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Direct Torque Control of a Doubly fed Induction Generator Driven By a Variable Speed Wind Turbine

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Abstract

In this paper a new direct torque control system is proposed and is applied to doubly fed induction generator driven by variable speed wind turbine. In this control system the rotor flux and the electromagnetic torque are estimated based on the rotor voltage and currents measurements. Control system response is based only on wind speed profile. The control strategy is based on keeping harmonics at low order under the constraint of unity rotor power factor and also under decreasing torque ripples. Results are obtained from simulations show a very fast dynamic response for the control system with sensorless operation under wind speed variation.

***Keywords**:* Direct torque control (DTC), doubly fed induction generator (DFIG), variable wind speed, turbine characteristics, grid connection, and voltage source converter (VSC).

LIST OF SYMOBLS

ρ is the air density (Kg/m^3)
C_p is the power coefficient
λ is the tip speed ratio
β is the pitch angle (deg.)
A is the area covered by the rotor (m^2)
p is differential operator (p = d/dt)
ω_t is the turbine speed (rad./sec.)
ω_r is generator rotor speed (rad./sec)
T_m is the mechanical torque (N.m)
T_e is the electromagnetic torque of the generator(N.m)
T_{tg} is an internal torque of the two mass model (N.m)
H_t is inertia constants of the turbine($Kg.m^2$)
H_g is the generator inertia constants ($kg.m^2$)
D is the damping coefficients of the turbine(N.sec)
D_g is the damping coefficients of generator (N.sec)
V is the instantaneous voltage (volt)
R is the resistance (ohm)
i is the instantaneous current (amper)
ω_e is slip electrical angular speed (rad./Sec.)
ω_s is stator angular speed (rad./Sec.)
ω_r is the rotor electrical angul speed (rad./sec.)
ω_b is the base angular speed (rad./Sec.)
L_m is the mutual inductance (H)
L_{ls} is the stator leakage inductance (H)
L_{lr} is the rotor leakage inductance (H)
ψ is the flux linkage (web.)
P is the active power (watt)
Q is the reactive power (VAR)
P is the number of pair poles

The subscripts
d - q indicate the direct and quadrature axis components.
s - r indicate stator and rotor quantities.
* indicates reference value

D_{tg} is the damping coefficient of the Flexible coupling (shaft)	e indicates the synchronous rotating reference frame.
K_{tg} is the shaft stiffness(N.m.sec/rad).	
v_w is the wind speed (m/sec.)	

1. Introduction

Worldwide concerns about the environmental pollution, that has led to increase interest in technologies for generating clean and renewable sources of electrical energy. As most renewable energy sources emit neither greenhouses gases nor other pollutants. These will form the basis of any long- term sustainable energy supply system [1]. Among various renewable energy sources, wind power is the most rapidly growing one. Since the fuel of the wind turbine is free, the generated kilowatts should be used as often as possible in the electricity. Wind energy costs nothing and is absolutely pollution-free [2].

The wind turbine system has two configurations. The first is the fixed speed system in which the generator is connected directly to the grid. The disadvantage of this concept is the power variation due to wind turbulence, that affects the power quality of the grid [3].

The second is the variable speed doubly fed induction generator (DFIG) which is the most widely used concept [4]. Due to its high performance, it controls the rotor speed thus the power variation due to wind can be reduced. Its capability to capture maximum power from wind energy compared to fixed speed concept and its low cost converters which handles only about 20-30% of the total power are advantages.

It is well known that the direct torque control (DTC) has an excellent dynamic performance compared to other control strategies for its rapid control about flux and torque. In generation system, the voltage regulation behavior during sudden change in rotor speed [5].

In this paper, a new direct torque control (DTC) strategy for doubly-fed induction generator (DFIG) is proposed to pursue a simple control structure, very fast dynamic response and high efficiency. The control technique proposed in this paper doesn’t use classical hysteresis band. It is replaced by logic look up table based only on the torque error , flux error and the operating sector.

The aim of the proposed control system is to keep the rotor power factor at unity by selecting the proper voltage vector, to provide very fast dynamic response and decrease torque ripples under wind speed variation.

A simulation is performed by Matlab/Simulink program under wind speed variation which lead to change the doubly fed induction generator speed from sub-synchronous to super- synchronous speed. Detailed results are obtained and explained below.

2. Wind Turbine and DFIG Model

A wind turbine consists of rotor that extracts kinetic energy from the wind and converts it into a rotating movement , which is then converted into electrical energy by the DFIG .

Connection between the turbine and the generator is through a low-speed shaft and a high-speed shaft and a gearbox in between [2].

Figure (1) shows the basic configuration of a DFIG wind turbine. The stator of the DFIG is directly connected to power grid and its rotor is connected to stator terminals through two voltage source converter (VSC). In order to produce electrical power fed to utility grid, the grid side converter (GSC) is controlled so as to obtain constant DC bus voltage, and the rotor side converter (RSC) is used to control the power through rotor, so that controlling power flow from DFIG and power grid is achieved. Since the main objective of grid side converter is to keep DC link voltage constant at any operating condition, so that in this paper the control system is applied only to rotor side converter (RSC) for simplicity.

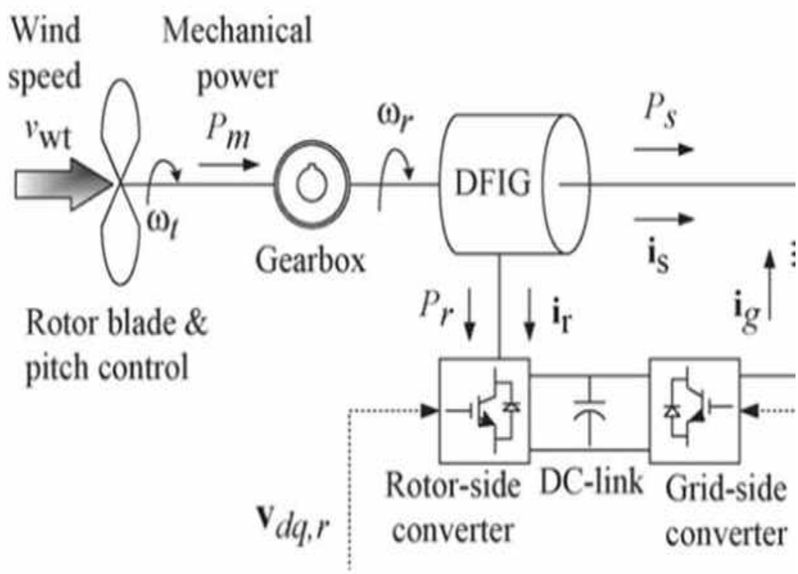


Figure 1 Basic configuration of wind turbine DFIG system.

