

Common Mode Output Waveforms Reduction for Matrix Converters Drives

Jordi Espina, Antoni Arias and Josep Balcells
Electronic Department
Universitat Politècnica de Catalunya
Email: espina@eel.upc.edu

Carlos Ortega
Electronic Department
Escola Universitària Salesiana de Sarrià
Email: cortega@euss.es

Abstract- This paper presents an alternative Space Vector Modulation (SVM) implemented in Matrix Converters (MC) which improves and reduces the Common Mode (CM) voltage and current output waveforms. The strategy is based on replacing the MC zero vectors for the rotating ones, which reduces the CM voltage derivative and therefore the leakage CM current. By reducing this CM current, which might flow inside the motor through the bearings and windings, the Permanent Magnet Synchronous Machine (PMSM) deterioration might be slowed down. The paper describes the novel SVM pattern and analyses the CM voltage and its leakage current. Simulation results based on PMSM drive are provided to corroborate the whole idea.

I. INTRODUCTION

Last two decades Matrix Converters (MC) have become more popular and attractive in industrial applications. The principal motivations are compact size, unnecessary reactive elements, power density and bidirectional power flow.

Several MC modulation techniques have been developed and they can be classified with the scalar ones [1], [2] and the vector ones [3], [4]. This paper is based on the double sided Space Vector Modulation (SVM) introduced by Casadei in 2002 [4].

The Common Mode (CM) voltage and current waveforms and its unwanted consequence are addressed in this paper based on the Casadei's SVM [4]. Actually, due to the fast change of Common Mode Voltage (CMV), the leakage currents, which are responsible for the bearings and windings degradation inside the machine, might appear. These leakage or CM currents, which flow through the parasitic capacitance, are a major cause for the machine's lifetime reduction.

There are a wide number of modulation strategies for reducing the CM for modern power converters. Some strategies used in MC have been adapted from voltage source inverter (VSI) and others have been arisen from new contributions using the advantages of MC. One of the most popular techniques to reduce CMV is to determine at any moment which of the zero vectors introduces the smallest amplitude to all output phases and consequently use it [5]. Another technique is based on reducing the voltage derivative and consequently apply the zero vector which minimizes such derivative [6]. Another SVM technique is based on using a couple of active vectors instead of zero vectors to complete the rest of sampling period [7], where these active vectors

should be opposite between them and have the smallest magnitude. Some similar strategy, but applied in direct torque control, was presented in [8]. A predictive strategy, which tries to forecast every moment which vector is the best option, has been presented in [9]. This strategy uses a Quality Function Minimization (QFM) which has in consideration different parameters: output voltage, input factor and CMV. This contribution is based on the use of all available vectors including the rotating ones.

Hardware implementation to reduce CMV is presented in [10], where a CM canceller is inserted between the input filter and the Matrix switches. This canceller consists of an H-bridge and a common-mode transformer, which is used to inject the undesirable common mode voltage.

This paper presents a modification of the double sided SVM [3]. The new strategy consists on replacing the zero vectors for the rotating ones. The use of these rotating vectors reduces the CM voltage derivations and therefore the CM leakage currents. In consequence, the lifetime of the motor is extended and its maintenance-period is enlarged.

II. MATRIX CONVERTER

The Matrix Converter is a direct AC-AC converter without intermediate reactive element, which is considered one of its qualities. Other advantages are less weight, compact size, low cost, power density and bidirectional power flow [11].

These advantages make MCs attractive for special applications such as compact drives, drives in hostile environments, military applications [12], aerospace [13], and renewal energy [14]. This potential market makes this converter attractive for hi-tech industries.

However, MC has some drawback like complex control, a higher number of power switches and ride through capability. All these drawbacks are being solved as the technology is getting mature and makes this converter a hot topic of research.

From Fig. 1, it can be noted that the three MC phases allows any output phase to be connected to any input phase [15]. Only two restrictions have to be considered, the input phase should never be short circuited and the output phase should never be unconnected. Therefore, just 27 switching configurations, shown in Table I, are possible.

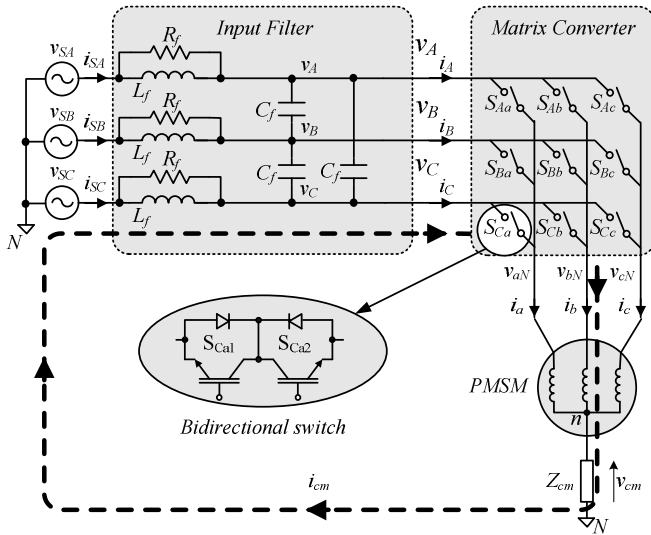


Fig. 1. Matrix Converter scheme and leakage path.

