DTC-SVM Control for Double Star Permanent Magnet Synchronous Machine (DSPMSM)

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Abstract

In this work, we are interested in improving the performance of the direct torque control (DTC) of a double star permanent magnet synchronous machine (DSPMSM) powered by two voltage inverters controlled by the technique of space vector modulation (SVM). The choice of this command (DTC -SVM) comes from the inherent deficiencies of conventional DTC, which includes variable switching frequency, torque ripple and complexity of implementation. System performance is tested and compared by simulation in MATLAB / Simulink in terms of instruction tracking, robustness to variations in external system elements, and expected method efficiency.

Keywords

Double Star Permanent Magnet Synchronous Machine (DSPMSM), Direct Torque Control (DTC), Space Vector Modulation (SVM).

I. MODELING OF THE DSPMSM

The most attractive and widely discussed type of multiphase machine is Double Star Machines. The latter are characterized by the multiphase structure having two three-phase stator windings mounted in a star and offset from each other by an electrical angle of 30 degrees. Among all the Double Star Machines used in electric propulsion, the Double Star Permanent Magnet Synchronous Machine (DSPMSM) is the most widely used. It has high reliability and good fault tolerance [1].

These machines represent for several years a growing interest in the field of electrical machines. They can be used for automotive electric traction systems, marine electric propulsion systems and wind turbines or for high-power industrial electrical applications [2].

In recent years, several techniques have been developed to improve the performance of these electrical machines. The Direct Torque Control (DTC) proposed by Depenbrock and Takahashi in the middle of the eighties is a vector control solution [3]. It was introduced especially for three-phase machines and several studies allowed applying this control technique on multi-phase machines. Like every command, the DTC has advantages and disadvantages, it has to be less dependent on the parameters of the machine (the stator resistance is theoretically the only parameter of the machine, which intervenes in the command) and to provide a faster response of the torque. Despite these advantages, this control scheme also has significant disadvantages, the instability problem such as the lack of control of the switching frequency of the inverter and the use of hysteresis bands generating electromagnetic torque ripples and noise in the machine [4].

II. MODELING OF THE DSPMSM

The machine that will be the subject of our study is a synchronous motor with double star permanent magnets, supplied by two SVM voltage inverters at two levels.

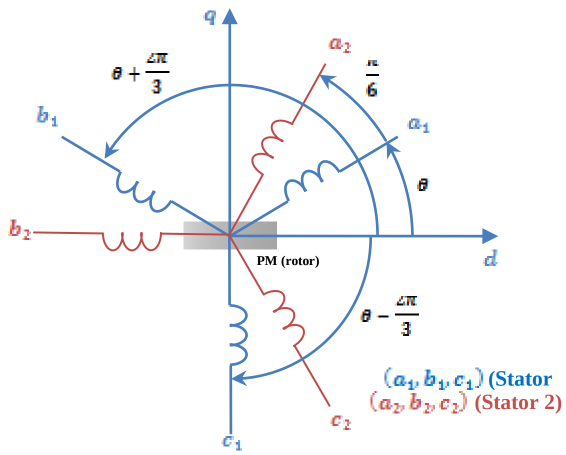


Fig.1. Schematic representation of the DSPMSM

The electromagnetic model of the said machine is a system with differential equations whose coefficients are periodic functions of time. Solving such a system is difficult. Indeed, the use of a suitable transformation of the variables makes it possible to circumvent this difficulty and obtain an easily exploitable model.

The theory relating to the Decomposition of Vector Space "Vector Space Decomposition (VSD)" [1], allows to obtain a practical model specific to the command based on a decoupling via the following transformation matrix which offers the passage of " a six-phase system to an equivalent decoupled system:

$$T = \frac{1}{\sqrt{3}}\begin{bmatrix} 1 & -1/2 & -1/2 & \sqrt{3}/2 & -\sqrt{3}/2 & 0 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 & 1/2 & 1/2 & -1 \\ 1 & -1/2 & -1/2 & -\sqrt{3}/2 & \sqrt{3}/2 & 0 \\ 0 & -\sqrt{3}/2 & \sqrt{3}/2 & 1/2 & 1/2 & -1 \\ 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 \end{bmatrix} \qquad (1)$$

Using this transformation, the complicated system of the machine is decomposed into three orthogonal and mutually decoupled subspaces namely: (α-β), (z1-z2) and (o1- o2).

