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Direct Torque Control – A Solution for Mono Inverter-Dual Parallel PMSM System

Maurice FADEL, Ngoc Linh NGUYEN, Ana LLOR

Abstract— **The objective of this paper is to present a Direct Torque Control (DTC) algorithm for controlling system composed by two Permanent Magnet Synchronous Motors (PMSM) operating in parallel, fed by a single power inverter. In this system, it is expected that both motors will get the same speed even if they have different conditions of load torque. The principle of DTC algorithm is considered as follows: The space vector plane is divided into 12 sectors of 30° each of four input information are considered, two related to the flux of each machine and two related to the torque. Based on these 16 combinations in 12 different sectors, a switching table is proposed to determine the best vector of voltage to be applied by the inverter. Simulation results in Matlab/Simulink indicated that the algorithm (DTC) is well adapted for the synchronism of this system over a wide range of operations.**

I. INTRODUCTION

Permanent magnet synchronous machines (PMSM) become more and more popular in industrial motor drive applications such as cars, ships and aircrafts where weight and volume are very important problems. Nowadays, more and more systems use several permanent magnet synchronous machines operating together. A classical system with multi-inverter and multi-machine comprises a three-phase inverter for each machine to be controlled. This structure can be resulted in a fully independent operation of each machine because the three-phase voltage systems are generated by different inverters. However, the number of power electronic components is then increased and the system will be heavy and bulky. Another approach is using only one three-phase inverter to supply several permanent magnet synchronous machines. According to this structure, the number of power electronic components is clearly reduced and the volume and the size of the system also decrease consequently. However, with this configuration, it is impossible to obtain the independent operation of each machine at different required speed. In fact, this configuration will be suitable for the applications in traction drive, textile industry and especially for actuators in aeronautic field.

Some studies have been done concerning control problems of these systems in [4] [5]. In [4], the two synchronous machines are controlled simultaneously. The quadrature current of each motor, which is proportional to the motor torque, is controlled, while the direct current, which relates to the energy optimization problem, is uncontrolled. Consequently, the power losses are increased. Ref. [5] uses master-slave structure to operate the system. The rotor position of the two motors is always compared. The motor with the higher load is set as the master one and the rest one is assigned as the slave and is fed by the same voltage as the master. According to this solution, the parameters of two machines must be identical or very close to get the best performances.

In this paper, a DTC is proposed in order to control the drive system which is presented in Fig.4. Two machines are controlled simultaneously by a special switching table composed by 16x12=192 different case. This method operates in variable switching frequency and the complexities of modulation techniques can be eliminated.

In the first part of this paper, the principle of DTC for one machine will be presented. The second part will consider the structure of mono inverter dual parallel PMSM system, controlled by the DTC approach. A first table is thus developed and when the two machines involve different loads a new table is proposed. The third part shows several simulation results which are stimulated under Matlab/Simulink environment to verify the system performance.

II. PRINCIPLE OF DTC FOR ONE MACHINE

The proposed control method can be classified as DTC and is represented in the PMSM control system, Figure 1. Direct torque control was introduced in Japan by Takahashi and Noguichi [13] and also in Germany by Depenbrock [14]. Principle of proposed method relies on a bang-bang control instead of a decoupling control which is the characteristic of vector control.

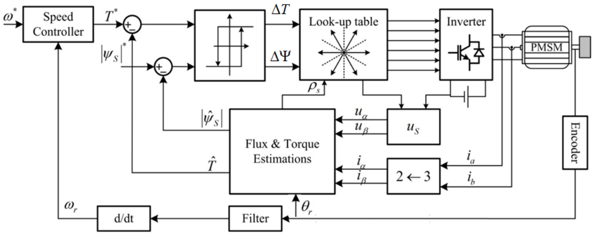

Figure 1. General scheme of DTC for a PMSM

The principle of DTC, as its name implies, is to control the electromagnetic torque and flux linkage directly and independently by the use of six or eight voltage space vectors found in lookup tables. The possible eight voltage space vectors used in DTC are shown in Figure 2. As shown in Figure 1, two hysteresis controllers are used, one for the torque control and the other for the stator flux. The objective of the DTC is to maintain the stator flux and torque control within the hysteresis bands close to their reference values by selecting the output voltage of the inverter. When the torque or the modulus of stator flux reaches the upper or lower limit of the hysteresis comparator, a single vector suitable voltage is applied during each sampling step (Ts) to bring the quantity

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involved within is hysteresis band. This scheme uses a flux and torque estimator from the currents and voltages stator measures. In our case we use also the mechanical position delivered by the encoder.