III. COMMON MODE VOLTAGE

This paper studies and shows the effect produced by the current that flows through the leakage paths inside the electrical machines. This leakage current is divided into two main paths: between windings and chassis and through bearings.

It is quite important to determine the parasitic impedance that appears inside the machines, because they create the unwanted leakage paths where the unwanted current can flow. Some studies have introduced different parasitic impedance models as [16], [17].

Other studies prove that the leakage currents are the main cause for bearing lifetime degradation [18], [19].

Fig. 1 shows the Common Mode Voltage (v_{CM}) and the leakage path. Where, Z_{cm} is the parasitic complex impedance which it is mainly composed for a capacitor.

The common-mode voltage v_{CM} at the motor's neutral point is showed in equation (1) [6], [7].

$$v_{CM} = \frac{(v_{aN} + v_{bN} + v_{cN})}{3} \quad (1)$$

Therefore, if a capacitor is intrinsically included between active parts of the motor, and one of them has fast and large commutations, then the leakage current will appear which will behavior like equation (2).

$$i_c = C \cdot \frac{dv}{dt} \quad (2)$$

IV. COMMON MODE REDUCTION MODULATION PATTERN

The rotating vectors are not usually used in modulation strategies because they lay in different position, so it is difficult to create a repetitive pattern. Whereas they introduce a common mode voltage equal to zero, provided that the input voltages are balanced.

TABLE I
MC OUTPUT VOLTAGE & INPUT CURRENT VECTORS

	$a b c$	$ \bar{v}_o $	α_o	$ \bar{i}_i $	β_i
+1	A B B	$2/3 v_{AB}$	0	$2/\sqrt{3} i_a$	$11\pi/6$
+2	B C C	$2/3 v_{BC}$	0	$2/\sqrt{3} i_a$	$\pi/2$
+3	C A A	$2/3 v_{CA}$	0	$2/\sqrt{3} i_a$	$7\pi/6$
+4	B A B	$2/3 v_{AB}$	$2\pi/3$	$2/\sqrt{3} i_b$	$11\pi/6$
+5	C B C	$2/3 v_{BC}$	$2\pi/3$	$2/\sqrt{3} i_b$	$\pi/2$
+6	A C A	$2/3 v_{CA}$	$2\pi/3$	$2/\sqrt{3} i_b$	$7\pi/6$
+7	B B A	$2/3 v_{AB}$	$4\pi/3$	$2/\sqrt{3} i_c$	$11\pi/6$
+8	C C B	$2/3 v_{BC}$	$4\pi/3$	$2/\sqrt{3} i_c$	$\pi/2$
+9	A A C	$2/3 v_{CA}$	$4\pi/3$	$2/\sqrt{3} i_c$	$7\pi/6$
-1	B A A	$-2/3 v_{AB}$	0	$-2/\sqrt{3} i_a$	$11\pi/6$
-2	C B B	$-2/3 v_{BC}$	0	$-2/\sqrt{3} i_a$	$\pi/2$
-3	A C C	$-2/3 v_{CA}$	0	$-2/\sqrt{3} i_a$	$7\pi/6$
-4	B A A	$-2/3 v_{AB}$	$2\pi/3$	$-2/\sqrt{3} i_b$	$11\pi/6$
-5	C B B	$-2/3 v_{BC}$	$2\pi/3$	$-2/\sqrt{3} i_b$	$\pi/2$
-6	A C C	$-2/3 v_{CA}$	$2\pi/3$	$-2/\sqrt{3} i_b$	$7\pi/6$
-7	B A B	$-2/3 v_{AB}$	$4\pi/3$	$-2/\sqrt{3} i_c$	$11\pi/6$
-8	C B C	$-2/3 v_{BC}$	$4\pi/3$	$-2/\sqrt{3} i_c$	$\pi/2$
-9	C C A	$-2/3 v_{CA}$	$4\pi/3$	$-2/\sqrt{3} i_c$	$7\pi/6$
0 _A	A A A	0	0
0 _B	B B B	0	0
0 _C	C C C	0	0
+r ₁	A B C	v_{JMAX}	$[v_{JMAX}]$	i_{oMAX}	$[i_{oMAX}]$
+r ₂	C A B	v_{JMAX}	$[v_{JMAX}+2\pi/3]$	i_{oMAX}	$[i_{oMAX}+2\pi/3]$
+r ₃	B C A	v_{JMAX}	$[v_{JMAX}+4\pi/3]$	i_{oMAX}	$[i_{oMAX}+4\pi/3]$
-r ₁	A C B	v_{JMAX}	$[-v_{JMAX}]$	i_{oMAX}	$[-i_{oMAX}]$
-r ₂	B A C	v_{JMAX}	$[-v_{JMAX}+2\pi/3]$	i_{oMAX}	$[-i_{oMAX}+2\pi/3]$
-r ₃	C B A	v_{JMAX}	$[-v_{JMAX}+4\pi/3]$	i_{oMAX}	$[-i_{oMAX}+4\pi/3]$