2.1. Wind turbine model

The algebraic relation between wind speed (v_w) and mechanical power extracted (P_m) is described by the following relation[6]:

$$P_m = 0.5\ \rho\ A\ v_w^3\ C_p(\lambda,\beta) \tag{1}$$

Where c_p is the power coefficient

$$C_p(\lambda,\beta) = 0.5\left(\frac{116}{\lambda i} - 0.4\ \beta - 5\right) e^{-21/\lambda i} \tag{2}$$

$$\lambda i = \left(\frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3}\right)^{-1} \quad (3)$$

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

The mechanical Torque of turbine is expressed as

$$T_m = \frac{P_m}{\omega_t} \quad (5)$$

The power coefficient C_p of a wind turbine is not constant but varies with wind speed , rotational speed of the turbine and the pitch angle β as shown in Figure(2).

In practice a wind turbine generator with good blade control C_p may reach a value of 0.5[7].

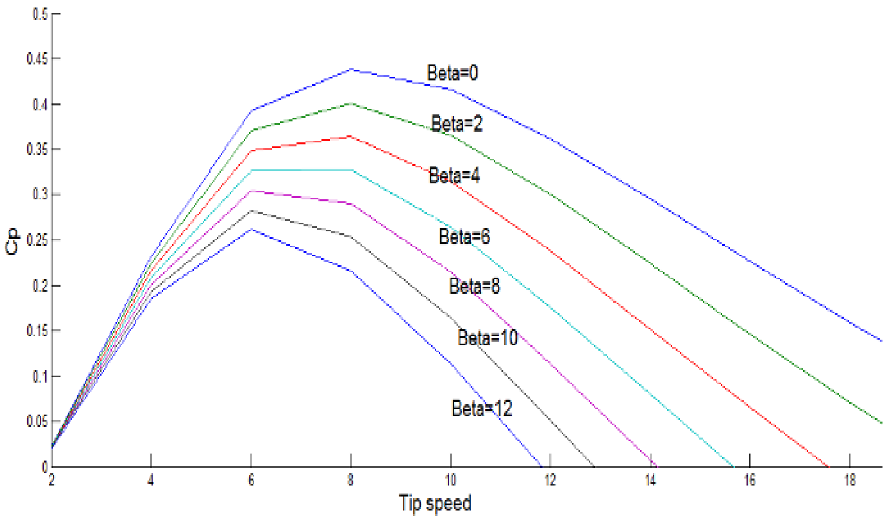


Figure 2 power coefficient versus tip speed ratio.

Pitch control is the most common method of controlling the aerodynamic power generated
by a turbine rotor, for newer larger wind turbines. Almost all variable-speed wind turbines use pitch control. Below rated wind speed the turbine should produce as much

Power as possible, i.e., using a pitch angle that maximizes the energy capture.

The block diagram used to represent the wind turbine is shown in Figure (3)

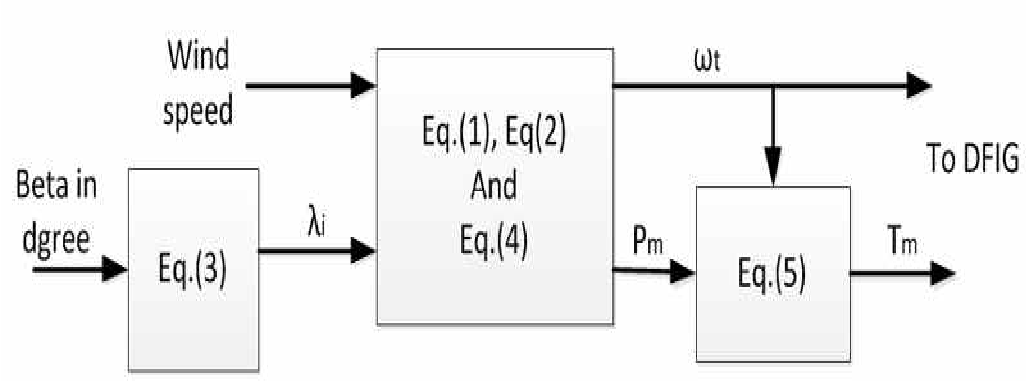


Figure 3 Block diagram of wind turbine.

2.2. Modeling of Shaft System

The equivalent model of a wind turbine and generator shafts are presented by two mass system as shown in Figure(4). The masses correspond to a large mass of the wind turbine rotor, masses for the gearbox wheels and a mass for generator respectively. Taking into account the stiffness and the damping factors for both shafts the dynamic equations can be written as [8] :

$$2H_t \quad p\omega_p = T_m - D_t\omega_t - D_{tg}(\omega_t - \omega_r) - T_{tg} \tag{6}$$

$$2H_g \quad p\omega_r = T_{tg} + D_{tg}(\omega_t - \omega_r) - D_g\omega_r - T_e \tag{7}$$

