Modeling and Control of Stand-Alone Doubly-Fed Induction Generator Used in Wind Energy Conversion Systems

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Abstract. Self-excited induction generators usually suffer from variable output voltage frequency and magnitude as the wind speed varies when it is used in stand-alone Wind Energy Conversion Systems (WECS). In this paper, it is proposed to use doubly-fed induction generators (DFIGs) instead of squirrel cage induction generators. The proposed controller is based on feeding part of the output power to the rotor circuit. The frequency of the injected voltage is adjusted at each mechanical speed to produce stator frequency at the nominal value. The magnitude of the injected voltage is adjusted to control the output voltage. The capability of the proposed controller is verified using a simulation model. The simulation results confirm that the proposed control maintains both the magnitude and frequency of the output voltage constant at the nominal values irrespective of the wind speed variations. The proposed controller is implemented for the sub-synchronous speeds and a further study is now conducted to extend the capability to the super-synchronous range.

Keywords: Doubly-fed induction generator, Wind turbine model, d-q modeling, indirect vector control.

1. INTRODUCTION

Doubly-fed induction generators (DFIGs) have been used as variable speed electric generator in wind energy conversion systems (WECSs) [1]. This type of generators is controlled by power converters with reduced power rating when compared with the machine electrical power output [2]. The stator winding is connected to the electrical mains and the rotor winding is connected to a bi-directional static power converter through slip-rings. They can be used as grid connected DFIGs or stand-alone DFIGs [2]. In a grid connected WECS employing DFIG, the grid imposes the magnitude and frequency of the machine terminal voltage.

Self-excited squirrel cage induction generators (SCIG) have been employed in stand-alone WECS. SCIG when employed in WECS usually suffer from variable output voltage magnitude and frequency. While the output voltage magnitude of the SCIG could be regulated by means of switching capacitors ON/OFF to the terminals of the generator, the variable output voltage frequency remains as a challenging problem [3]. To overcome this problem, however, an AC-DC-AC power converter is used between the generator and the load in order to obtain constant load voltage magnitude and frequency irrespective of the wind speed variation. However, the resulting system is costly.

In this paper, we propose stand-alone WECS which employs a DFIG instead of SCIG. The proposed system is shown in FIGURE 1. It consists of a stand-alone DFIG with an isolated load connected the stator. The rotor of the DFIG is connected to a battery through rotor side converter (RSC). Also the battery is connected to the load through load side converter (LSC). The study in this paper shows that in addition to power exchange control, the output voltage magnitude and frequency of the DFIG is mainly controlled by the magnitude, direction and speed of the rotating magnetic field produced by the rotor winding. The speed of rotation of the rotor shaft is a function of the wind speed and load conditions. So, the operation of the DFIG varies from sub-synchronous speed to super-synchronous speed for variable speed wind turbine operation. The change of rotational speed requires control of stator flux linkage and frequency it to maintain the magnitude and frequency of the output voltage at desired values for different output power from the DFIG.

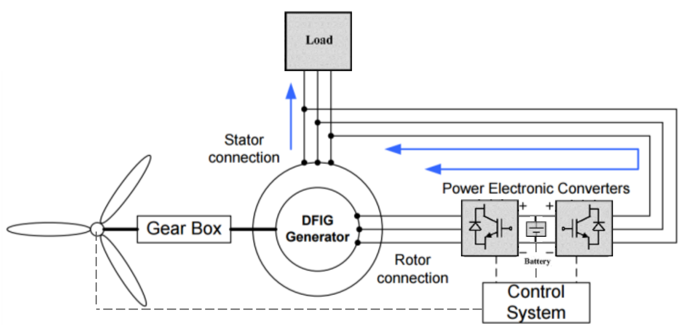


FIGURE 1. Stand-alone DFIG scheme used in variable-speed wind turbines.

The objective of this paper is to obtain constant magnitude and frequency of output voltage from DFIG in sub-synchronous speed modes of operation. Indirect vector control is used to control the power and voltage produced from the DFIG. All equations are expressed in d-q synchronously rotating frame for simplification.

2. WIND TURBINE

The wind power is given by [4]:

$$P_w = \frac{1}{2}\rho A V_w^3 \qquad (1)$$

$$A = \pi R^2 \qquad (2)$$

where,

V_w is the wind speed (m/s).
A is the crossing the surface area (m^2).
R is the radius of rotor blades of wind turbine (m).
ρ is the air density = 1.225 kg/m3 at 15°C and normal pressure.

The effective mechanical power P_t which is transferred to the wind turbine rotor is reduced by the power coefficient CP [5], [6]. The extracted mechanical power from the turbine can thus be expressed as follows [3], [7], [8]:

$$P_t = \frac{1}{2}\rho \pi R^2 V_w^3 C_P \qquad (3)$$

C_P is function of various factors such as wind speed, the speed of rotation of the wind turbine, and the pitch angle β of the rotor blades. Usually the power coefficient C_P is determined as a function of the tip speed ratio λ which is expressed as [3], [7], [8]:

$$\lambda = \frac{\omega_t R}{V_w} \qquad (4)$$

Where,

ω_t is the turbine rotor speed.

