U.P.B. Sci. Bull., Series C, Vol. 81, Iss. 2, 2019 ISSN 2286-3540

DIRECT TORQUE CONTROL (DTC-SVM) OF PMSG BASED IN WIND ENERGY CONVERSION SYSTEM

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This paper presents a comparative study between two strategies for the direct torque control (DTC) of the permanent magnet synchronous generator (PMSG) based on wind energy conversion system (WECS). The first method is a conventional direct torque control DTC and it is based on hysteresis controllers where the torque and the flux are regulated by these controllers. The second one is direct torque control by space vector modulation strategy (DTC-SVM) where the torque and flux are regulated by PI controllers. The simulation results are implemented by using MATLAB/SIMULINK. The main feature of the proposed (DTC-SVM) strategy is the reduction of torque and flux ripples. The proposed approach can be considered as an alternative solution to the control of PMSG.

Keywords: PMSG, direct torque control, space vector modulation (SVM), wind turbine

1. Introduction

Wind energy is one of the oldest sources of energy used by mankind, comparable only to the use of animal force and biomass since several thousand years. In Europe, wind wheels were introduced around 1200, being mainly used for grinding and the construction knowledge was relatively high and improved through trial and error.

Later on, theories were developed, for instance those of Euler, providing the tools to introduce new designs and, thus, to substantially improve the efficiency of energy conversion. Many windmills were built and operated in different countries.

Actually we use this energy to produce electricity by various methods and equipment, but this has advantages and disadvantages; an advantage consists in being a clean source of energy which does not pollute the air like power plants that rely on combustion of fossil fuels; wind turbines do not produce atmospheric emissions that cause acid rain or greenhouse gasses. The disadvantages can be

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summarized in the following: wind unpredictability, limited resource, storage issues, and installation costs.

In the middle of 80s, new strategies for the torque of induction motor were presented by I. Takahashi and T. Noguchi as Direct Torque Control (DTC) and by M. Depenbrock as Direct Self Control (DSC). Those methods thanks to the other approach to control of IM have become alternatives for the classical vector control– FOC.

In our studies, we have developed a new technique to reduce torque and flux oscillations by imposing a constant modulation frequency. This technique is called DTC at constant modulation frequency (DTC-SVM). Furthermore, the paper presents a comparative study between conventional DTC and (DTC-SVM) to control the inverters at two levels to improve the performance characteristics and full efficiency of a wind turbine at variable speed to drive a PMSG. The resulting simulation models have been implemented using MATLAB / Simulink.

2. Wind Generation System

The mechanical power extracted from the wind can be expressed as follows:

$$P_m = \frac{1}{2}.C_p(\lambda)\rho\pi R^2 V^3 \tag{1}$$

$$\lambda = \frac{\Omega_t . R}{V} \tag{2}$$

where ρ is the air density (kg/m3), R is the blade radius (m), V is the wind speed (m/s), Cp (λ,β) represents the power coefficient, and can have a value between (0.4÷0.5). It could be expressed as:

$$C_p(\lambda,\beta) = C_1(C_2\frac{1}{A} - C_3\beta - C_4)e^{-C_5\frac{1}{A}} + C_6.\lambda \tag{3}$$

$$\frac{1}{A} = \frac{1}{\lambda + 0.008.\beta} - \frac{0.0035}{1+\beta^2} \tag{4}$$

C1=0.5872, C2=116, C3=0.4, C4=5, C5=21, C6=0.0085

where β is the pitch angle and (λ) is the tip speed ratio.

The output mechanical torque of the wind turbine Tm is given by

$$T_m = \frac{P_m}{\Omega_t} \tag{5}$$

3. Modeling the PMSG

The model of PMSG was developed in the (d, q) synchronous reference frame, the equations governing the PMSG are given by the equations (6), (7), (8), [8].

$$\begin{cases} V_{sd} = -R_s . I_{sd} - L_{sd} \dfrac{dI_{sd}}{dt} + \omega_r L_{sq} . I_{sq} \\ V_{sq} = -R_s . I_{sq} - L_{sq} \dfrac{dI_{sq}}{dt} - \omega_r L_{sd} . I_{sd} + \omega_r . \varphi_f \end{cases} \tag{6}$$

$$J \frac{d\Omega}{dt} = T_m - T_{em} - f\Omega \tag{7}$$

$$T_{em} = \frac{3}{2} p(\Phi_{sd} Isq - \Phi_{sq} Isd) \tag{8}$$

where:

V_{sd}, V_{sq} : the direct and quadrature component of the stator voltages;
i_{sd} ,i_{sq}: the direct and quadrature component of the stator currents;
L_{sd} ,L_{sq} : the direct and quadrature component of the stator inductances;
R_s : the stator resistance;
Ω : the mechanical speed of the rotor;
W_r : the electrical speed of the rotor;
Φ_f: the permanent magnet flux linkage;
T_{em}: the electromagnetical torque;
T_m: the mechanical torque;
P : the number of the pole pairs.

4. DTC for the PMSG

4.1. Classical DTC Principle and Scheme

PMSG is controlled by DTC technique. This method was used for induction machines by Takahashi and Noguchi to small and medium power application. DTC technique is based on the direct control of the stator flux and electromagnetic torque for PMSG. In this technique, the stator flux can be estimated as follows [2].

$$\begin{cases} \overline{\Phi}s\ (t) = \int_0^t (\overline{V}s - R_S\ \overline{I}_S\ )dt \\ \hat{\Phi}_S = \sqrt{\hat{\Phi}_{S\alpha}^2 + \hat{\Phi}_{S\beta}^2} \\ \delta = Arctg\ \dfrac{\hat{\Phi}_{S\beta}}{\hat{\Phi}_{S\alpha}} \end{cases} \tag{9}$$

$$\begin{cases} \hat{\Phi}_{S\alpha} = \int_0^t \left(V_{S\alpha} - R_S I_{S\alpha} \right) dt \\ \hat{\Phi}_{Sb} = \int_0^t \left(V_{S\beta} - R_S I_{S\beta} \right) dt \end{cases} \tag{10}$$

where: φs and Φs are respectively the vector and the magnitude of the stator flux, and Rs the stator resistance [2].

The voltages $V_{s\alpha}$ and $V_{s\beta}$ are obtained from controls (S_a, S_b, S_c) and measuring the voltage V_c. The voltages $V_{s\alpha}$ and $V_{s\beta}$ are obtained from controls (S_a, S_b, S_c) and measuring the voltage V_{dc} and applying the Concordia transformation.

$$\begin{cases} V_{S\alpha} = \sqrt{\dfrac{2}{3}}\, v_{dc} \left(S_a - \dfrac{1}{2}\left(S_b + S_c \right) \right) \\ V_{S\beta} = \sqrt{\dfrac{1}{2}}\, v_{dc} \left(S_b - S_c \right) \end{cases} \tag{11}$$

$S_i = 1$ the phase is connected to the supply positive polarity;

$S_i = 0$ the phase is connected to the supply negative polarity.

The stator-current space vector is derived from the measured currents i_a, i_b, and i_c:

$$\begin{cases} i_{S\alpha} = \sqrt{\dfrac{3}{2}}\, i_{sa} \\ i_{S\beta} = \sqrt{\dfrac{1}{2}}\, \left(i_{sb} - i_{sc} \right) \end{cases} \tag{12}$$

The electromagnetic torque T_{em} of the generator can be evaluated as follows:

$$\hat{T}_{em} = p\left(\hat{\Phi}_{S\alpha}\, I_{S\beta} - \hat{\Phi}_{S\beta}\, I_{S\alpha} \right) \tag{13}$$

The basic model of the conventional DTC for PMSG is shown in Fig.1, The amplitude of the stator flux and the calculated electromagnetic torque are compared to their reference values in the hysteresis comparators.

4.2. Simulation Results and Discussions

We present the results of simulations, using simulations in Matlab. In Fig.5 and Fig. 7, the reference values of stator flux and electromagnetic torque are almost mingled with the estimated value. The ripples of the torque and the stator flux for PMSG are irregular. This is explained by the DTC control method where the stator currents are not directly controlled, but they are changing and depending on the selected voltage vector, [3,4]. The simulation stator flux trajectory is presented in Fig. 2.