$$pT_{tg} = K_{tg}(\omega_t - \omega_r) \tag{8}$$

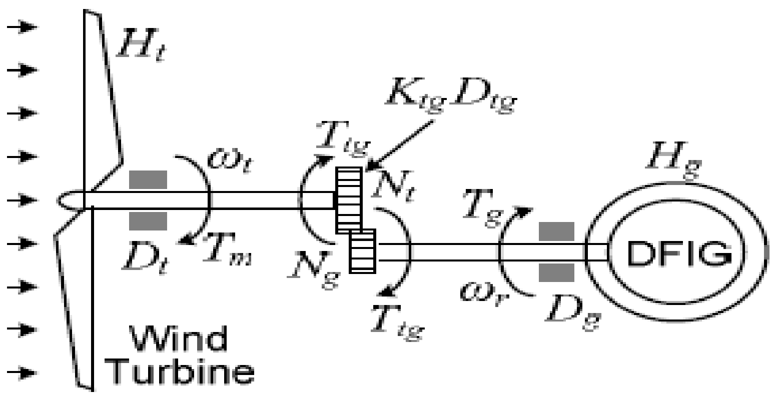


Figure 4 Two mass system of wind turbine and generator shafts

2.3. Modeling of the Induction Generator

The mathematical dynamic model of the DFIG in d-q form can be written as following [9]:

$$\frac{1}{\omega b}\frac{d\psi_{ds}}{dt} = \mathbf{R_s\, i_{ds}+\omega_s\psi_{qs} + V_{ds}} \tag{9}$$

$$\frac{1}{\omega b}\frac{d\psi_{qs}}{dt} = \mathbf{R_s\, i_{qs}+\omega_s\psi_{ds} + V_{qs}} \tag{10}$$

$$\frac{1}{\omega b}\frac{d\psi_{dr}}{dt} = \mathbf{R_r\, i_{dr}+(\omega s-\omega r)\ \psi qr + V_{dr}} \tag{11}$$

$$\frac{1}{\omega b}\frac{d\psi_{qr}}{dt} = \mathbf{R_r i_{qr}+(\omega_s-\omega_r)\ \psi_{dr}+V_{qr}} \tag{12}$$

The d-q stator and rotor fluxes are described as :

$$\left.\begin{aligned}
\Psi_{ds} &= -\ (L_{ls}+L_m)\ i_{ds} - L_m\ i_{dr}\ ,\\
\Psi_{qs} &= -\ (L_{ls}+L_m)\ i_{qs} - L_m\ i_{qr}\\
\Psi_{dr} &= -\ (L_{lr}+L_m)\ i_{dr} - L_m\ i_{ds}\ ,\\
\Psi_{qr} &= -\ (L_{lr}+L_m)\ i_{qr} - Lm\ i_{qs}
\end{aligned}\right\} \tag{13}$$

The electrical active and reactive power delivered by the stator circuit are given by:

$$\left.\begin{aligned}
P_s &= 1.5(P/2)(V_{ds}\ i_{ds}+V_{qs}\ i_{qs}),\\
Q_s &= 1.5(P/2)(V_{ds}\ i_{qs}-V_{qs}\ i_{ds})
\end{aligned}\right\} \tag{14}$$

Where P is the number of pole pairs.

The electrical active and reactive power delivered by the rotor circuit are given by:

$$\left.\begin{aligned}
P_r &= 1.5(P/2)(V_{dr}\ i_{dr}+V_{qr}\ i_{qr}),\\
Q_r &= 1.5(P/2)(V_{dr}\ i_{qr}-V_{qr}\ i_{dr})
\end{aligned}\right\} \tag{15}$$

The electromagnetic torque based on rotor flux and rotor current components can be expressed as,

$$\mathbf{T_e=1.5(P/2)}\ (\Psi_{qr}\, i_{dr} - \Psi_{dr}\, i_{qr}) \tag{16}$$

3. Design of Rotor flux and electromagnetic torque Estimators for DTC

It is assumed that stator flux is aligned with d^e ,so that (ψ_{qs} =0). And also stator flux is assumed to be constant, so that $\frac{d\psi_{ds}}{dt}$ =0 [10].

Under rotating synchronous reference frame V^e_{ds} =0 ,and V^e_{qs}= Vm [11]. Under these considerations the previous four order model of the DFIG becomes a two order model based only on the rotor flux and rotor voltage for simplicity[12]. thus:

$$\frac{1}{\omega b}\frac{d\psi^{e}{}_{dr}}{dt} = R^{e}{}_{r}\, i^{e}{}_{dr} + (\omega_s - \omega_r)\, \psi^{e}{}_{qr} + V^{e}{}_{dr} \quad (17)$$

$$\frac{1}{\omega b}\frac{d\psi^{e}{}_{qr}}{dt} = R^{e}{}_{r}\, i^{e}{}_{qr} + (\omega_s - \omega_r)\, \psi^{e}{}_{dr} + V^{e}{}_{qr} \quad (18)$$

The reference value of rotor flux can be calculated according to the utility condition of stator active power, stator voltage and stator power factor according to the following equations:

$$i^{*}{}_{qs} = (2/3)P^{*}{}_{s} / V^{*}{}_{qs} \quad , \quad (19)$$

$$i^{*}{}_{ds} = (2/3)Q^{*}{}_{s} / V^{*}{}_{qs} \quad (20)$$

$$i^{*}{}_{qr} = -\left(\frac{Ls+Lm}{Lm}\right) * i^{*}{}_{qs}, \quad (21)$$

$$i^{*}{}_{dr} = \frac{-1}{Lm}\left(\frac{(V^{*}qs + Rs\, i^{*}qs)}{\omega_s} + (L_s+L_m)\, i^{*}{}_{ds}\right) \quad (22)$$