For a wind turbine, the most simple and commonly used way to describe the C_P (λ, β) is as follows [7], [6], [4]:

$$C_P(\lambda,\beta) = C_1\left(C_2 - C_3\beta - C_4\beta^2 - C_5\right)e^{-c6} \ (5),$$

where,

$C_1 = 0.5$, $C_2 = 116 * \lambda_i$, $C_3 = 0.4$, $C_4 = 0$, $C_5 = 5$, $C_6 = 21 * \lambda_i$ and:

$$\lambda_i = \frac{1}{\lambda + .08\beta} - \frac{0.035}{1+\beta^3} \qquad (6)$$

The turbine mechanical torque can be expressed as follows [4], [3]:

$$T_t = \frac{P_t}{\omega_t} = \frac{\rho \pi R^2 V_w^3}{2\omega_t} C_P \qquad (7).$$

The mechanical torque that obtained from (7), is defined as a reference torque in the control loop for the DFIG, and drives the generator through the gear box. FIGURE 2 to FIGURE 5 show the wind turbine variables with different wind speed values.

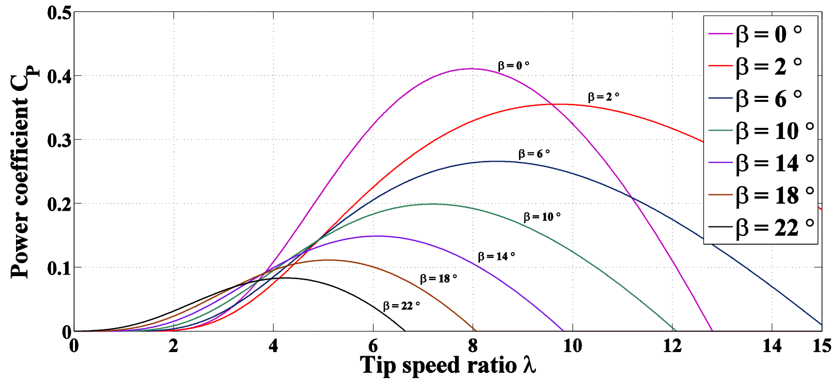


FIGURE 2. Power Coefficient C_P as function of tip speed ratio λ and blades angle β wind speed equal 5.5 m/s.

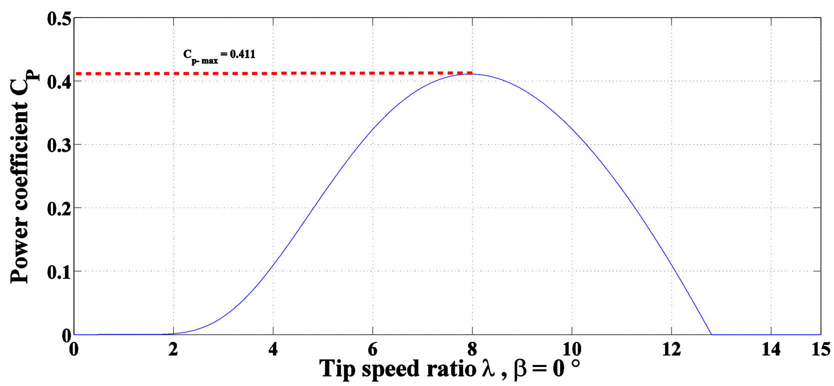


FIGURE 3. Power Coefficient C_P as function of tip speed ratio λ at $\beta = 0^o$.

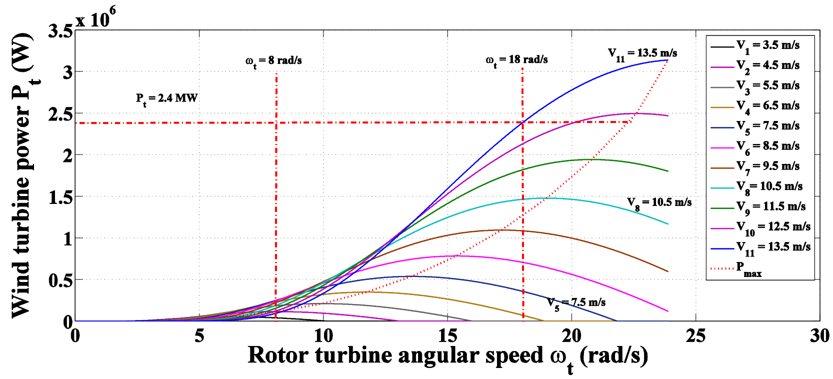


FIGURE 4. Wind turbine power P_t with the rotor turbine angular speed ω_t at different wind speed V_w.

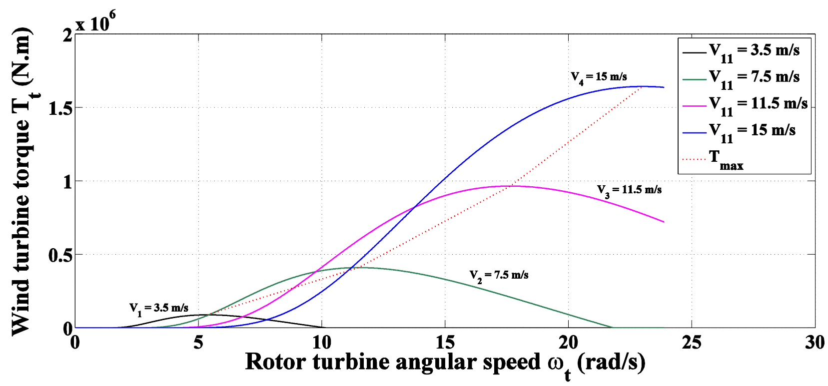


FIGURE 5. Wind turbine Torque T_t with the rotor turbine angular speed $\omega_t$at different wind speed V_w.

