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Doubly Fed Induction Generator-Based Wind Turbine Modelling and Simulation Using MATLAB/Simulink

Mohamed Gad El-Moula*
Department of Electric Engineering, Faculty of Engineering, University of Beni-Suef

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ABSTRACT

Abstract - The effective control of a doubly fed induction generator for variable speed wind power generation is presented in this work. Since their voltage source converters can only manage a small portion of the entire output power in steady-state conditions, DFIGs are frequently utilized in variable speed wind energy conversion systems (WECS). The DFIG's rotor circuit uses a back-to-back power electronic converter (AC-DC-AC), which enables the generator to operate in both sub-synchronous and super-synchronous modes. This paper describes in detail how the rotor, grid side, and pitch angle controllers are controlled and implemented. The goal of the grid side converter is to adjust for reactive power and maintain a constant dc-link voltage instead of adding a compensating device, like an SVC or banks of capacitors, in parallel with the machine, which can cause overvoltage and other issues. The rotor-side converter uses the vector control technique to regulate the rotor speed and enable decoupled control between the active and reactive powers. Coordination between the rotor side controller and pitch angle will be used to prevent system failure during wind gusts. Using Matlab Simulink, the control system's performance is demonstrated.

1. INTRODUCTION

In recent years Environmental pollution has grown to be a significant issue in people's daily lives, and the prospect of an energy crisis has prompted scientists to create new clean and renewable energy generation technologies. Potential options for an eco-friendly energy production system include wind power in addition to solar, hydro, and tidal energy. Among them, harnessing wind energy seems to be the most promising renewable energy source and is expanding at the highest rate (about 20% per year) in the power sector [1]. Renewable energy sources have become increasingly integrated into the power supply network in recent years. In this regard, the production of wind energy has been crucial. Wind turbines based on doubly-fed induction generators (DFIG) have unquestionably emerged as one of the top technologies for wind turbine manufacturers, proving to be an economical, dependable, and efficient option [1]. The most widely utilized generator wind energy conversion technology is the DFIG, which makes up around half of the nominal capacity of installed wind turbines globally [2]. One of the best options for variable speed wind energy conversion systems is DFIGs

*Corresponding Author:
E-mail: mohamed.gad@eng.bsu.edu.eg

due to a number of their features [3]. Because it has the benefit of using a fractional power converter [4] [3].

A rotor-connected power converter may regulate the generator speed system with this setup to within ±30% of the synchronous speed [2]. Field orientated control (FOC) can fully regulate the generator, achieving good decoupling of the generator's active and reactive power, even though the converter has a lower power rating [4]. It is possible to operate both above and below synchronous speed [2]. The development of sophisticated and dependable control methods for DFIGs has drawn a lot of interest in recent years due to their extensive use in wind turbine systems.

The most widely used application in wind energy conversion is vector control [10]. Through independent regulation of the rotor current vector's quadrature components, this technique enables a decoupled control of WTS's active and reactive power. Wind turbines' growing presence in electrical power systems is starting to affect how the system behaves overall, and managing a power system just by managing large-scale power plants will no longer be sufficient. Studying how wind turbines behave within the power system and how they interact with loads and other generating equipment is crucial. In the literature, the majority of DFIG wind turbine control strategies [8][15] are predicated on generating the most electricity under optimal economic exploitation circumstances, given that all generated energy can be supplied to the grid.

Here, the wind turbine runs at maximum efficiency across a broad range of wind speeds while maintaining the required power factor or generating voltage and staying within the rated power. Nonetheless, the wind turbines are now required to control both active and reactive power in accordance with the power set points that are determined by the wind turbine control system, which takes into account the power requirements and generation capacity. Thus, the current article's main focus is on the analysis of DFIG wind turbine control.

2. THE WIND POWER SYSTEM

The mechanical power generated by a wind turbine is determined by aerodynamics, and [10, 11]:

$$P_m = \frac{1}{2}\rho A C_p(\lambda,\beta) v_w^3 \tag{1}$$

Where ρ is the air density (kg/m3), is the wind speed (m/s), (A= π R²) is swept area covered by the rotor (m2), and Cp is the power coefficient which is a function of both tip speed ratio, λ, and blade pitch angle β (deg). The efficiency of the wind turbine blades' power coefficient Cp can be analytically estimated as [16]:

$$C_p(\lambda,\beta) = 0.517 - \left(\frac{116}{\lambda_i} - 0.4\beta - 5\right) e^{-\frac{21}{\lambda_i}} + 0.0068\lambda \tag{2}$$

and,

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

The expressions in Eqs. (2) and (3) show that Cp depends on the blade pitch angle β, and the tip speed ratio λ, which is defined as:

$$\lambda = \frac{\omega_t R}{V_{wind}} \tag{4}$$

Where ω_t the angular velocity of wind turbine and R is blade radius. The turbine power characteristics are illustrated as shown in Figure 2. The pitch angle of 0° is used in this study because it results in the highest power coefficient.