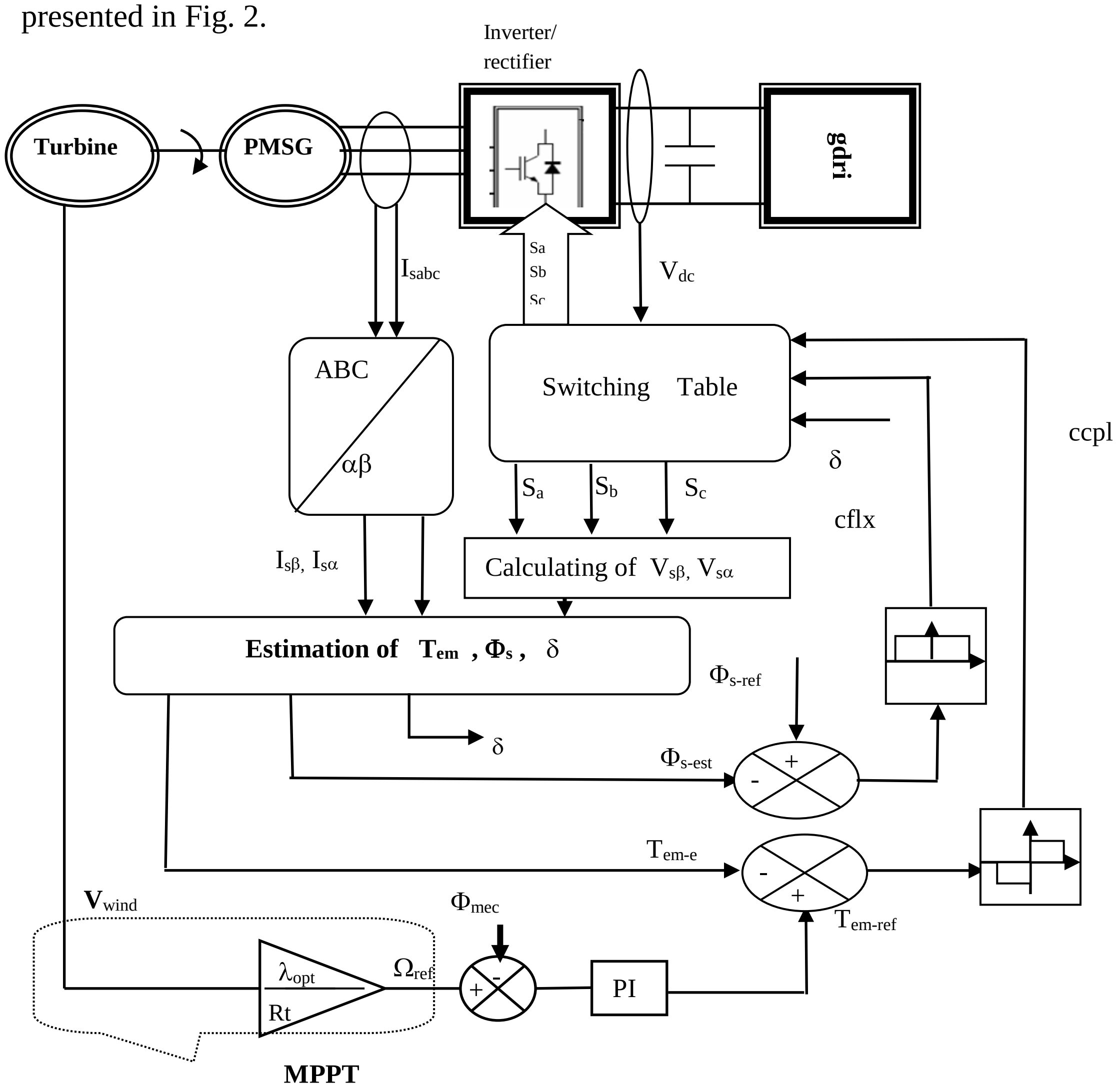

Fig.1- Diagram DTC control for PMSG.

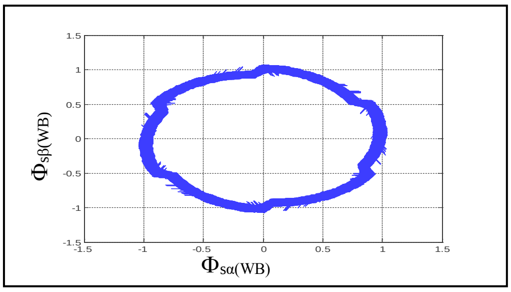

Fig.2. Stator flux trajectory.

