MODELING AND CONTROL THE SET OF MATRIX CONVERTER-TWO FIVE-PHASE WHEEL MOTORS (2 PMSM) FOR DRIVING AN ELECTRIC TRACTION SYSTEM

Mohammed. BENALI YOUCEF
Development Laboratory of Electrical Drives,
University of Oran, Algeria
mohamed.benaliyoucef@univ-usto.dz

Abdelkader. DJAHBAR
University of Chlef – Algeria.
a_djahbar@yahoo.fr

Benyouness. MAZARI
Development Laboratory of Electrical Drives, University of Oran, Algeria.
mazari_dz@yahoo.fr

Abstract: *The present work is relating to the development and the Inclusion of the statics converters to supply the multi-machines systems, in the electric traction field.*

To minimize the size and the number of power converters then to use two machines in series in an electric traction system. We have integrated a single three to five phase matrix converter, rather than use a five-phase inverter, to supply two five-phase wheel motors (2 PMSM), for driving an electric traction system.

A three to five phase matrix converter is most easily provides five variable voltages, is controlled to supply by five alternating currents, which they interact to cause the two series connected five-phase PMSM to rotate.

This study shows the functionality of the proposed matrix converter, which it is the same as the inverter, by providing the current required for the vector control and the pilotage of the two five phases PMSM at different loading conditions of the electric traction drive system.

Keywords: *Matrix converter, wheel motors, five-phase permanent magnet synchronous machines (PMSM), Electric traction system, and vector control.*

1. Introduction.

During the last years, the electric traction drive systems are among the most commonly used topics; they became indispensable, as they have attracted the attention of many researchers in industry and scientific research. Moreover, due to the accelerated development of power electronics and electrical networks, which led to open a large field to introduce several types of machinery and power converters, all depends on the kind of traction system, location, and available technology. Due to the importance of more power density, the power factor and the efficiency of permanent magnet synchronous machines, they have been are used as direct drive systems [1], even more, if they are polyphase. For all these reasons, they are interested in reducing the stress applied to the switches and coils. [2]

It has also found that the five-phase PMSM with a distributed winding is the best suited for high-speed applications, as in high speed and range torque of electric traction systems drive. [3], [4].

However, The serial connection becomes possible between the five-phase PMSMs; it is also examined under the acceptance of the sinusoidal magneto-motive force and becomes possible to control the two machines in a single group independently, [5] Although the single five-phase matrix converter can power the drive system. It also ensures the control of bidirectional flow power, by using the AC-AC conversion using semiconductor switches.

The development concentration focused on new power converter topologies in one single step to produce more than three phases. [6], [7].

In this Paper, the power supply topology of the matrix converter circuit figure 1, which proposed in the electric traction drive system, on the way to transmuting the electrical energy to the two series-connected five-phase PMSM.

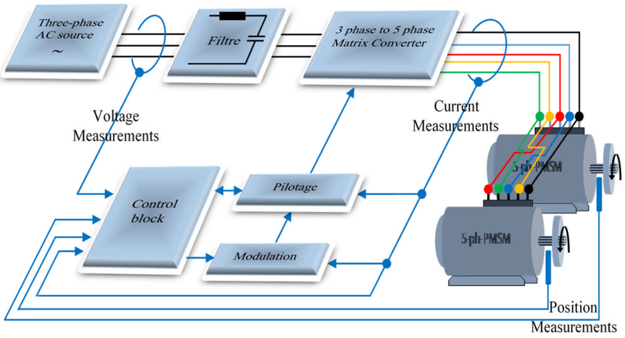

Fig. 1. Five phase matrix converter feeds two five-phase PMSM in an electric traction system.

1. Three to five phase matrix converter.

The used three to five phase matrix converter that its basic diagram given by figure 2.

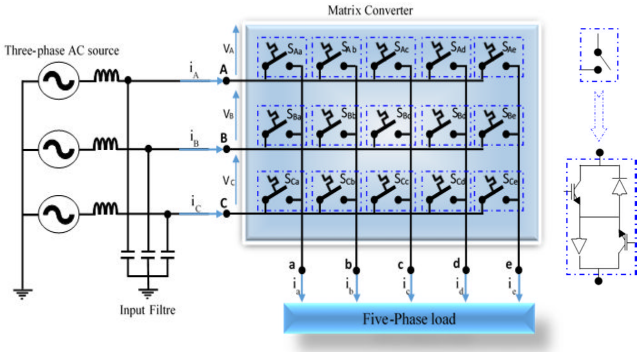

Fig.2.Three-to-five phase matrix converter's basic diagram.

This converter characterized by the matrix topology of fifteen bidirectional switches S_{ij}.

