

Three-Level Direct Torque Control Based on Space Vector Modulation with Balancing Strategy of Double Star Synchronous Machine

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Abstract: This work relates to the study of direct torque control based on space vector modulation of a salient-pole double star synchronous machine. The machine is supplied by two three-level diode-clamped voltage source inverters shared the same capacitor divider. However, a very important issue in using diode-clamped inverters is the ability to guarantee the stability of the DC-link capacitor voltages. To overcome this problem the multilevel space vector modulation with balancing strategy is proposed to suppress the unbalance of DC-link capacitor voltages. Simulations results are given to show the effectiveness of the proposed control approach.

Key words: Double Star Synchronous Machine; Multi-Level Inverter; Direct Torque Control; Space Vector Modulation; Balancing strategy.

1. Introduction

Multiphase machines have been studied for a long time, but recently they have gained attention in the research community and industry worldwide [1]. The specific application areas are the main motivation of this increased interest. Electric ship propulsion, locomotive traction, electric and hybrid electric vehicles, more-electric aircraft, and high-power industrial applications can be counted as the main applications [2]. Multiphase machines are perceived to offer many advantages such as improved magneto-motive force waveforms, reduced line voltages and increased efficiencies. The consequential benefits of these are reduced torque pulsations, lower losses, reduced acoustic noise and reduced power ratings of supply converters [3]. However, these benefits are depended on machine topology, supply angle shift, winding configuration and design details.

In multiphase machine drive systems, more than three-phase windings are implemented in the same stator of the electric machine. One common example of such structure is the double star synchronous motor (DSSM). This motor has two sets of three-phase windings spatially phase shifted by 30 electrical degrees and each set of three-phase stator windings is fed by a three-phase voltage source inverter [4].

Nowadays, multilevel inverters have become a very attractive solution for medium and high power application areas. Several topologies of multilevel inverters have been proposed in the technical literatures [5]. Among these topologies, diode-clamped inverter (DCI) represents one of the most interesting solutions, to increase voltage and power levels and to achieve high quality voltage waveforms. Unfortunately, DCI has an inherent problem of DC-link

capacitors voltages variations [6]. Stabilizing the DC-side capacitor voltages is a challenging task. Several methods are proposed to solve this problem. Some of these methods are presented in [7]. Another interesting solution based on multilevel space vector modulation is recognized to be able to keep capacitors balance using redundant switch modes[6].

In the other hand, the multilevel direct torque control (DTC) of electrical drives has become an attracting topic in research and academic community over the past decade. Like an every control method has some advantages and disadvantages, DTC method has too. Some of the advantages are presented in [8]. The basic disadvantages of DTC scheme using hysteresis controllers are the variable switching frequency, the current and torque ripple. In order to overcome these problems, the DTC using space vector modulation (SVM) technique was proposed [6]. The basis of the DTC-SVM methodology is the calculation of the required voltage space vector to compensate the flux and torque errors at each sampling period.

The purpose of this paper is to propose a multilevel DTC method with efficient dc-voltages balancing control method dedicates to multiphase drive.

This paper is organized as follows. Firstly, the model of the DSSM is presented in the section 2. In the section 3, the three-level inverter modelling is described. The section 4 introduces the DTC-SVM approach. The section 5 is devoted to the simulation results of the three-level DTC-SVM without balancing strategy. The section 6 is reserved to the balancing control strategy of DC link capacitor voltages. Simulation results of three-level DTC-SVM with balancing strategy are discussed in the section 7. Finally, conclusions are drawn in the last section.

2. Double Star Synchronous Machine Model

The DSSM stators voltages equations are as follows:

$$v_{sk} = Ri_{sk} + \frac{d}{dt}\phi_{sk}, k = 1, 2 \quad (1)$$

Where v_{sk} are stator voltages, i_{sk} are stator currents, ϕ_{sk} are stator flux. The stator resistance matrix for each star is a diagonal 3×3 matrix given by: $R = \text{Diag} [R_s \ R_s \ R_s]$.