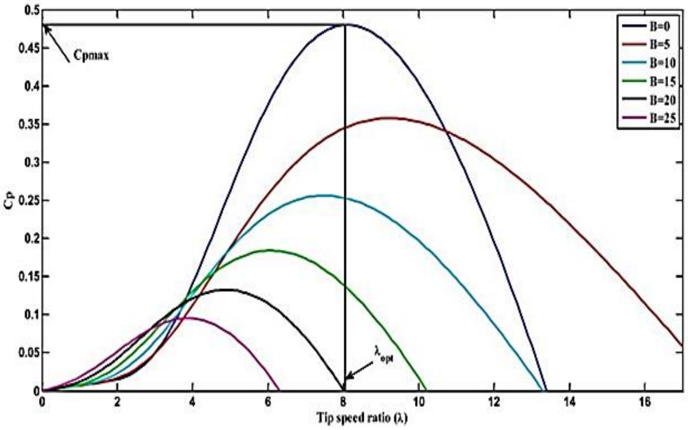


Fig. 1. Shows the relation between Cp and λ for different pitch angles. The maximum value of the power coefficient,

C_{pmax} ≈ 0.48, is obtained at β = 0° and λ = λ_{opt} ≈ 8.1. The torque produced by the wind turbine T_m is given by the following equation [12]

$$T_m = \frac{P_m}{\omega_t} = \frac{\rho\pi R^3 v_w^2\, C_p(\lambda,\beta)}{2} \tag{5}$$

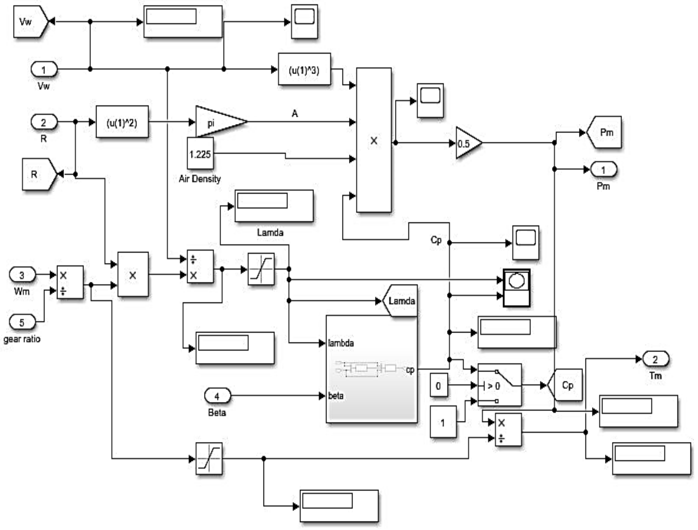


Fig. 2. Simulink model of wind turbine

2.1 Mechanical Drive Train Model

The dynamics of a wind turbine are frequently represented using a two-mass model, as in [13]. What distinguishes the two-mass model of the wind turbine from other models is the benefit of its controllers' universal design, which can be applied in wind turbines of various sizes. The two-mass model incorporates the wind turbine's adaptability as long as the modes are present [14]. Equation (6) gives the mechanical model of a two-mass wind turbine.

$$\frac{d}{dt}\omega = \frac{p}{2\,J}\left(T_m - T_e - C_f\omega\right) \tag{6}$$

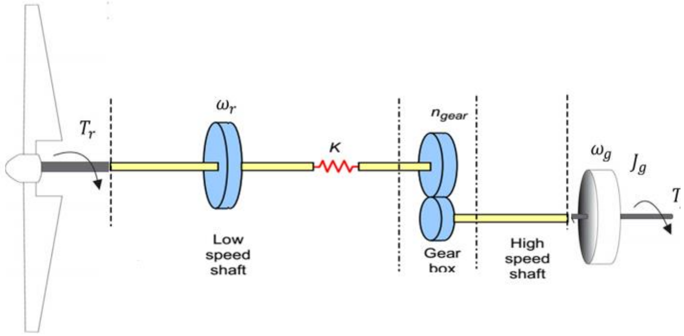


Fig. 3. Configuration of drive Train With wind turbine

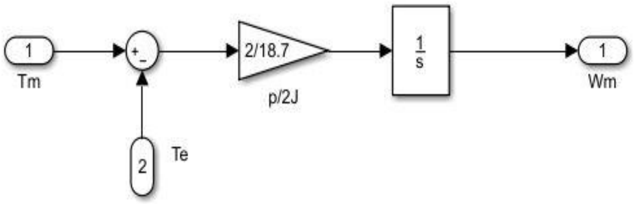


Fig. 4. Simulink model of Drive Train

Where ω is the mechanical speed of the shaft, P is the number of poles of the machine, C_f is the friction coefficient, J is the inertia of the rotor, Tm is the mechanical torque generated by wind turbine, and $\mathrm{T_e}$ is the electromagnetic torque generated by the machine. Two-mass drive-train model is used for the simulation study in this paper.