In order to reduce the complexity of the nonlinear model, we adopt the simplifying assumptions regarding sinusoidally distributed windings and the neglect of magnetic saturation and iron losses:

We define the new variables of the machine, expressed in the new frame of reference ((α-β), (z1- z2), (o1- o2)), which are obtained by diagonalizing the matrix of inductors, by the matrix T:

$$[V_{\alpha\beta}] = [R_s][i_{\alpha\beta}] + \frac{d}{dt}[\Psi_{\alpha\beta}] \qquad (2)$$

$$[\Psi_{\alpha\beta}] = [L_{\alpha\beta}][i_{\alpha\beta}] + \begin{bmatrix}\cos\theta \\ \sin\theta\end{bmatrix}\Psi_{PM} \qquad (3)$$

$$[V_{z_{1,2}}] = [R_s][i_{z_{1,2}}] + [L_z]\frac{d}{dt}[i_{z_{1,2}}] \qquad (4)$$

$$[\Psi_{z_{1,2}}] = [L_z][i_{z_{1,2}}] \qquad (5)$$

$$[V_{o_{1,2}}] = [R_s][i_{o_{1,2}}] + [L_o]\frac{d}{dt}[i_{o_{1,2}}] \qquad (6)$$

$$[L_{\alpha\beta}] = \begin{bmatrix} \frac{(L_d+L_q)}{2} + \frac{(L_d-L_q)}{2}\cos 2\theta & \frac{(L_d-L_q)}{2}\sin 2\theta \\ \frac{(L_d-L_q)}{2}\sin 2\theta & \frac{(L_d+L_q)}{2} - \frac{(L_d-L_q)}{2}\cos 2\theta \end{bmatrix}$$

Ld, Lq: direct and quadratic inductances.
Lz, Lo: transformed stator inductances.
Ψ_{PM}: Flux produced by permanent magnet.
θ: Electrical angle between phase a1 and rotor position.

The passage to the Park benchmark is obtained by applying the following rotation matrix:

$$T_r = \begin{bmatrix} \cos\theta & \sin\theta & 0 & 0 & 0 & 0 \\ -\sin\theta & \cos\theta & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

The electrical equations of the machine are written:

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{d}{dt}\begin{bmatrix} \Psi_d \\ \Psi_q \end{bmatrix} + \begin{bmatrix} -\Psi_q \\ \Psi_d \end{bmatrix} \qquad (7)$$

$$\begin{bmatrix} \Psi_d \\ \Psi_q \end{bmatrix} = \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \Psi_{PM} \\ 0 \end{bmatrix} \qquad (8)$$

$$\Gamma_{em} = p(i_q\Psi_d - i_d\Psi_q) \qquad (9)$$

With: p is the number of pairs of poles.

The model of the machine obtained in the Park repository is similar to the model of the classic single star machine.

III. SVM TECHNIQUE

The Pulse Width modulation technique permits to obtain three phase system voltages, which can be applied to the controlled output. Space Vector Modulation (SVM) principle differs from other PWM processes in the fact that all three drive signals for the inverter will be created simultaneously [5]. The implementation of SVM process in digital systems necessitates less operation time and also less program memory.

The SVM algorithm is based on the principle of the space vector u*, which describes all three output voltages ua, ub and uc:

$$u^* = \frac{2}{3}(ua + ub + a2.uc) \qquad (10)$$

Where a = -1/2 + j. V3/2   we can distinguish six sectors limited by eight discrete vectors u0…u7 (fig: - inverter output voltage space vector), which correspond to the 23 = 8 possible switching states of the power switches of the inverter.