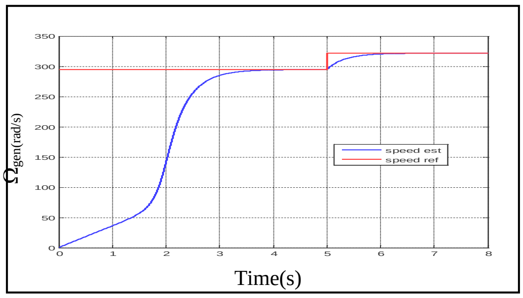

Fig .4. The speed of rotation by MPPT(rad/s).

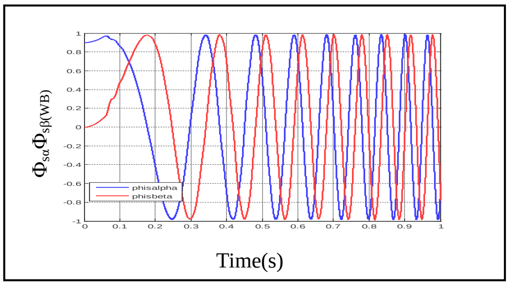

Fig.3. $\Phi_{s\alpha(WB)}$ and $\Phi_{s\beta(WB)}$ in Concordia.

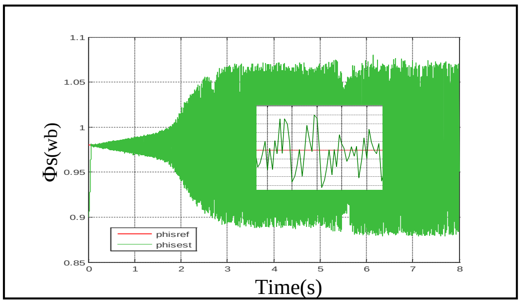

Fig .5. Magnitude of stator flux $\Phi_{s\text{-}ref}$ and $\Phi_{s\text{-}est}$.

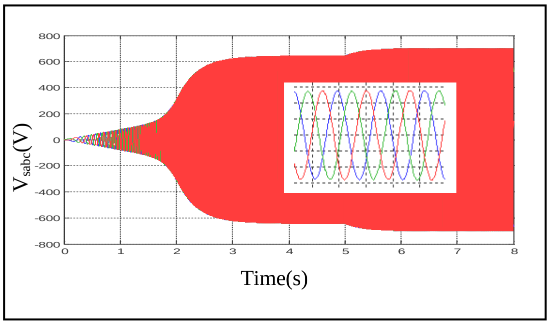

Fig .6.Voltage V_{sabc} for generator.

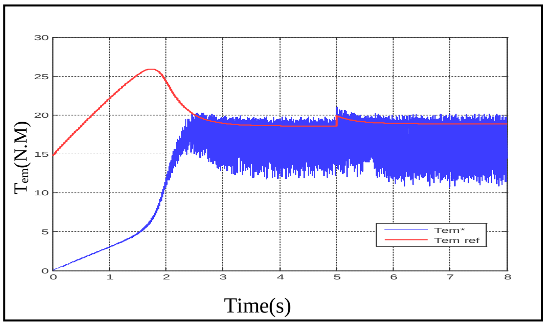

Fig .7. Electromagnetic torque $T_{em\text{-}ref}$ and $T_{em\text{-}est}$.

5. Improvement of DTC by (DTC-SVM)

The performance of DTC applied to the synchronous machine depends on the dynamic and static characteristics of the converter associated to the machine. Generally, pulse width modulation techniques are used to control the power switches for controlling AC machines [8].

If the power transistors control minimizes switching losses, it alters the voltages applied to the electrical machine. Pulse width modulation techniques are multiple, thus, the choice of one of them depends on the type of control applied to the machine. Moreover, the modulation frequency of the converters and the constraints of the harmonics are set by the user [2].

For the rectifier of our control system, we use the technique of vector modulation. The principle of this method is the determination of the time portions (modulation duration) that must be allocated to each voltage vector during the sampling period. The close command (SVM) is used to determine the ignitions sequences and the converter components extinctions in order to minimize the harmonics of the applied voltages [5].

To check the performance of this technique (SVM), a simulation of the PMSG in Matlab / Simulink is used.