2.2 Modelling of DFIG

The DFIG is composed of the up of the rotor and stator windings. Slip rings are present. The three-phase covered windings of the stator are connected to the grid by a three-phase transformer. The rotor consists of three-phase insulated windings, just like the stator. Slip rings and brushes are used to connect the rotor windings to an external fixed circuit, allowing the control rotor current to be injected into or removed from the windings [15–18]. Following assumptions form the basis of the DFIG model. Figure 5. Below shows the DFIG's stator can's steady state equivalent electric circuit.

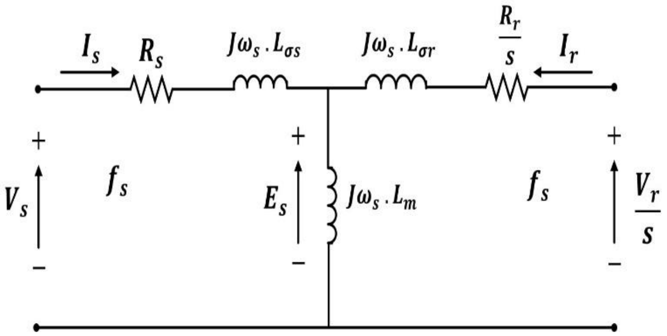


Fig. 5. Equivalent circuit of the DFIG referred to stator.

The equations are calculated using direct (d) and quadrature (q) axis representation in the synchronous reference frame. The stator and rotor voltages are given by:

$$V_{ds} = R_s I_{ds} + \frac{d\lambda_{ds}}{dt} - \lambda_{qs}\omega_s \tag{7}$$

$$V_{qs} = R_s I_{qs} + \frac{d\lambda_{qs}}{dt} + \lambda_{ds}\omega_s \tag{8}$$

$$V_{dr} = R_r I_{dr} + \frac{d\lambda_{dr}}{dt} - \lambda_{qr}\omega_r \qquad (9)$$

$$V_{qr} = R_r I_{qr} + \frac{d\lambda_{qr}}{dt} + \lambda_{dr}\omega_r \qquad (10)$$

Where V_{ds},V_{qs}, V_{dr}, andV_{qr}: stator and rotor voltages in the dq frame, respectively. I_{ds},I_{qs}, I_{dr} andI_{qr}: stator and rotor current in the dq frame, respectively. R_s , R_r , ω_s and ω_r: stator and rotor phase resistances and angular velocity, respectively.

Where is the flux linkages are given by the expressions:

$$\lambda_{ds} = L_s I_{ds} + L_m I_{dr} \qquad (11)$$

$$\lambda_{qs} = L_s I_{qs} + L_m I_{qr} \qquad (12)$$

$$\lambda_{dr} = L_r I_{dr} + L_m I_{ds} \qquad (13)$$

$$\lambda_{qr} = L_r I_{qr} + L_m I_{qs} \qquad (14)$$

Where λ_{ds} , λ_{qs} are the fluxes along the dq axis stator. λ_{dr}, λ_{qr} are the fluxes along with the dq axis rotor. L_s, L_r are stator and rotor phase leakage inductances, respectively, L_m is stator–rotor mutual inductance.

$$L_s = L_{\boldsymbol{\sigma s}} + L_m \qquad (15)$$

$$L_r = L_{\boldsymbol{\sigma r}} + L_m \qquad (16)$$

Where $L_{\boldsymbol{\sigma s}}$ and $L_{\boldsymbol{\sigma r}}$ are the self-inductances of the stator and the rotor respectively.

The developed electromagnetic torque is given by:

$$\mathrm{T_e} = \frac{3}{2}(\lambda_{\mathrm{qs}}\mathrm{I_{dr}} - \lambda_{\mathrm{ds}}\mathrm{I_{qr}}) \qquad (17)$$

A decoupled control of the active and reactive power by the stator flux orientation to obtain separate control of the powers generated by the wind system. Controlling the dq-axes rotor currents of the DFIG will also allow for control of the stator reactive power and electromagnetic torque. The stator field revolves continuously at synchronous speed. The stator flux vector, which depicts the phase and amplitude of the flux, serves as the field symbol. Selecting the two-phase dq and placing the stator flux vector on the d-axis will allow it to write the two-phase dq related to the rotating stator field.