A. Model of the Permanent Magnet Synchronous Motor

In this work, we consider non-salient PMSM and the electrical and mechanical equations in stationary reference frame (α,β) are expressed as follows:

$$u_\alpha = R_s.i_\alpha + \frac{d\Psi_\alpha}{dt} \qquad u_\beta = R_s.i_\beta + \frac{d\Psi_\beta}{dt} \tag{1}$$

with

$$\Psi_\alpha = L.i_\alpha + \Psi_f.\cos(\Theta_s)\ ;\ \Psi_\beta = L.i_\beta + \Psi_f.\sin(\Theta_s) \tag{2}$$

and

$$T = p.(\Psi_\alpha.i_\beta - \Psi_\beta.i_\alpha) \quad (3) \text{ and} \left|\Psi_s\right| = \sqrt{\Psi_\alpha^2 + \Psi_\beta^2} \tag{4}$$

In steady state the torque can be expressed by:

$$T = 3.p.\frac{\psi_s}{L}.\psi_f.\sin(\delta) \tag{5}$$

where $u_\alpha, u_\beta, i_\alpha, i_\beta, L, \Psi_\alpha$ *and* Ψ_β are respectively stator voltages, stator currents, inductance and flux-linkages. Ψ_f is the flux generated by the permanent magnet, R_s the stator resistance, T the torque and $\omega_s = p.\omega_r$ (where ω_r is the rotor speed), Θ_s the electric position and p the number of poles pair, δ the angle between emf and the stator voltage (E,Vs) .

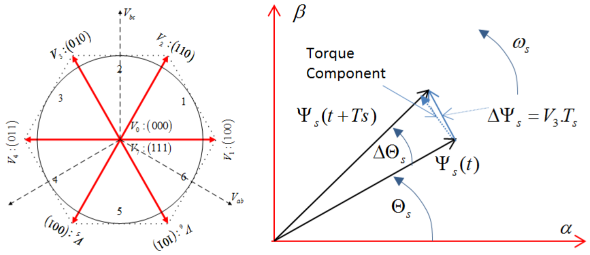


Figure 2. DTC Principle - Behavior in the sector 1

According to the relation (5) the torque evolves in the same direction that δ and that the module of the flux $\left|\Psi_s\right|$. With this it is simple to define a table [1] in order to determine the vector to apply according the errors sign of torque ΔT and flux $\Delta\psi_s$ relate to the sector (S1 to S6) in which is localize the vector flux.

Many authors improved this solution while defining 12 sectors what assures a better tracking of the references.

TABLE I. CLASSICAL DTC FOR ONE PMSM WITH 6 SECTORS

$\Delta\Psi_s$ ΔT	S_1	S_2	S_3	S_4	S_5	S_6
↘ ↘	V_5	V_6	V_1	V_2	V_3	V_4
↘ ↗	V_3	V_4	V_5	V_6	V_1	V_2
↗ ↘	V_6	V_1	V_2	V_3	V_4	V_5
↗ ↗	V_2	V_3	V_4	V_5	V_6	V_1

Other evolutions consisted in defining a working to constant switching frequency in order to limit the losses.

III. MONO INVERTER – DUAL PARALLEL PMSM

In the case of multi-machine system, the number of power electronic switches can be important. To optimize the system volume and weight, this number can be reduced. Consequently, the machines are connected in parallel configuration. Each inverter leg is thus shared with all the machines. In the studied system, two 3-phases PMSM are connected in parallel. The two machines are also linked and exactly the same voltage (frequency and modulus) is applied to them. In such a system the DC bus voltage is shared. It implies that both machines run at the same velocity in steady state. Such a system has already been developed for induction motors, especially in the railway traction or in the textile [12]. The problem for PMSM is the stability. For induction motors, the velocity of the rotor depends indeed on the load torque, even if the load is not the same for the both machines, there is no instability risk. In case of synchronous machines, the stator and rotor fields have to be synchronous. This stability is normally insured by the auto-piloting of the two machines. With only one inverter used for the two motors, it is not possible to control both machines. Fig. 3 depicts the electromagnetic torque versus the angle δ for a synchronous machine.

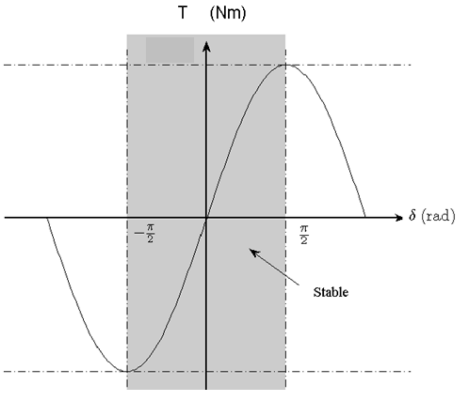


Figure 3. Torque versus δ angle

The evolution of T (δ) is sinusoidal. If the load torque is suddenly changed, the rotor position does not immediately change contrary to the angle δ (the current loop being faster than the velocity loop). In the stable operation zone ($\delta < \pi/2$), the increase of the angle δ leads to the increase of the electromagnetic torque. So the steady state is again stable. However if the δ angle runs over $\pi/2$, there is no more stability.