The input voltages are given by:

$$\begin{bmatrix} V_A(t) \\ V_B(t) \\ V_C(t) \end{bmatrix} = V_{im} \begin{bmatrix} cos(\omega_i t) \\ cos(\omega_i t + \frac{2\pi}{3}) \\ cos(\omega_i t + \frac{4\pi}{3}) \end{bmatrix} \qquad (1)$$

Such as $\omega_i = 2\pi f_i$: the pulsation of the input voltages. The desired output voltages when the fundamental pulsation $\omega_o = 2\pi f_o$ and the amplitude $v_{om} = q.v_{im}$ (q is the amplitude conversion ratio) given by:

$$\begin{bmatrix} V_a(t) \\ V_b(t) \\ V_c(t) \\ V_d(t) \\ V_e(t) \end{bmatrix} = V_{om} \begin{bmatrix} cos(\omega_o t) \\ cos(\omega_o t - \frac{2\pi}{5}) \\ cos(\omega_o t - \frac{4\pi}{5}) \\ cos(\omega_o t - \frac{6\pi}{5}) \\ cos(\omega_o t - \frac{8\pi}{5}) \end{bmatrix} \qquad (2)$$

Each waveform of the desired output voltage v_j (j=a, b, c, d, e; the previous system considers only the fundamental) it is synthesized by hashing the three input voltages v_i (i=A, B, C), means of the switches S_{ij}. The waveform of the output voltage of one phase is, therefore, a set of portions taken input voltages.

The switches for synthesizing the same output phase are actuated in sequence and cyclically such that the sum of their intervals conduction time during a sequence k is constant and equal to T_s figure 3 [8] [9]. $T_s = 1/f_s$ is the time sequential.

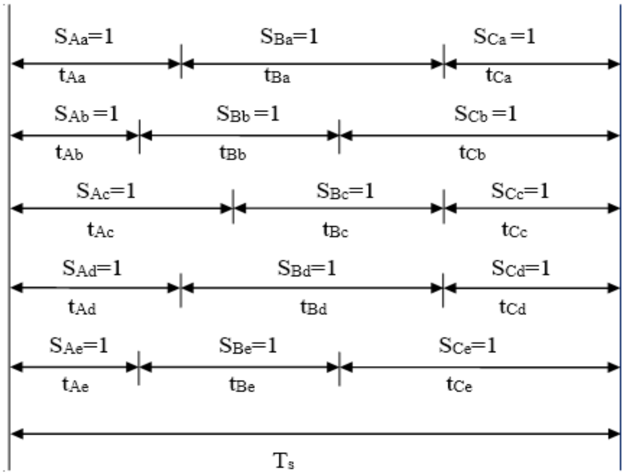

Fig. 3. Period of the switches conduction.

The $m^{(k)}_{ij}$ are duty cycles (coefficients utilization) of the switches S_{ij} during the k^th^ sequence.

$$m_{ij}^{k} = \frac{t_{ij} \text{ of the } k^{th} \text{ sequence}}{T_s} \qquad (3)$$

With the following restrictions (i=A, B, C and j=a, b, c, d, e)

$$\sum_{i=1}^{3} m_{ij}^{k} = m_{1j}^{k} + m_{2j}^{k} + m_{3j}^{k} \quad \text{and} \quad 0 < m_{ij}^{k} < 1 \qquad (4)$$

The mean values of the five output voltages at the k^th^ sequence are:

$$\begin{cases} V_a^k = V_{Aa}^k m_{Aa}^k + V_{Ba}^k m_{Ba}^k + V_{Ca}^k m_{Ca}^k \\ V_b^k = V_{Ab}^k m_{Ab}^k + V_{Bb}^k m_{Bb}^k + V_{Cb}^k m_{Cb}^k \\ V_c^k = V_{Ac}^k m_{Ac}^k + V_{Bc}^k m_{Bc}^k + V_{Cc}^k m_{Cc}^k \\ V_d^k = V_{Ad}^k m_{Ad}^k + V_{Bd}^k m_{Bd}^k + V_{Cd}^k m_{Cd}^k \\ V_e^k = V_{Ae}^k m_{Ae}^k + V_{Be}^k m_{Be}^k + V_{Ce}^k m_{Ce}^k \end{cases} \qquad (5)$$

2. Matrix converter control.

The aim of the idealized matrix converter control is to find the pulsation sequences so that the slippery average of the phase voltages at the output is a modulated sinusoidal form, the amplitude, and frequency of the fundamental wave of the output voltage must be variable, to achieve this there are mainly two methods:

- Direct method or scalar algorithm (Venturini, Roy).
- Indirect method (vector modulation) Kastner Rodrigue.

3.1 Scalar algorithm of ROY

Roy algorithm is a typical method among several methods of developed modulation so that the switches actuating signals calculated directly from the measurements of instantaneous input voltages followed by a comparison of these relative magnitudes according to the algorithm below [10]:

- The index **M** to assign one of the three phase voltages input having a different polarity to the others;
- The index **L** to assign the lowest tension in the absolute value of the others.
- Assign the index **K** to the third voltage.

For : J= {a, b, c, d, e}.

$$\begin{cases} m_{LJ} = \frac{(V_j - V_M)V_L}{1.5V_{im}^2} \\ m_{KJ} = \frac{(V_j - V_M)V_K}{1.5V_{im}^2} \\ m_{MJ} = 1-(m_{LJ} - m_{KJ}) \end{cases} \qquad (6)$$

3.2 Switching angles:

The Fourier spectrum of each signal in principle depends only on input voltages, frequency f_S, and the sequential time intervals of switches S_{ij} conduction.

