Conférence Internationale en Automatique & Traitement de Signal (ATS-2017)
Proceedings of Engineering and Technology – PET
Vol.22 pp.16-21

Direct Power Control with Space Vector Modulation of a DFIG for Wind Energy Conversion System

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Abstract— **This paper deals with analysis of Direct Power Control (DPC) strategy based on space-vector modulation (SVM) for a doubly fed induction generator (DFIG) used in wind energy conversion system. The (DPC-SVM) is applied to control the active and reactive powers exchanged between the stator of the DFIG and the grid with ensuring a Maximum Power Point Tracking (MPPT) of a wind energy conversion system. In order to control the DFIG, direct power control and space-vector modulation (DPC-SVM) are combined to replace the hysteresis controllers used in the classical DPC. The active and reactive powers are controlled by PI regulators. Simulation results with (DPC-SVM) for DFIG are presented to illustrate the feasibility of the proposed control strategy. The proposed (DPC-SVM) method produces a fast and robust power response without the need of complex structure and algorithms.**

Keywords— **Wind energy conversion system (WECS), Doubly fed induction generator (DFIG), Direct power control (DPC), Space vector modulation (SVM), Maximum power point tracking (MPPT), field-oriented control (FOC), RSC (Rtor Side Converter).**

I. INTRODUCTION

Wind energy generation systems using doubly fed induction generator (DFIG) present an interesting option in the electrical generation domain due to the exceptional advantages. Indeed, using such this generator allows using small converters rating about 30% of the DFIG rating. Also, wind conversion system, using DFIG, allows variable speed operation over a restricted and large range. Compared to fixed speed wind turbines, those, functioning with variable speed, ensure increased energy exploitation and decreased mechanical constraints on the wind turbine[1],[2]. For the DFIG applied in our system, the windings of the stator are connected, directly, to a three phase grid. For the rotor windings, they are associated to a bidirectional back-to-back converter. This converter allows controlling the active and reactive power. In the literature, DPC is the most used method which can be applied for the DFIG based wind turbines. This method is characterized by its simplicity. It presents an alternative control strategy formulation which has the major advantage that it does not necessitate decomposition into symmetric components. In our work, we present an improved method of the DPC. This method differs from the classical DPC by using Space Vector Modulation (SVM) which ensures the back to back convertor operation with constant frequency modulation[3],[4],[5].

In this work, a new direct active and reactive power control using SVM technique is presented. This strategy is applied for a DFIG based wind turbine conversion system. This control method allows directly calculating the reference value of the rotor voltage for each switching period [4].This method is based on using the calculated active and reactive machine powers besides. In order to prove the effectiveness of the proposed strategy, simulation results of the overall system which is presented in Fig.1 are presented and discussed.

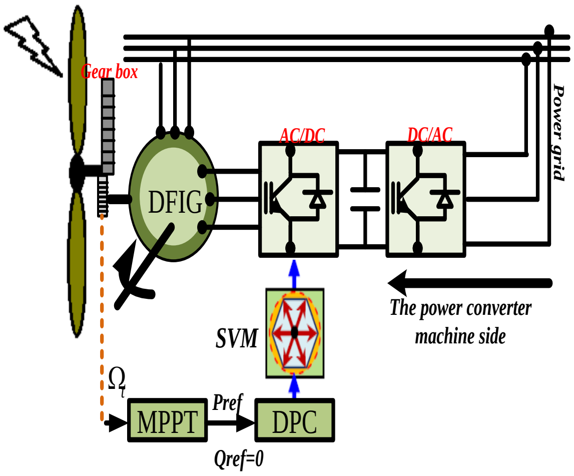

Fig. 1.Overall system.

II- MODELING OF WIND TURBINE

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

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

Where $C_p(\lambda,\beta)$ is the power coefficient. It is given by the following relation:

$$C_p(\lambda,\beta) = \frac{1}{2}\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{\frac{-21}{\lambda_i}} \tag{2}$$

Where λ_i and λ are given, respectively, by equation (3) and (4)

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

$$\lambda = \frac{\Omega_t R}{V} \tag{4}$$

Where: β: Pitch Angle(rad), R : Turbine Blade Radius(m) ,ρ : Air Density(Kg/m^3), A : Area covered by the rotor (m^2) ,V :

ISSN 2356-5608

Wind Speed (m/s), λ : Tip Speed Ratio, Ω_t :turbine Speed (rad/s),[1],[5],[6].