The original six dimensional system of the machine can be decomposed into three orthogonal subspaces (α, β), (z_1, z_2) and (z_3, z_4), using the following matrix transformation:

$$[T] = \frac{1}{\sqrt{3}} \begin{pmatrix} \cos(0) & \cos\left(\frac{2\pi}{3}\right) & \cos\left(\frac{4\pi}{3}\right) & \cos(\gamma) & \cos\left(\frac{2\pi}{3}+\gamma\right) & \cos\left(\frac{4\pi}{3}+\gamma\right) \\ \sin(0) & \sin\left(\frac{2\pi}{3}\right) & \sin\left(\frac{4\pi}{3}\right) & \sin(\gamma) & \sin\left(\frac{2\pi}{3}+\gamma\right) & \sin\left(\frac{4\pi}{3}+\gamma\right) \\ \cos(0) & \cos\left(\frac{4\pi}{3}\right) & \cos\left(\frac{2\pi}{3}\right) & \cos(\pi-\gamma) & \cos\left(\frac{\pi}{3}-\gamma\right) & \cos\left(\frac{5\pi}{3}-\gamma\right) \\ \sin(0) & \sin\left(\frac{4\pi}{3}\right) & \sin\left(\frac{2\pi}{3}\right) & \sin(\pi-\gamma) & \sin\left(\frac{\pi}{3}-\gamma\right) & \sin\left(\frac{5\pi}{3}-\gamma\right) \\ 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 \end{pmatrix} \quad (2)$$

To express the stator equations in the rotor reference frame, the following rotation transformation is adopted:

$$P(\theta) = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \quad (3)$$

The Park model of the DSSM in the rotor reference frame (d - q) is defined by the following equations system:

$$\begin{cases} v_d = R_s i_d + \frac{d\phi_d}{dt} - \omega\phi_q \\ v_q = R_s i_q + \frac{d\phi_q}{dt} + \omega\phi_d \end{cases} \quad (4)$$

Where: v_d, v_q are d - q axis stator voltages, i_d, i_q are d - q axis stator currents, and ϕ_d, ϕ_q are d - q axis stator flux.

The stator flux components are given by:

$$\begin{cases} \phi_d = L_d i_d + M_{fd} i_f \\ \phi_q = L_q i_q \end{cases} \quad (5)$$

With L_d, L_q are d - q stator inductances, and M_{fd} is the mutual inductance between d axis stator and rotor.

The rotor voltage equation is given by:

$$v_f = R_f i_f + \frac{d\phi_f}{dt} \quad (6)$$

Where v_f, i_f are voltage and current of rotor excitation respectively, ϕ_f is the flux of rotor excitation, and R_f is the rotor resistance.

The mechanical equation is given by:

$$J \frac{d\Omega}{dt} = T_{em} - T_L - f_r \Omega \quad (7)$$

With T_{em}, T_L are electromagnetic and load torques, Ω is the rotor speed, J is the moment of inertia, and f_r is the friction coefficient.

The electromagnetic torque generated by the machine is:

$$T_{em} = p(\phi_d i_q - \phi_q i_d) \quad (8)$$

3. Three-Level DCI Modelling

Figure 1 shows the circuit of a three-level diode clamped inverter and the switching states of each leg of the inverter. Each leg is composed of two upper and lower switches with anti-parallel diodes. Two series DC-link capacitors split the DC-bus voltage in half, and six clamping diodes confine the voltage across the switches within the voltage of the capacitors, each leg of the inverter can have three possible switching states; 2, 1 or 0. When top switches S_{ak1} and S_{ak2} are turned ON, switching state is 2 [9]. When the switches S_{ak3} and S_{ak4} are turned ON, switching state is 0. When the switches S_{ak2} and S_{ak3} are turned ON, switching state is 1. So there exist 27 kinds of switching states in three-phase three-level inverter.