The purpose of synthesis the output voltage returns to formulate the equations of switching angles; so that

the first harmonic of the output voltage have the same form as the expression (2).
The hash frequency $(fs = w_s/2\pi)$ selected such as that $(f_s \geq 20.max\ (f_i\ , f_o))$.
During the kth sequence, the output voltages of the Matrix converter given by:

$$V_J = \begin{cases} V_K & \text{if: } 0 \leq t\text{-}(k\text{-}1)^{(K)}\, T_s \leq m_{KJ}^{(K)}\, T_s \\ V_L & \text{if: } m_{KJ}^{(K)}\, T_s \leq t\text{-}(k\text{-}1)^{(K)}\, Ts \leq (m_{KJ}^{(K)} + m_{LJ}^{(K)})\, Ts \\ V_M & \text{if : } (m_{KJ}^{(K)} + m_{LJ}^{(K)})\, Ts \leq t\text{-}(k\text{-}1)^{(K)}\, Ts \end{cases}$$

$$\text{and} \quad t\text{-}(k\text{-}1)\, Ts \leq (m_{KJ}^{(K)} + m_{LJ}^{(K)} + m_{MJ}^{(K)})\, Ts$$

For J= {a, b, c, d, e}.

4. Model and layout of the connected machines:

Taking for modeling all the standard assumptions of the general theory of electrical machines that are applicable [11] [12], even for to the sinusoidal distribution of the resulting field in the machine.
The phases of machines offset by a $n\alpha = 2\pi$, n is the phase number of the used machine. [2].
According to the connection diagram of figure 4, the phase voltages of the two machines and the relationship between the output currents of the matrix converter and the phase currents of the two machines given by:

$V_a = V_{as1} + V_{as2}$ and $i_a = i_{as1} = i_{as2}$
$V_b = V_{bs1} + V_{cs2}$ and $i_b = i_{bs1} = i_{cs2}$
$V_c = V_{cs1} + V_{es2}$ and $i_c = i_{cs1} = i_{es2}$
$V_d = V_{ds1} + V_{bs2}$ and $i_d = i_{ds1} = i_{bs2}$
$V_e = V_{es1} + V_{ds2}$ and $i_e = i_{es1} = i_{ds2}$

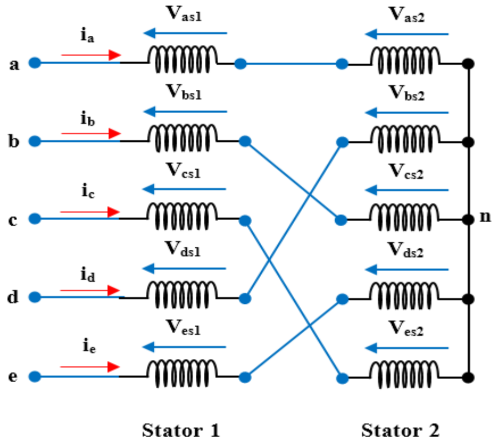

Fig. 4. Connection diagram of the two series five phase PMSM.

For generalizing, the used machines have the same parameters; the presented electrical circuit model can be given in the matrix form by:

$$[V_{abcde}] = R_s[i_{abcde}] + d/dt\ [\emptyset_{abcde}]$$

$$\begin{bmatrix} V_{asn} \\ V_{bsn} \\ V_{csn} \\ V_{dsn} \\ V_{esn} \end{bmatrix} = \begin{bmatrix} R_{sn} & 0 & 0 & 0 & 0 \\ 0 & R_{sn} & 0 & 0 & 0 \\ 0 & 0 & R_{sn} & 0 & 0 \\ 0 & 0 & 0 & R_{sn} & 0 \\ 0 & 0 & 0 & 0 & R_{sn} \end{bmatrix} \begin{bmatrix} i_{asn} \\ i_{bsn} \\ i_{csn} \\ i_{dsn} \\ i_{esn} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} f_{asn} \\ f_{bsn} \\ f_{csn} \\ f_{dsn} \\ f_{esn} \end{bmatrix} \qquad (7)$$

As n is the number of used machines, in our case n = 1, 2
The flow equation is:

$$[\emptyset_{abcde\ sn}] = [L_{sn}]\ [i_{abcde\ sn}] + [\emptyset_{mn}]$$

We denote by:

- L_{sn} the self-inductance coefficient of a stator winding.
- R_{sn} The resistance of a stator phase.
- $\emptyset_{mn}$ Represents the total flow through the winding.