$$\lambda_{\mathrm{qs}} = 0 \qquad (18)$$

$$\lambda_{\mathrm{ds}} = \lambda_{\mathrm{s}} \qquad (19)$$

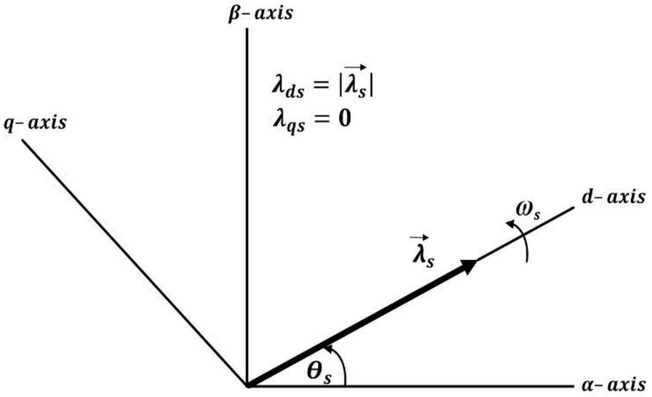


Fig. 6. D-axes aligned with the stator flux space vector.

$$V_{ds} = 0 \qquad (20)$$

$$V_{qs} = V_s = \lambda_s\omega_s \qquad (21)$$

$$\lambda_s = L_s I_{ds} + L_m I_{dr} \qquad (22)$$

$$0 = L_s I_{qs} + L_m I_{qr} \qquad (23)$$

$$\lambda_{dr} = L_r I_{dr} + L_m I_{ds} \qquad (24)$$

$$\lambda_{qr} = L_r I_{qr} + L_m I_{qs} \qquad (25)$$

3. 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]. The DFIG model demands that all quantities be expressed in the stator flux reference frame, with the flux leakage orientated along the d axis, in order to achieve a decoupled control of active-reactive powers fig.7.

3.1. Field Oriented Control Strategy

A synchronously spinning d-axis frame, with the d-axis aligned with the stator flux vector location (fig. 7), is used to regulate the rotor-side converter. Decoupled control between the stator's active and reactive powers is achieved with this method. Since the stator is connected to the grid, the impact of the stator resistance can be disregarded [12] and the stator flux can be maintained at a constant value. If the voltage dropped in the stator resistance has been disregarded, the stator flux can be regarded as constant because it is directly coupled to the grid [13] [12], the voltage equations, flux equations currents equations and stator active and reactive powers equations can be simplified in study state as :

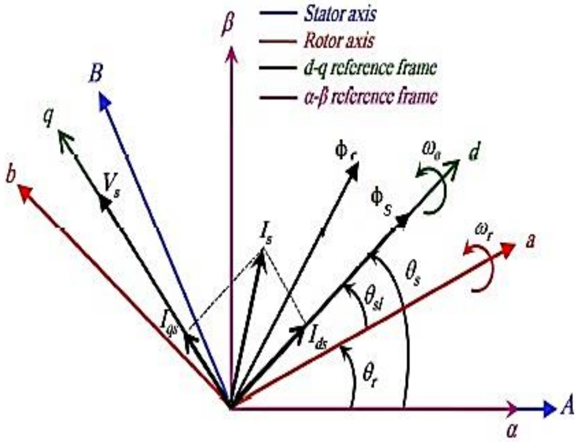


Fig.7. Stator Field oriented control technique

3.2. Rotor Side Converter

The rotor side converter's objective is to regulate the stator terminal's reactive power and active power (rotor speed) separately. Fig. 8 shows the rotor side converter's general control architecture. In the stator-flux oriented reference frame, a synchronously rotating reference frame, the induction generator is operated with its d-axis aligned along the stator-flux vector position in order to decouple the electromagnetic torque and the rotor excitation current [14]. Both the rotor speed (outer) control loop and the rotor current (inner) control loop are regulated by the standard proportional-integral (PI) controllers.

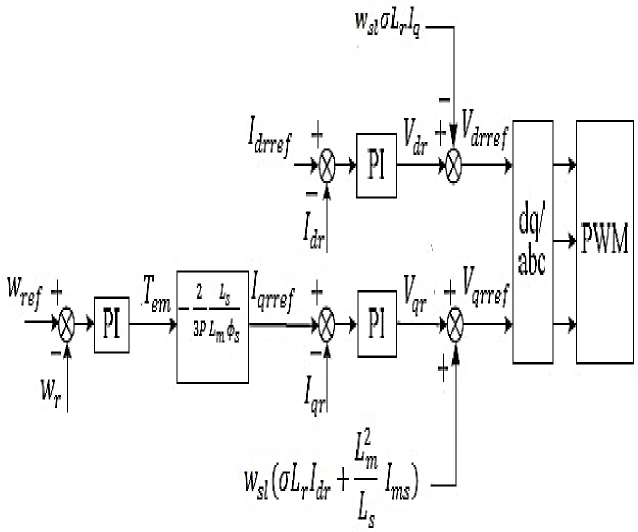


Fig. 8. Control scheme of the rotor side converter

3.3 Grid Side Converter

The goal of the grid side converter control is to ensure that the converter operates with unity power factor and to keep the DC-link capacitor voltage at a predetermined level. Figure 6 displays the grid side converter's control scheme. With its d-axis aligned along the grid-voltage vector position, the converter control functions in the grid voltage oriented reference frame, an asynchronously rotating reference frame, to achieve the independent control of active and reactive power flowing between the grid and the grid side converter [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.