As function of λ, the power coefficient Cp is varies, it is given by Fig.2.

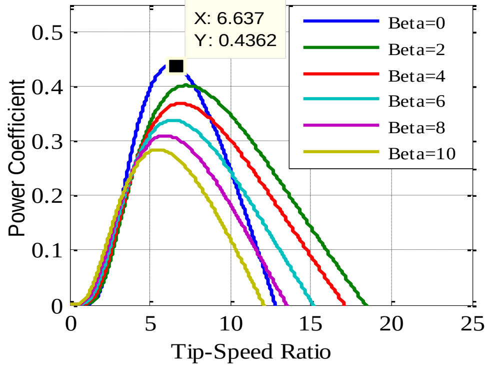

Fig.2. Power coefficient curve of a variable-pitch wind turbine.

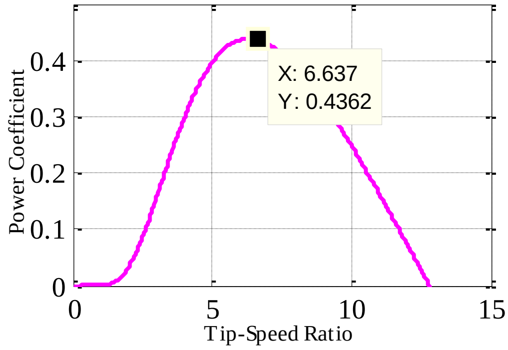

Fig. 3.Power coefficient Curve

Fig.3. indicates that when β = 0, there exists a maximum point = $C_{p-mac} = 0.4362$ attained by $\lambda_{opt} = 6.637$

The wind turbine operate on the locus of the maximum power point P_{opt} . This locus, named the MPPT-curve, is given by this equation:

$$P_{opt} = K_{opt}\Omega_t^3 \tag{5}$$

$$K_{opt} = \frac{1}{2}\rho\pi R^5 \frac{C_{p-\max}}{\lambda^3{}_{opt}} \tag{6}$$

The kinetic energy developed by the wind is also maximized. The reference torque that is delivered to the generator can be calculated by equation(7) ,[8].

$$T_{opt} = \frac{1}{2}\rho\pi R^5 \left(\frac{C_{p-\max}}{\lambda^3{}_{opt}}\right)\Omega_t^2 \tag{7}$$

When the generator generates the reference torque T_{opt} , the generated energy is at a maximum value as shown in fig.4.

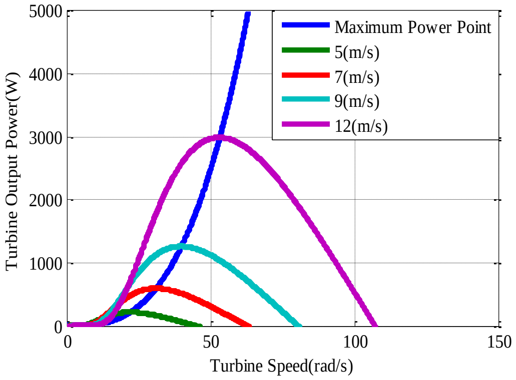

Fig.4. MPPT control

III- MODELING OF THE DFIG

In this section, we present the DFIG modeling in the d-q reference frame which is rotating at synchronous speed[6], [7].