3. DOUBLY-FED INDUCTION GENERATOR MODEL

3.1 Generator Equations

The equations describing a stand-alone DFIG application, is the same as grid-connected operation. Its dynamic model is based on d-q synchronously rotating reference frame, by using Park's transformation instead of abc frame for time variant independent, and can be expressed as follows [3], [9], [10], [11]:

Stator winding voltages equations:

$$v_{qs} = R_s i_{qs} + \frac{d\psi_{qs}}{dt} + \omega_s \psi_{ds} \quad (8),$$

$$v_{ds} = R_s i_{ds} + \frac{d\psi_{ds}}{dt} - \omega_s \psi_{qs} \quad (9).$$

Rotor windings voltages equations:

$$v_{qr} = R_r i_{qr} + \frac{d\psi_{qr}}{dt} + (\omega_s - \omega_m)\psi_{dr} \qquad (10),$$

$$v_{dr} = R_r i_{dr} + \frac{d\psi_{dr}}{dt} - (\omega_s - \omega_m)\psi_{qr} \qquad (11).$$

Active and reactive power equations:

$$P_s = \frac{3}{2}\left(v_{qs} i_{qs} + v_{ds} i_{ds}\right) \qquad (12),$$

$$Q_s = \frac{3}{2}\left(v_{qs} i_{ds} - v_{ds} i_{qs}\right) \qquad (13),$$

$$P_r = \frac{3}{2}\left(v_{qr} i_{qr} + v_{dr} i_{dr}\right) \qquad (14),$$

$$Q_r = \frac{3}{2}\left(v_{qr} i_{dr} - v_{dr} i_{qr}\right) \qquad (15).$$

The torque equations are given

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right) L_m \left[i_{qs} i_{dr} - i_{ds} i_{qr} \right] \qquad (16),$$

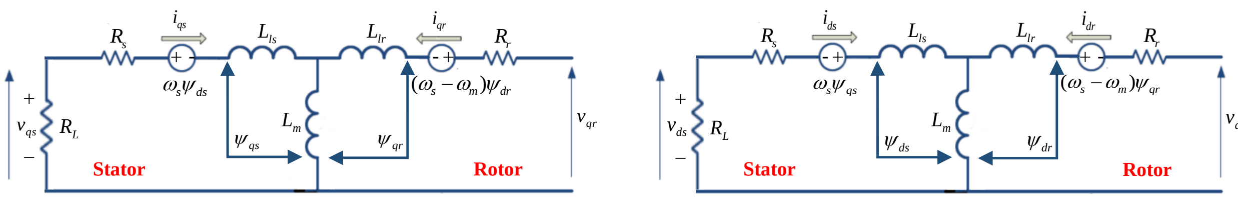
$$\omega_m = \int \frac{P}{2J} \left[T_e - T_l \right] dt \qquad (17),$$

where,

v_{qs}, v_{ds},v_{qr}, v_{dr}	are stator and rotor voltages component respectively (v) .
i_{qs}, i_{ds},i_{qr}, i_{dr}	are stator and rotor currents component respectively (A).
R_s,R_r	are stator and rotor winding resistance per phase (Ω).
ω_s	is angular frequency of the voltages and currents of the stator windings (elec. rad/s) or the angular speed of the synchronously reference frame.
ω_m	is the angular frequency of the rotor (elec. rad/s).
P_s, P_r, Q_s, Q_r	are the stator and rotor power, (W), reactive power, (VAR), respectively.
T_e	is the electromagnetic torque developed by the DFIG (N.m).
T_l	is load torque applied to the DFIG (N.m)

P, J	are the number of poles of DFIG and rotor inertia (Kg.m^2) respectively.

Equations (8) through (11) can be visualized as shown in the equivalent circuits depicted in FIGURE 6.



(a) (b)

FIGURE 6. Dynamic d – q equivalent circuits of DFIG in synchronously rotating reference frame.

3.2 ROTOR INPUT VOLTAGES EQUATIONS

To control both the magnitude and frequency of stator voltage, the rotor input voltage is controlled [7], [12], [10]. This is achieved by controlling the magnitude, frequency, phase shift, and phase sequence of the rotor voltage is achieved by using a three-phase RSC connected to the rotor terminals of the DFIG. The same parameters are also used to control both the active and reactive.

The proposed system of the stand-alone DFIG can be operated in two modes of operation according to the power captured by the wind and the output power from the generator. At sub-synchronous mode the rotational speed of the rotor is less than the synchronous speed of the generator and the RSC transfer the power from the battery to the generator. At super-synchronous mode the rotational speed of the rotor is more than the synchronous speed of the generator and RSC transfer the power from the generator to the battery. Also battery can support the load through the LSC in case of low power captured from the wind. This paper investigates the stand-alone WECS employing DFIG when operated in sub-synchronous mode of operation.