Note , $L_s=L_{ls}+L_m$

Then from equation (13) we can obtain d-q rotor flux (reference values). And the reference value of rotor flux will be

$$\psi^{*}{}_{r} = (\Psi^{2}{}_{dr} + \Psi^{2}{}_{qr})^{0.5} . \quad (23)$$

Figure (5) indicates calculating reference value of rotor flux

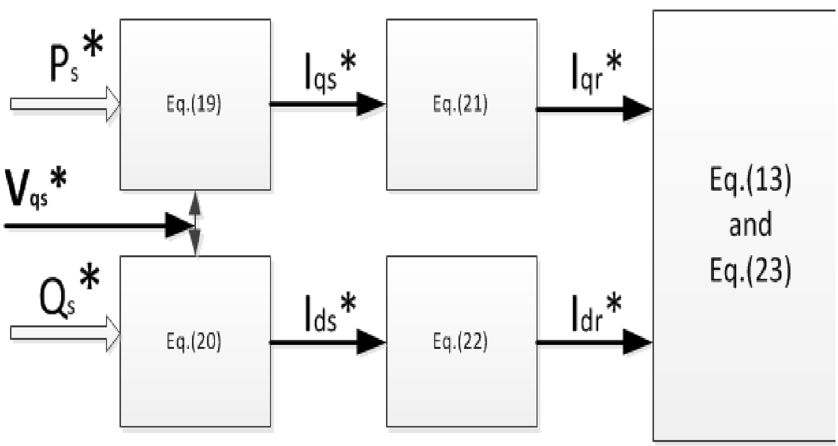


Figure 5 calculating reference value of rotor flux

The reference value of the electromagnetic torque can be obtained from the two mass model as shown in figure (6)

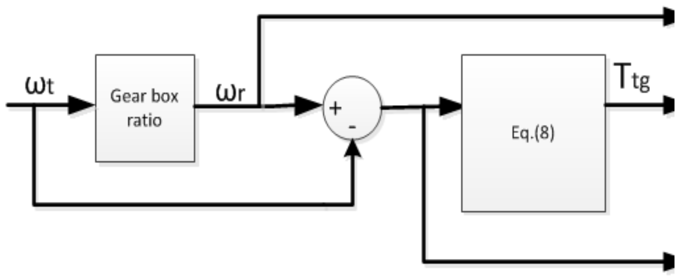


Figure 6 calculating reference value of electromagnetic torque

4. Complete System configuration

The objective of the RSC is to govern both the stator-side active and reactive powers independently, while the objective of the GSC is to keep the dc-link voltage constant regardless of the magnitude and direction of the rotor power. In this paper the dc- link voltage is assumed to be constant and the DTC is applied only to RSC. The DTC allows very fast torque responses and flexible control for the RSC of the DFIG .In DTC it is possible to control machine flux and electromagnetic torque by the selection of the optimum inverter switching modes.
Figure (7) shows the basic concept of the DTC system.

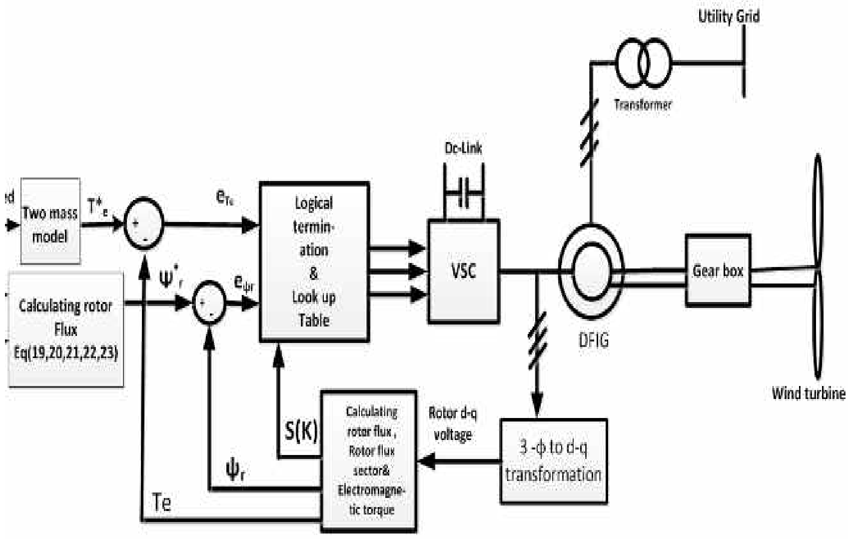


Figure 7 The proposed control scheme of a DFIG driven by a wind turbine based on DTC

Both error of torque and flux are terminated in order to provide logic outputs then the terminated logic signal and rotor flux position are fed to the look up table in order to generate switching action which is fed to the voltage source

converter (VSC). Replacing the classical hysteresis band by the logic look up table makes the selection of the switching action more and more flexible, decrease torque ripples whatever is the wind speed, and keeps switching constant.
If $e_{Te}>0$ the logic output is set to 1, if $e_{Te}<0$ the logic output is set to -1& if $e_{Te}=0$ the logic output is set to 0. Also for rotor flux error, if $e_{\psi}>0$ the logic output is set to 1& if the $e_{\psi}<0$ the output logic is set to 0. Figure (8) shows how the output logic is obtained. The frequency of the reference signal is calculated according to the rotor slip frequency (for constant switching frequency), and the amplitude is according the error limitations (upper and lower values). Then the terminated errors and the operating sector (ϴr) are fed to logic look up table in order to obtain the appropriate switching actions which is fed to voltage source converter to obtain the rotor voltage. Table (1) indicates the voltage vectors under super-synchronous and sub-synchronous speed which is built at the constraint of unity rotor power factor.

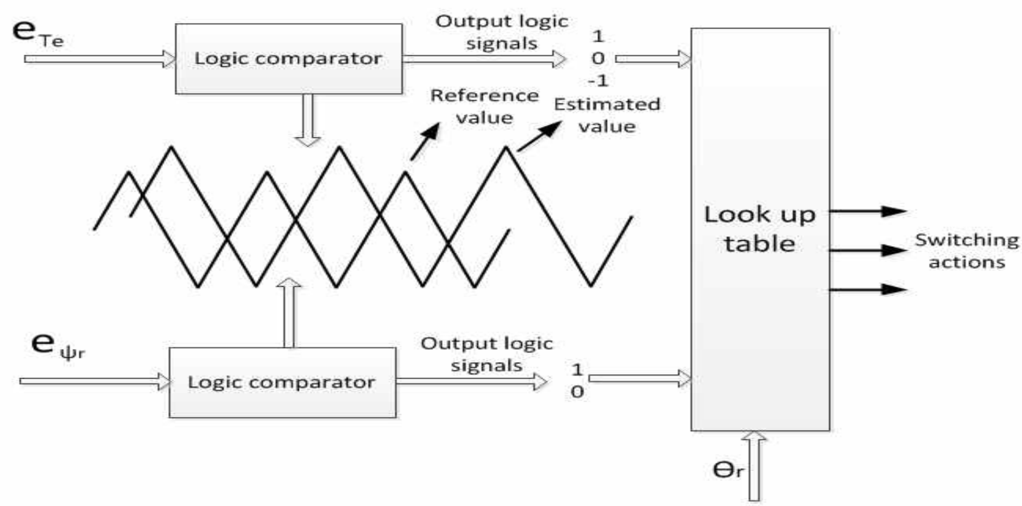


Figure (8)