For a PMSM with decoupled phases, we use the Clark transformation (C), the expression of the relation between the new variables (α, β, x, y, 0) and the primary variables of phases given by:

$$f\,(\alpha, \beta) = [C]\ f(a, b, c, d, e)$$

$$\begin{bmatrix} V_\alpha^{MC} \\ V_\beta^{MC} \\ V_x^{MC} \\ V_y^{MC} \\ V_o^{MC} \end{bmatrix} = C \begin{bmatrix} V_{as1} & + & V_{as2} \\ V_{bs1} & + & V_{cs2} \\ V_{cs1} & + & V_{es2} \\ V_{ds1} & + & V_{bs2} \\ V_{es1} & + & V_{ds2} \end{bmatrix} = \begin{bmatrix} V_{\alpha s1} & + & V_{xs2} \\ V_{\beta s1} & - & V_{ys2} \\ V_{xs1} & + & V_{\alpha s2} \\ V_{ys1} & + & V_{\beta s2} \\ & 0 & \end{bmatrix} \qquad (8)$$

$$[C] = \sqrt{2/5} \begin{bmatrix} 1 & \cos(\alpha) & \cos(2\alpha) & \cos(3\alpha) & \cos(4\alpha) \\ 0 & \sin(\alpha) & \sin(2\alpha) & \sin(3\alpha) & \sin(4\alpha) \\ 1 & \cos(2\alpha) & \cos(4\alpha) & \cos(6\alpha) & \cos(8\alpha) \\ 0 & \sin(2\alpha) & \sin(4\alpha) & \sin(6\alpha) & \sin(8\alpha) \\ \sqrt{1/2} & \sqrt{1/2} & \sqrt{1/2} & \sqrt{1/2} & \sqrt{1/2} \end{bmatrix} \qquad (9)$$

$$\begin{aligned} i_\alpha^{MC} &= i_{\alpha s1} = i_{xs2} \\ i_\beta^{MC} &= i_{\beta s1} = -i_{ys2} \\ i_x^{MC} &= i_{xs1} = i_{\alpha s2} \\ i_y^{MC} &= i_{ys1} = i_{\beta s2} \end{aligned} \qquad (10)$$

To express all the quantities in the same reference frame. We project the stator magnitudes in a rotating reference frame (d, q) shifted by φ on the fixed reference frame (α, β),(x, y) of the two machines [13], we calculate this transformation from the Rotation matrix D such that:

$$D_S = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & \\ \sin(\theta) & \cos(\theta) & \\ & & [I]^{3\times 3} \end{bmatrix} \qquad (11)$$

The model equations of the two series connected five-phase PMSM in the reference frame (d, q) and the torque relations given respectively by (12) and (13).

$$\begin{cases} V_d^{MC} = (R_{s1}+R_{s2})i_d^{MC} + \left(l_{s1}+\frac{5}{2}m_{s1}\right)\frac{d}{dt}i_d^{MC} + l_{s2}\frac{d}{dt}i_d^{MC} - \omega_1\left(l_{s1}+\frac{5}{2}m_{s1}\right)i_q^{MC} \\ V_q^{MC} = (R_{s1}+R_{s2})i_q^{MC} + \left(l_{s1}+\frac{5}{2}m_{s1}\right)\frac{d}{dt}i_q^{MC} + l_{s2}\frac{d}{dt}i_q^{MC} + \omega_1\left(l_{s1}+\frac{5}{2}m_{s1}\right)i_d^{MC} + \sqrt{\frac{5}{2}}\omega_1\phi f_1 \\ V_x^{MC} = (R_{s1}+R_{s2})i_x^{MC} + l_{s1}\frac{d}{dt}i_x^{MC} + \left(l_{s2}+\frac{5}{2}m_{s2}\right)\frac{d}{dt}i_x^{MC} - \omega_2\left(l_{s2}+\frac{5}{2}m_{s2}\right)i_y^{MC} \\ V_y^{MC} = (R_{s1}+R_{s2})i_y^{MC} + l_{s1}\frac{d}{dt}i_y^{MC} + \left(l_{s2}+\frac{5}{2}m_{s2}\right)\frac{d}{dt}i_y^{MC} + \omega_2\left(l_{s2}+\frac{5}{2}m_{s2}\right)i_x^{MC} + \sqrt{\frac{5}{2}}\omega_2\phi f_2 \end{cases} \quad (12)$$

$\emptyset_{fn}$: Total flux due to the magnets and which closes on the stator.

m_{sn} : The coefficient of mutual inductance between the stator phases.

n: is the number of the used machines, in our case n = 1, 2

$$\begin{cases} T_{e1} = p\left((L_d - L_q)i_d^{MC}i_q^{MC} + \sqrt{\frac{5}{2}}\Phi_{f_1}i_q^{MC}\right) \\ T_{e2} = p\left((L_x - L_y)i_x^{MC}i_y^{MC} + \sqrt{\frac{5}{2}}\Phi_{f_2}i_y^{MC}\right) \end{cases} \quad (13)$$

5. Vector control of the two-five-phase PMSM

In traction systems, two DC motors connected in series to use only one cutter. The independent torque control can perform by using the Vector Control [14], [12] and [13].

With the five-phase PMSM by serially connecting the stator windings in an appropriate manner figure 4, it becomes possible to control the two machines in a drive system (traction system) independently (vector control principles).