Where, \bar{v}_o is output voltage vector, \bar{i}_i is input current vector, ± 1 - ± 9 are active vectors, 0_A - 0_C are zero vectors and $\pm r_1$ - $\pm r_3$ are rotating vectors [4],[15].

Fig. 2 is composed for three subfigures which show three principal regions of sector 1, the two edges and center. These figures show the main voltage created by MC using a standard SVM with zero vectors. Where, the reference output voltage vector is at sector 1 and the input voltage vector phase is split in -30° , 0° and 30° inside of sector 1.

The Fig. 3 shows the SVM modulation pattern proposed when using the rotating vectors instead of the zero ones. Either the three positive or negative rotating vectors must be used in each pattern in order to keep the fundamental voltage unchanged as shown in Fig. 4.

The same duty cycles obtained for the three nulls vectors will be applied for the three rotating ones.

Notice how in Fig. 3 the common voltage (v_{Nn}) is equal to zero whenever the rotating vectors are applied.

The main improvement using rotating vectors is the reduction of the number of dv/dt for each period.

Fig. 4 shows graphically the composition and behavior of output voltage vector using rotating vectors. In this case the rotating vectors have 0° phase and the output voltage is inside of sector 1.

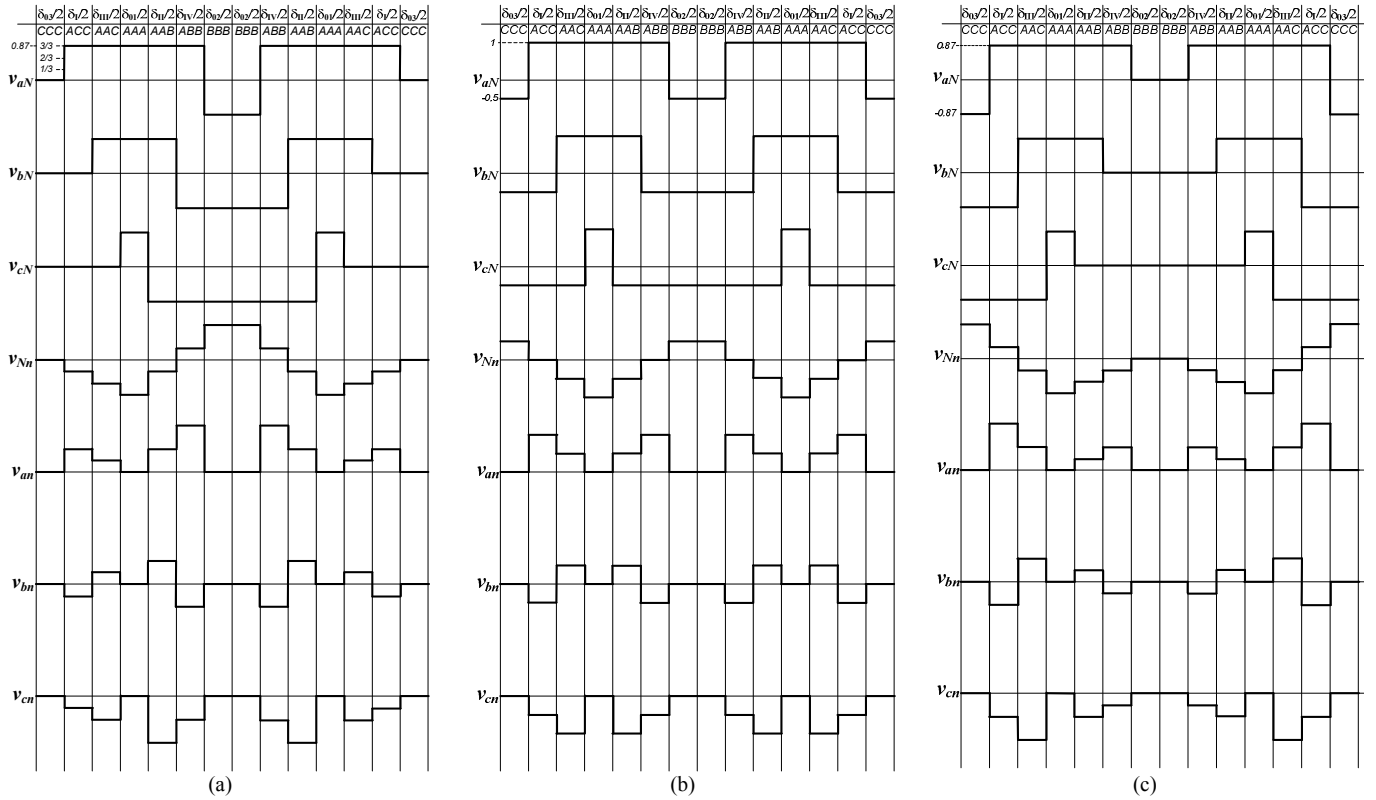


Fig. 2 Modulation switching pattern using zero vectors. When input vector lies at (a) -30° , (b) 0° and (c) 30° . ($\delta_1, \delta_2, \delta_3, \delta_4, \delta_5, \delta_6, \delta_7, \delta_8$ are the SVM duty-cycles).

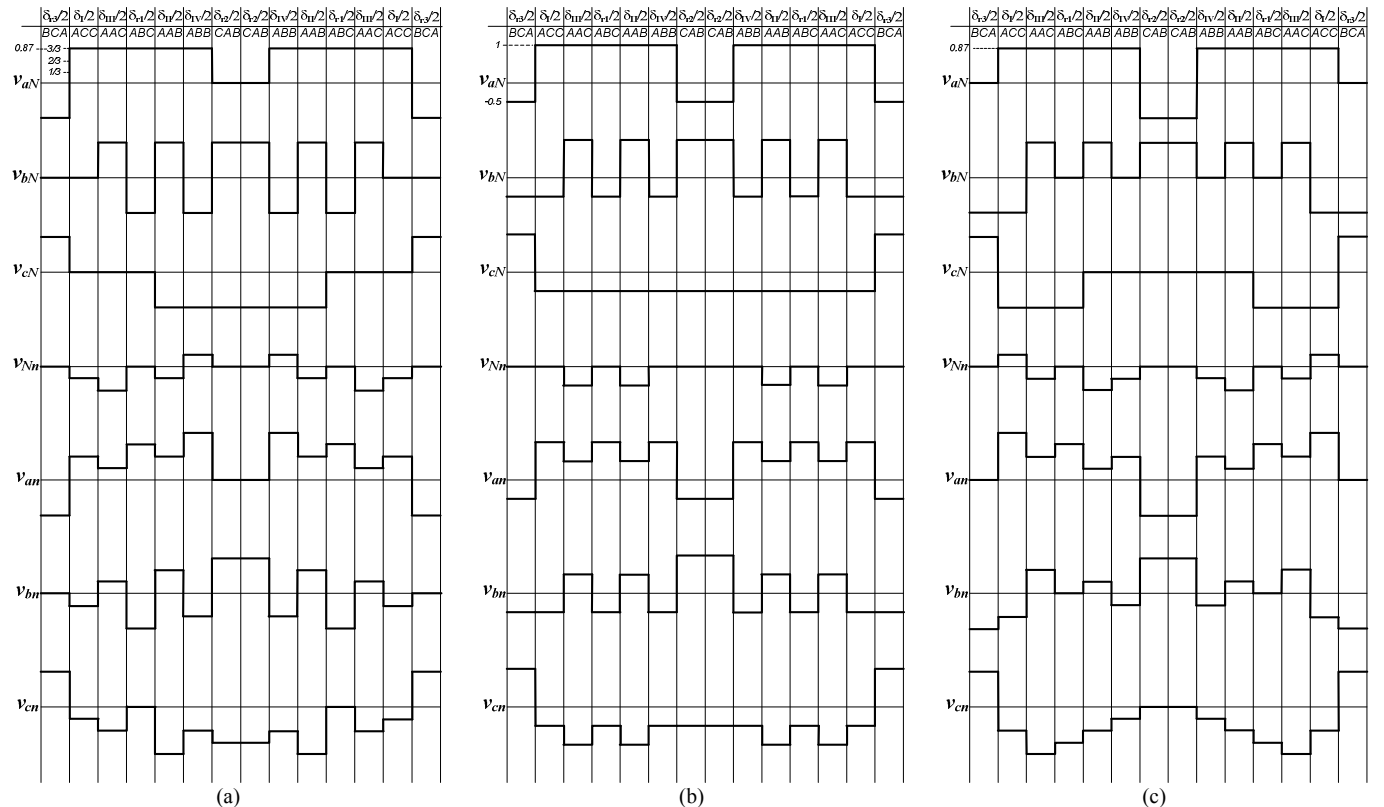


Fig. 3 Modulation switching pattern using rotating vectors. When the input voltage vector lies at (a) -30° , (b) 0° and (c) 30° . ($\delta_1, \delta_2, \delta_3$ are the rotating vectors duty-cycles).