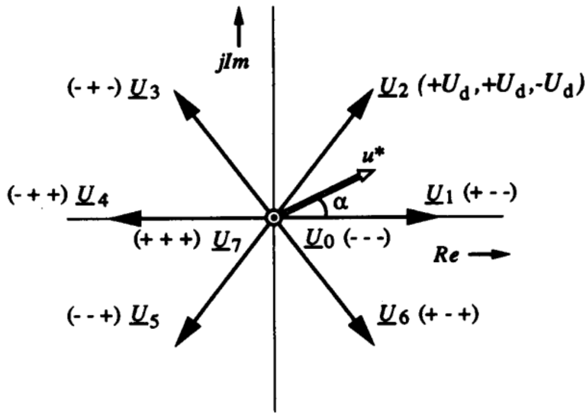


Fig.2. Space vector Modulation

The amplitude of u0 and u7 equals 0. The other vectors u1…u6 have the same amplitude and are 60 degrees shifted.

By varying the relative on-switching time Tc of the different vectors, the space vector u* and also the output voltages ua, ub and uc can be varied and is defined as:

ua = Re (u*)
ub = Re (u* . a-1)
uc = Re (u* . a-2)

During a switching period Tc and considering for example the first sector, the vectors u0, u1 and u2 will be switched on alternatively.

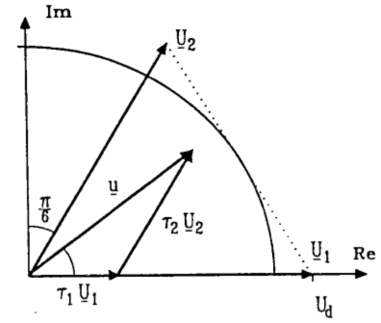


Fig.3. Definition of the Space vector

Depending on the switching times t0, t1 and t2 the space vector u* is defined as:

u* = 1/Tc . (t0 . u0 + t1 . u1 + t2 . u2)

u* = t0 . u0 + t1 . u1 + t2 . u2

u* = t1 . u1 + t2 . u2

(5)

Where

t0 + t1 + t2 = Tc and

t0 + t1 + t2 = 1

t0, t1 and t2 are the relative values of the on switching times.

They are defined as: t1 = m . cos (a + p/6)

t2 = m . sin a

t0 = 1 - t1 - t2

Their values are implemented in a table for a modulation factor m = 1. Then it will be easy to calculate the space vector u* and the output voltages ua, ub and uc. The voltage vector u* can be provided directly by the optimal vector control laws w1, v_{sa} and v_{sb}. In order to generate the phase voltages ua, ub and uc corresponding to the desired voltage vector u* the SVM strategy is proposed.

IV. DIRECT TORQUE CONTROL (DTC) OF THE DSPMSM

The direct torque control (DTC) based on the orientation of the stator flow uses the instantaneous values of the voltage vector. A three-phase converter can provide eight instantaneous basic voltage vectors, of which two are zero [6][7].

The phase-to-neutral voltages of the different phases of the two stars of the machine are expressed, according to the states of the switches of the two inverters which supply it, by the equation below:

$$\begin{bmatrix} V_{a1} \\ V_{b1} \\ V_{c1} \\ V_{a2} \\ V_{b2} \\ V_{c2} \end{bmatrix} = \frac{E}{3} \begin{bmatrix} 2 & -1 & -1 & 0 & 0 & 0 \\ -1 & 2 & -1 & 0 & 0 & 0 \\ -1 & -1 & 2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2 & -1 & -1 \\ 0 & 0 & 0 & -1 & 2 & -1 \\ 0 & 0 & 0 & -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S_{a1} \\ S_{b1} \\ S_{c1} \\ S_{a2} \\ S_{b2} \\ S_{c2} \end{bmatrix}$$

Using the matrix T, the voltage vectors in the new frame of reference are expressed by the following equation:

$$\begin{bmatrix} V_{\alpha} \\ V_{\beta} \\ V_{z1} \\ V_{z2} \\ V_{01} \\ V_{02} \end{bmatrix} = T \begin{bmatrix} V_{a1} \\ V_{b1} \\ V_{c1} \\ V_{a2} \\ V_{b2} \\ V_{c2} \end{bmatrix} \qquad (11)$$

According to the VSD theory, the three-phase double has 64 different voltage vectors. A decimal number, corresponding to the binary numbers [Sa1 Sb1 Sc1 Sa2 Sb2 Sc2], is used to represent each vector. Where (S = Sa1, Sb1, Sc1, Sa2, Sb2, Sc2) corresponds to the switching states of the inverter switches and E the DC bus voltage. Thus, in the two subspaces (α-β) and (z1-z2), there are 60 non-zero vectors and 4 other "zero" nulls (0,7,56,63), represented in the two figures 4 and 5.