6. Space Vector Modulation Technique for PMSG

This technique of direct control by (SVM) constitutes a new methodological approach, where the control of the magnitudes such as flux and torque are deported at the level of the switching cells control.

The "algorithmic control" layer is provided from the external instructions of the speed or the position, and the references of the flux and the torque [2].

The control laws of the inverter switches are generally derived heuristically, and, on the basis of the flux and the torque information, it determines the most appropriate switch.

Its main features being the removal of the hysteresis regulators and the vector selection table, it eliminates the problems associated with this method. With this control method, the inverter operates at constant frequency, since a space vector modulation is applied to the output vector of the command. This vector is called the "desired stator flux increment vector", and the input components of the modulation algorithm will be obtained from it [8].

The objective of this method is to realize a direct control of the stator flux in an axis (α, β) linked to the stator. Therefore, we will consider two flux vectors: the estimated stator flux vector and the reference flux vector. The polar components of these two vectors are obtained from their projections on the reference frame (α, β). From these components, the desired stator flux increment vector is calculated at a given instant.

The space vector modulation will be applied to this vector to obtain the switching states of the inverter. Thus, we have defined a synchronous DTC control block that requires the polar components of the estimated flux and the reference flux.

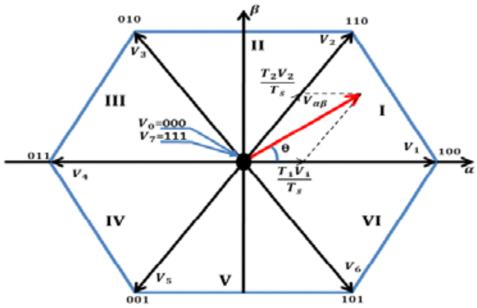

Fig. 8. Projection of the Reference Voltage Vector.

Fig. 8, shows the case where the reference vector is in sector 1 and the adjacent vectors are represented by V_1 and V_2 .

In the case of sector 1, the reference voltage vector Vs-ref is given by:

$$\bar{V}_{s\,ref}T_s = \bar{V}_0 T_0 + \bar{V}_1 T_1 + \bar{V}_2 T_2 \tag{14}$$

$$T_S = T_0 + T_1 + T_2 \tag{15}$$

Where, T_0, T_1 and T_2 are the work times of basic space voltage vectors, V_0, V_1 and V_2, respectively. The sequence corresponding to the vector V_1 is applied during the duration T_1 and the V_0 sequence is applied during the duration T_0. The sequence which corresponds to the vector V_2 is inactive because the duration T_2 is zero. Away from the vector V_1 and approaching the vector V_2, T_1 decreases and T_2 increases. When the vector $V_{s\text{-}ref}$. reaches the vector V_2, T_1 will be zero and T_2 will be maximum.

7.The Steps of the SVM Technique Implementation

7.1. Determination of the Reference Voltages ($V_{s\alpha}$, $V_{s\beta}$)

The determination of the voltages $V_{s\alpha}$, $V_{s\beta}$ is obtained by the following transformation.

$$\begin{bmatrix} v_{s\alpha} \\ v_{s\beta} \end{bmatrix} = \begin{bmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{bmatrix} \begin{bmatrix} v_{sd} \\ v_{sq} \end{bmatrix} \tag{16}$$

7.2. Determination of Sectors

The sector is determined according to the position of the vector $V_{s\text{-}ref}$. In the complex frame (α β), as this position presents the phase δ of this vector defined as a sequence.

$$\delta = arctg\left(\frac{V_{s\beta ref}}{V_{s\alpha ref}}\right) \tag{17}$$

The Table 1 determines the sector Si (i = 1, 2, 3, 4, 5, 6) for different angles δ

Table 1.

Identification of the sector.