When the DFIG generator rotates at sub-synchronous the rotor frequency is adjusted to maintain the stator frequency at the nominal value as follows [11]:

$$\omega_r = \omega_s - \omega_m \tag{18),}$$

where

ω_r is angular frequency of the voltages and currents of the rotor windings (elec.rad/s).

The equations of the rotor input voltage can be expressed in abc frame as follows:

$$v_{ar} = V_m \cos(\omega_r t + \phi) \tag{19),}$$

$$v_{br} = V_m \cos(\omega_r t + \phi - 120^\circ) \tag{20),}$$

$$v_{cr} = V_m \cos(\omega_r t + \phi + 120^\circ) \tag{21),}$$

where

v_{ar}, v_{br},v_{cr} is the instantaneous value of the rotor input voltages per phase (V).

V_m is the amplitude of the rotor input voltage per phase (V). Φ is the phase shift angle (degrees).

Variables in (19), (20), (21) can be expressed in $d_r^s - q_r^s$ reference frame fixed on the rotor, as shown in FIGURE 7, by using Clark's transformation as follows [11]:

$$v_{qr}^s = V_m \cos(\omega_r t + \phi) \tag{22}$$

$$v_{dr}^s = -V_m \sin(\omega_r t + \phi) \tag{23}$$

Then the variables in (22) and (23) can be expressed in $d_r - q_r$ synchronously rotating reference frame by using Park's transformation as follows [11]:

$$v_{qr} = V_m \cos(\phi) \tag{24}$$

$$v_{dr} = -V_m \sin(\phi) \tag{25}$$

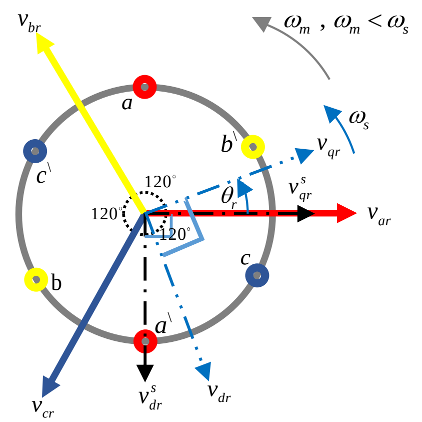


FIGURE 7. Transformation of rotor abc reference frame to d_r-q_r synchronously rotating reference frame at sub-synchronous speed.

Where the angle between two reference frames $d_r - q_r$ and $d_r^s - q_r^s$ is equal to [11]:

$$\theta_r = (\omega_s - \omega_m)t \tag{26}$$

4. VECTOR CONTROL OF DFIG

Indirect vector control method is applied to the DFIG to control the stator output power and voltage. This method can be achieved by the orientation of the d-axis in the direction of stator flux as shown in FIGURE 8 [3], [13], [10]. The control equations can be obtained by setting the following condition [1]:

$$\psi_{qs} = 0, \quad \psi_{ds} = \psi_s = \text{const} \tag{27}$$

Then the machine equations of the DFIG in the synchronously rotating d-q reference frame (8) to (16) will be modified. By substitute (27) in stator and rotor flux linkage equations then [3], [9]:

$$i_{qs} = -\frac{L_m}{L_s} i_{qr} \tag{28}$$

$$i_{ds} = \frac{\psi_{ds}}{L_s} - \frac{L_m}{L_s} i_{dr} \tag{29}$$

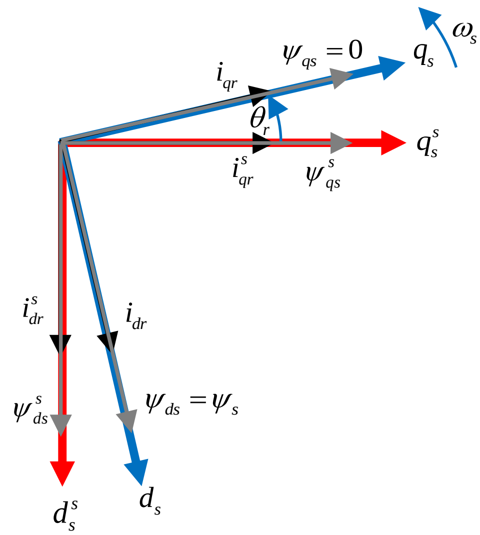


FIGURE 8. Phasor diagram for stator flux oriented vector control.