In this case, the increase of the angle δ leads indeed to a decrease of the electromagnetic torque value. It is so necessary to control the δ angle to be sure that its value remains lower than $\pi/2$. So the stability is guaranteed if:

$$\frac{dT}{d\delta} > 0 \Rightarrow \delta \in (-\pi/2;\pi/2) \tag{6}$$

To ensure the stability of this system operating with unknown and variable loads we have already developed a solution that is described in the following patent[1]. It is a master-slave switching control law in order to pilot the inverter from the information of the machine may become unstable. Thus the operation is stable regardless of the loads of the 2 PMSM.

Improving the dynamic performance of the system we propose to develop a DTC control law in order to pilot two PMSM in parallel with only one inverter.

The structure of this system is shown in Fig.4.

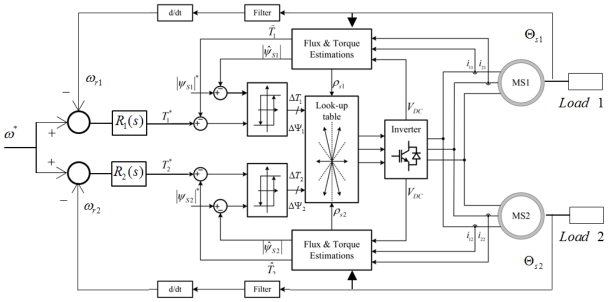


Figure 4. DTC Principle for Dual parallel PMSM

This diagram reveals 2 speed regulators in order to generate 2 references of torque $\left(T_1^*, T_2^*\right)$. The references of flux $\left(\psi_{s1}^*, \psi_{s2}^*\right)$ are the same ones on the 2 machines. The principle is the same as for one machine, but in this case the switching table has 4 inputs ($2^4 = 16$ cases) and it is necessary to determine the configuration of the inverter satisfying the 4 inputs simultaneously.

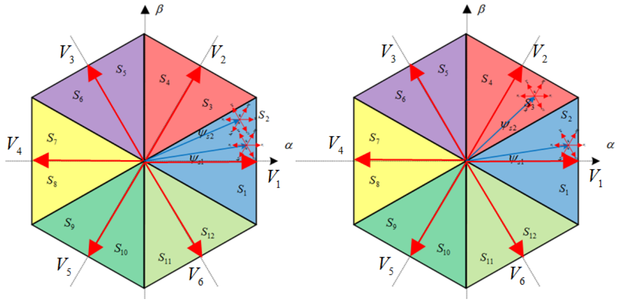


Figure 5. Space vector with 12 sectors

To increase the precision of control we consider now 12 sectors of 30° distributed in a uniform way according to figure 5. For the definition of the switching table we must consider 2 very different cases. Either the 2 vectors of flux are in the same sector (left figure) or the 2 vectors are in different sectors considered as adjacent (right figure). According to these situations the vector selected will be different.

A. Case where the 2 vectors of flux are located in the same sectors

In this case, the voltage selection table is built based on the following rules (TABLE II):

- The case in the box with green color (line 6, 7, 10, 11), all requirements conflict with each other. Therefore, the null vector always is chosen.
- The case in the box with pink color (line 1, 4, 13, 16), all requirements are suitable with each other. Therefore, the vectors are chosen are the same with the case 1 machine.
- The cases in the box with yellow color (line 2, 3, 14, and 15); all requirements have only one conflict with each other. There are two solutions to choose the suitable vectors. If exist the average vector between two required vectors of two machines, this vector will be chosen. In others the even vectors $\left(V_2, V_4, V_6\right)$ are chosen.

TABLE II. WHEN THE 2 VECTORS FLUX ARE IN THE SAME SECTOR

N°	$\Delta\Psi_{s1}$	$\Delta\Psi_{s2}$	ΔT_1	ΔT_2	S_1, S_2	S_3, S_4	S_5, S_6	S_7, S_8	S_9, S_{10}	S_{11}, S_{12}
1	0	0	0	0	V_5	V_6	V_1	V_2	V_3	V_4
2	0	0	0	1	V_4	V_5	V_6	V_1	V_2	V_3
3	0	0	1	0	V_4	V_5	V_6	V_1	V_2	V_3
4	0	0	1	1	V_3	V_4	V_5	V_6	V_1	V_2
5	0	1	0	0	V_6	V_6	V_2	V_2	V_4	V_4
6	0	1	0	1	$V_{0/7}$	$V_{0/7}$	$V_{0/7}$	$V_{0/7}$	$V_{0/7}$	$V_{0/7}$
7	0	1	1	0	$V_{0/7}$	$V_{0/7}$	$V_{0/7}$	$V_{0/7}$	$V_{0/7}$	$V_{0/7}$
8	0	1	1	1	V_2	V_4	V_4	V_6	V_6	V_2
9	1	0	0	0	V_6	V_6	V_2	V_2	V_4	V_4
10	1	0	0	1	$V_{0/7}$	$V_{0/7}$	$V_{0/7}$	$V_{0/7}$	$V_{0/7}$	$V_{0/7}$
11	1	0	1	0	$V_{0/7}$	$V_{0/7}$	$V_{0/7}$	$V_{0/7}$	$V_{0/7}$	$V_{0/7}$
12	1	0	1	1	V_2	V_4	V_4	V_6	V_6	V_2
13	1	1	0	0	V_6	V_1	V_2	V_3	V_4	V_5
14	1	1	0	1	V_1	V_2	V_3	V_4	V_5	V_6
15	1	1	1	0	V_1	V_2	V_3	V_4	V_5	V_6
16	1	1	1	1	V_2	V_3	V_4	V_5	V_6	V_1