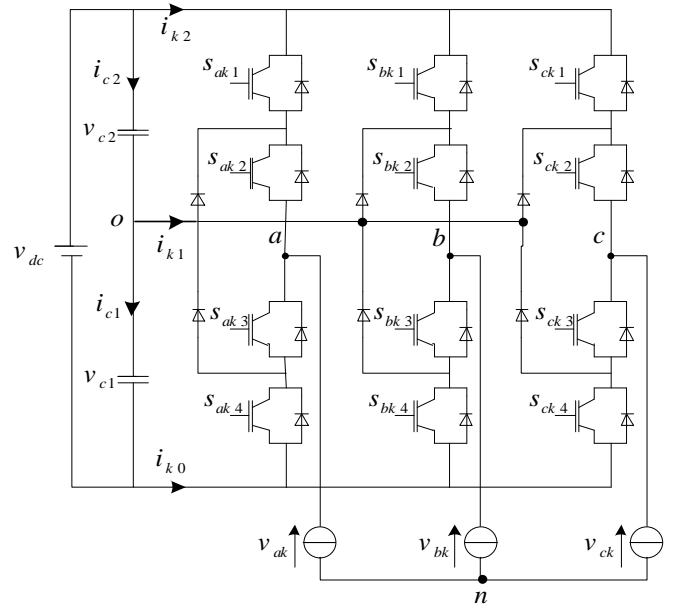


Fig. 1. Three-level DCI ($k=1$ for first inverter and $k=2$ for second inverter).

Functions of connection are given by:

$$\begin{cases} F_{xk2} = s_{xk1} s_{xk2}, & x = a, b, c \\ F_{xk1} = s_{xk3} s_{xk2} \end{cases} \quad (9)$$

The phase voltages v_{ak}, v_{bk}, v_{ck} can be written as:

$$\begin{pmatrix} v_{ak} \\ v_{bk} \\ v_{ck} \end{pmatrix} = \begin{pmatrix} 2F_{ak2} - F_{bk2} - F_{ck2} & 2F_{ak1} - F_{bk1} - F_{ck1} \\ 2F_{bk2} - F_{ak2} - F_{ck2} & 2F_{bk1} - F_{ak1} - F_{ck1} \\ 2F_{ck2} - F_{ak2} - F_{bk2} & 2F_{ck1} - F_{ak1} - F_{bk1} \end{pmatrix} \begin{pmatrix} v_{c1} + v_{c2} \\ v_{c1} \end{pmatrix} \quad (10)$$

The space vector diagram of a three-level inverter is showed in figure 2. The 27 switching states of three levels inverter corresponds to 19 different space vectors. Based on their magnitude, the space vectors are divided into four groups, these vectors have different effects on neutral point voltage variations [9].

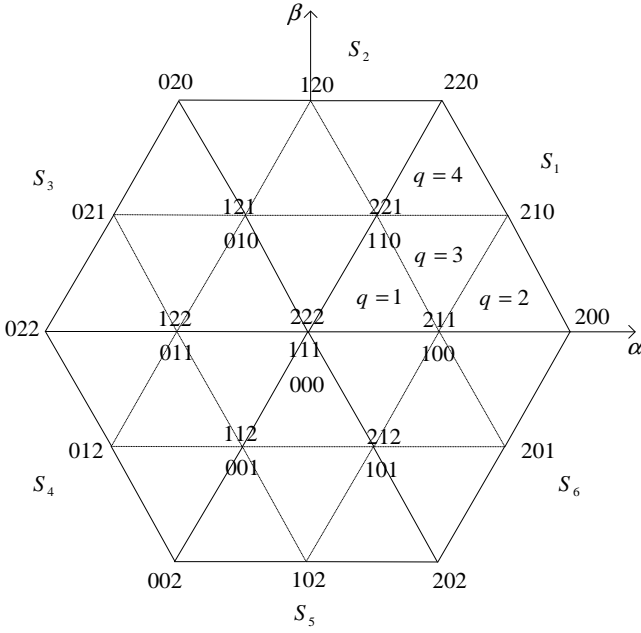


Fig. 2. Space vector diagram showing switching states for the first three-level DCI.