Stator voltage components are given by the following equations.

$$V_{ds} = R_s I_{ds} + \frac{d}{dt}\varphi_{ds} - w_s\varphi_{qs} \tag{8}$$

$$V_{qs} = R_s I_{qs} + \frac{d}{dt}\phi_{qs} - w_s\phi_{ds} \tag{9}$$

The rotor voltage components are given by the following equations.

$$V_{dr} = R_r I_{dr} + \frac{d}{dt}\phi_{dr} - (w_s - w_r)\phi_{qr} \tag{10}$$

$$V_{dr} = R_r I_{qr} + \frac{d}{dt}\phi_{qr} + (w_s - w_r)\phi_{dr} \tag{11}$$

For the stator and rotor flux components, they are given by equations (12).

$$\begin{cases} \varphi_{ds} = L_s I_{ds} + L_m I_{dr} \\ \varphi_{qs} = L_s I_{qs} + L_m I_{qr} \\ \varphi_{dr} = L_r I_{dr} + L_m I_{ds} \\ \varphi_{qr} = L_r I_{qr} + L_m I_{qs} \end{cases} \tag{12}$$

Equation (13) presents the DFIG electromagnetic torque expression.

$$T_{em} = -\frac{3}{2} p \frac{L_m}{L_r}\left(\varphi_{ds} I_{qr} - \varphi_{qs} I_{dr}\right) \tag{13}$$

Equation (17) and (118) give, respectively, generator active and reactive powers in the d-q reference frame rotating at ω_s speed.

$$P_s = \frac{3}{2}\left(V_{ds} I_{ds} + V_{qs} I_{qs}\right) \tag{14}$$

$$Q_s = \frac{3}{2}\left(V_{qs} I_{ds} - V_{ds} I_{qs}\right) \tag{15}$$

IV - FIELD ORIENTED CONTROL FOR THE DFIG

The rotor side converter is controlled in a synchronously d-q reference frame rotating at ω_s speed. When the d axis is oriented according to the stator flux vector, such as given in

Fig5, we can obtain a decoupled control of the stator active and reactive powers. [2][3]

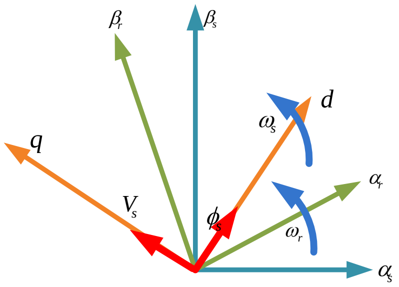

Fig.5. Stator field oriented control technique

In this case, the stator flux components are given by the following equations:

$$\phi_{ds} = \phi_s \tag{16}$$

$$\phi_{qs} = 0 \tag{17}$$

Applying the stator flux equations presented previously, we lead to a decoupled power control. Indeed, as given by equation (21) and equation (22) the component on q axis of the rotor current controls the DFIG active power. Concerning the reactive power, it is controlled by the direct component of the same current. [1] [2]

$$P_s = -\frac{3}{2}\frac{L_m}{L_s}V_s I_{qr} \tag{18}$$

$$Q_s = \frac{3}{2}V_s\left(\frac{V_s}{L_s w_s} - \frac{L_m}{L_s} I_{dr}\right) \tag{19}$$

Where: $K_\sigma = \frac{3}{2}\frac{L_m}{\sigma L_s L_r}$, $\sigma = 1 - \frac{L_m^2}{L_s L_r}$

The Rotor voltages are equal:

$$V_{rd}^* = \left(K_{p1} + \frac{K_{i1}}{S}\right)\left(Q_s^* - Q_s\right) + \omega_{sa}\frac{P_s}{K_\sigma \omega_s \phi_{ds}} \tag{20}$$

$$V_{rq}^* = \left(K_{p2} + \frac{K_{i2}}{S}\right)\left(P_s^* - P_s\right) + \omega_{sa}\left(\frac{L_r}{L_m} - \frac{Q_s}{K_\sigma \omega_s \phi_{ds}}\right) \tag{21}$$

Where ω_{sa} is slip angular frequency.

V- SVM- CONTROL OF ACTIVE & REACTIVE POWER.

The conventional DPC simply selects the switching states of the converter from an optimal switching table, based on the instantaneous errors between active and reactive powers and their references. This simple strategy can guarantees its good dynamic performance. However, the conventional DPC has several drawbacks which make it difficult to be applied in the Doubly Fed Induction Generator based wind power generation system. [9],[10],[11].