δ	0≤δ≤π/3	π/3≤δ≤2π/3	2π/3≤δ≤π	π≤δ≤4π/3	4π/3≤δ≤5π/3	5π/3≤δ≤2π
Sector S_i	S_1	S_2	S_3	S_4	S_5	S_6

7.3. Calculation of the Variables (X, Y, Z)

The determination of the periods T_1 and T_2 is given by a simple projection, Fig.8.

where:

$$\begin{cases} V_{s\beta-ref} = \dfrac{T_2}{T_s}|V_2|.cos\left(30^\circ\right) \\ V_{S\alpha-ref} = \dfrac{T_1}{T_s}|V_1| + x \\ X = \dfrac{\left(V_{S\beta-ref}\right)}{tg\,(60^\circ)} \end{cases} \tag{18}$$

The periods of application of each vector are given by:

$$\begin{cases} T_1 = \dfrac{T_S}{2E}(3V_{s\alpha-ref} - \sqrt{3}V_{s\beta-ref}) \\ T_2 = \sqrt{3}\,\dfrac{T_S}{E}V_{s\beta-ref} \end{cases} \tag{19}$$

The time of application of these vectors can be given by the following variables X, Y, Z

$$\begin{cases} X = \sqrt{3}\dfrac{T_s}{E}V_{s\beta-ref} \\ Y = \dfrac{T_s}{2E}(3V_{s\alpha-ref} + \sqrt{3}V_{s\beta-ref}) \\ Z = \dfrac{T_s}{2E}(3V_{s\beta-ref} - 3.V_{s\alpha-ref}) \end{cases} \quad (20)$$

7.4. Calculation of T_1 And T_2 for Each Sector

The determination of sector (i) is based on the argument of the reference voltage such that:

$$\delta = arctg\left(\frac{V_{s\beta ref}}{V_{s\alpha ref}}\right) \quad (21)$$

Where

$$(i-1)\frac{\pi}{3} \le \delta \le i\frac{\pi}{3} \quad (22)$$

The times T_1 and T_2 of application of the adjacent vectors for each sector expressed by the values of X, Y and Z are tabulated hereafter

Table 2.

Durations of the sector boundary vectors

SECTOR	1	2	3	4	5	6
T_I	-Z	Y	X	Z	-Y	-X
T_{I+1}	X	Z	-Y	-X	-Z	Y

7.5. Generation of the Modulating Signals T_{aon} T_{bon} and T_{con}

The three necessary cyclical ratios are:

$$\begin{cases} T_{aon} = \dfrac{T_S - T_i - T_{i+1}}{2} \\ T_{bon} = T_{aon} + T_i \\ T_{con} = T_{bon} + T_{i+1} \end{cases} \quad (23)$$

The last step is to assign the right duty cycle (T_{xon}) to the right motor phase according to the sector.

7.6. Generation of the Series of Pulses S_a, S_b and S_c

The determination of the control signals (S_a, S_b, S_C) as functions of T_{xon} is given by the following Table 3.

Table. 3

Assigned duty cycles to the PWM outputs

Sector	1	2	3	4	5	6
S_a	T_{aon}	T_{bon}	T_{con}	T_{con}	T_{bon}	T_{aon}
S_b	T_{bon}	T_{aon}	T_{aon}	T_{bon}	T_{con}	T_{con}
S_c	T_{con}	T_{con}	T_{bon}	T_{aon}	T_{aon}	T_{bon}

8. Simulation Results and Discussions For (DTC-SVM)

To show the efficiency and the performance of the proposed method (DTC-SVM), we simulated the behavior of the training system represented by the block diagram in Fig. 9.

To analyze the wind turbine system, our study is done by a change in wind speed (11 m / s to 12 m / s), Fig.16.

The simulation results of DTC-SVM are shown in Figs.10 to 16. We can see from the simulation results, that the flux and torque ripples are significantly reduced.

In the SVM algorithm, the switching frequency is constant. Also, many vectors (IGBT states) are selected to adjust the torque and ripple flux in each sample, while in the case of conventional DTC a single vector is selected for adjusting ripples inside torque hysteresis bands and flux regulators [1].

It can be seen that the speed reaches the reference speed without exceeding it. It is important to notice that the control system demonstrates good performance and that torque ripple is significantly reduced compared with the case of conventional DTC.

It is to remark that the performance of the control is markedly improved with the introduction of SVM vector modulation.

From the simulation results, we can see that the steady-state performance DTC-SVM is much better than the classic DTC [6, 7].