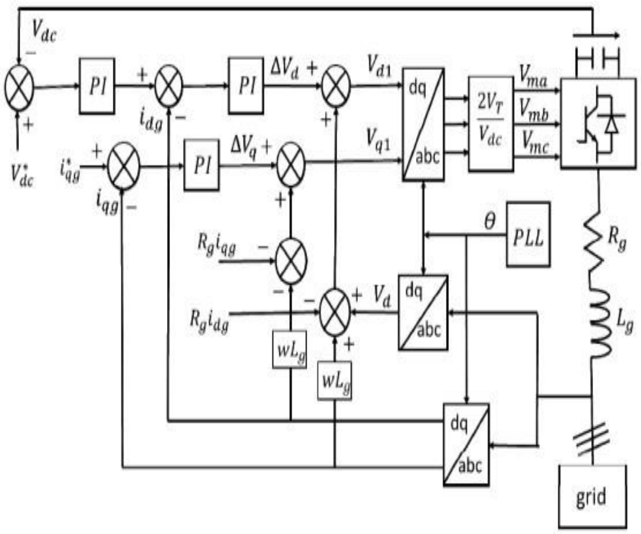


Fig.9. Control scheme of the grid side converter

3.4. Pitch Angle Controller

The pitch angle controller only activates when the input wind power surpasses the rated machine power since it is impossible to regulate the rotor speed by raising the generator power in such circumstances without causing damage [15]. By altering the wind's angle of attack on the turbine blades, the pitch controller restricts the maximum power that can be drawn from the aero generator to the machine's rated power. Figure 10 shows the turbine in relation to wind speed.

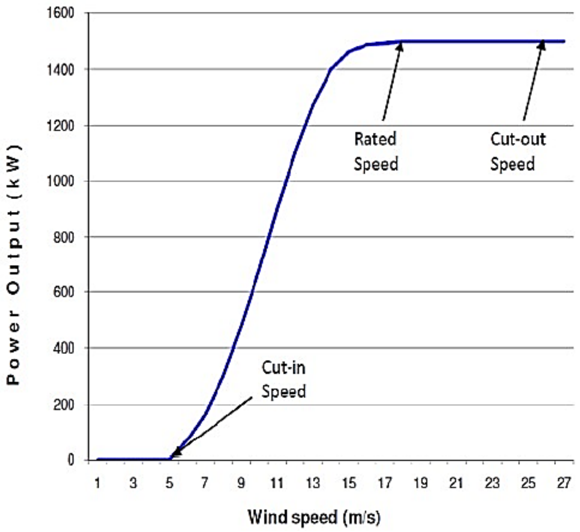


Fig.10. DFIG operation under different wind speeds

4. SIMULATION RESULTS

The rated power of the DFIG wind turbine under consideration in this work is 1.5 MV and 575 V. The wind turbine managed by the suggested control systems has been modeled in the MATLAB/Simulink environment in order to assess the control systems. Simulated wind turbines with unity.power factor (zero reactive power) has been used. The system can function independently of weather conditions (wind changes) without the risk of DFIG damage because to the pitch angle control mechanism that controls the mechanical power produced by the aerodynamic.

Table 1. 1.5 MW system parameters.