The voltage drop of the stator resistance is very small in comparison with the load voltage of DFIG, therefore the stator resistance influence can be neglected. Assume three phase resistive load is connected across the terminals of DFIG with value of R_L (Ω) per phase then:

$$v_{qs} = -R_L i_{qs} \quad (30)$$

$$v_{ds} = -R_L i_{ds} \quad (31)$$

Substitute (31) in (8) and (9) and neglect R_s then:

$$v_{qs} = \omega_s \psi_{ds} \quad (32)$$

$$v_{ds} = 0 \quad (33)$$

Substitute (32) and (34) in (36) and substitute (33) and (35) in (37) then:

$$\omega_s = \frac{R_L L_m}{\psi_{ds} L_s} i_{qr} \quad (34)$$

$$\psi_{ds} = L_m i_{dr} \quad (35)$$

Substitute (39) in (33) then:

$$i_{ds} = 0 \quad (36)$$

Substitute (32), (39), (40) in (20) then:

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left(-\frac{L_m}{L_s}\right)\psi_{ds} i_{qr} \quad (37)$$

Substitute (32), (36), (40), in (16) then:

$$P_s = \left(\frac{3}{2}\right)\left(-\frac{L_m}{L_s}\right)\omega_s \psi_{ds} i_{qr} \qquad (38)$$

Substitute (37) and (40) in (17) then:

$$Q_s = 0 \qquad (39)$$

Equations (36), (39), and (42) show that the terminal voltage and stator active power can be controlled by controlling the values of input rotor currents i_{qr} and i_{dr}.. This can be achieved by using a voltage-fed current-regulated inverter RSI. The values of rotor input voltage can be obtained by substitute (14), (15), (32) and (33) in (10) and (11) as follows:

$$v_{qr} = R_r i_{qr} + \frac{d}{dt}\left[\left(L_r - \frac{L_m^2}{L_s}\right) i_{qr}\right] + (\omega_s - \omega_m)(L_r i_{dr}) \quad (40)$$

$$v_{dr} = R_r i_{dr} + \frac{d}{dt}(L_r i_{dr}) - (\omega_s - \omega_m)\left[\left(L_r - \frac{L_m^2}{L_s}\right) i_{qr}\right] \quad (41)$$

Also to control the DFIG stator voltage frequency ω_s the angular frequency ω_r of the rotor currents must be regulated according to the variable mechanical speed of the DFIG ω_m from the relations in (18) [3], [13].

5. SIMULATION RESULTS

The performance of the proposed DFIG control for stand-alone WECS can be verified by using MATLAB/Simulink package. A 2 MW DFIG and 2.4 MW wind turbine are modelled as shown in FIGURE 9, the data are given in Appendix I**.**

The behavior of stand-alone WECS employing DFIG when operated in sub-synchronous mode at different wind speeds and load conditions is studied. The frequency and the magnitude of the output voltage are controlled by controlling the magnitude, frequency and phase shift of the rotor input voltage and hence the rotor input currents. Two cases of wind speed are considered, first case is 5.5 m/s and other case is 6.5 m/s. From the wind turbine characteristics the wind speed can be set as shown in FIGURE 10. At those wind speeds the DFIG can produce electrical power from the mechanical wind power as illustrated in FIGURE 11. For the same wind speed the generated power has different values depending on the load conditions. Negative values of power means power is supplied by the DFIG while positive values indicate that power is consumed by the DFIG. FIGURE 12 and FIGURE 13 shows generator electromagnetic torque and speed.

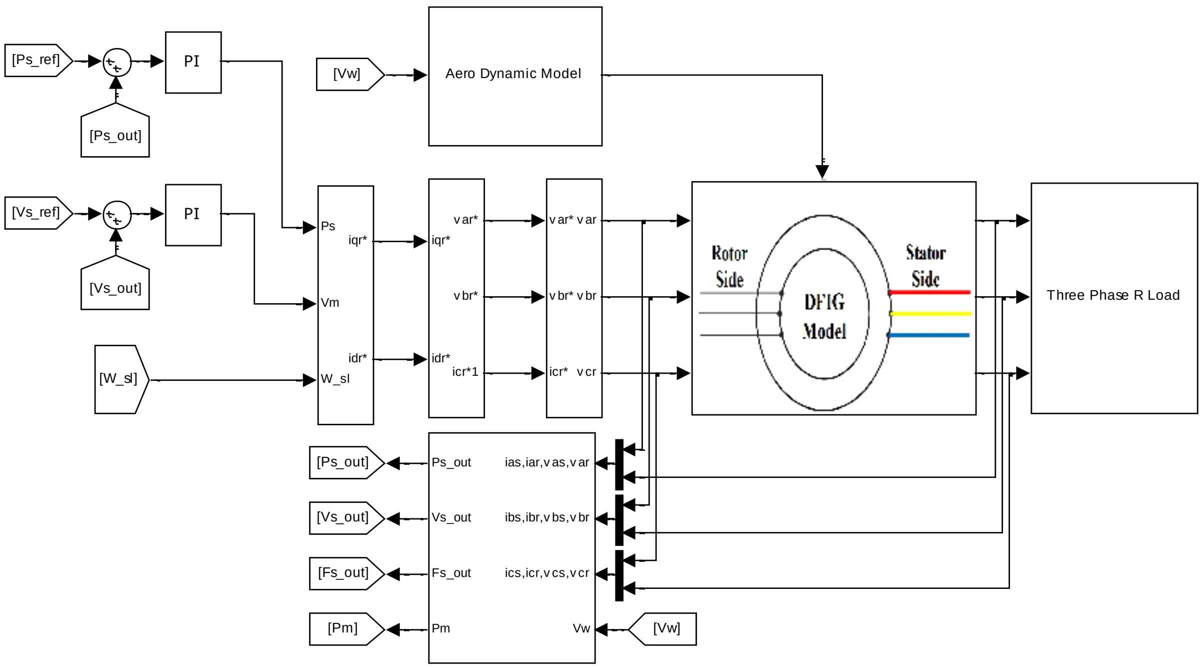


FIGURE 9. Schematic block diagram of the DFIG MATLAB model system.