Where, $$\Theta_r = \tan^{-1}\left(\frac{\psi_{dr}}{\psi_{qr}}\right) \quad (24)$$

The phasor diagram shown in Figure (9) indicates how the voltage vector selection is made.

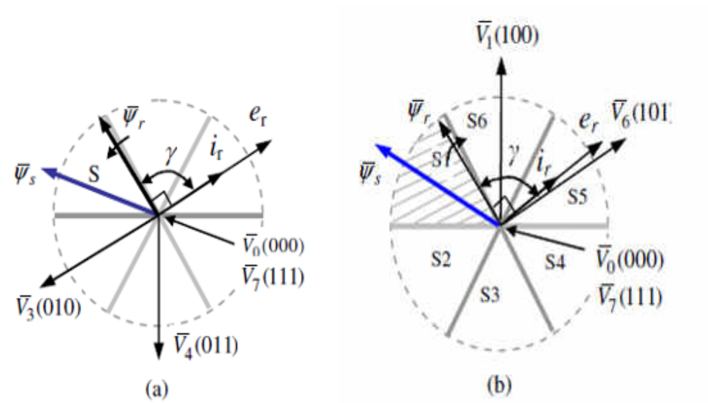


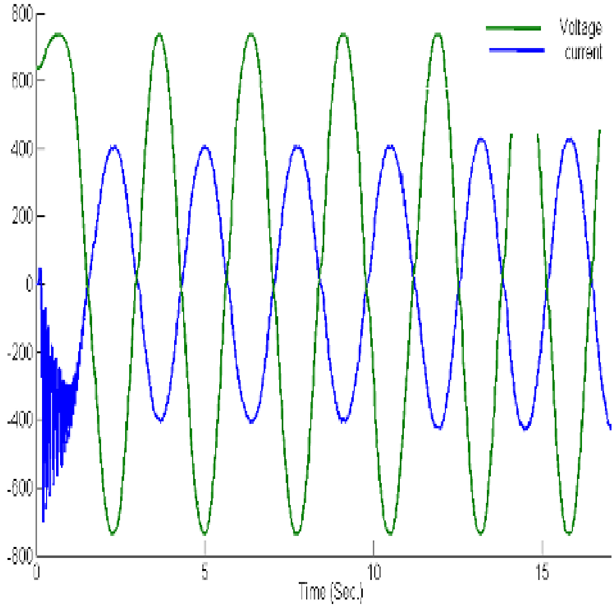
Figure 9 Rotor voltage vectors (a) sub-synchronous, (b) super-synchronous.

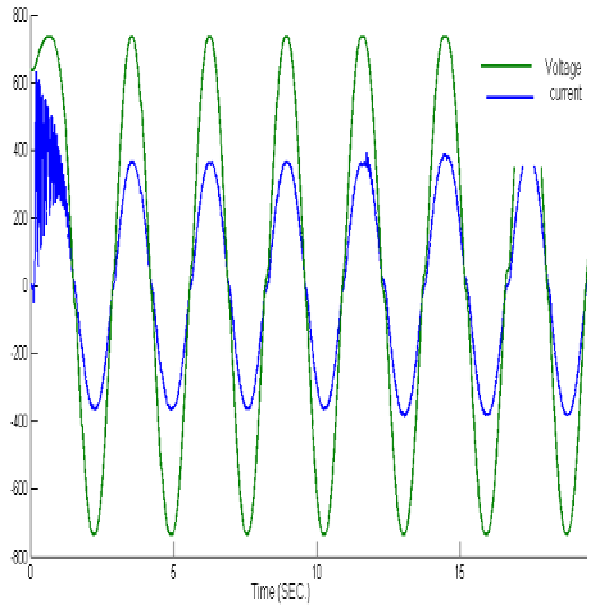
Table 1 rotor voltage vectors selection

DFIG speed	$e_{\psi r}$	e_{Te}	S(1)	S(2)	S(3)	S(4)	S(5)	S(6)
Sub.synchronous speed	1	1	V2	V3	V4	V5	V6	V6
		0	V7	V0	V7	V0	V7	V0
		-1	V6	V1	V2	V3	V4	V5
	0	1	V3	V4	V5	V6	V1	V2
		0	V0	V7	V0	V7	V0	V7
		-1	V5	V6	V1	V2	V3	V4
Super synchronous speed	1	1	V6	V1	V2	V3	V4	V5
		0	V7	V0	V7	V0	V7	V0
		-1	V1	V2	V3	V4	V5	V6
	0	1	V5	V6	V1	V2	V3	V4
		0	V0	V7	V0	V7	V0	V7
		-1	V4	V5	V6	V1	V2	V3

4. Simulation results and Discussions

Matlab /Simulink program is used to carry out simulation of DFIG driven by wind turbine under variable wind speed. Simulation is performed under sub-synchronous and super-synchronous speeds (wind speed changed from 12.5 m/sec to 17.5 m/sec). The generated rotor voltage by the proposed control system is shown in figure (10). In this figure rotor has unity power factor at both sub- synchronous and super- synchronous speed but the peak value of rotor current is higher at super-synchronous speed . In order to make transition from sub-synchronous to super synchronous speed the rotor phase sequence is changed according to the voltage vector obtained from the voltage vector of the look up table and then applied to source converter (VSC).