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

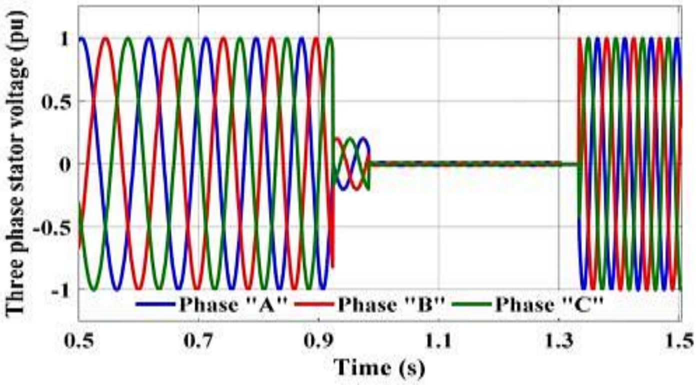


Fig.11. Three-phase stator voltage

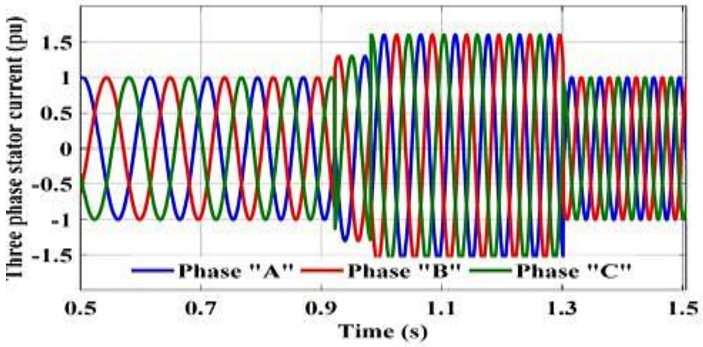
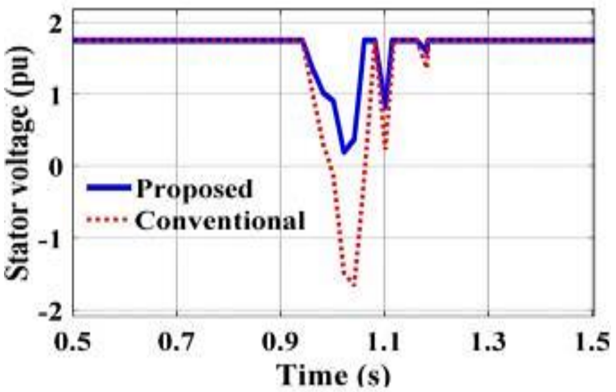
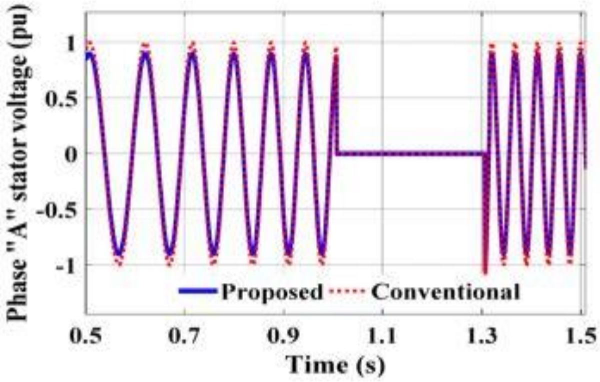


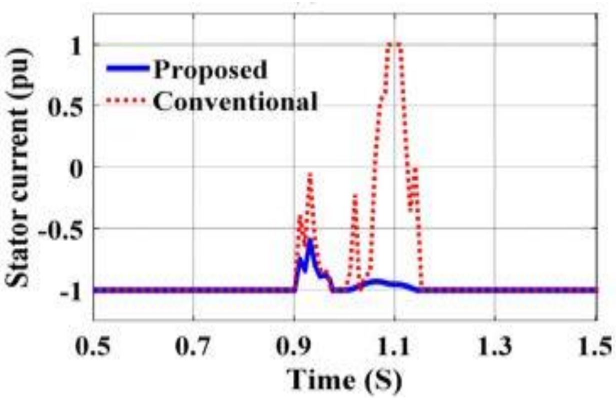
Fig.12. Three-phase stator current


Stator voltage (pu)
2
1
0
-1
-2
Proposed
Conventional
0.5
0.7
0.9
1.1
1.3
1.5
Time (s)

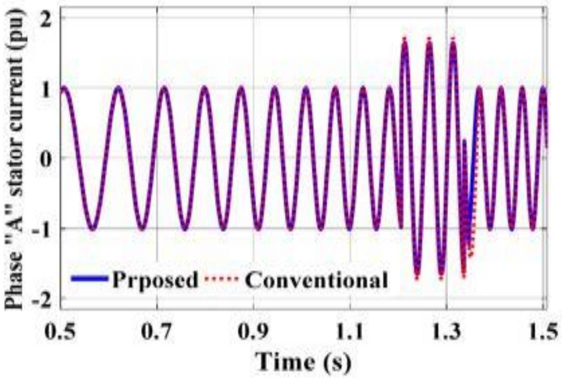
(a)


Phase "A" stator voltage (pu)
1
0.5
0
-0.5
-1
Proposed
Conventional
0.5
0.7
0.9
1.1
1.3
1.5
Time (s)

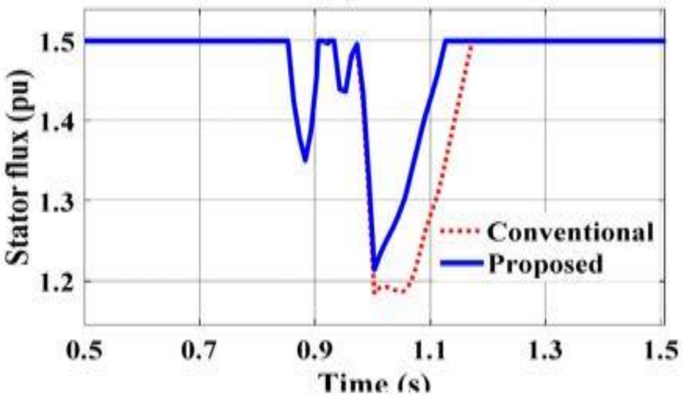
(b)