The controlled values of iqr and idr for rotor input currents, vqr and vdr for rotor input voltages is shown in FIGURE 14 and FIGURE 15. As mention before the frequency of the rotor input voltages must be changed with the change of rotational speed of DFIG as shown in FIGURE 16. Controlling of rotor input parameters with the different load conditions and generator speed make us to obtain the required magnitude and frequency for the output voltage of the stator, the results shown in FIGURE 17, FIGURE 18 and FIGURE 19. Note that the actual power produced from the DFIG is slightly less than the reference power due to electrical power losses in the generator as shown in FIGURE 20.

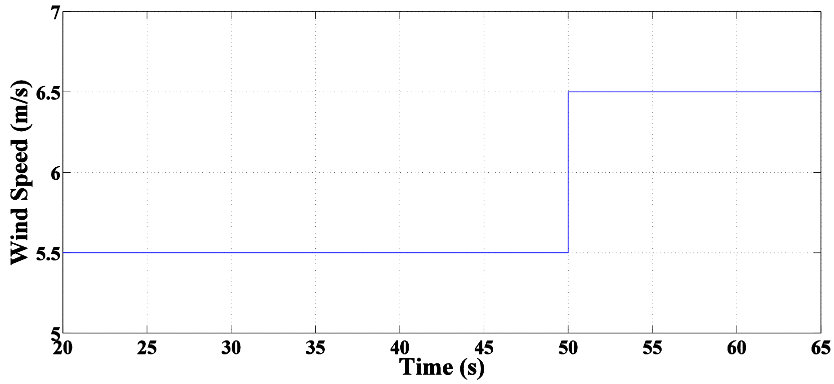


FIGURE 10. Wind speed profile.

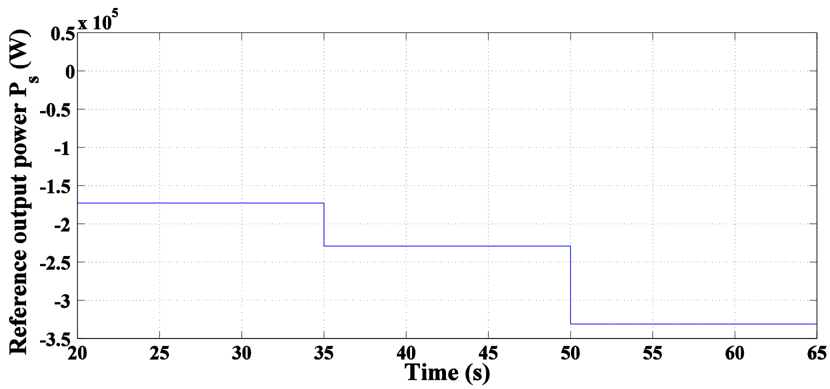


FIGURE 11. Reference output power from the wind turbine.

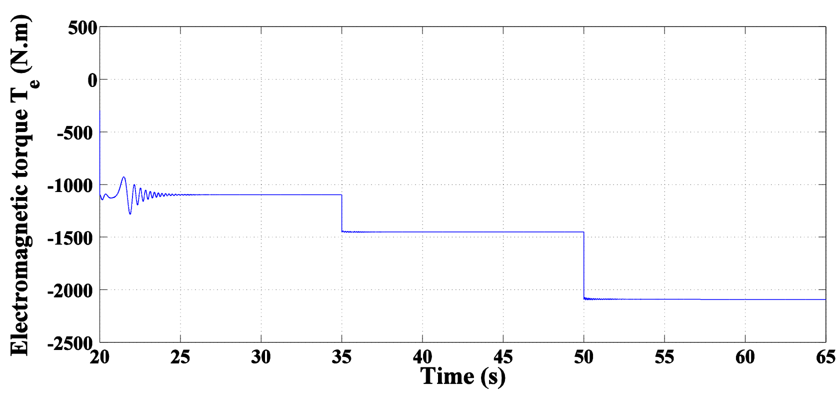


FIGURE 12. Electromagnetic torque of DFIG under sub-synchronous speed.

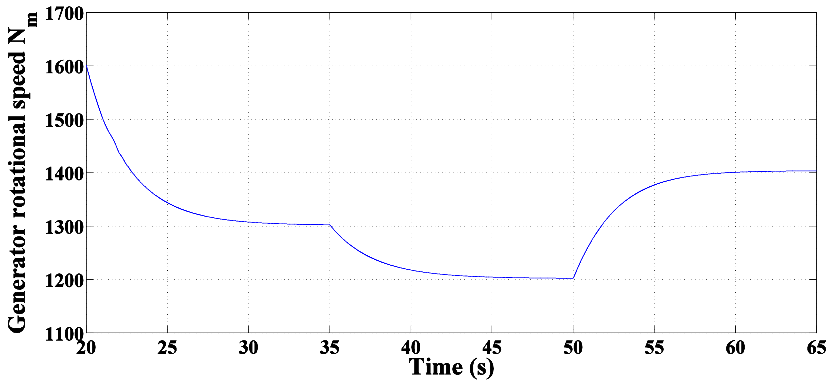


FIGURE 13. DFIG Rotor rotational speed.