In order to simplify three-level SVM algorithm, the reference voltage vector is only synthesized by the three basic voltage vectors within the minimum equilateral triangular area in which the reference voltage vector locates.

In figure 3, the reference voltage vector v^* is supposed to locate in the A region of the sector S_1 which consists of four equilateral triangular regions.

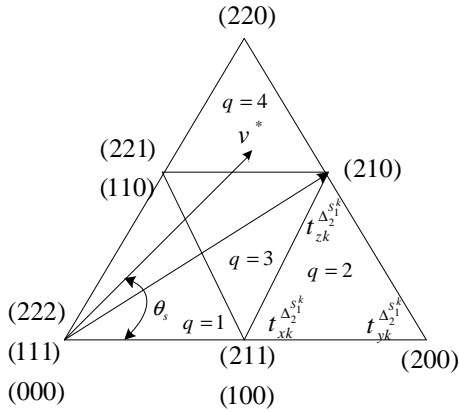


Fig. 3. Synthesized vectors in the first sector

Similarly, if v^* locates in another area such as $q \in \{1, 2, 3, 4\}$ of the sector S_1 , the modulation durations of the related basic vectors can be calculated. With the symmetry of the six sectors, the modulation durations of the basic vectors can be obtained easily when the reference voltage vector locates in other sectors.

4. Direct Torque Control Based on Space Vector Modulation

The main idea the DTC-SVM control strategy is to force the torque and stator flux to approach their reference by applying in one switching period several voltage vectors. This control

algorithm uses prefixed time intervals within a cycle period and in this way a higher number of voltage space vectors can be synthesized with respect to those used in basic DTC technique [10].

The stator voltage estimator computed using equation (10) is given by:

$$\begin{pmatrix} \hat{v}_\alpha \\ \hat{v}_\beta \end{pmatrix} = [T] \begin{pmatrix} \hat{v}_{s1} \\ \hat{v}_{s2} \end{pmatrix} \quad (11)$$

$$\text{With: } \hat{v}_{s1} = [\hat{v}_{a1} \quad \hat{v}_{b1} \quad \hat{v}_{c1}], \quad \hat{v}_{s2} = [\hat{v}_{a2} \quad \hat{v}_{b2} \quad \hat{v}_{c2}]$$

The stator flux is estimated from the measure of stator current and voltage and their transformation in the α - β subspace. So:

$$\begin{cases} \hat{\phi}_\alpha = \int_0^t (\hat{v}_\alpha - R_s i_\alpha) d\tau + \hat{\phi}_\alpha(0) \\ \hat{\phi}_\beta = \int_0^t (\hat{v}_\beta - R_s i_\beta) d\tau + \hat{\phi}_\beta(0) \end{cases} \quad (12)$$

The stator flux magnitude and its angle are given by:

$$\begin{cases} |\hat{\phi}_s| = \sqrt{\hat{\phi}_\alpha^2 + \hat{\phi}_\beta^2} \\ \hat{\theta}_s = \arctan\left(\frac{\hat{\phi}_\beta}{\hat{\phi}_\alpha}\right) \end{cases} \quad (13)$$

The presented control strategy is based on simplified stator voltage equations described in stator flux oriented x - y coordinates. The rotation transformation (14) transforms command variables in stator flux reference frame x - y to the stationary reference α - β :

$$\begin{pmatrix} v_{\alpha1}^* \\ v_{\beta1}^* \end{pmatrix} = [P(\theta_s)] \begin{pmatrix} v_x^* \\ v_y^* \end{pmatrix}, \quad \begin{pmatrix} v_{\alpha2}^* \\ v_{\beta2}^* \end{pmatrix} = [P(\theta_s - \gamma)] \begin{pmatrix} v_x^* \\ v_y^* \end{pmatrix} \quad (14)$$