B. Case where the 2 vectors of flux are located in 2 adjacent sectors

In this case, the voltage selection table is built based on the following rules (TABLE III&IV):

- In two adjacent sector, always exist two states satisfy absolutely two machine which is described by the pink color.
- If two vectors are continuous, the vector is chosen is the vector suitable with the machine has the flux vector is in the bigger sector.
- If two vector are odd, the vector is chosen is an average vector:

$$\left(V_1 + V_3 \rightarrow V_2\right)\ \left(V_3 + V_5 \rightarrow V_4\right)\ \left(V_5 + V_1 \rightarrow V_6\right)$$

- Null vector will be chosen if
    - two vectors are opposite: $\left(V_1 + V_4\right)\ \left(V_2 + V_5\right)\ \left(V_3 + V_6\right)$
    - two vectors are even: $\left(V_2 + V_4\right)\ \left(V_4 + V_6\right)\ \left(V_6 + V_2\right)$

TABLE III. WHEN THE 2 VECTORS FLUX ARE IN THE ADJACENT SECTOR (S1 TO S6)

N°	$\Delta\Psi_{s1}$	$\Delta\Psi_{s2}$	ΔT_1	ΔT_2	S_2	S_1	S_3	S_4	S_5	S_6
1	0	0	0	0	V_6	V_4	V_6	V_6	V_6	V_2
2	0	0	0	1	V_4	$V_{0/7}$	$V_{0/7}$	V_6	$V_{0/7}$	V_6
3	0	0	1	0	$V_{0/7}$	V_4	V_4	$V_{0/7}$	V_6	$V_{0/7}$
4	0	0	1	1	V_4	V_2	V_4	V_4	V_4	V_6
5	0	1	0	0	V_6	V_5	V_6	$V_{0/7}$	V_1	V_2
6	0	1	0	1	V_4	V_6	$V_{0/7}$	$V_{0/7}$	V_2	V_6
7	0	1	1	0	V_2	V_4	$V_{0/7}$	$V_{0/7}$	V_6	V_4
8	0	1	1	1	V_3	V_2	$V_{0/7}$	V_4	V_4	V_5
9	1	0	0	0	V_6	$V_{0/7}$	V_6	V_1	$V_{0/7}$	V_2
10	1	0	0	1	$V_{0/7}$	$V_{0/7}$	V_2	V_6	$V_{0/7}$	$V_{0/7}$
11	1	0	1	0	$V_{0/7}$	$V_{0/7}$	V_4	V_2	$V_{0/7}$	$V_{0/7}$
12	1	0	1	1	$V_{0/7}$	V_2	V_3	V_4	V_4	$V_{0/7}$
13	1	1	0	0	V_6	V_6	V_6	V_2	V_2	V_2
14	1	1	0	1	$V_{0/7}$	V_6	V_2	$V_{0/7}$	V_2	$V_{0/7}$
15	1	1	1	0	V_2	$V_{0/7}$	$V_{0/7}$	V_2	$V_{0/7}$	V_4
16	1	1	1	1	V_2	V_2	V_2	V_4	V_4	V_4

TABLE IV. WHEN THE 2 VECTORS FLUX ARE IN THE ADJACENT SECTOR (S7 TO S12)

N°	$\Delta\Psi_{s1}$	$\Delta\Psi_{s2}$	ΔT_1	ΔT_2	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}
1	0	0	0	0	V_2	V_2	V_2	V_4	V_4	V_4
2	0	0	0	1	$V_{0/7}$	V_2	$V_{0/7}$	V_2	V_4	$V_{0/7}$
3	0	0	1	0	V_6	$V_{0/7}$	V_2	$V_{0/7}$	$V_{0/7}$	V_2
4	0	0	1	1	V_6	V_6	V_6	V_2	V_2	V_2
5	0	1	0	0	V_2	$V_{0/7}$	V_3	V_4	$V_{0/7}$	V_4
6	0	1	0	1	$V_{0/7}$	$V_{0/7}$	V_4	V_2	$V_{0/7}$	$V_{0/7}$
7	0	1	1	0	$V_{0/7}$	$V_{0/7}$	V_2	V_6	$V_{0/7}$	$V_{0/7}$
8	0	1	1	1	$V_{0/7}$	V_6	V_6	V_1	V_2	$V_{0/7}$
9	1	0	0	0	V_2	V_3	$V_{0/7}$	V_4	V_5	V_4
10	1	0	0	1	V_4	V_2	$V_{0/7}$	$V_{0/7}$	V_4	V_6
11	1	0	1	0	V_6	V_4	$V_{0/7}$	$V_{0/7}$	V_6	V_2
12	1	0	1	1	V_5	V_6	V_6	$V_{0/7}$	V_2	V_1
13	1	1	0	0	V_2	V_4	V_4	V_4	V_6	V_4
14	1	1	0	1	V_4	$V_{0/7}$	V_4	$V_{0/7}$	$V_{0/7}$	V_6
15	1	1	1	0	$V_{0/7}$	V_4	$V_{0/7}$	V_6	V_6	$V_{0/7}$
16	1	1	1	1	V_4	V_6	V_6	V_6	V_2	V_6