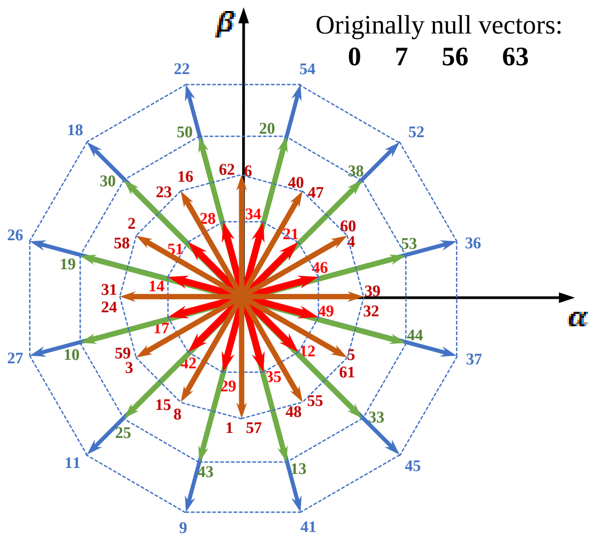


Fig.4. Vector space diagram in (α-β)

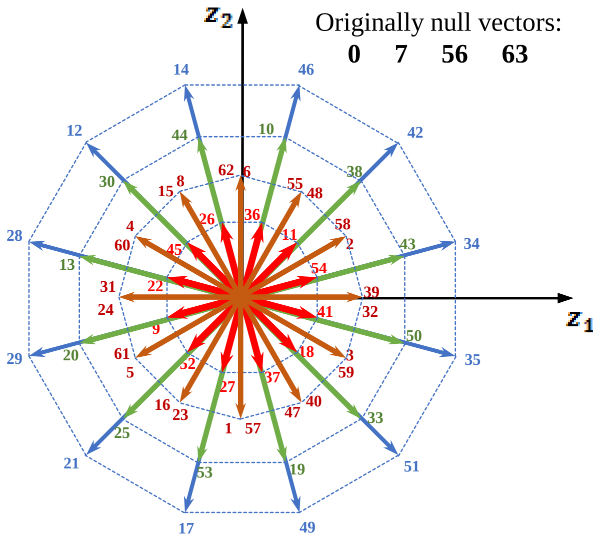


Fig.5. Vector space diagram in (z1-z2)

According to the two figures 3 and 4, the voltage vector determined in the subspace (α-β), can be broken down into 4 dodecagons with different amplitudes (from interior to exterior: D1, D2, D3, D4). Their amplitude is given by the following equation:

$$\begin{cases} U_{D1} = \frac{\sqrt{(2-\sqrt{3})}}{\sqrt{3}} E \\ U_{D2} = \frac{1}{\sqrt{3}} E \\ U_{D3} = \frac{\sqrt{2}}{\sqrt{3}} E \\ U_{D4} = \frac{\sqrt{(2+\sqrt{3})}}{\sqrt{3}} E \end{cases}$$

The voltage vectors of maximum amplitude in (α-β) obtain minimum amplitude in (z1-z2), while the others keep the same amplitude.

In (α-β), the 12 vectors of maximum amplitude in which 12 sectors are chosen, are given in figure 6. The choice of these vectors makes it possible to have low amplitude in (z1-z2), in in order to guarantee the least harmonic content of the stator current in (z1-z2), and to reduce stator losses.

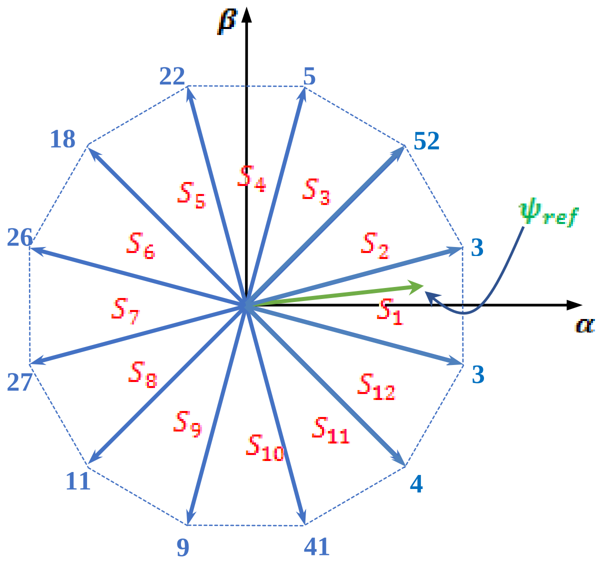


Fig.7. Diagram of 12 vectors of maximum amplitude in (α-β)