With:

$$[P(\theta_s)] = \begin{bmatrix} \cos(\theta_s) & -\sin(\theta_s) \\ \sin(\theta_s) & \cos(\theta_s) \end{bmatrix}$$

The stator voltage equations in x - y frame are:

$$\begin{cases} v_x = R_s i_x + \frac{d\phi_x}{dt} \\ v_y = R_s i_y + \omega_s \phi_s \end{cases} \quad (15)$$

The torque expression is simplified to:

$$\hat{T}_{em} = p |\hat{\phi}_s| i_y \quad (16)$$

Figure 4 represents the DTC-SVM control of double star synchronous machine.

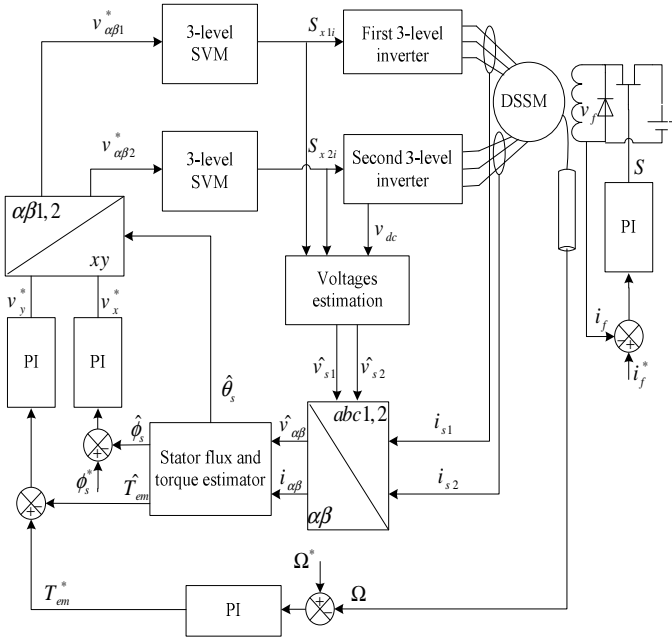


Fig. 4. DTC-SVM of DSSM (with $j=1, 2, 3$ or 4).

5. Comparative Study

To verify the validity of the three-level DTC-SVM strategy, the system was simulated using the DSSM parameters given in Appendix. The simulation results are obtained using the following DC link capacitors values $C_1 = C_2 = 1\text{mF}$. The DC side of the inverter is supplied by a constant DC source $v_{dc} = 600\text{V}$.

The control system was tested under deferent operating conditions such as sudden change of load torque and step change in reference speed.

The DSSM is accelerating from standstill to reference speed 100 rad/s . The system is started with full load torque ($T_L = 11\text{ N.m}$). Afterwards, a step variation on the load torque ($T_L = 0\text{ N.m}$) is applied at time $t = 1\text{ s}$. And then a sudden reversion in the speed command from 100 rad/s to -100 rad/s was introduced at 1.5 s . The obtained DTC-SVM results are presented in figure 5.

As it can be seen from these figures, the speed response is merged with the reference one and the flux is very similar to the nominal case and independent of the torque. Thus, the decoupling between electromagnetic torque and stator flux is ensured in the beginning and during all the control process. The speed controller intervenes to face this variation and ensures the system follows its suitable reference speed.

It is important to note that the problem of the unbalance of the two DC voltages of the intermediate capacitors filter. Indeed, the voltages v_{c1} increase and the voltages v_{c2} decrease. In order to improve the performance of three-level DTC-SVM for DSSM, a three-level DTC-SVM based on balancing mechanism is proposed.