To generate the switching signals in SVM instead of switching table and hysteresis controller PI controllers are used to track the errors between active and reactive power.

The diagram of the proposed DPC for a DFIG system is shown in Fig. 7. The controller contains two PI controllers, -one for active power and one for reactive power-, and a SVM unit Space vector modulation.

The principle of (SVM) is to reconstruct the vector V-ref from eight voltage vectors. The 6 switches can take 23 different states, these 8 states are coded [S0,S1,S2,S3,S4,S5,S6 S7].

Modulation space Vector control the switches to switch PWM gradually from one state to the next, or S1 to S6 represented active switching ([011] [001] [010] [101] [100] [110]) and two zero voltage vectors, S0 and S7, corresponding to switching states ([000] and [111]).

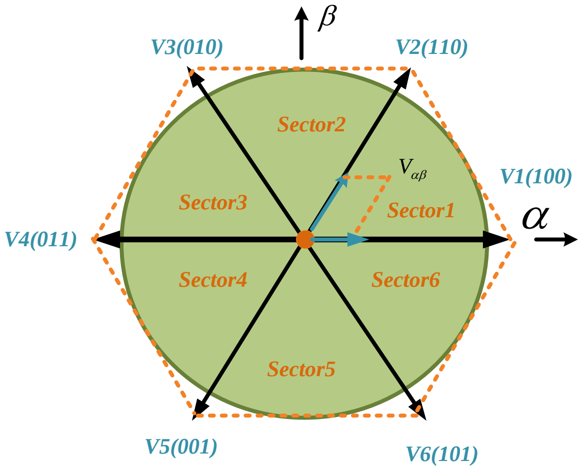

Fig.6. Basic Voltage vectors and reference vector

A.Sector Judgment

To applying the SVM technology, firstly it is requested to determine the sector which the voltage vector is within.[11] Considering that the expression of vector in the (α - β) coordinate is suitable for controlling implementation, the following procedure is used for determining the sector.

When $V_\beta \succ 0$

$A = 1$

When $\frac{\sqrt{3}}{2}V_\alpha - \frac{1}{2}V_\beta \succ 0$

$B = 1$

When $-\frac{\sqrt{3}}{2}V_\alpha - \frac{1}{2}V_\beta \succ 0$

$C = 1$

Then the sector containing the voltage vector can be decided according to $N = A + 2B + 4C$, listed in table I.

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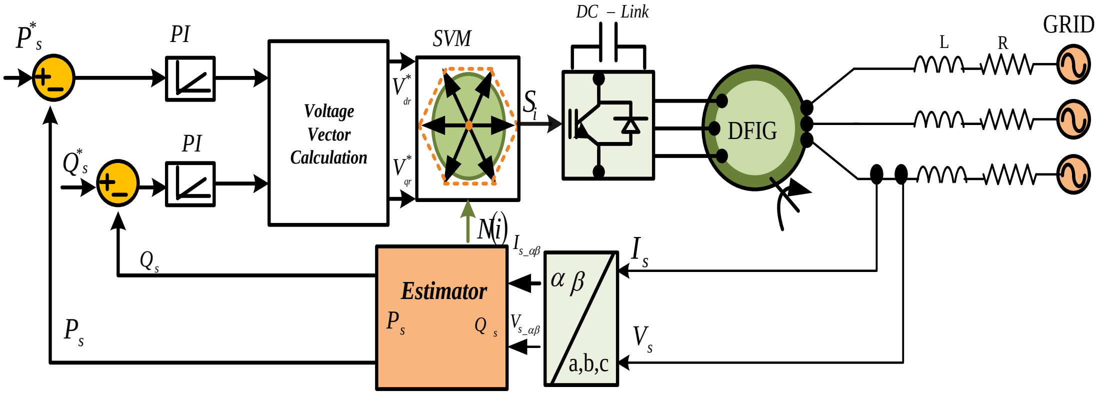