In the switching table relating to the classic DTC control strategy for DSPMSM, the torque and the flux are estimated. Next, stator flux and torque regulators are used to generate the voltage vectors at the inverter level using a switching table, as shown in Fig.6.

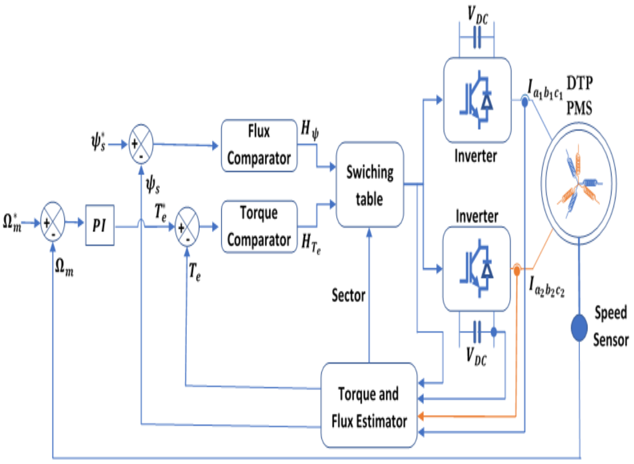


Fig.6. Conventional DTC diagram for DSPMSM

The subspace (α-β) is divided into 12 sectors; each sector is delimited by two vectors maximum, as shown in figure 7. When the stator flux is in sector k, the vector responsible for the increase in flux and torque is V (k + 2) and the responsible of the reduction in flux and torque is V (k-4). The vector V (k + 3) leads to the reduction of the flux but the increase in the torque and the vector V (k-3) leads to an increase in the flux but a reduction in the torque.

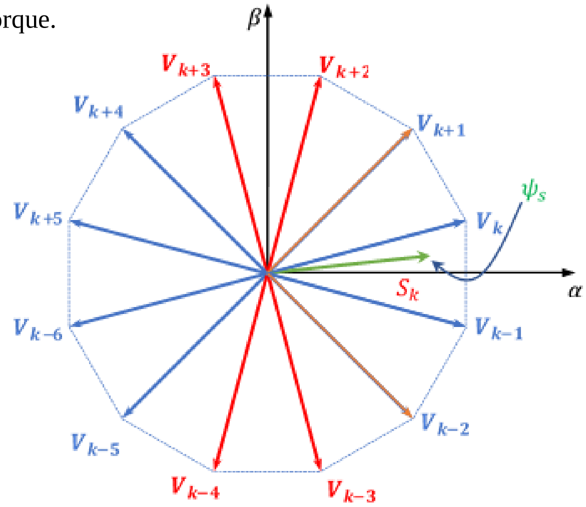


Fig.8. Voltage vector selection where the stator flux is located in sector k

Torque and flux hysteresis regulators are used to generate an appropriate voltage vector according to the following table:

	k Sector					
H_ψ	1			-1		
H_{T_e}	1	0	-1	1	0	-1
Applied vector	V_{k+2}	V_{zero}	V_{k-3}	V_{k+3}	V_{zero}	V_{k-4}