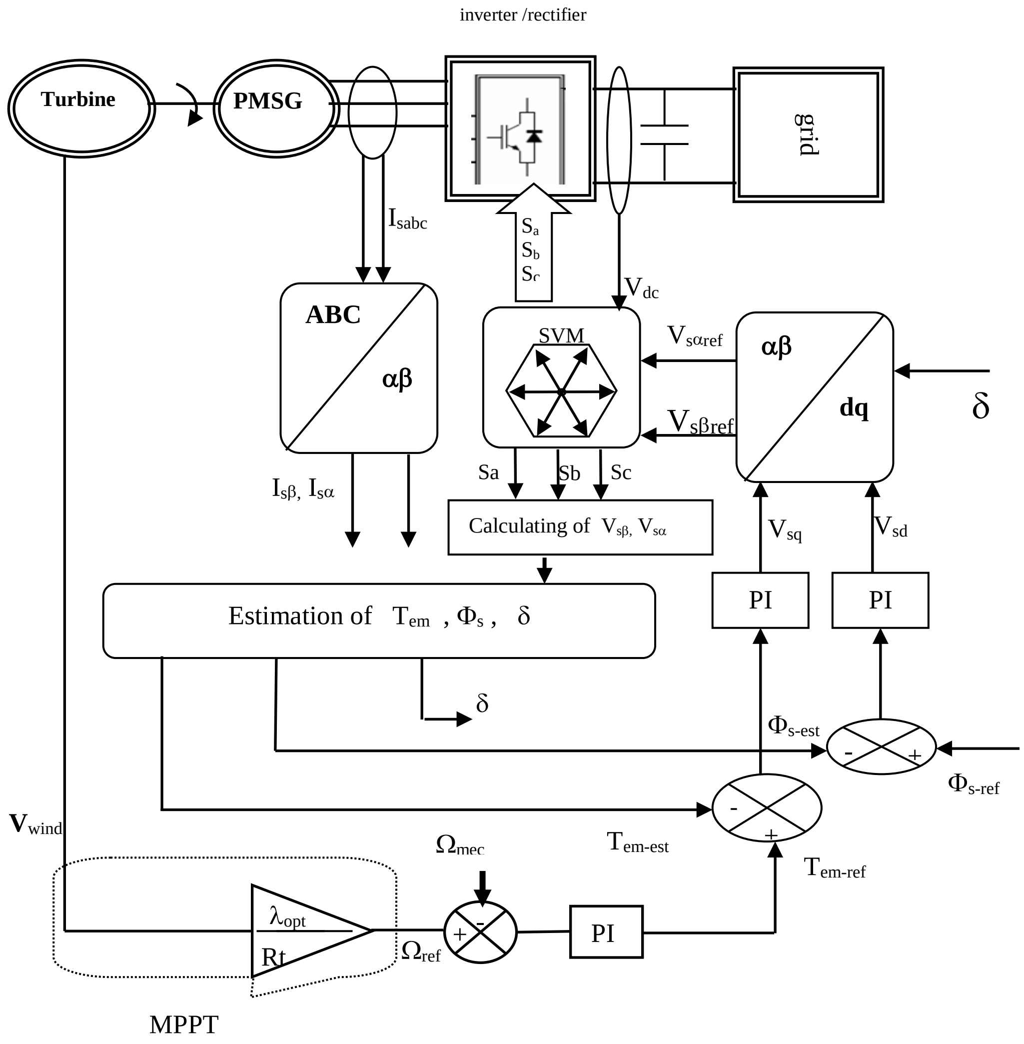

Fig. 9. Block scheme of DTC-SVM with parallel structure.

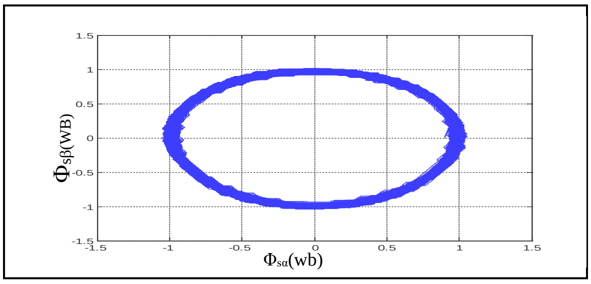

Fig 10. Stator flux trajectory.