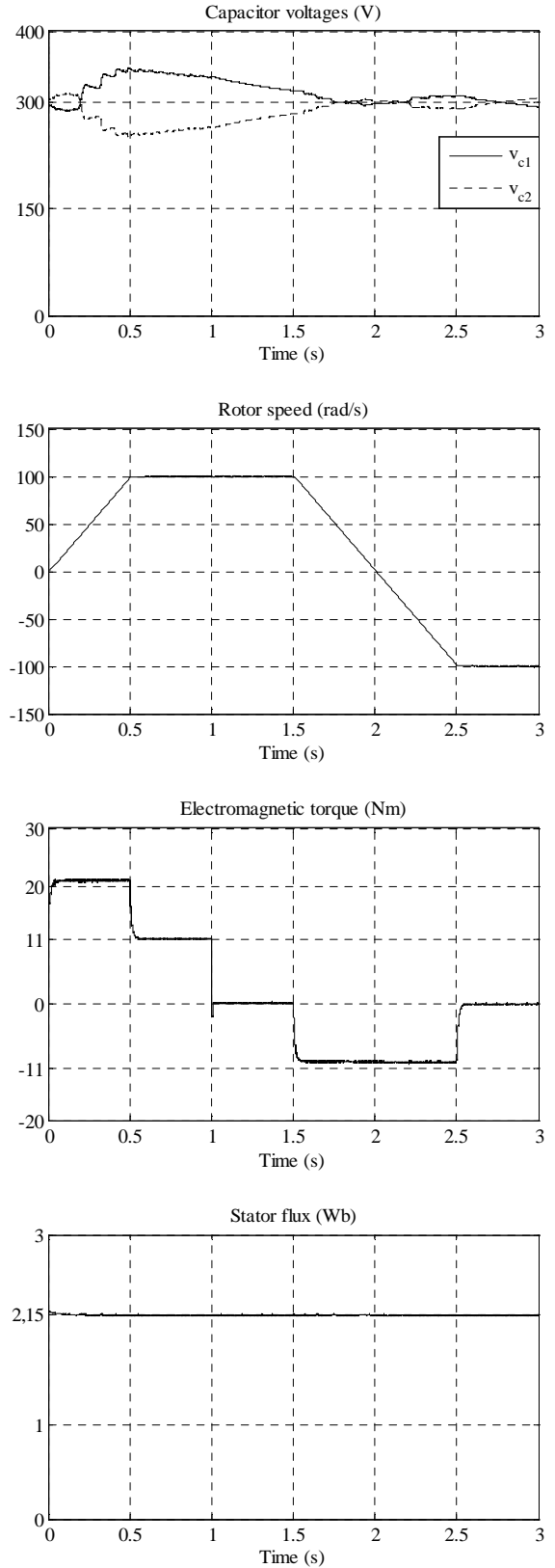


Fig. 5. Dynamic responses of three-level DTC-SVM without balancing strategy for DSSM.

6. Voltage Balancing Theory

The total energy of the two condensers is given by:

$$J = \frac{1}{2} \sum_{j=1}^2 C_j v_{cj}^2 \quad (17)$$

Assuming that all capacitors are identical, $C_1=C_2=C$. Based on appropriate selection of redundant vectors, J can be minimized (ideally reduced to zero) if the capacitor voltages are maintained at voltage reference values of $v_{dc}/2$. The mathematical condition to minimize J is:

$$\frac{dJ}{dt} = C \sum_{j=1}^2 \Delta v_{cj} \frac{dv_{cj}}{dt} = \sum_{j=1}^2 \Delta v_{cj} i_{cj} \quad (18)$$

Where Δv_{cj} is a voltage deviation of capacitor C_j , $\Delta v_{cj} = v_{cj} - (v_{dc}/2)$ and i_{cj} is the current through capacitor C_j . The capacitor currents i_{cj} in (18) are affected by the DC-side intermediate branch currents i_{k2} and i_{k1} . These currents can be calculated if the switching states used in the switching pattern are known. Thus, it is advantageous to express (18) in terms of i_{k2} and i_{k1} . The DC-capacitor current is expressed as:

$$i_{c2} = i_{c1} + \sum_{k=1}^2 i_{k1} \quad (19)$$

Considering a constant net-link DC voltage

$$\sum_{j=1}^2 \Delta v_{cj} = 0 \quad (20)$$

From (20) it is possible to deduced the following equation

$$\sum_{j=1}^2 i_{cj} = 0 \quad (21)$$

The common current through all capacitors is not considered in the process since it does not contribute to voltage drifts of capacitors. Solving (19) and (21), yields

$$i_{cj} = \frac{1}{2} \sum_{m=1}^2 m \left(\sum_{k=1}^2 i_{km} \right) - \sum_{m=j}^2 \left(\sum_{k=1}^2 i_{km} \right) \quad (22)$$