(a) (b)

Figure 10 Rotor voltage and current.(a) under sub- synchronous.
(b) under super-synchronous.

Figure (11) indicates stator voltage under the two previous conditions wind speed changed from 12.8 to 17.5 m/sec. (sub- synchronous and super-synchronous speed). In this figure the stator voltage appears as constant dc voltage in the synchronous rotating frame d^e-q^e [11]. The dc value is peak value of stator voltage . As shown in figure (10) the peak value of the output stator voltage is higher at super-synchronous speed than in sub- synchronous speed.

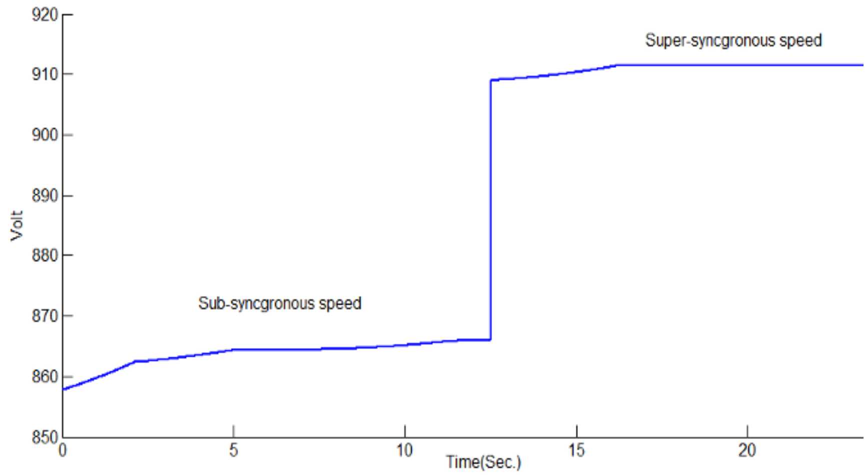
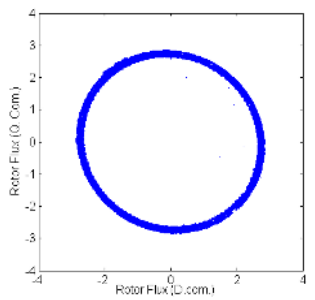
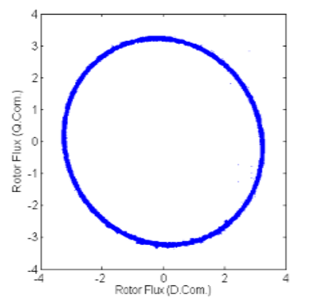


Figure 11 stator voltage

Figure(12) shows the rotor flux paths in the d-q plane, where under super-synchronous speed the rotor flux is more than under sub-synchronous speed. The increase in the rotor flux under super-synchronous speed covers the DFIG reactive power and supplies reactive power to the grid.



(a)



(b)

Figure 12 Rotor Flux (a) sub-synchronous (b) super-synchronous

Another simulation is carried out to obtain the wind speed profile shown in Figure (13). The period from 1sec. to 5.7 sec represents sub-synchronous speed (10.8 m/sec.) , the period from 5.7 sec to 11.5 sec represents super-synchronous speed (15.4 m/sec.), and again wind speed decreases to sub-synchronous speed (13.2 m/sec.) from 11.5 to 12.5 sec.

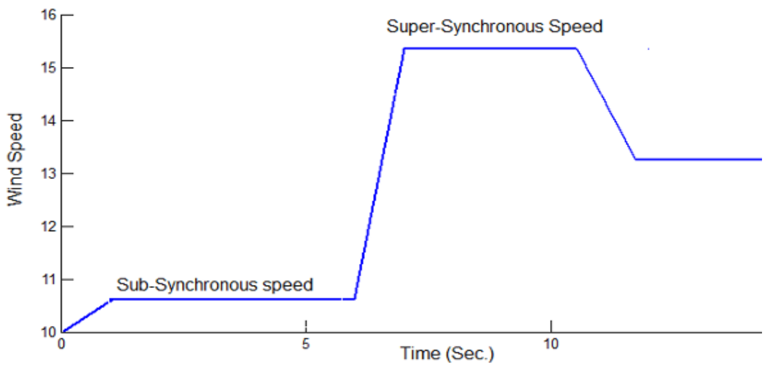


Figure 13 Wind speed profile

Figure (14) indicates the electro-magnetic torque, the reference and the calculated values. The calculated value has low order of ripples.

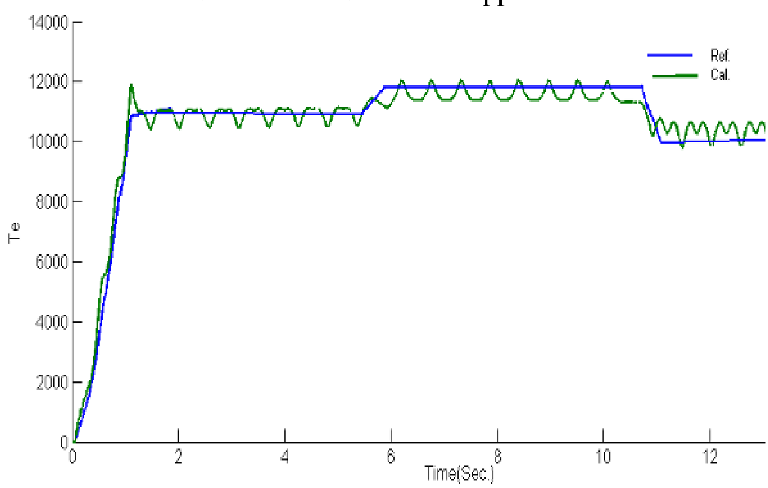


Figure 14 Electro-magnetic Torque

Figure (15) indicates operation of the DFIG under sub- synchronous speed. Under this condition the DFIG rotor absorbs active power from the utility grid so that the total active power fed to the grid decreases (Pt=Ps-Pr), while under super-synchronous speed both rotor and stator of the DFIG supplies active power to the utility grid (Pt=Ps+Pr),so that the total active power fed to the grid increases.