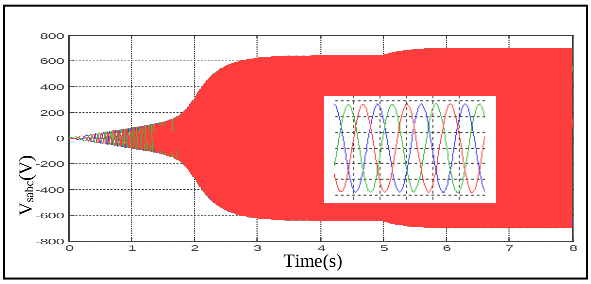

Fig 14.Voltage V_{sabc} for generator.

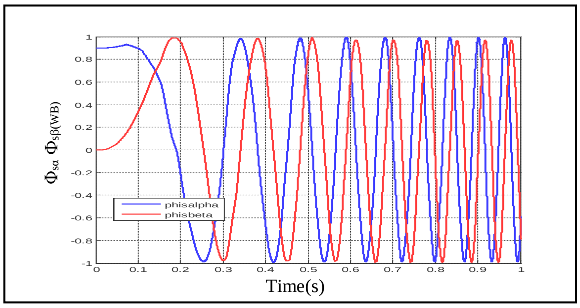

Fig 11. $\Phi_{s\alpha(WB)}$ and $\Phi_{s\beta(WB)}$ in Concordia.

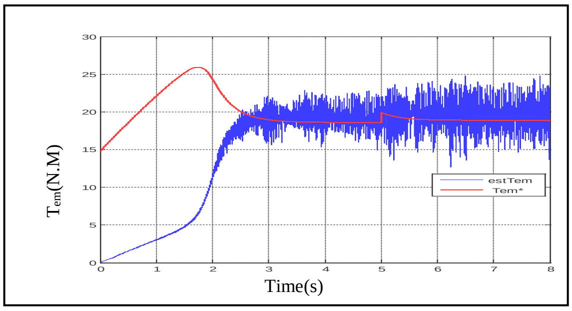

Fig 15- Electromagnetic torque $T_{em\text{-}ref}$ and $T_{em\text{-}est}$.

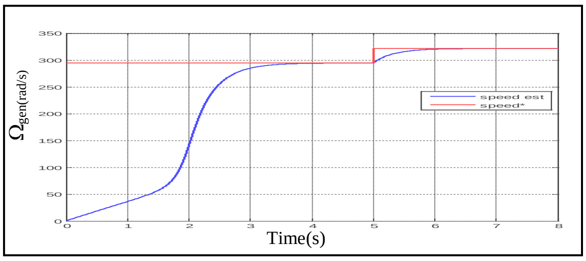

Fig 12. The speed of rotation by Mppt(rad/s).

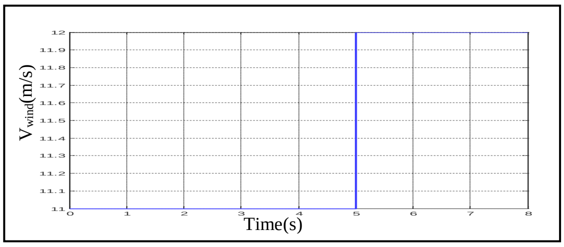

Fig 16. The wind speed used (11m/s at 12m/s).

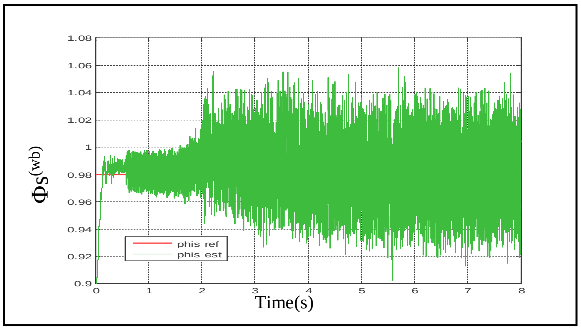

Fig 13. Magnitude of stator flux Φs-ref and Φs-est .

9. Conclusion

This paper presents a comparison study between DTC-SVM and classical DTC. The wind turbine system is controlled by the MPPT strategy and operates at maximum power. The simulation results obtained for the DTC-SVM illustrate a considerable reduction in torque and flux ripples compared to the classical DTC. DTC-SVM technique has also simple structure and provides dynamic behavior comparable with classical DTC. Furthermore, the proposed approach is characterized by much better parameters in steady state operation. In addition, significant improvements in dynamic performance system, robustness and stability, when the DTC– SVM is applied [6].

R E F E R E N C E S

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