Table.1. Switch table applied to DSPMSM

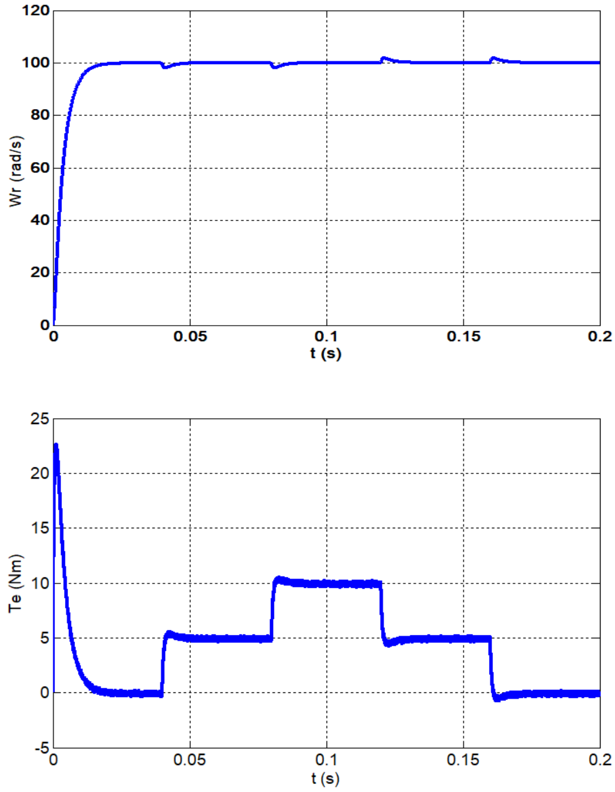
The generated torque and flux control signals, Hψ and HTe, are defined as follows:

$$H_{T_e} = \begin{cases} 1 & if\ T_e^* - T_e \geq \varepsilon_T \\ 0 & if\ T_e^* - T_e = 0 \\ -1 & if\ T_e^* - T_e \leq \varepsilon_T \end{cases} \quad (12)$$

$$H_{\psi} = \begin{cases} 1 & if\ \psi_s^* - \psi_s \geq \varepsilon_{\psi} \\ -1 & if\ \psi_s^* - \psi_s \leq \varepsilon_{\psi} \end{cases} \quad (13)$$

V. SIMULATION RESULTS AND INTERPRETATION

The operation of the inverter-machine unit was simulated using MATLAB / Simulink software. Two cases are to be realized: the hybrid control and the Classical SVM control. The machine used has the following characteristics:
Rs=0.8Ω; Ld=Lq=0.0011H; Φf=0.2 Wb; p=2