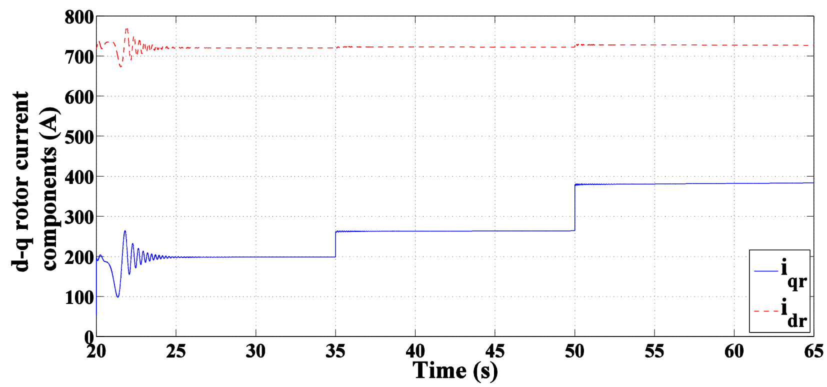


FIGURE 14. i_{qr} and i_{dr} components required under sub-synchronous speed with different load conditions.

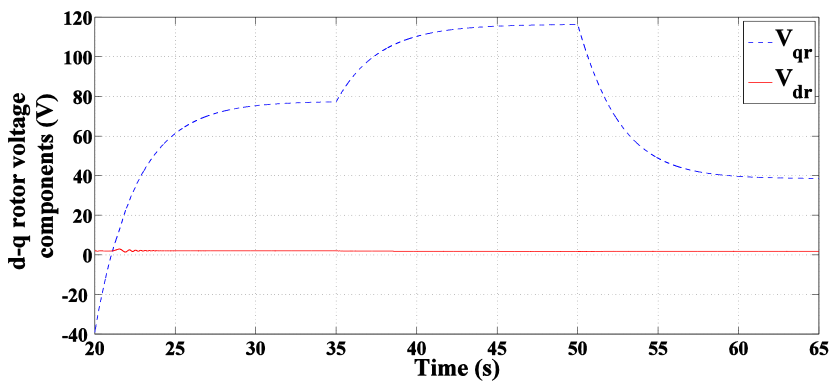


FIGURE 15. v_{qr} and v_{dr} components required under sub-synchronous speed with different load conditions.

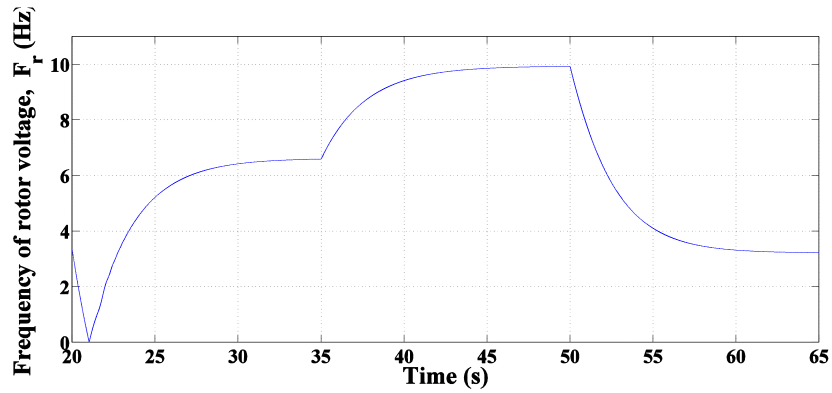


FIGURE 16. Required frequency for rotor input voltages under sub-synchronous speed with different load conditions.

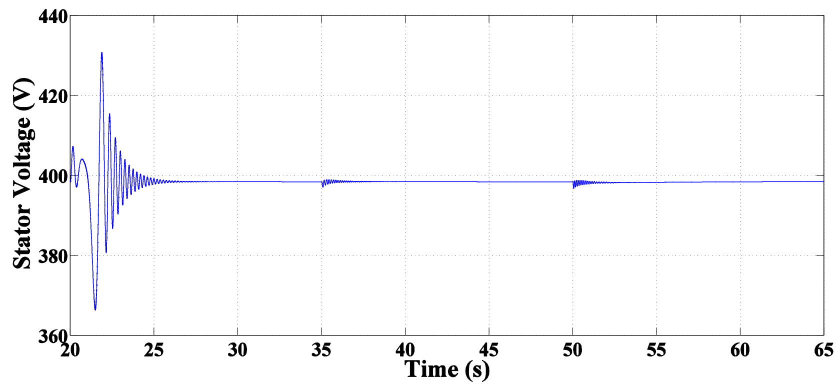


FIGURE 17. R.M.S phase value for stator output voltage under sub-synchronous speed with different load conditions.