Where: $m=1, 2$. By substituting i_{cj} into (18), the following condition to achieve voltage balancing is deduced:

$$\sum_{j=1}^2 \Delta v_{cj} \left(\frac{1}{2} \sum_{m=1}^2 m \left(\sum_{k=1}^2 i_{km} \right) - \sum_{m=j}^2 \left(\sum_{k=1}^2 i_{km} \right) \right) \leq 0 \quad (23)$$

Substituting Δv_{c2} calculates from (20), in (23) yields

$$\Delta v_{c1} \left(\sum_{k=1}^2 i_{k1} \right) \geq 0 \quad (24)$$

Applying the averaging operator, over one sampling period, to (24) results in:

$$\frac{1}{T} \sum_{KT}^{(K+1)T} \Delta v_{c1} \left(\sum_{k=1}^2 i_{k1} \right) dt \geq 0 \quad (25)$$

Assuming that the capacitor voltages can be assumed as constant values over one sampling period and consequently (25) is simplified to:

$$\Delta v_{c1}(K) \left(\frac{1}{T} \int_{KT}^{(K+1)T} \left(\sum_{k=1}^2 i_{k1} \right) dt \right) \geq 0 \quad (26)$$

From (26) the cost function is given by:

$$J_k = \Delta v_{c1}(K) \left(\sum_{k=1}^2 \bar{i}_{k1}(K) \right) dt \quad (27)$$

Where: $\Delta v_{c1}(K)$ is the voltage drift of C_1 at sampling period K , and $\bar{i}_{k1}(K)$ is the averaged value of the first DC-side intermediate branch current. Current $\bar{i}_{k1}(K)$ should be computed for different combinations of adjacent redundant switching states over a sampling period and the best combination which maximizes (26) is selected. If the reference vector is in the triangle $\Delta_q^{S_i^k}$ ($i=1, \dots, 6$, $q=1, \dots, 4$), and $t_{x_k}^{\Delta_q^{S_i^k}}, t_{y_k}^{\Delta_q^{S_i^k}}, t_{z_k}^{\Delta_q^{S_i^k}}$ are times of application presented in figure 2, $\bar{i}_{k1}^{S_i^k}$ current is expressed by:

$$\bar{i}_{k1}^{S_i^k} = \frac{1}{T} \begin{bmatrix} i_{1x_k}^{S_i^k} & i_{1y_k}^{S_i^k} & i_{1z_k}^{S_i^k} \end{bmatrix} \begin{bmatrix} t_{x_k}^{\Delta_q^{S_i^k}} & t_{y_k}^{\Delta_q^{S_i^k}} & t_{z_k}^{\Delta_q^{S_i^k}} \end{bmatrix}^T \quad (28)$$

Where $i_{1x_k}^{S_i^k}, i_{1y_k}^{S_i^k}$ and $i_{1z_k}^{S_i^k}$ are the charging currents to the states of commutation x_k, y_k and z_k in the triangle $\Delta_q^{S_i^k}$ minimizing the function cost J .

7. Simulation results for DTC-SVM with balancing strategy

The proposed balancing strategy is tested by some numerical simulations to verify its effectiveness in the steady-state and dynamic. Figure 6 presents the simulation results obtained in the same conditions as in figure 5.

In figure 6 as can be seen the speed follows its reference value while the electromagnetic torque returns to its reference value with a little error. These results show that this variation leads to the variation in the electromagnetic torque.