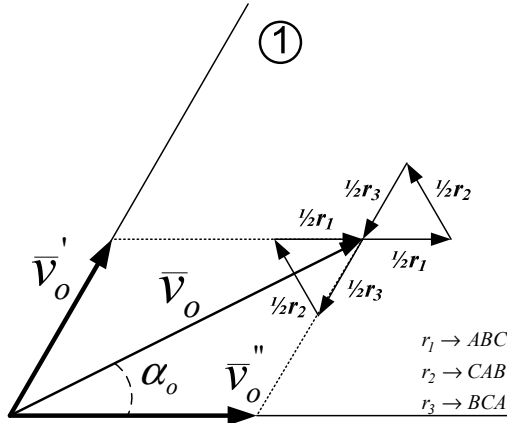


Fig. 4 Output voltage vector composition with rotating vectors.

In every instant of time the position of rotating vectors will be different but if they are equilibrate then their addition will be zero and consequently their contribution too. Equations (3) and (4) show voltage and current contribution in common-mode.

$$v_{aN} + v_{bN} + v_{cN} = 0 \quad (3)$$

$$i_a + i_b + i_c = 0 \quad (4)$$

V. SIMULATION RESULTS

In order to do this simulation, the set-up and load applied are next: Matrix model with input filter effect, SVM [4], control field oriented control FOC and permanent magnet synchronous motor (PMSM) with technical characteristics showed in Table II.

TABLE II
MOTOR PMSM YASKAWA

Output power	200 W	Lq	8.6 mH
Rated current	2 A	Magnet flux	0.046 Wb
Voltage	100 V	Rated torque	0.64 Nm
Pole pairs	4	Rated speed	3000 r.p.m
Stator resistance	2.5 Ω	Friction	1·10 ⁻⁴ Nm·s
Ld	8.3 mH	Inertia	0.2·10 ⁻⁴ kg·m ²

The simulations showed in this section illustrate a comparative between SVM using zero vectors and other using rotating vectors. To appreciate with more detail, it has showed a complete double-side commutation that will permit appreciate switch differences. Furthermore for each SVM strategy has showed when output voltage vector is in sector 1 and input voltage vector lies at -30° , 0° and 30° , where they give a repetitive pattern for the rest of sectors.

Fig. 6 and Fig. 7 show the comparative between zero vectors strategy and rotating vectors. Where: v_{aN} , v_{bN} , v_{cN} are the phase voltage between matrix output and ground grid N . v_{Nn} represents the voltage showed in equation (1) and v_{an} , v_{bn} ,

v_{cn} are voltages between output and ground motor. These voltages can be appreciated on Fig. 1.

A simple overview can appreciate that the number of dv/dt on voltage v_{Nn} has been reduced. This reduction varies depending of the position of input voltage inside each sector, where the maximum reduction is located at the centre of sector and it decreases when the input vector voltage approximates of sector's edges. This reduction achieved stays between 11% until 33.34% where they appears on edges (-30° , 30°) and center (0°) respectively.

Experimental measures have been carried out to determine the impedance there between windings and chassis. The instrument used to take the impedance is a vector network analyzer of Rohde&Schwarz, which is an impedance analyzer for high frequency. It can realize a frequency sweep where it permits to know with detail the impedance model. Fig. 5 shows the impedance measured on the Yaskawa PMSM.

From Fig. 5 complex impedance model can be extracted, however important simplification can be applied because the system is simplified to a first order capacitive model, which is the real leakage current path for the CMV. The capacitor value obtained is 80pF approx.

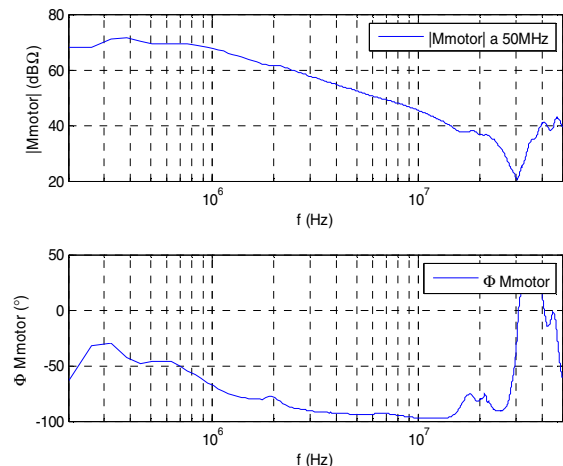


Fig. 5. Motor's impedance measure between windings and chassis.

Figs. 8 show the current in CM (i_{CM}) which flows through the previously obtained parasitic capacitor within one switching period. Fig. 8.a shows i_{CM} when input vector is at -30° , Fig. 8.b shows i_{CM} with input voltage at 0° and Fig.8.c shows i_{CM} when input voltage at 30° . Moreover Figs. 9 also show i_{CM} current with same set-up but using rotating vector instead of zero vectors.

A brief overview it can be observed that current amplitude from strategy using rotating vectors is less than strategy using zero vectors. That confirms the previous simulation results.

VI. CONCLUSIONS

This paper has been focused on the reduction of the Common Mode leakage currents when using Matrix Converters fed Drives.

