother recovery values under constant and variable wind speeds. Whilst in case1, the DFIG has stability, performance at the steady state besides risk stability of dynamic state, and under random wind speed when the large disturbances are occurring. However, this case study has a good response of DFIG terminal voltage at a steady state without any unbalanced voltage problems, which usually happens in DFIG penetrated to the power grid. Generally, every case study presents effective control of some DFIG parameters and with drawbacks in the others, meanwhile case2 study has better response results. The main advantage of this study is to estimate the values of reference parameters using frequency coordinated control method. Using this method control, the DFIG owned a wide-range control option, depending on the PI controller parameters.

REFERENCES

- [1] H. T. Jadhav, R. Roy. A Critical Review on the Grid Integration Issues of DFIG based Wind Farms. Environment and Electrical Engineering (EEEIC), Rome: 2011.
- [2] Eknath Vittal, Mark O'Malley, and A. Keane. A Steady-State Voltage Stability Analysis of Power Systems With High Penetrations of Wind. IEEE Transactions on power systems, 2010. 25(1): 433-442.
- [3] Johan Morren, Sjoerd W. H. de Haan, Wil L. Kling, and J.A. Ferreira. Wind Turbines Emulating Inertia and Supporting Primary Frequency Control. IEEE Transactions on power systems, 2006. 21(1): 433-434.
- [4] Krause, G., ed. From Turbine to Wind Farms - Technical Requirements and Spin-Off Products. 2011, InTech Janeza Trdine 9, 51000 Rijeka, Croatia: First published March, 2011, Printed in India. 231.
- [5] Zhang, Z.S., Y.Z. Sun, J. Lin, and G.J. Li. Coordinated frequency regulation by doubly fed induction generator-based wind power plants. IET Renewable Power Generation, 2012. 6(1): 38.
- [6] Wong, K.C., S.L. Ho, and K.W.E. Cheng. Direct Voltage Control for Grid Synchronization of Doubly-fed Induction Generators. Electric Power Components and Systems, 2008. 36(9): 960-976.
- [7] Holdsworth, L., J.B. Ekanayake, and N. Jenkins. Power system frequency response from fixed speed and doubly fed induction generator-based wind turbines. Wind Energy, 2004. 7(1): 21-35.
- [8] Chang-Chien, L.-R., W.-T. Lin, and Y.-C. Yin. Enhancing Frequency Response Control by DFIGs in the High Wind Penetrated Power Systems. IEEE Transactions on Power Generation, 2011. 26(2): 710-718.
- [9] Ping-Kwan Keung, H.B. Pei Li, and B.T. Ooi. Kinetic energy of wind-turbine generators for system frequency support. IEEE Transactions on power systems, 2009. 24(1): 279-287.
- [10] Divya, K.C., P.S. Nagendra Rao. Effect of Grid Voltage and Frequency Variations on the Output of Wind Generators. Electric Power Components and Systems, 2008. 36(6): 602-614.
- [11] Ekanayake, J., N. Jenkins. Comparison of the response of doubly fed and fixed-speed induction generator wind turbines to changes in network frequency. IEEE Transactions on Energy Conversion, 2004. 19(4): 800-802.
- [12] Rogério G. de Almeida, J.A.P. Lopes. Participation of Doubly Fed Induction Wind Generators in System Frequency Regulation. IEEE Transactions on power systems, 2007. 22(3): 944-950.
- [13] BinWu, Yongqiang Lang, Navid Zargari, and S. Kouro. Power conversion and control of wind energy systems. IEEE on Power Engineering, ed. M. E.El-Hawary. 2011, Hoboken, New Jersey: John Wiley and Sons, Inc.
- [14] Okedu, K.E. Participation of Energy Capacitor System in Hydrogen Production, Voltage and Frequency Control in Wind Generation. Pacific Journal of Science and Technology, 2011. 12(1): 605-612.
- [15] Ronan Doherty, Alan Mullane, Gillian (Lalor) Nolan, Daniel J. Burke, Alexander Bryson, and M. O'Malley. An assessment of the impact of wind generation on system frequency control. IEEE Transactions on power systems, 2010. 25(1): 452-460.
- [16] Yuan-zhang SUN, Zhao-sui ZHANG, Guo-jie LI, and J. LIN. Review on frequency control of power systems with wind power penetration. International Conference on Power System Technology, Hangzhou - China: 2010.