Stator current (pu)
1
0.5
0
-0.5
-1
Proposed
Conventional
0.5
0.7
0.9
1.1
1.3
1.5
Time (S)

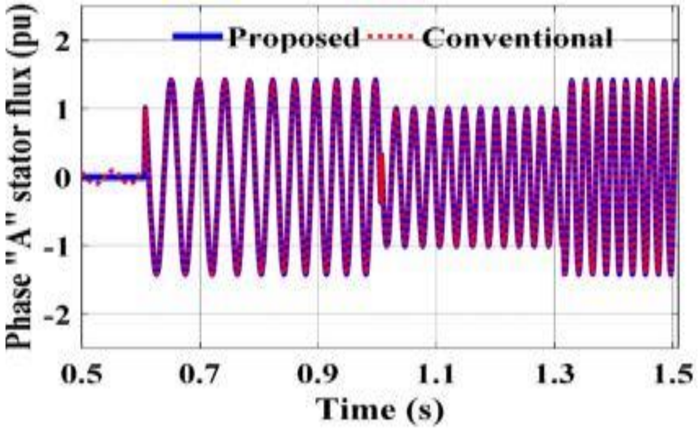
(c)


Phase "A" stator current (pu)
2
1
0
-1
-2
Prposed
Conventional
0.5
0.7
0.9
1.1
1.3
1.5
Time (s)

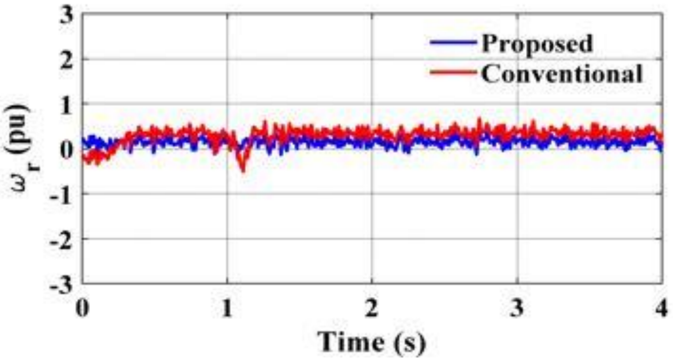
(d)


Stator flux (pu)
1.5
1.4
1.3
1.2
Conventional
Proposed
0.5
0.7
0.9
1.1
1.3
1.5
Time (s)

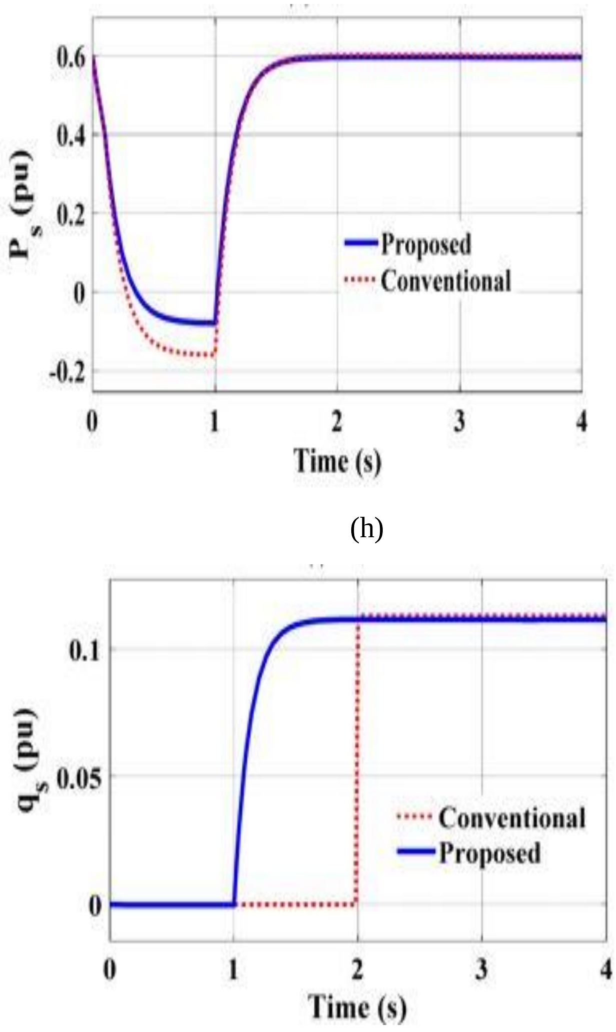
(e)


Phase "A" stator flux (pu)
2
1
0
-1
-2
Proposed
Conventional
0.5
0.7
0.9
1.1
1.3
1.5
Time (s)

(f)


ω_r (pu)
3
2
1
0
-1
-2
-3
Proposed
Conventional
0
1
2
3
4
Time (s)

(g)



(h)

(i)

Fig. 12: (**a**) Stator voltage response; (**b**) stator voltage phase A response; (**c**) stator current response; (**d**) stator current phase A response; (**e**) stator flux response; (f) stator flux phase A response; (**g**) angular rotor speed response; (**h**) real power response; (**i**) reactive power response.