IV. FIRST SIMULATIONS RESULT

With an aim of validating this proposal, here some simulations carried out using MATLAB-SIMULINK in 2 different cases. The test is carried out with identical loads on the 2 machines then with different loads.

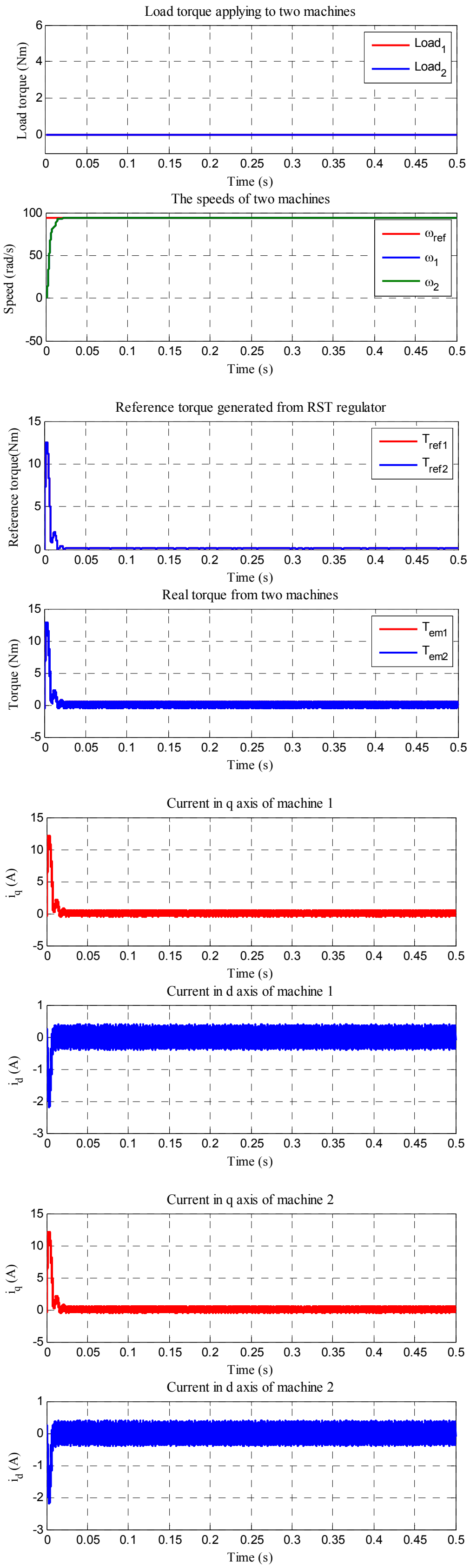


Figure 6. Same loads

When the loads are different tables III and IV are used whereas for identical loads only table II is used.