Fig.7. Schematic diagram of the proposed DPC for a DFIG system

TABLE I

THE SECTOR CONTAINING THE VOLTAGE VECTOR VERSUS N

Sector	I	II	III	IV	V	VI
N	3	1	5	4	6	2

B. Calculation of operation time of fundamental vectors.

Table II lists the operation times of fundamental vectors against sector N. t1 and t2 refer to the operation times of two adjacent non-zero voltage space vectors in the same zone[13]. The sum of t1 and t2 must be smaller than or equal to PWM modulation period T. For every sector, commutation duration is calculated from the values of X, Y and Z given by the following equations.

$$Z = \frac{T\left(-\sqrt{3}V_\alpha + V_\beta\right)}{\sqrt{2}V_{dc}} \qquad (22)$$

$$Y = \frac{T\left(\sqrt{3}V_\alpha + V_\beta\right)}{\sqrt{2}V_{dc}} \qquad (23)$$

$$X = \sqrt{2}T\left(\frac{V_\beta}{V_{dc}}\right) \qquad (24)$$

TABLE II

CALCULATION OF t1 AND t2

Sector N	I	II	III	IV	V	VI
t1	Z	Y	-Z	-X	X	-Y
t2	-Y	-X	X	Z	-Y	-Z

C. Calculation of switching time

The modulating signals, $T_{aon}, T_{bon}, T_{con}$, are determined by the following equations[12] :

$$T_{aon} = \frac{T - T_1 - T_2}{4} \qquad (25)$$

$$T_{bon} = T_{aon} + \frac{T_1}{2} \qquad (26)$$

$$T_{con} = T_{bon} + \frac{T_2}{2} \qquad (27)$$

The switch Time T_a,T_b ,T_c can be determined by relation with eatch sector and times $T_{aon}, T_{bon}, T_{con}$ shoing in table III.

TABLE III

CALCULATION OF SWITCHING OPERATING TIME.

	Sector					
	1	2	3	4	5	6
Ta	taon	tbon	tcon	tcon	tbon	taon
Tb	tbon	taon	taon	tbon	tcon	tcon
Tc	tcon	tcon	tbon	taon	taon	tbon

VI- SIMULATION RESULTS

To testify the proposed optimal control strategy, some simulations of dynamics performances for DFIG wind power generating system are implemented.

Simulations have been carried out with Matlab-simulink tools to ensure the effectiveness of the Direct Power control of DFIG.

The waveforms of active power and reactive power are shown in fig . It is clearly for the proposed scenario, reference of reactive power is maintained to 0VAR. For the reference of active power, it is given by MPPT. The Measured active and reactive powers of the DFIG follow perfectly their reference

The parameters of ours system are given in table IV.

TABLE IV

DOUBLY FED INDUCTION GENERATOR PARAMETRS

Parameter	Value
Rated power P_n (W)	800
Stator inductance L_s (H)	0.6703
Rotor inductance Lr (H)	0.6675
Mutual inductance L_m (H)	0.6146
Stator resistance R_s (Ω)	8
Rotor resistance Rr (Ω)	7.3
Number of pair of poles p	2

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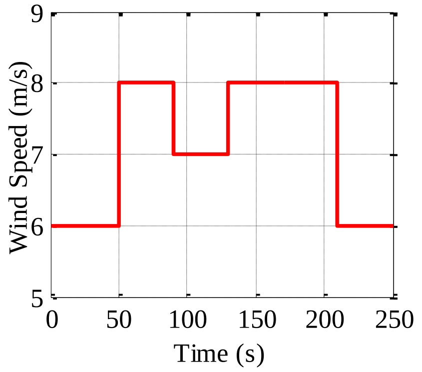

Fig.8.Wind Speed.