Among the control strategies, the polyphase machines require only two currents to control the flow and torque. Both equations (V_d, V_x) are completely independent; we can control each machine with its vector control dedicated figure 5. We often use that which consists in keeping the component i_d and i_x in zero values, the torques controlled by the components i_q and i_y only, even for speed control [15], [16].

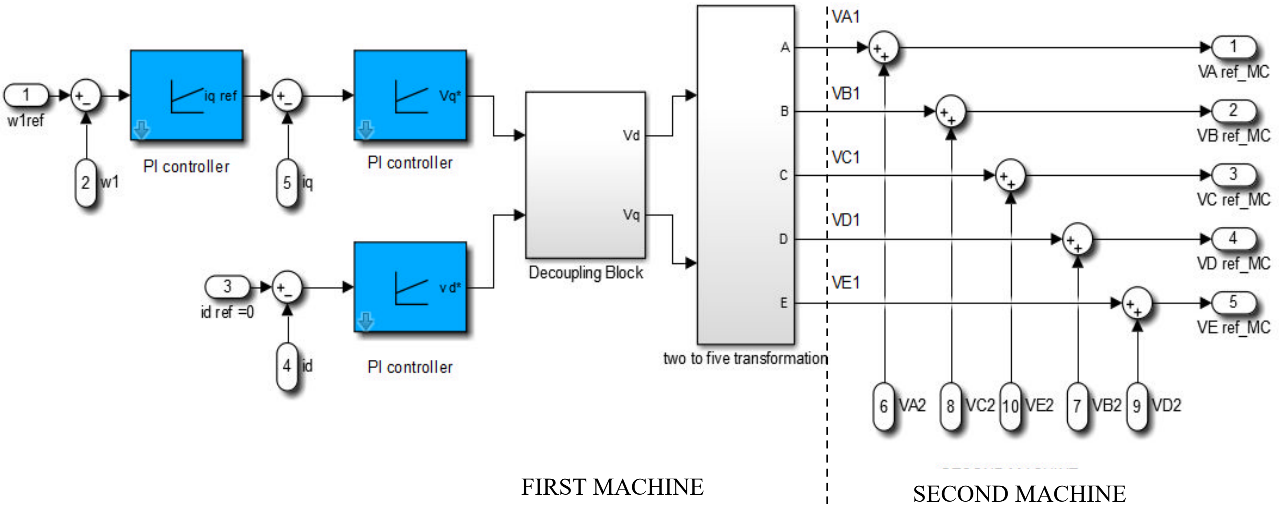

Fig. 5. Vector control Diagram Block of two five-phase PMSM supplied by a single five-matrix converter

6. Simulation results and discussion

6.1 Matrix Converter Output Voltage

The output voltage of the 3-to-5 phase matrix converter *Va [V]* and its harmonic spectrum (f_i=f_o=50Hz) presented in figure 6.

6.2 Decoupling test

We have tested by simulation the vector control rule (Decoupling) of the two five-phase series PMSM supplied by a five-phase matrix converter, with the application of two different setpoints of speed.

Where the first machine runs according to the setpoint 1500 rpm; with a load torque applied at t = 0.5s (Tl= 5N.m), on the other hand, the second machine runs according to the setpoint 750 rpm without applying a load torque, then we replicate the same test between the two machines figures 7-14.

From the obtained results, we note after the decoupling test that:

The speed curve perfectly follows its reference and which reached it very quickly with a standards response time. The effect of the disturbance is removed (due to the load torque), and the electromagnetic torque stabilizes at the value of five

N.m, the response of the two currents components clearly shows the decoupling introduced by the vector control of the two series connected five-phase PMSM. The currents id and i_x are with zero values; the current i_q is the image of the couple $T_{e1}$and i_y is the image of the couple T_{e2}.

As can be seen, the excitation of both machines is independent. All amounts remain undisturbed in both machines during the torque transients. Moreover, the application of the load torque to one of the machines does not have any impact on the torque in the other motor, and vice versa. According to these results, we have obtained the completely decoupled control.

According to the simulation results, concerning the performance achieved by the association of a single Matrix converter-two five-phase series PMSM, has the same performance as the association of a single Inverter-two five-phase series PMSM.

6.3 Traction System application

For this test, we used by simulation the vector control law of the two five-phase series PMSM fed by a single five phase matrix converter, with the application of the one-speed setpoint for the whole system. We supposed that our set of Machines-single converter is one of electric traction system part, which integrates two wheels motors (two PMSM) supplied by a five-phase matrix converter, the setpoint of control for this system is a speed test profile, which expresses the evolution of the traction vehicle speed.

According to the results of simulation of the last test, the two machines have the same performances; they turn at the same rate during all the time of test profile. From the obtained results it is suitable to add the application (two PMSM in series) to the electric traction vehicles figures 15 and 16.