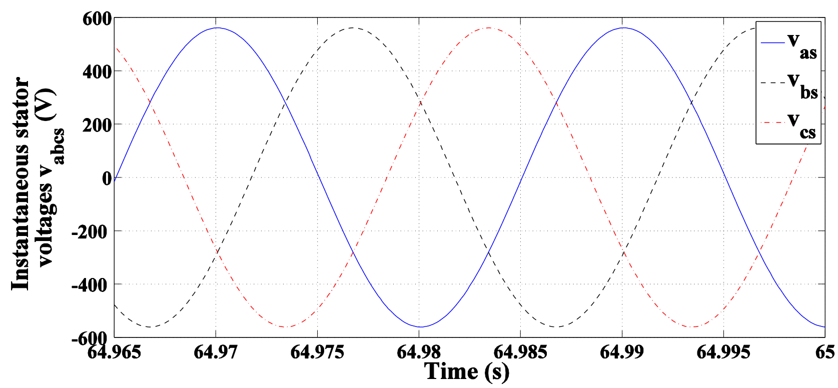


FIGURE 18. Instantaneous phase value of stator output voltages.

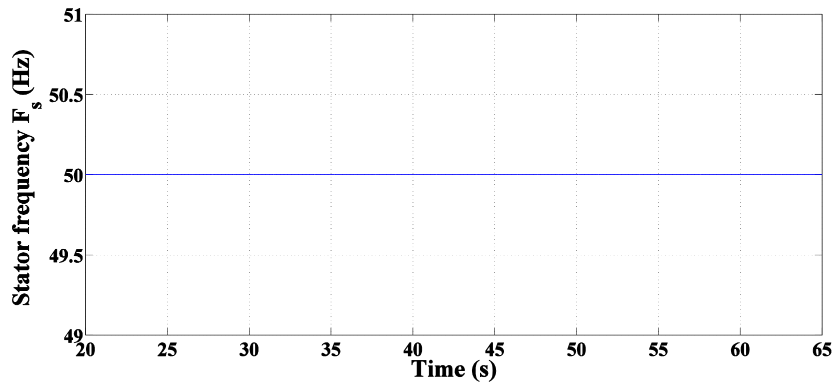


FIGURE 19. Frequency of stator output voltage under sub-synchronous speed under with different load conditions.

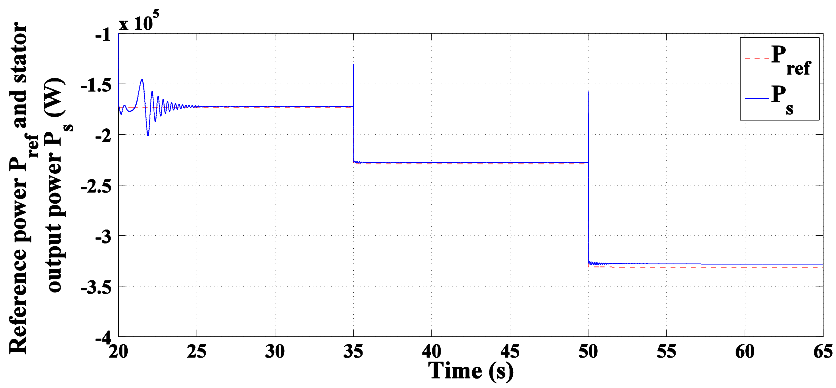


FIGURE 20. Stator output active power with respect to reference power under sub-synchronous speed mode with different load conditions.

CONCLUSIONS

The problem of variable output voltage and frequency are usually associated with self-excited induction generators. In this paper, it is proposed to use DFIG which is controlled to maintain constant stator voltage and frequency at various speed. The proposed controller is based on using a supplementary loop to feedback portion of the stator output to the rotor input. The frequency of the injected voltage is adjusted at each speed to obtain the nominal stator frequency ($\omega_s = \omega_m + \omega_r$). The value of the injected voltage is adjusted to produce the nominal stator voltage. The capability of the proposed controller is verified by using simulation model. The operation is verified over a wide operating range. The proposed controller is implemented for the sub-synchronous speed range and a further study is continued to extend the performance for both sub-synchronous and super-synchronous speeds.

APPENDIXE I

Parameters of wind turbine and DFIG in table (1) and table (2) [4].

TABLE 1. Turbine Parameters

Parameter	Value
Radius of rotor blades	42 m
Nominal wind speed	12.5 m/s
Variable speed ratio (minimum–maximum turbine speed)	9 – 18 rpm
Optimum tip speed ratio λ_{opt}	7.2
Maximum power coefficient C_{pmax}	0.44
Air density ρ	1.1225 Kg/m^3

TABLE 2. DFIG main parameters

Parameter	Value
Nominal stator active power	2 MW
Nominal torque	12732 N.m
Stator voltage	690 V
Stator frequency	50 Hz
Nominal speed	1500 rpm
Speed range	900-2000 rpm
Pole pairs	2
Turns ratio	0.34
Magnetizing inductance L_m	2.5×10^{-3} H
Stator leakage inductance L_{ls}	87×10^{-6} H
Rotor leakage inductance L_{lr}	87×10^{-6} H
Stator resistance R_s	0.026 Ω
Rotor resistance R_r	0.026 Ω
inertia J_m	90 $Kg.m^2$

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