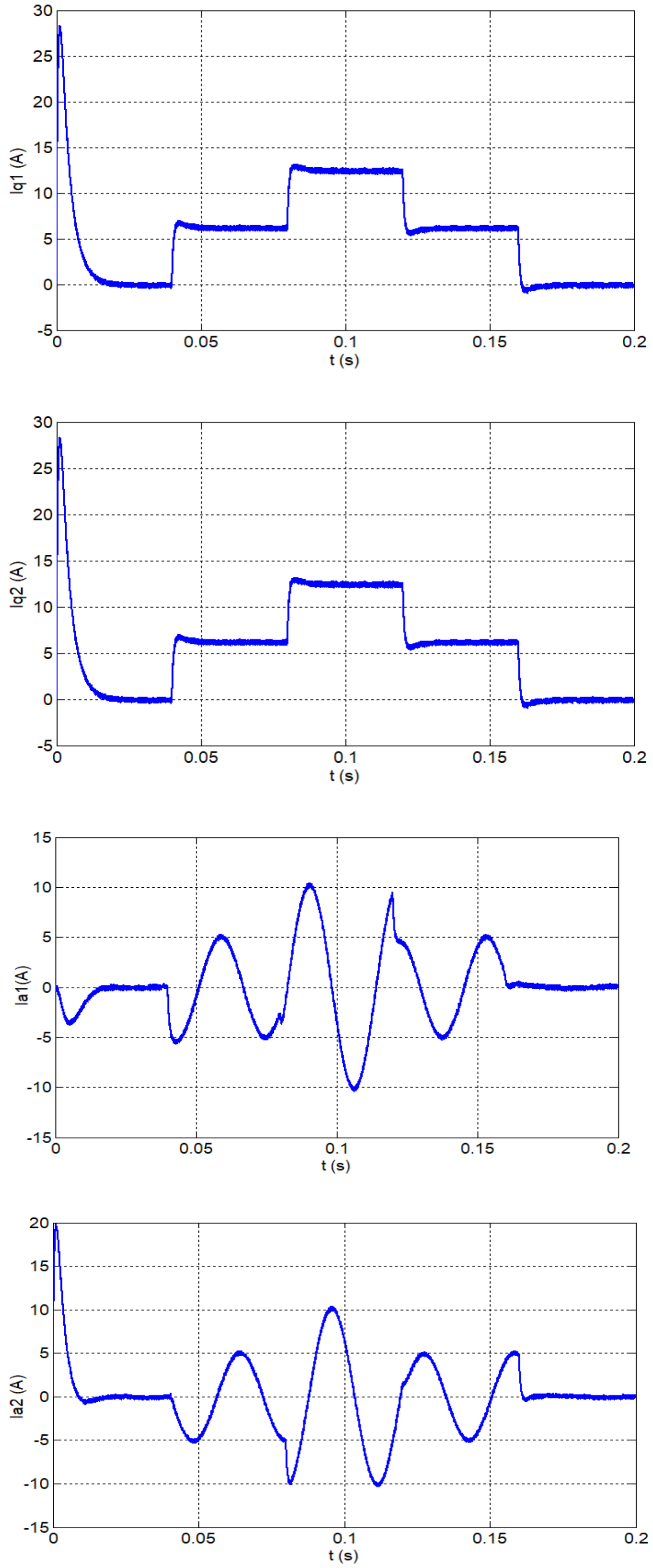


Fig.9. SIMULATION RESULTS

Figure 9 shows the evolution of the behavior of the DSPMSM under varying load conditions. After a no-load start for a reference speed of 100 rad / s, we introduced a

variable load torque (5Nm at t = 0.04s, 10Nm at t = 0.08s, 5Nm at t = 0.12s and 0Nm at t = 0.16s). We obtained satisfactory answers for the various electrical and mechanical quantities, because the impacts of the variation of the load do not have a significant influence on its values.
The speed reaches its reference very quickly, the shape of the electromagnetic torque increases and follows its reference, same remark for the quadrature currents (iq1,2) and the stator phase current (ia1,2) perfectly follow the variation of the load.

VI. CONCLUSION

In this paper, we presented the direct torque control (DTC) of a double star permanent magnet synchronous machine (DSPMSM) powered by two voltage inverters controlled by the technique of space vector modulation (SVM). Direct torque control based on space vector modulation (DTC-SVM) preserve DTC transient merits, furthermore, produce better quality steady-state performance in a wide speed range. At each cycle period, SVM technique is used to obtain the reference voltage space vector to exactly compensate the flux and torque errors. The torque ripple of DTC-SVM in low speed can be significantly improved.

REFERENCES

1. Y. Zhao and T. A. Lipo, "Space Vector PWM Control of Dual Three-Phase Induction Machine Using Vector Space Decomposition", IEEE Trans. Ind. Applicat., vol.31, no.5, pp.1100-1109, Sept./Oct. 1995.
2. *K. Pieńkowski*, "Analysis and Control of Dual Stator Winding Induction Motor". Archives Of Electrical Engineering, **vol**.61, no.3, Sept, 2012, pp. 421 -438.
3. Z. Boudjema, R. Taleb, Y. Djeririand A. Yahdou A, "A Novel Direct Torque Control Using Second Order Continuous Sliding Mode Of A Doubly Fed Induction Generator For A Wind Energy Conversion System". Turkish Journal of Electrical Engineering & Computer Sciences, vol. 25, no. 2, January,201 7, pp. 965- 975
4. D. Vivek and D. Rohtash," Comparative Study of Direct Torque Control of Induction Motor Using Intelligent Techniques". Canadian Journal on Electrical and Electronics Engineering, vol. 2, no. 11,November, 2011, pp. 550-556.
5. Bindal, Ranjit Kumar, and Inderpreet Kaur. "Comparative analysis of different controlling techniques using direct torque control on induction motor." Next Generation Computing Technologies (NGCT), 2016 2nd International Conference on. IEEE, 2016.
6. O. Ouledali, et al., "Direct Torque Fuzzy Control of PMSM based on SVM," Volume 74, Pages 1314-1322, August 2015.
7. F. Longfei, et al., "Simulation Research on Direct Torque Control for Brushless DC Motor, " International Conference on Intelligent Systems Research and Mechatronics Engineering (ISRME), China, 2015.