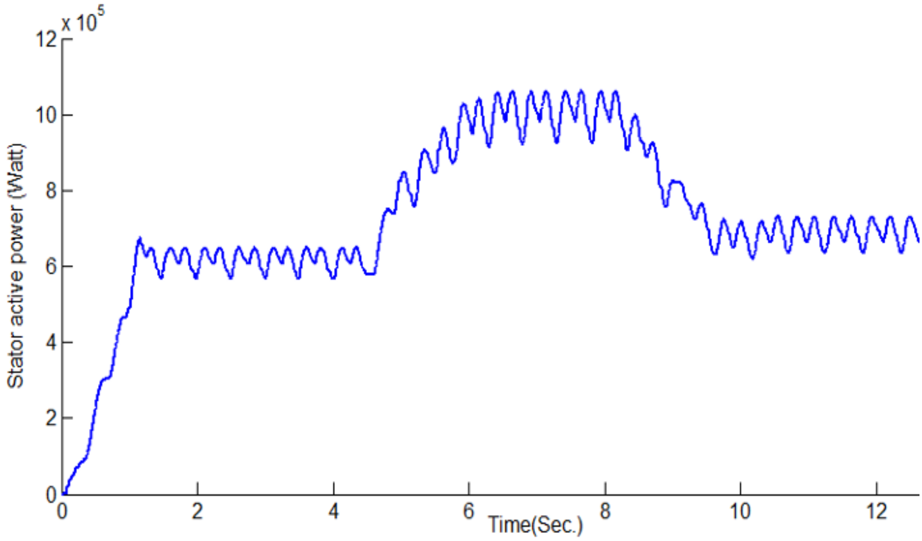


Figure 15 (a) stator Power

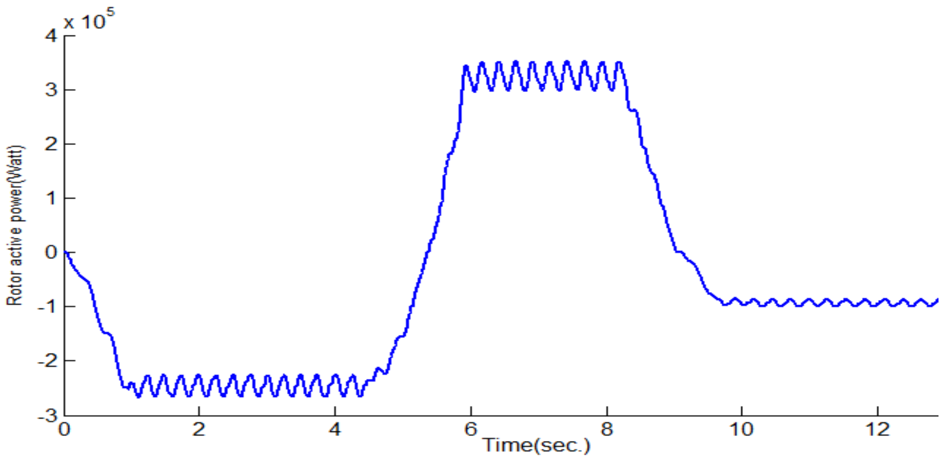


Figure 15 (b) Rotor Power

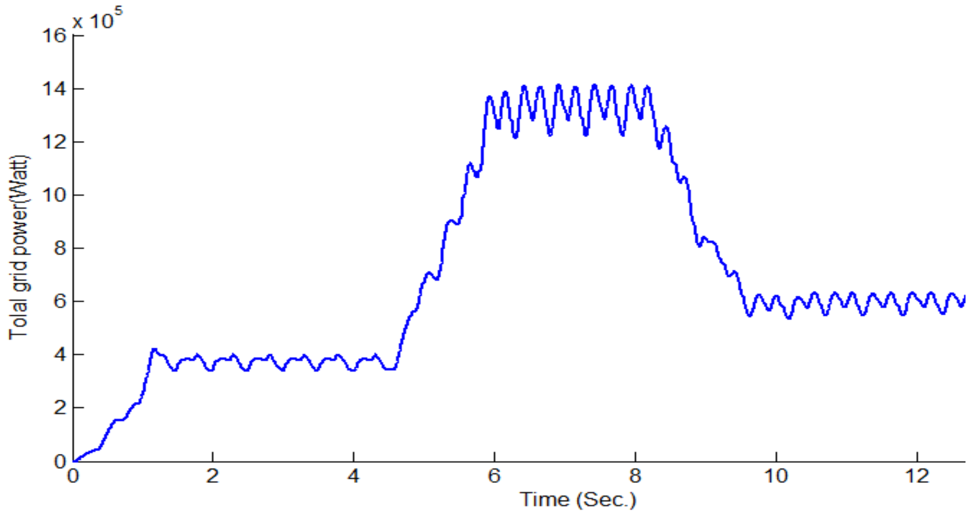


Figure 15 (c) Grid Power

Figure(14) (a) stator power. (b) Rotor power. (c) power fed to grid. under sub-synchronous and super-synchronous speed.

Figure (16) indicates the stator reactive power. The period from 1 sec to 5.7 sec the DFIG absorbs reactive power from the utility grid (+Q is fed to the DFIG) , but from 5.7 sec to 11.5 sec the DFIG supplies reactive power to the utility grid (-Q is fed to the grid). Again from 11.5 sec to 12.5 sec the DFIG absorbs reactive power from the utility grid.