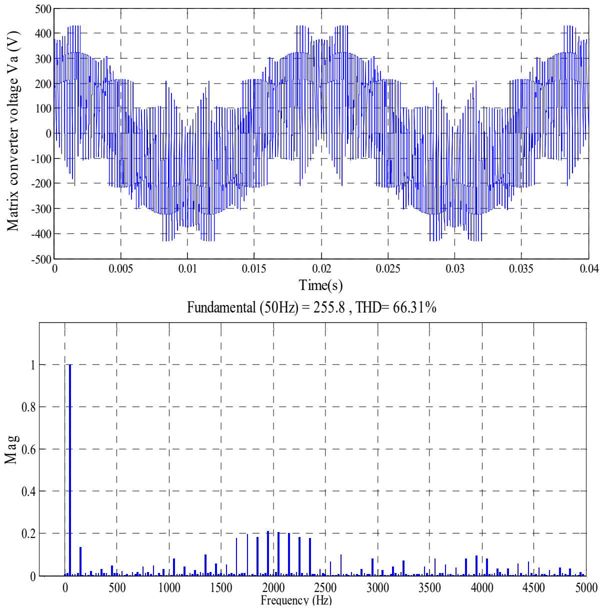

Fig. 6. Output voltage of the 3-to-5 phase matrix converter *Va [V]* and its harmonic spectrum

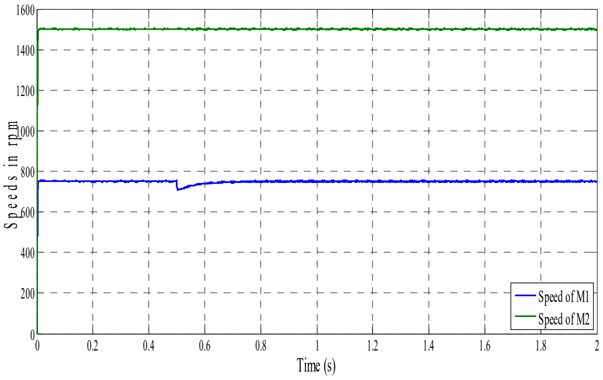

Fig. 7.Speeds of the two machines (M1&M2) with load torque application at 0.5s for M1.

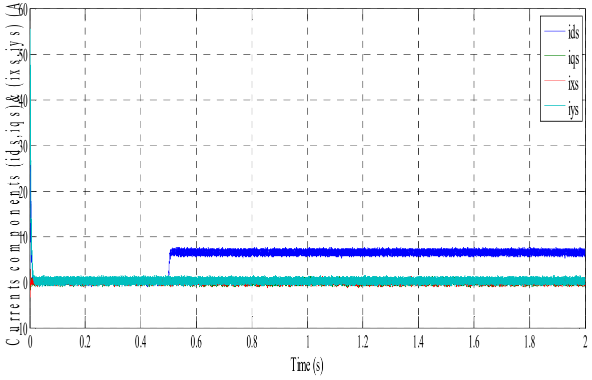

Fig. 8. Currents components of the two machines (M1&M2) with load torque application at 0.5s for M1.

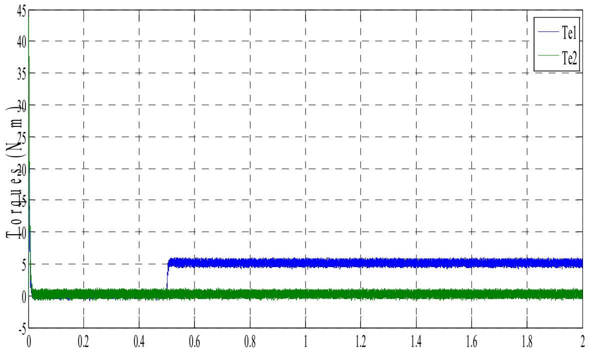

Fig. 9. Torques of the two machines (M1&M2) with load torque application at 0.5s for M1.

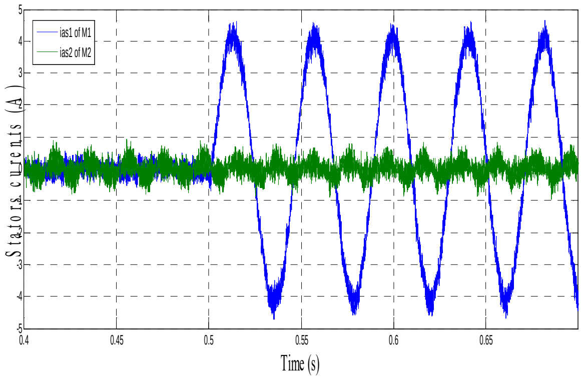

Fig. 10. Stators Currents of the two machines (M1&M2) with load torque application at 0.5s for M1.