5. CONCLUSION

In this work, the field oriented control technique (FOC) is used to demonstrate vector control of DFIG integrated in a wind energy conversion system. For a wind-driven DFIG system, the field-oriented control scheme has been created to regulate the grid-side and rotor-side converters. First, the synthesis of a proportional-integral controller (PI) and the modeling of wind turbines and generators have been produced. The efficiency of the suggested system has been verified through computer simulation. The study's findings support the notion that grid-connected wind energy conversion systems with vector control of DFIG provide good dynamic performance. However, mastering the variation of DFIG parameters is necessary for its application.

Abbreviations

The following abbreviations and notations are used in this manuscript:

DFIG	Doubly fed induction generator
RES	Renewable energy sources
PWM	Pulse width modulation
WECS	Wind energy conversion systems
ω_r	Rotational speed of turbine
Vw	Wind speed
$\boldsymbol{\lambda}$	Tip speed ratio
β	Blade pitch angle
U	Voltage
R	Resistance
Pw	Power wind turbine
CP	Polynomial function of λ and β

6. REFERENCES

[1] Wei Qiao, Integrated control of wind farms, facts devices and the power network using neural networks and adaptive critic designs. Master's thesis, Georgia Institute of Technology, Ph.D. dissertation, 2008.

[2] Ralph Kennel Mohamed Abdelrahem, ChristophHackl, Application of extended kalman filter to parameter estimation of doubly fed induction generators in variable-speed wind turbine systems. IEEE, 2015

[3] Juan Yuz E. Ricardo Perez., Cesar Silva J. and Gonzalo Carrasco R. Experimental sensorless vector control performance of a dfig based on an extended kalman filter. IEEE, 2012.

[4] J. Clare R. Pena and G. Asher. Doubly fed induction generator using back-to-back PWM converters and its application to variable-speed wind energy generation. EEE Proc. Elec. Pow. Appl, 143:231 241, 1996.

[5] S. Alepuz R. Cardenas, R. Pena and G. Asher. Overview of control systems for the operation of dfig in wind energy

applications. IEEE Transactions on Industrial Electronic, 60:2776{2796, July 2013.

[6] E. Levi. Magnetic variables control. In Wiley Encyclopedia of Electrical and Electronics Engineering. Wiley, 1999.

[7] IEEE Emil Levi Hamid A. Toliyat, Mona Raina, “A review of induction motor parameter estimation techniques” IEEE transactions on energy conversion, 18, June 2003.

[8] Lei, Y, Mullane, A., Lightbody G., Yacamini: “Modelling of the wind turbine with a doubly fed induction generator for grid integration studies” IEEE Trans. Energy Convers21 (1), 257–264 (2006).

[9] Seyed Zeinolabedin Moussavi and Reza Atapour, “Dynamic Modelling and Control of Doubly Fed Induction Generator Variable Speed Wind Turbine” Faculty of Electrical and Computer Engineering, Shahid Rajaee Teacher Training University, Tehran, Iran.

[10] K.Kerrouchea, A. Mezouarb, Kh. Belgacema “Decoupled Control of Doubly Fed Induction Generator by Vector Control for Wind Energy Conversion System”. Department of Electrical Engineering, Faculty of Sciences Engineering, MoulayTahar University, Saida 20000, Algerie.

[11] XinJing. “Modeling and control of a doubly-fed induction generator for wind turbine-generator systems” Master's thesis, Marquette University 2012.

[12]A. Massoum. Djeriri, A. Meroufel And Z.Boudjema. “A comparative study betweenfield oriented control strategy and direct power control strategy for dfig”. *Journal of Electrical Engineering*.

[13] Pena, R., Clare, J.C., Asher, G.M. “Doubly fed induction generator using back-to-back PWM converters and its application to variable speed wind-energy generation” *IEEE Proceedings on Electric Power Applications* 143(3), 231–241 (1996).

[14] Nasir Abdulai Boakye Boateng “Real-time simulation of a doubly-feed induction generator based wind power system real-time digital simulator”. PhD thesis, University of Tennessee at Chattanooga, Tennessee, May 2013.

[15] De Almeida, R.G., Castronuovo, E.D., Lopes, “Optimum generation control in wind parks when carrying out system operator requests”. IEEE Trans. Power Syst. 21(2), 718–725 (2006).