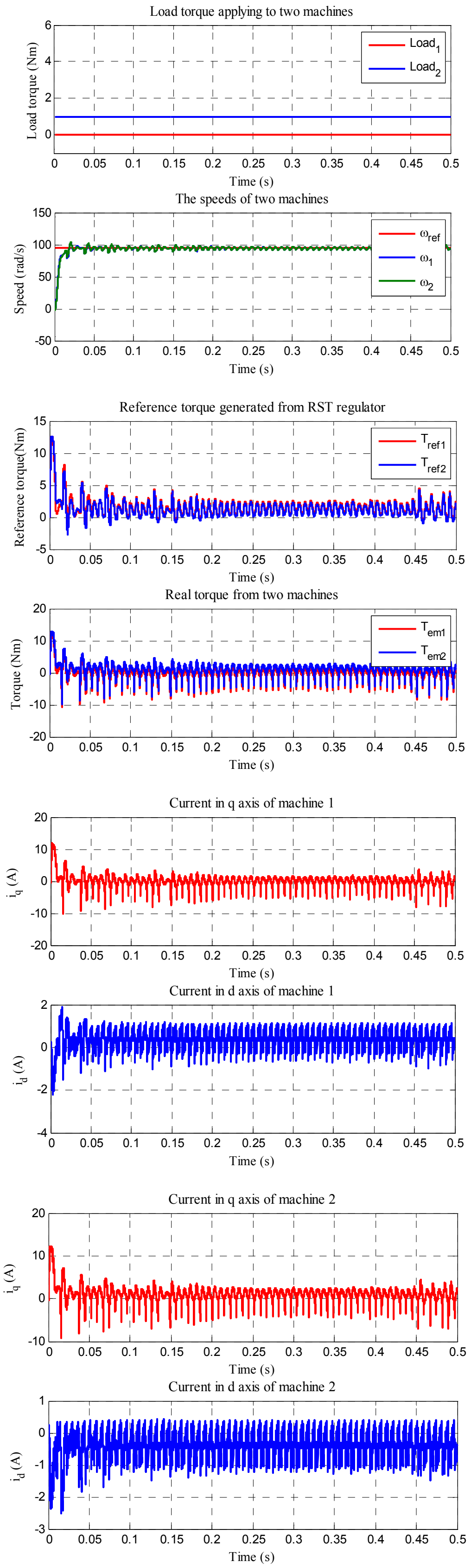


Figure 7. With different loads

On figure 6 the 2 machines do not involve a load and the speed control is perfectly assured. The currents on the axes d and q, on each machine, are guaranteed.

On figure 7, the two machines involve different loads. The vectors flux of each machine can be in different sectors. It is observed that speed is controlled around the speed of reference. However one observes oscillations on the components of the currents for the axes d and q. The currents on the axes d are not null in average value what involves additional joule losses. It is possible to improve this operation by generating different tables. We develop this in the following paragraph.

V. NEW TABLE FOR DTC DUAL PARALLEL PMSM

We always consider the 2 cases characterized by the presence of the 2 vectors of flux in the same sector or then on adjacent vectors. The step will consist has to privilege the vector flux when that is possible.

A. Two stator flux vectors are in the same sector

The principle which is used to determine the voltage vector with the aim meeting the requirements of both machines is pointed out as follow:

- In the critical case, the demands of two machines are absolutely different. Therefore, the null vector is chosen;
- In the second case, two machines have one demand in common, either the torque or the flux. Like this, the suitable voltage of each machine will never be opposite. Supposed that the suitable vector for the first machine is noted as V_1 and for the second machine is V_2. If there is an average vector located in the middle of V_1 and V_2, this vector will be chosen. In others, the vector will be chosen depending on the position of flux vector of each machine.
- The final case, favorable case, it is the easiest case. Because the two machines have the same demands for the torque and the flux, they also need the same voltage vector. This behavior is described by the table V.

B. Case where the 2 vectors of flux are located in 2 adjacent sectors

In this case, with 6 basic sectors, there are twelve combination sectors. According to these sectors and requirements about the voltage vector of each machine, another table will be built. Some general conditions also are inferred:

- Although locating in two adjacent sectors, there are the states that both machines have the same demands of torque and flux. These states are distinguished by the purple color. Meanwhile, in the critical case as shown in table VI and VII, the requirements for torque and flux of both machines are completely conflict with each other, however, the voltage vectors does not conflict any more. The voltage vector will be chosen according to the average rule;
- Another special case can be happened, the two suitable voltage vectors for two machines are also two adjacent vectors. The vector will be determined based on the position of the two flux vectors;