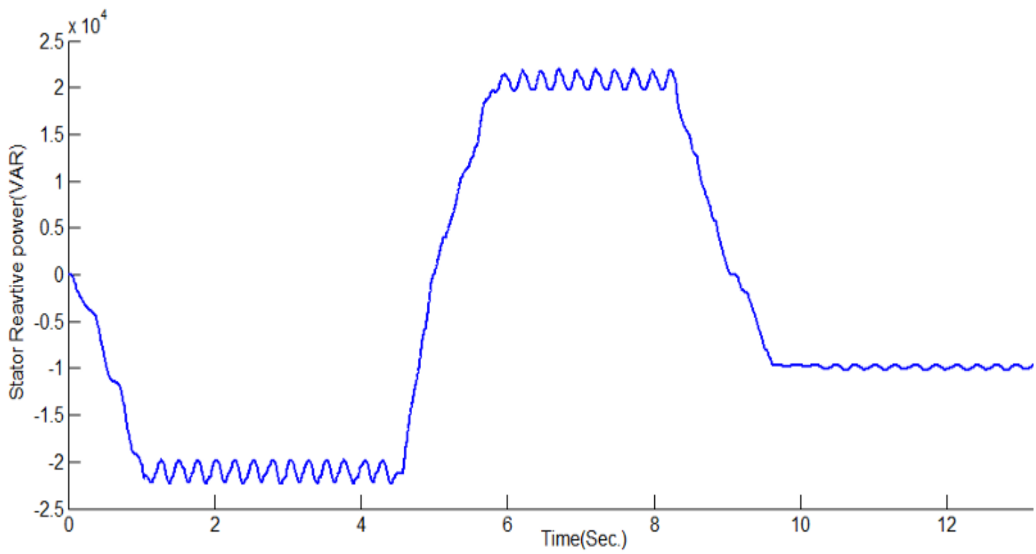


Figure 16 Stator Reactive Power

5. CONCLUSION

This paper presents a very simple implementation of DTC system is applied to DFIG driven by wind turbine under variable wind speed. Obtained results indicate that, variation in stator voltage is about 10% of its rated value which is considered to be accepted value for grid connection between DFIG and the utility power grid, and also the transition from sub-synchronous speed to super-synchronous speed is very fast and is made by changing phase sequence of rotor voltage.

The advantages of this control system are,

(1) It depends only on the input wind speed profile without using any measurement or sensing devices.

(2) The control is simple since no PI regulators are used. Thus, problems related to parameter tuning and machine parameter dependence are eliminated.

(3) It Provides very fast dynamic response under variation of wind speed .

(4) It Keeps torque ripples at a desired lower level under variable wind speed

(5) Finally using this control algorithm makes integration of wind farms in the electrical power utility grid very easy.

APPENDIX

Table(2) indicates Parameters and data specifications of the DFIG and wind turbine used in the simulation.

P	850 KW
V	890V
F	58 Hz
R_s	0.003058 ohm
R_r	0.0045387 ohm
L_m	$67.848*10^{-4}$ H
L_s	$1.157*10^{-4}$ H
L_r	$1.7952*10^{-4}$ H
H_t	4.17 $Kg.m^2$
H_g	0.54 $Kg.m^2$
D_{tg}	365
K_{tg}	1.16 N.m.sec/rad
nominal wind speed	14 m/sec
swept area	2122 m^2

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التحكم المباشر في عزم المولدات الحثيه ثنائية التغذية المدارة بتربينات الرياح متغيرة السرعة

تعتبر طاقة الرياح أحد مصادر الطاقه الجديده والمتجدده التي تستخدم في توليد الطاقه الكهربائيه ،وتحظي طاقة الرياح كبير علي مستوي العالم نظرا لانها تعتبر بديلا لمصادر الطاقه التقليديه المستخدمه حاليا كالفحم والبترول وذلك لما تسببه هذه المصادر التقليديه من تلوثا للبيئه، فضلا عن كونها مصادر غير متجدد ه وتنضب يوما بعد يوم.ولذلك زاد الاهتمام والابحاث حول كيفية استخدام واستغلال طاقة الرياح لانتاج الطاقه الكهربائيه .

ينتاول هذا البحث تطبيق طريقة التحكم المباشر في العزم علي المولدات الحثية ثنائية التغذية المدارة بطاقة الرياح وذلك للتحكم في الطاقه الكهربيائيه الناتجه من المولد اثناء التغيرات المفاجئه في سرعة الرياح، حيث تم استخدام برنامج المحاكاه المتلاب لعمل محاكاه للطريقه المقترحه وتقييمها .كما تم تقسيم البحث الي عدة فقرات كالتالي:

الفقره الاولي : تتناول مقدمه عن اسباب استخدام المولد الحثي ثنائي التغذية عن غيره من المولدات ،وكذلك الابحاث المنشوره المتعلقه بالموضوع واخر ما توقفت عنده هذه الابحاث.

الفقره الثانيه: تتناول كيفية تمثيل تربينة الرياح باستخدام برنامج المتلاب.

الفقره الثالثه : تتناول كيفية التمثيل الرياضي للاجزاء الميكانيكيه المستخدمه في الربط بين التربيه الهوائيه والمولد.

الفقره الرابعه : تتناول كيفية تمثيل المولد الحثي ثنائي التغذيه رياضيا داخل برنامج المتلاب.

الفقره الخامسه :تتناول حساب قيمة النهائيه لكل من الفيض المغناطيسي وقيمة العزم المغناطيسي .

الفقره السادسه: تتناول كفية تصميم طريقة التحكم المباشر في عزم المولدات الحثيه ثنائثة التغذيه حيث تم عرض طريه جديده تعتمد علي عدم استخدام حثاثات للسرعه او للموقع وكذلك عدم استخدام المنظمات المعتمده علي المعدلات التكامليه.

الفقره السابعه : تناولت توضيح شامل للطريقه الجديده المستخدمه من خلال تطبيق واستخدام برنامج المتلاب ،حيث أظهرت النتائج مميزات الطريقه المقترحه من حيث بساطة التصميم،سرعة الاستجابه لاي متغيرات في سرعة الرياح ،فضلا عن عدم استخدام أية انواع من الحثاثات أو المنظمات المعتمده علي المعدلات التكامليه. هذا مما يجعل استخدام وزراعة مولدات الرياح داخل منظومة القوي الكهربائيه أمرا سهلا وحيوي.