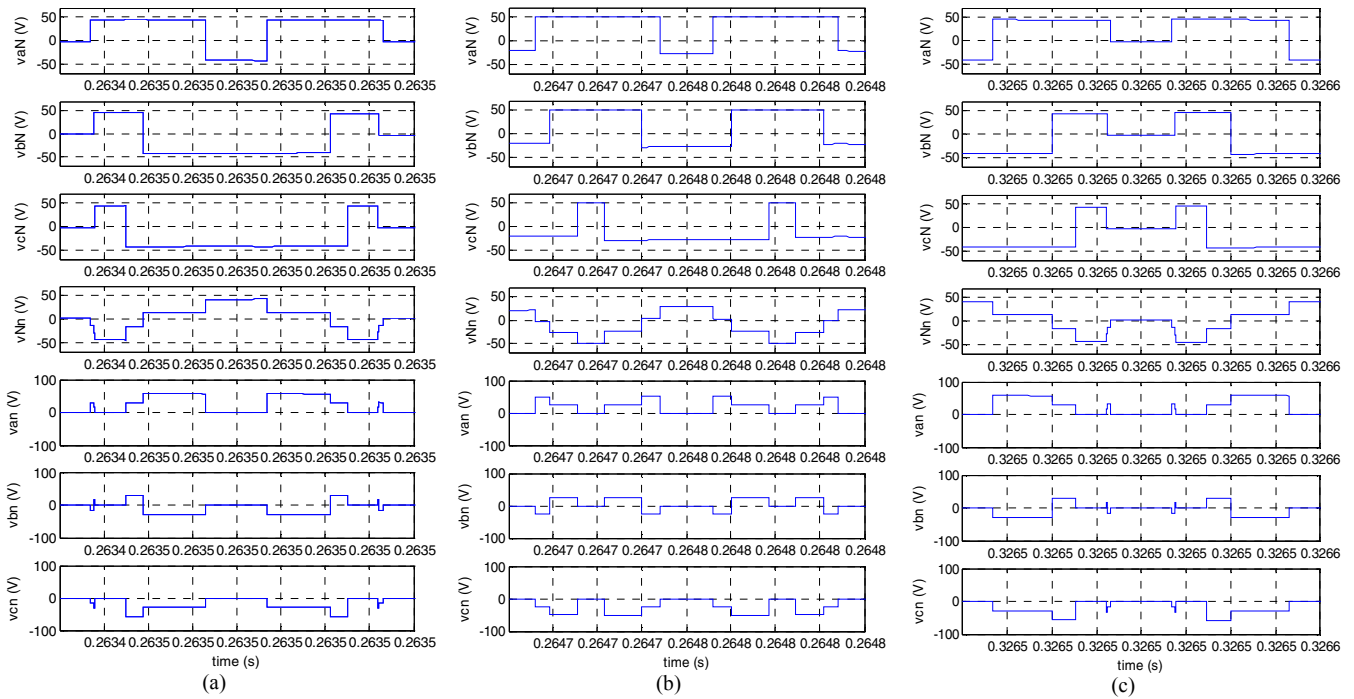


Fig 6 Switching pattern using zero vectors. When input vector lies at (a) -30° , (b) 0° , (c) 30° .