It can be observed also that the proposed balancing strategy is able to guarantee capacitor voltages balance even during the abovementioned transits. In addition, the tracking capability is further improved. Moreover, the decoupling control between torque and stator flux is always confirmed.

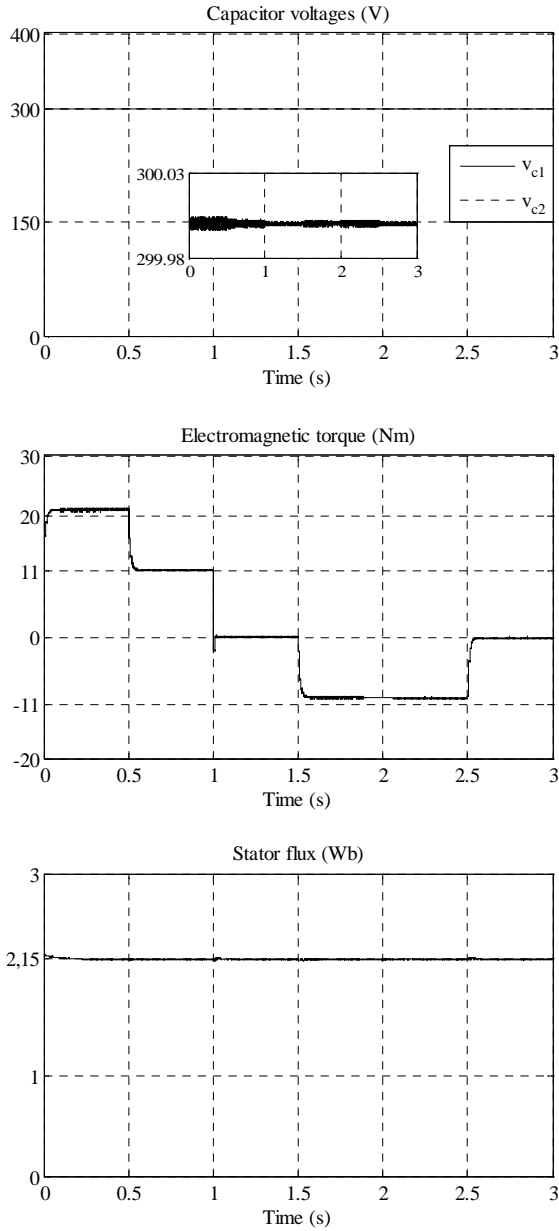


Fig. 6. Dynamic responses of three-level DTC-SVM with balancing strategy for DSSM.

8. Conclusion

In this paper, the multilevel DTC-SVM method applied on DSSM fed by two three-level inverters is presented. First, the dynamic modeling of a synchronous machine equipped with more than one three-phase sets on the stator is presented. After that, the study is focused on the balancing problem of the input voltages of three-level DCI using a DTC endowed by an appropriate balancing strategy. Simulations at different operating conditions have been carried out. The simulation results verify that the proposed DTC-SVM scheme with balancing strategy achieves a fast torque response and low torque ripple, in comparison to the DTC-SVM scheme without balancing strategy, in a wide range of condition variations such as sudden change in the command speed, reverse operation and step change of the load. This study confirms as expected that the proposed balancing strategy of the input DC voltages is more than necessary to improve the performances of the DSSM fed by two three-level DCI.

10. Appendix

Double star synchronous machine parameters are gathered in Table1.

5 kW, 2 poles, 232 V, 50 Hz

Components	Rating values
Stator resistance (R_s)	2.35 Ω
Rotor resistance (R_f)	30.3 Ω
d-axis stator inductance (L_d)	0.3811H
q-axis stator inductance (L_q)	0.211H
Rotor inductance (L_f)	15 H
Mutual inductance (M_{fd})	2.146 H
Moment of inertia (J)	0.05Nms ² /rad
Friction coefficient (f)	0.001Nms/rad

Table 1. DSSM parameters.

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