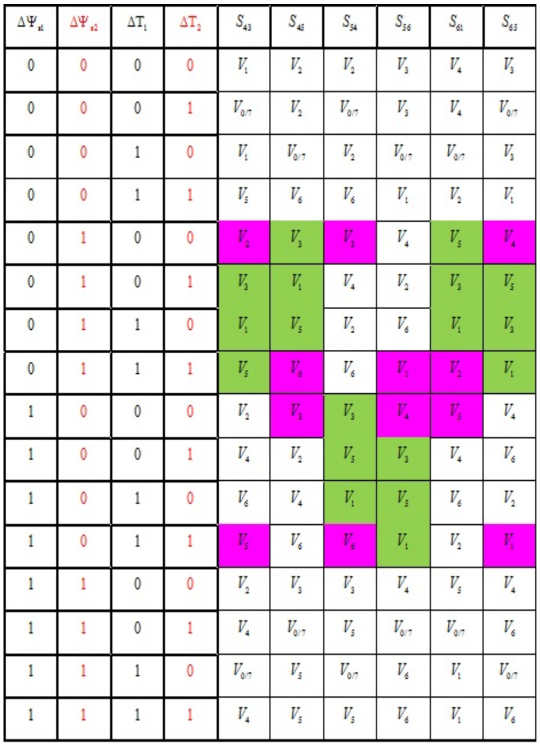
TABLE V. NEW TABLE WHEN THE 2 VECTORS FLUX ARE IN THE SAME SECTOR

N°	$\Delta\Psi_{s1}$	$\Delta\Psi_{s2}$	ΔT_1	ΔT_2	S_1,S_2	S_3,S_4	S_5,S_6	S_7,S_8	S_9,S_{10}	S_{11},S_{12}
1	0	0	0	0	V_5	V_6	V_1	V_2	V_3	V_4
2	0	0	0	1	V_4	V_5	V_6	V_1	V_2	V_3
3	0	0	1	0	V_4	V_5	V_6	V_1	V_2	V_3
4	0	0	1	1	V_3	V_4	V_5	V_6	V_1	V_2
5	0	1	0	0	V_5/V_6	V_6/V_1	V_1/V_2	V_2/V_3	V_3/V_4	V_4/V_5
6	0	1	0	1	$V_{0/7}$	$V_{0/7}$	$V_{0/7}$	$V_{0/7}$	$V_{0/7}$	$V_{0/7}$
7	0	1	1	0	$V_{0/7}$	$V_{0/7}$	$V_{0/7}$	$V_{0/7}$	$V_{0/7}$	$V_{0/7}$
8	0	1	1	1	V_3/V_2	V_5/V_4	V_6/V_5	V_1/V_6	V_2/V_1	V_3/V_2
9	1	0	0	0	V_6/V_5	V_1/V_6	V_2/V_1	V_3/V_2	V_4/V_3	V_5/V_4
10	1	0	0	1	$V_{0/7}$	$V_{0/7}$	$V_{0/7}$	$V_{0/7}$	$V_{0/7}$	$V_{0/7}$
11	1	0	1	0	$V_{0/7}$	$V_{0/7}$	$V_{0/7}$	$V_{0/7}$	$V_{0/7}$	$V_{0/7}$
12	1	0	1	1	V_2/V_3	V_3/V_4	V_4/V_5	V_5/V_6	V_6/V_1	V_1/V_2
13	1	1	0	0	V_6	V_1	V_2	V_3	V_4	V_5
14	1	1	0	1	V_1	V_2	V_3	V_4	V_5	V_6
15	1	1	1	0	V_1	V_2	V_3	V_4	V_5	V_6
16	1	1	1	1	V_2	V_3	V_4	V_5	V_6	V_1

TABLE VI. NEW TABLE WHEN THE 2 VECTORS FLUX ARE IN THE ADJACENT SECTOR (S1 TO S6)

N°	$\Delta\Psi_{s1}$	$\Delta\Psi_{s2}$	ΔT_1	ΔT_2	S_2	S_1	S_3	S_4	S_5	S_6
1	0	0	0	0	V_5	V_4	V_5	V_6	V_6	V_1
2	0	0	0	1	V_5	$V_{0/7}$	$V_{0/7}$	V_6	$V_{0/7}$	V_1
3	0	0	1	0	$V_{0/7}$	V_4	V_5	$V_{0/7}$	V_6	$V_{0/7}$
4	0	0	1	1	V_3	V_2	V_3	V_4	V_4	V_5
5	0	1	0	0	V_6	V_5	V_6	V_1	V_1	V_2
6	0	1	0	1	V_4	V_6	V_1	V_5	V_2	V_6
7	0	1	1	0	V_2	V_4	V_5	V_3	V_6	V_4
8	0	1	1	1	V_3	V_2	V_3	V_4	V_4	V_5
9	1	0	0	0	V_6	V_5	V_6	V_1	V_1	V_2
10	1	0	0	1	V_5	V_1	V_2	V_6	V_4	V_1
11	1	0	1	0	V_1	V_3	V_4	V_2	V_5	V_3
12	1	0	1	1	V_3	V_2	V_3	V_4	V_4	V_5
13	1	1	0	0	V_6	V_5	V_6	V_1	V_1	V_2
14	1	1	0	1	$V_{0/7}$	V_1	V_2	$V_{0/7}$	V_3	$V_{0/7}$
15	1	1	1	0	V_2	$V_{0/7}$	$V_{0/7}$	V_3	$V_{0/7}$	V_4
16	1	1	1	1	V_2	V_1	V_2	V_3	V_3	V_4

TABLE VII. NEW TABLE WHEN THE 2 VECTORS FLUX ARE IN THE ADJACENT SECTOR (S7 TO S12)



$\Delta\Psi_{s1}$	$\Delta\Psi_{s2}$	ΔT_1	ΔT_2	S_{43}	S_{45}	S_{54}	S_{56}	S_{61}	S_{65}
0	0	0	0	V_1	V_2	V_2	V_3	V_4	V_3
0	0	0	1	$V_{0/7}$	V_2	$V_{0/7}$	V_3	V_4	$V_{0/7}$
0	0	1	0	V_1	$V_{0/7}$	V_2	$V_{0/7}$	$V_{0/7}$	V_3
0	0	1	1	V_5	V_6	V_6	V_1	V_2	V_1
0	1	0	0	V_2	V_3	V_3	V_4	V_5	V_4
0	1	0	1	V_3	V_1	V_4	V_2	V_3	V_5
0	1	1	0	V_1	V_5	V_2	V_6	V_1	V_3
0	1	1	1	V_5	V_6	V_6	V_1	V_2	V_1
1	0	0	0	V_2	V_3	V_3	V_4	V_5	V_4
1	0	0	1	V_4	V_2	V_5	V_3	V_4	V_6
1	0	1	0	V_6	V_4	V_1	V_5	V_6	V_2
1	0	1	1	V_5	V_6	V_6	V_1	V_2	V_1
1	1	0	0	V_2	V_3	V_3	V_4	V_5	V_4
1	1	0	1	V_4	$V_{0/7}$	V_5	$V_{0/7}$	$V_{0/7}$	V_6
1	1	1	0	$V_{0/7}$	V_5	$V_{0/7}$	V_6	V_1	$V_{0/7}$
1	1	1	1	V_4	V_5	V_5	V_6	V_1	V_6