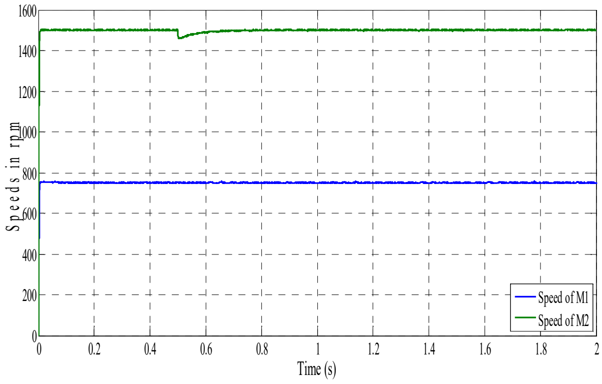

Fig. 11.Speeds of the two machines (M1&M2) with load torque application at 0.5s for M2.

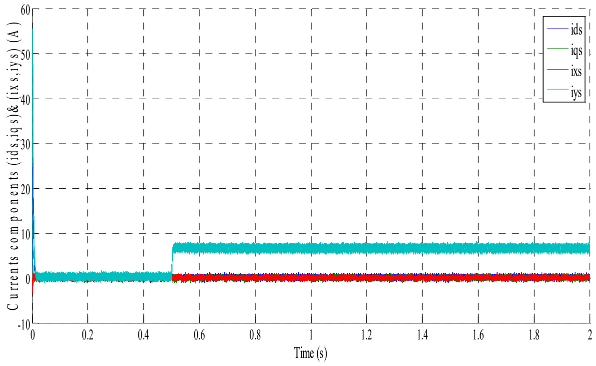

Fig. 12. Currents components of the two machines (M1&M2) with load torque application at 0.5s for M2.

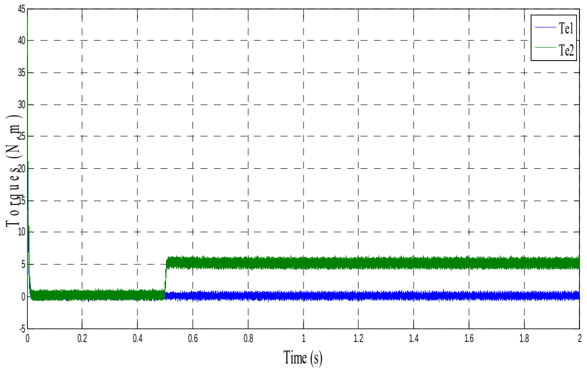

Fig. 13. Torques of the two machines (M1&M2) with load torque application at 0.5s for M2.

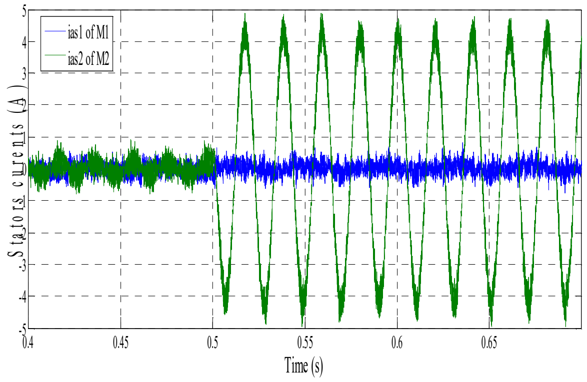

Fig. 14. Stators Currents of the two machines (M1&M2) with load torque application at 0.5s for M2.

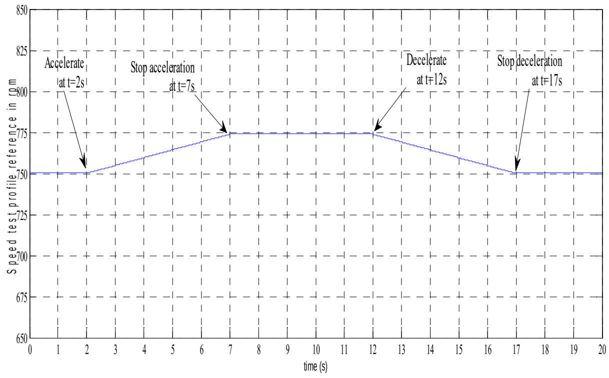

Fig. 15. Speed test profile reference for the two machines in rpm.

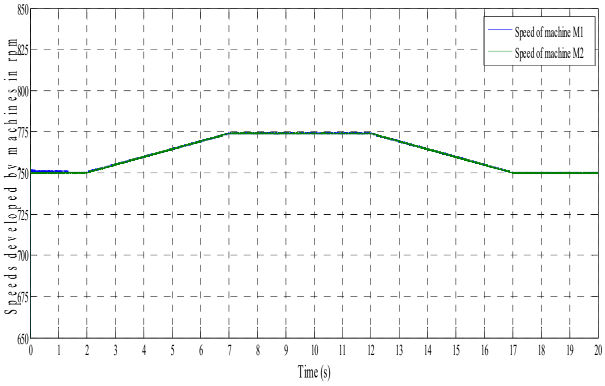

Fig. 16. Speed developed by the two machines in rpm.

7. Conclusion

Our work is to improve the performance and to drive the multi-machines system (two five-phase series connected PMSM) with a three-to-five phase matrix converter, we have selected this set (multi-machine-single converter) because it is an essential element in electric traction system.