- [17] Janaka Ekanayake, N. Jenkins. Comparison of the response of doubly fed and fixed-speed induction generator wind turbines to changes in network frequency. IEEE Transaction on Energy Conversion, 2004. 19(4): 800-802.
- [18] Murty, P.S.R., Operation and Control in Power Systems. 2008, 4-4-309, Giriraj Lane, Sultan Bazar, Hyderabad - 500 095 A.P.: BS publications.
- [19] Salles, M.B.C., A.J.S. Filho, and A.P. Grilo. A Study on the Rotor Side Control of DFIG-based Wind Turbine during Voltage Sags Without Crowbar System. in International Conference on Renewable Energy Research and Applications (ICRERA) 2012. Nagasaki: Renewable Energy Research and Applications (ICRERA).
- [20] Chondrogiannis, S., M. Barnes. Stability of doubly-fed induction generator under stator voltage orientated vector control. IET Renewable Power Generation, 2008. 2(3): 170-180.
- [21] Jinsik Lee, Jinho Kim, Yeon-Hee Kim, Yeong-Han Chun, Sang Ho Lee, Jul-Ki Seok, and Y.C. Kang. Rotor Speed-based Droop of a Wind Generator in a Wind Power Plant for the Virtual Inertial Control. Journal of Electrical Engineering and Technology, 2013. 8(5): 1021-1028.
- [22] Elhassan, Z., T. Yi, and L. Yang. Comparative study of voltage oriented and frequency coordinated control of grid connected doubly fed induction generator. Journal of Renewable and Sustainable Energy, 2014. 6(2): 023120-1-023120-17.
- [23] Zakieldeen, E., Y. Tang, and Y. Li. Proposed Control Method of Doubly Fed Induction Generator Rotor Side Converter Based on System Frequency Regulation. Applied Mechanics and Materials, 2014. 548-549: 806-814.
- [24] Behera, R.K., W. Gao. A Novel Controller Design for Grid-side Converter of Doubly Fed Induction Generator for Wind Power Interface: An Experimental Investigation. Electric Power Components and Systems, 2010. 38(14): 1531-1545.
- [25] Shuhui Li, T.A. Haskew. Analysis of Decoupled d-q Vector Control in DFIG Back-to-Back PWM Converter. Power Engineering Society General Meeting, Tampa, FL: 2007.
- [26] Gonzalo Abad, Jess Lpez, Miguel A. Rodrguez, Luis Marroyo, and G. Iwanski, Doubly Fed Induction Machine Modeling and Control for Wind Energy Generation IEEE Press on power Engineering. 2011, Hoboken, New Jersey: John Wiley and Sons, Inc.
- [27] Li, S., T.A. Haskew, Y.-K. Hong, and L. Xu. Direct-current vector control of three-phase grid-connected rectifierinverter. Electric Power Systems Research, 2011. 81(2): 357-366.
- [28] Jorge Martnez, Philip C. Ker, Pedro Rodriguez, and R. Teodorescu. Parameterization of a synchronous generator to represent a doubly fed induction generator with chopper protection for fault studies. Wind Energy, 2011. 2011(14): 107.
- [29] Zhan Xu, Z. Pan. Influence of Different Flexible Drive Train Models on the Transient Responses of DFIG Wind Turbine. in International conference on Electrical Machines and Systems (ICEMS). 2011. Beijing, China: IEEE.
- [30] Nicholas W. Miller, William W. Price, and J.J. Sanchez-Gasca. Dynamic Modeling of GE 1.5 and 3.6 Wind Turbine-Generators. GE-Power Systems Energy Consulting, U.S.A2003.
- [31] Koutroulis, E., K. Kalaitzakis. Design of a Maximum Power Tracking System for Wind-Energy-Conversion Applications. IEEE Transaction on Industrial Electronics, 2006. 53(2)(2): 486-494.
- [32] Soares Orlando, Gonalves Henrique, Martins Antnio, and C. Adriano. Nonlinear control of the doubly-fed induction generator in wind power systems. Renewable Energy, 2010. 35(8): 1662-1670.
- [33] Okedu, K.E. A Study of Wind Farm Stabilization Using DFIG or STATCOM Considering Grid Requirements. Engineering Science and Technology Review, 2010. 3(1): 200-209.
- [34] J. G. Slootweg, S. W. H. de Haan, H. Polinder, and W.L. Kling. General Model for Representing Variable Speed Wind Turbines in Power System Dynamics Simulations. IEEE Transactions on power systems, 2003. 18(1): 144-151.
- [35] M. Mohseni, S. Islam, and M.A.S. Masoum. Fault ride-through capability enhancement of doubly-fed induction wind generators. IET Renewable Power Generation 2011. 5(5): 368376.

Zakieldeen M. E. Elhassan Zakieldeen M. E. Elhassan is an Assistant Professor in College of Engineering, Karary University he is a head of Electrical and Computer Engineering Department. He received the M.Sc. degree and Ph. D. degree in Electrical Engineering from Karary University-Sudan and Southeast University-China in 2007 and 2015. His research area includes Solar Energy, Renewable Energy Sources and Power System Control. Dr. Zakieldeen has more than 6 academic publications and he is a reviewer for many journals and conferences. Now he is teaching High Voltage Techniques for graduate students, and Electrical Machine control, Electrical Machine conversion, Special Machine, power systems and electrical circuit theory for junior students at Karary University.

Abusabah I. A. Ahmed Abusabah I. A. Ahmed is an Assistant Professor in College of Engineering, Karary University. He received the M.Sc. degree and Ph. D. degree in Electronic Engineering from University of Electronic Science and Technology of China in 2013 and 2017. His research area includes Robotics Control, Predictive and Adaptive Control and Neural Networks. Dr. Abusabah I. A. Ahmed has 7 academic publications and he is a reviewer for two journals and many conferences. Now he is teaching Soft Computing in Control Systems for graduate students, and Control Theory, Automatic Control, Modern Control, Optimal Control and Electronic Measurements for junior students at Karary University.

Othman Hassan Abdalla Othman Hassan Abdalla is an Associate Professor in College of Engineering, Karary University. He received the M.Sc. degree and Ph. D. degree in Electronic Engineering from Iraq University and North China Electric Power University in 2006 and 2014. His research area includes Power Electronics, and Machine Drives. Dr. Othman Hassan Abdalla has more than 7 academic publications and he is a reviewer for two journals and many conferences. Now he is teaching Machine Drive Systems for graduate students, and Power Electronics, Electronic Circuits for junior students at Karary University.