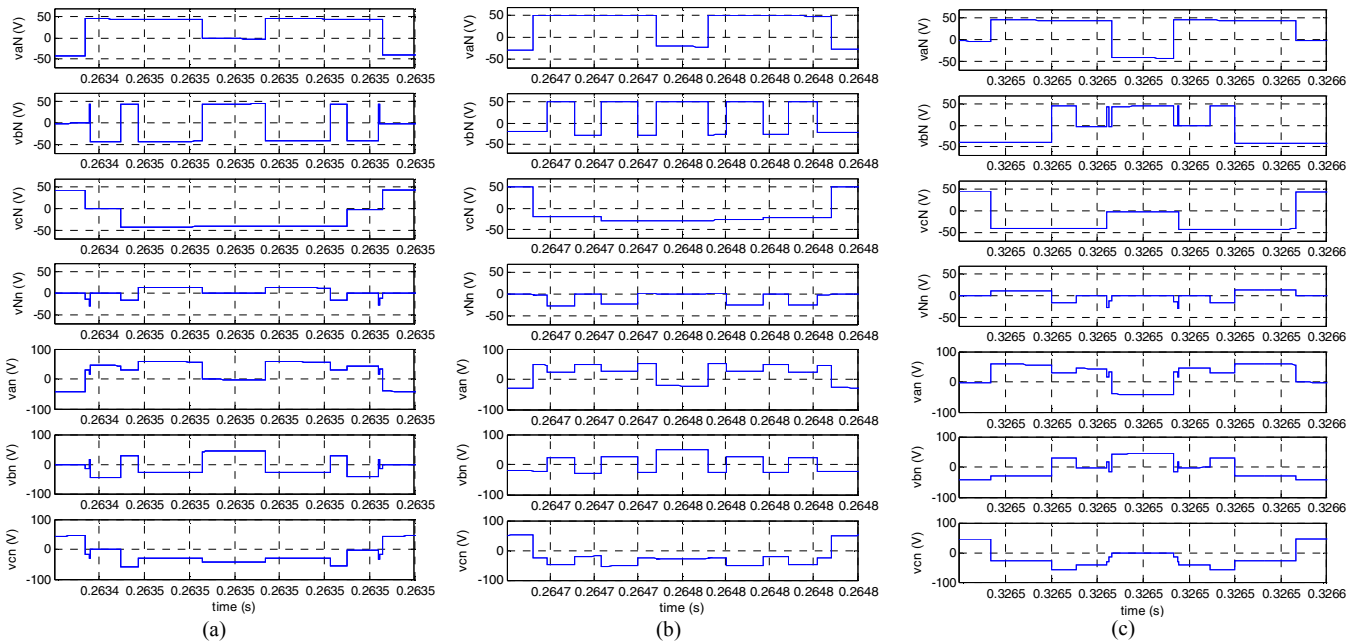


Fig 7 Switching pattern using rotating vectors, When input vector lies at (a) -30° , (b) 0° , (c) 30° .

A brief Matrix Converter and Common mode voltage overview have been introduced. The substitution of the zero Matrix Converters vectors for the rotating ones in such pattern has been the main contribution for the Common Mode reduction.

This new Space Vector Modulation pattern reduces the unwanted leakage current that flows through stators windings and bearings, without changing the fundamental output voltages and input currents. Simulation results show a potential Common Mode derivative voltage reduction range from 11% to 33.34%, depending of the input vector's

position. This reduction is not enough to solve the problem with machine lifetime reduction but it is a good outset to solve it.

Currently, it is carried out the switching frequency and losses evaluations of this novel modulation pattern.

ACKNOWLEDGMENT

The authors acknowledge the financial support received from "Ministerio de Ciencia e Innovación de España" for realizing this work under "TEC2007-61582" research project.

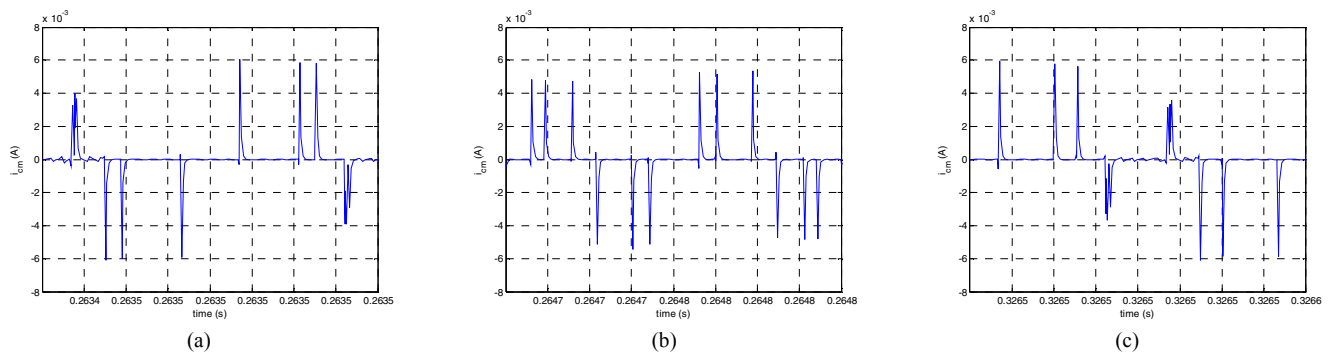


Fig. 8 Current i_{CM} with zero vectors (a) Sector 1 at -30° . (b) Sector 1 at 0° (c) Sector 1 at 30° .

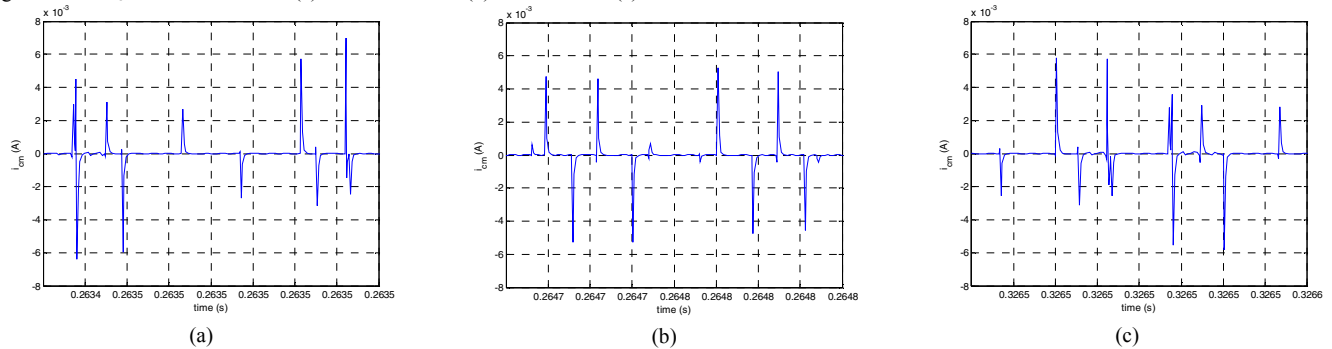


Fig. 9 Current i_{CM} with rotating vectors (a) Sector 1 at -30° . (b) Sector 1 at 0° (c) Sector 1 at 30°