We have briefly seen the modeling of the used converter and one of its control algorithms, then the model of the two five-phase series connected PMSM, we have based in this modeling on the general theory of electrical machines and the d-q axis model.

After that, we have tested the decoupled vector control of that system, by using a single five-phase matrix converter.

We have obtained a completely decoupled control by the independent vector control, which allowed decoupling the flux control and the torque for the two machines, which leads to control several machines in series and with different types of polyphase machines.

The performance obtained from the association of a single Matrix converter-two five-phase series connected PMSM has the same performance as the association of a single Inverter-two five-phase series PMSM.

Moreover, we can reduce the size of the converter, Matrix converter (AC-AC) instead of the inverter.

As an Outlook to use this system (matrix converter-SMM) in the hybrid electric traction vehicle by the study of power management in real time.

References

1. D.Siva Krishna and C.Srinivasa Rao, "*Speed Control of Permanent Magnet Synchronous Motor Based on Direct Torque Control Method*" EEE Department, G.Pulla Reddy Engineering College, Kurnool, A.P, India International Journal of Advances in Science and Technology, Vol. 2, No.3, 2011.
2. A. Sellam, B. Dehiba, M. B. Benabdallah, M. Abid, N.B. Bouiadjra, B. Bensaid, and M. Djouhri, "*A Vectorial modeling for the Permanent Magnet Synchronous Machine (polyphase) based on multimachine approach*" International Journal of Electrical Engineering and Informatics - Volume 5, Number 1, March 2013.
3. T. Finken, M. Hombitzer, and K. Hameyer, "*Study and Comparison of several Permanent- their Applicability in Electric Vehicles Magnet excited Rotor Types regarding Permanent-Magnet excited Rotor Types regarding their Applicability in Electric Vehicles*" IEEE Conference: E mobility - Electrical Power Train, 2010.
4. R. Krishnan "*Permanent Magnet Synchronous and Brushless DC Motor Drives*," Electrical and Computer Engineering Department Virginia Tech Blacksburg, Virginia, U.S.A. 2010.
5. M. Jones, E. Levi, "*Combining Induction and Synchronous Machines in a Seven-Phase Series Connected Three-Motor Drive*", EPE-PEMC'04, Riga (Latvia), CDROM, September 2004.
6. Mohammad Saleh, Atif Iqbal, SK. Moin Ahmed, Akhtar Kalam, and Haitham Abu-Rub *"Carrier-based pulse width modulation technique for a three-to-five phase matrix converter for supplying five-phase two-motor drives"* International Journal of Engineering, Science and Technology Vol. 2, No. 10, 2010, pp. 67-78.
7. Atif Iqbal, Sk Moin Ahmed, and Haitham Abu-Rub *"Space Vector PWM Technique for a Three-to-Five-Phase Matrix Converter"* IEEE transactions on industry applications, Vol. 48, No. 2, March/April 2012.
8. Wheeler P. W., Clare J. C., Empringham L., Bland M. and Kerris K. G., " Matrix converters: A vector controlled MCT matrix converter induction motor drive with minimized commutation times and enhanced waveform quality," IEEE industry applications Magazine, pp. 59-65, JAN/FEB 2004.
9. Gusia S., "Modélisation des systèmes électroniques de puissance à commande MLI : Application aux actionnements électriques", Thèse de Doctorat, Université catholique de Louvain, France, 2005.
10. G. Roy, L. Duguay, S. Manias and G. E. April " *Asynchronous operation of cyclo-converter with improved voltage gain by employing a scalar control algorithm*" In Conf. Rec. IEEE-IAS Annu. Meeting, 1987, pp. 889–898.
11. D.C. White, H.H. Woodson, "*Electromechanical Energy Conversion*," New York, NY: John Wiley and Sons, 1959.
12. Atif Iqbal "*Modeling and control of series-connected five phase and six phase two motor drives*" A thesis submitted in partial fulfillment of the requirements of Liverpool John Moores University for the degree of Doctor of Philosophy, August 2005.
13. M. Jones E. Levi, S.N. Vukosavic, H.A. Toliyat and Atif Iqbal "*Modeling, Control and Experimental Investigation of a Five-Phase Series-Connected Two Motor Drive with Single Inverter Supply*," IEEE Trans. on Industry Applications, vol. 54, no. 3, June2007.
14. J. N. Verhille, A. Bouscayrol, P. J. Barre, J.C. Mercieca, J. P. Hautier, E. Semail, "*Torque tracking strategy for anti-slip control in railway traction systems with common supplies*", IEEE-IAS'04, Seattle (Washington), vol. 4. pp. 2738-2745, October 2004.
15. M. NEKKAZ and A. DJAHBAR "*Modeling and Vector Control of two five-phase synchronous magnet permanent machines (PMSM) connected in series*" Journal of Electrical Engineering (JEE); 2016.
16. E. Levi, M. Jones, S. Vukosavic, and H. Toliyat, "*A five-phase two-machine vector controlled induction motor drive supplied from a single inverter*," European Power Electronics (EPE) and Drives Journal, vol. 14, no. 3, pp. 38 48, 2004.