VI. NEW SIMULATIONS RESULT

With these new tables (V, VI and VII), we propose to test the behavior when the 2 machines involve different loads.

The simulation results are shown in Fig.8. The performance of the whole system is improved clearly. At steady state, the speeds of two machines are equal and follow the reference. The oscillation does not exist any more.

About torque response, it can be seen that, the torque of the second machine is close to its reference value. However, for the first machine, there is a big difference between the real torque and the reference value. Theoretically, it means that the first machine will not be able to come to desired speed. In fact, this thing did not happen and the synchronism of two PMSMs is still obtained.

It can be explained when considering the value of d-currents of both machines. We can see that for the second machine, d-current is ripple but close to zero. Meanwhile, this value for the first machine is around 2(A). Thank to this, the speed of first machine can come to the reference.

Besides, we also can observe a better control of the currents on the axes q. The currents on the axes q remain disturbed but the amplitude of the ripple is decreased considerably. Therefore, the evolution speed is satisfactory. It also means that the new table is better.

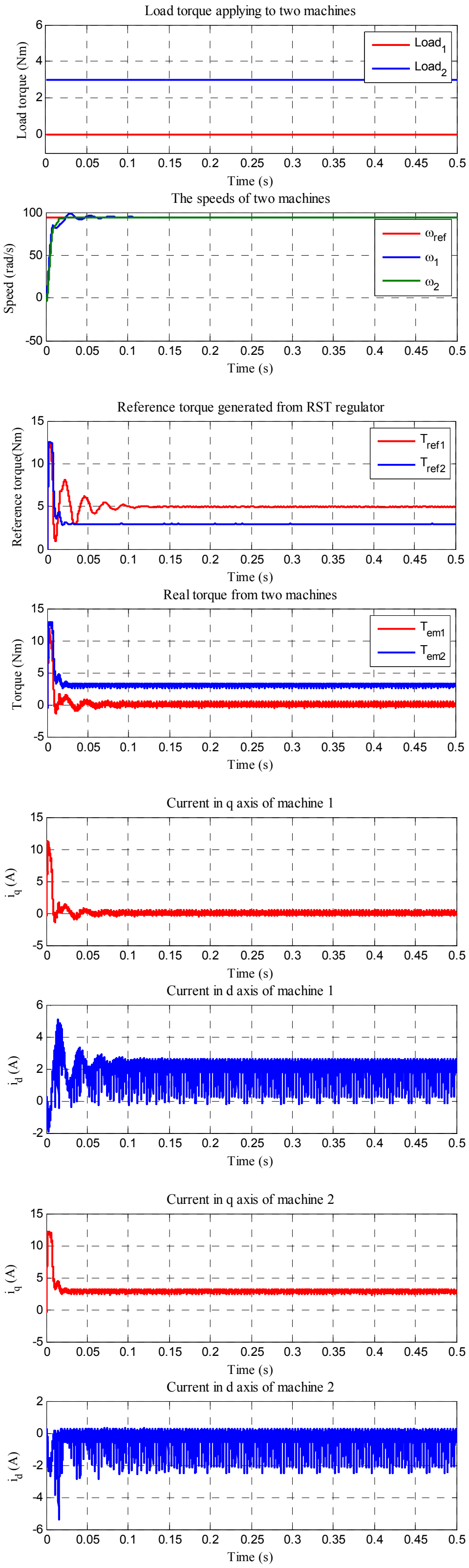


Figure 8. Behaviour with the new table

VII. CONCLUSION

Simulation results have shown that it is possible to control a system including two PMSM in parallel powered by an inverter using DTC algorithm. The systems can response timely to the change of the load and the set point.

When the two machines involve different loads the choice of the voltage vector generated by the inverter can be only the result of a compromise because it is not possible to meet the two requirements at the same time. The fact of giving the priority to the vector flow guaranteed a satisfying control of the torque even if the currents in the axes d are not optimized.

Study in this paper just focuses on parallel operation of only two machines because of the large number of cases when the number of machines is increased. However, we can also use the idea of master/slave in [1][5] to choose the suitable machines to be controlled.

For the continuation of work, we also envisage an operation without position encoder.

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