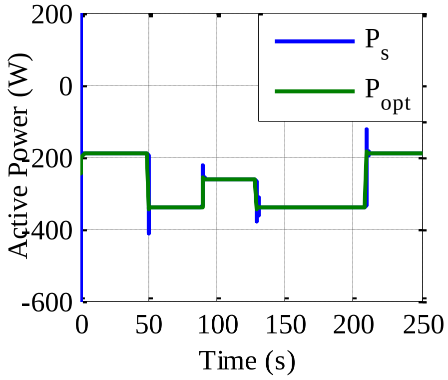

Fig.9.Active Power

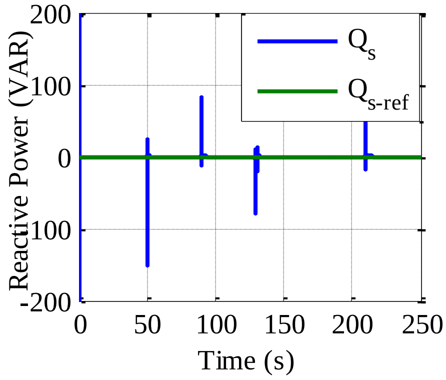

Fig.10. Reactive Power

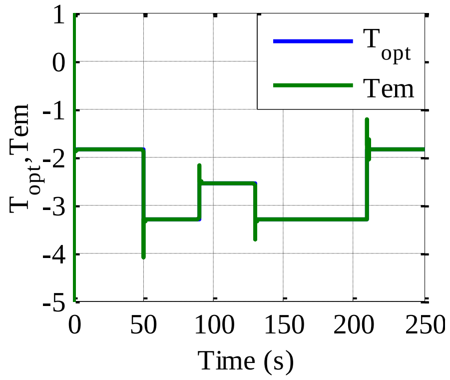

Fig.11. Electromagnetique Torque, Mechanical Torque reference.

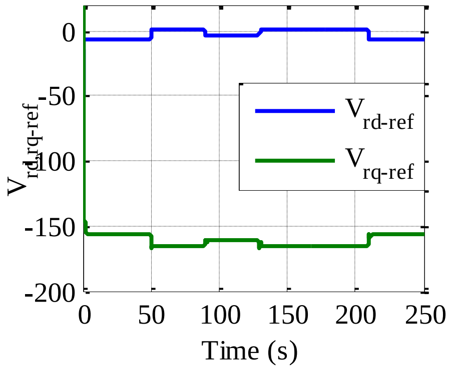

Fig.12. Rotor Voltage Reference.

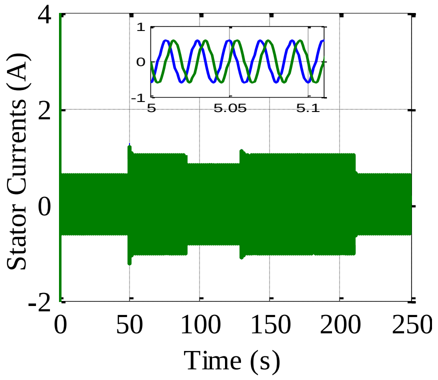

Fig.13. Stator Currents.

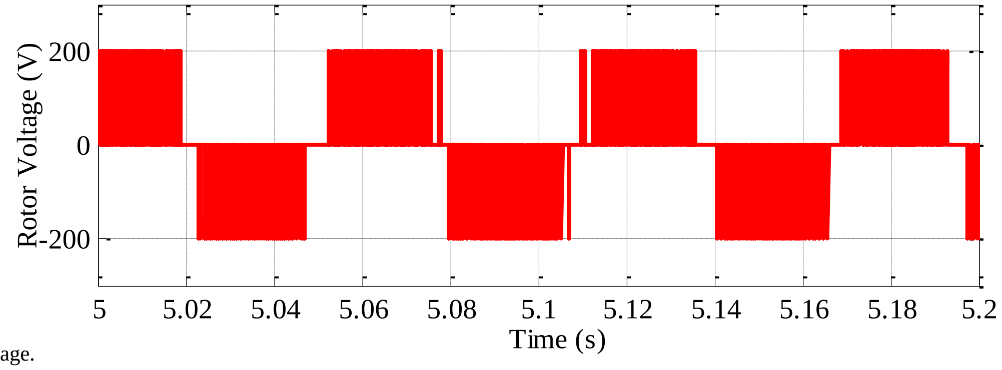

Fig.14. Rotor Voltage.

In this section, the wind is oscillating around (8m/s). As can be seen, in the scenario present in Fig15, the active power follow perfectly its reference, the average of reactive power is maintained to zero. The strategy DPC -SVM control is capable of providing accurate tracking for active and reactive power. Notice that , a sinusoidal waveform of the current injected to the grid is established.