REFERENCES

- [1] A. Alesina and M. Venturini, "Solid-state power conversion: A Fourier analysis approach to generalized transformer synthesis," *IEEE Trans. Circuits Syst.*, vol. CAS-28, pp. 319–330, Apr. 1981
- [2] A. Alesina and M. G. B. Venturini, "Analysis and design of optimum amplitude nine-switch direct AC–AC converters," *IEEE Trans. Power Electron.*, vol. 4, pp. 101–112, Jan. 1989.
- [3] L. Huber and D. Borojovic, "Space vector modulation with unity input power factor for forced commutated cycloconverters" in *Conf. Rec. IAS Annu. Meeting*, 1991, pp. 1032–1041.
- [4] D. Casadei, G. Serra, A. Tani and L. Zarri, "Matrix Converter Modulation Strategies A new General Approach Based on Space-vector Representation of the Switch State" *IEEE Trans. Industrial Electronics*, vol 49, No 2, April 2002.
- [5] H. Ju Cha and P. N. Enjeti, "An Approach to Reduce Common-Mode Voltage in Matrix Converter" *IEEE Trans. Industrial Applications*, vol 39, No 4, July/August 2003.
- [6] J. Kang and et al. "Common-Mode Voltage Characteristics of Matrix Converter-Driven AC Machines" in *Conf IAS Annu Meeting*, 2005, pp. 2382–2387.
- [7] H. Lee, H. M. Nguyen and E. Jung, "A Study on Reduction of Common-Mode Voltage in Matrix Converter with Unity Input Power Factor and Sinusoidal Input/Output Waveforms" in *Annual Conf IECON*, 6–10 November, 2005.
- [8] C. Ortega, A. Arias and C. Caruana, "Common Mode Voltage in DTC drives using Matrix Converters" in *Conf ISIE*, 2008, pp 526–531.
- [9] R. Vargas, U. Ammann, J. Rodriguez and J. Pontt, "Predictive Strategy to Control Common-Mode Voltage in Loads Fed by Matrix Converters" *IEEE Trans. Industrial Electronics*, vol 55, No 12, December 2008.
- [10] F. Yue, P. Wheeler and J. Clare, "Cancellation of 3rd Common-mode Voltage Generated by Matrix Converter" in *conf IECON*, 2005.
- [11] J. Kolar, T. Frielli, F. Krismer and S. Round, "The essence of three phase AC/AC converter system" *Przeglad Elektrotechniczny*, pp 14–29, July 2008.
- [12] T. Podlesak and D. Katsis, "A 150-kVA Vector-Controlled Matrix Converter Induction Motor Drive" *IEEE Trans Industrial Applications*, vol 41, No3, May/June 2005.
- [13] M. Aten, C. Whitley, G. Towers, P. Wheeler, J. Clare and K. Bradly, "Dynamic performance of a matrix converter driven electro-mechanical actuator for an aircraft rudder" in *conf PEMD*, vol 1, pp 326–331, April 2005.
- [14] S. Zhang and K.J. Tseng, "Modeling, Simulation and Analysis of Conducted Common-Mode EMI in Matrix Converters for Wind Turbine Generators" in *Conf EPE-PEMC*, September, 2008.
- [15] P. Wheeler, J. Rodriguez, J. Clare, L. Empringham and A. Weinstein, "Matrix Converter: A Technology Review" *IEEE Trans. Industrial Electronics*, vol 49, No 2, April 2002.
- [16] M. Cacciato, A. Consoli, G. Scarcella and A. Testa, "Reduction of Common Mode Currents in PWM Inverter Motor Drives" in *conf IAS*, vol 1, pp 707–714, 1997.
- [17] F. Costa, C. Vollaie and R. Meuret, "Modeling of Conducted Mode Perturbations in Variable-Speed Drive Systems" *IEEE Trans. Electromagnetic Compatibility*, vol 47, No 4, November 2005.
- [18] J. Olilla and T. Hammar, "On the bearings currents in medium power variable speed AC drives" in *Conf EMDC*, May 1997.
- [19] D. Busse and J. Erdam, "Bearing currents and their relationship to PWM Drives" *IEEE Trans. Power Electronics*, vol 12, No 2, March 1997.