ISSN 2356-5608

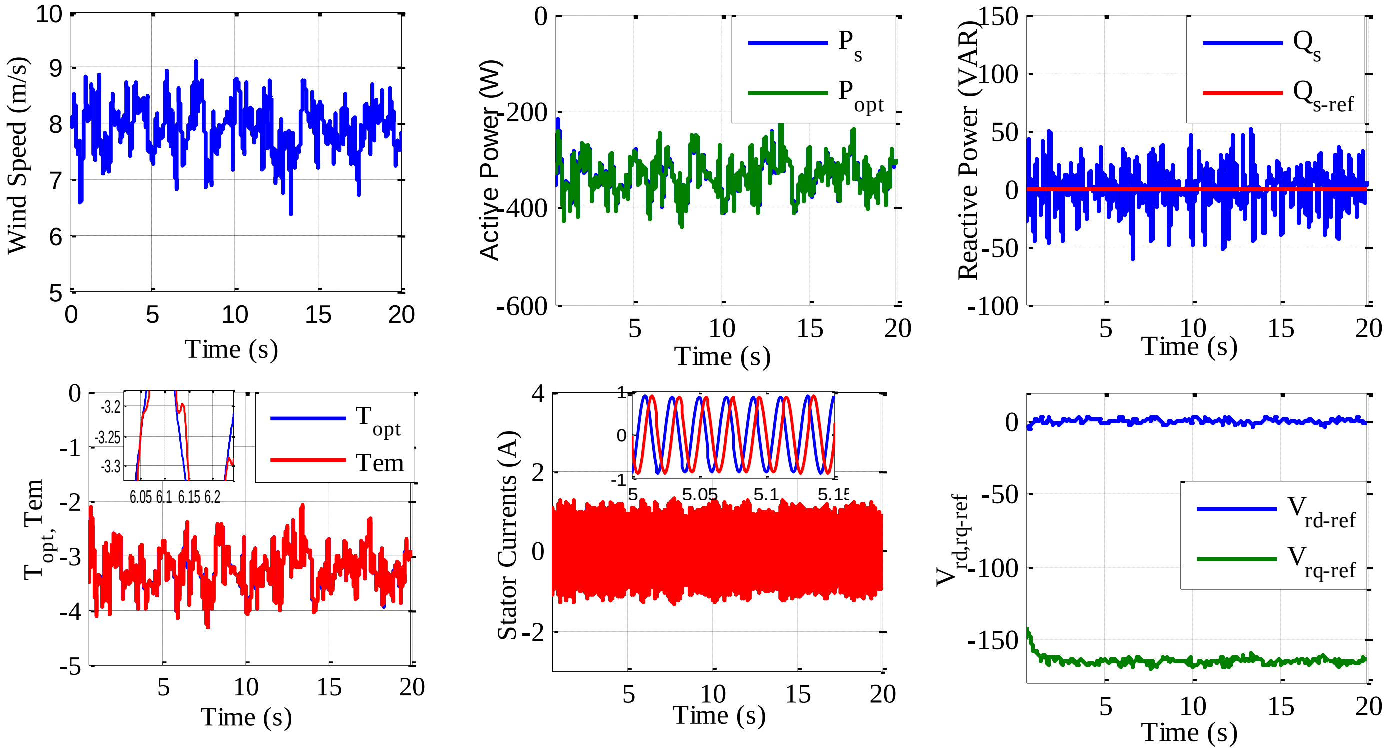

Fig.15. Simulation results under oscillating wind speed.

VII- CONCLUSIONS

This paper analyzes and examines a power control of doubly Fed Induction Generator (DFIG) using space vector modulation . The SVM control is applied to rotor side converter for active and reactive power control and voltage regulation of wind turbine. This approach is validated by modeling using Matlab_Simulink and simulation results can prove the excellent performance of this control as improving power quality and stability of wind turbine.

The simulation results of direct active and reactive power control method have proved the excellent performance of this control.

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