ELectronics EXpress

IEICE Electronics Express, Vol.7, No.4, 281–287

Space Vector Modulation strategy to reduce the Common Mode perturbations in Matrix Converters

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Abstract: An alternative Space Vector Modulation (SVM) strategy which reduces the Common Mode (CM) perturbations when using Matrix Converters (MC) is presented in this work. The proposed method maintains the conventional SVM pattern but the zero vectors, which have been shown to introduce not only high CM voltage values but also high CM voltage time derivative. Hence the three zero vectors are replaced by three rotating ones, in such a way that the fundamental output voltage vector and the input current direction remains both unchanged. Results of the proposed SVM strategy driving a Permanent Magnet Synchronous Machine (PMSM) are provided to confirm the effectiveness of the method.

Keywords: Common Mode Voltage, Space Vector Modulation, Matrix Converter, EMC

Classification: Electromagnetic compatibility (EMC)

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DOI: 10.1587/elex.7.281
Received December 29, 2009
Accepted January 20, 2010
Published February 25, 2010

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1 Introduction

The CM voltage produced by modern power converters is known as one of the main sources of early motor winding failure and bearing deterioration. Moreover, high frequency components and large amplitudes of the CM voltage between the machine neutral point and ground have been shown to generate high frequency currents to the ground path and induced shaft voltage [1], reducing the machine operational life. Several methods to reduce the CM voltage have been proposed in the literature [1, 2], however, these methods seem to be limited to three-phase Voltage Source Inverter (VSI) systems.

In the last decade, Matrix Converters (MC) have received considerable attention as they are becoming a good alternative to the standard VSI. Recently, a variety of modulation strategies to mitigate the effects of the CM voltage at the output of MCs are appearing in the literature. For instance in [3], a new modulation pattern selects the absolute lowest input phase voltage as a zero vector without changing the active voltage vectors. Also, the reduction of the CM voltage time derivatives are addressed in [4], developing a new Pulse-Width Modulation (PWM) pattern which selects voltages vectors with the lowest contribution to the CM voltage amplitude. In [5], the zero vectors of the conventional SVM [6] are replaced by two active vectors with the same amplitude and opposite direction. The selection of the voltage

DOI: 10.1587/elex.7.281
Received December 29, 2009
Accepted January 20, 2010
Published February 25, 2010

input phase with the minimum absolute value, as a zero vector, is proposed in [7] for a Direct Torque Control using MC. Based on a predictive algorithm, a quality function which minimizes the CM voltage is proposed in [8]. Hardware modifications have been also proposed, inserting a CM voltage canceller between the input filter and the MC [9].

This paper proposes an alternative double-sided SVM pattern for MC by replacing the zero vectors by a set of three rotating ones, in such a way that the fundamental output voltage vector remains unchanged. A significant reduction of the CM voltage, its time derivatives and the CM leakage currents is achieved with the proposed method without increasing the system complexity.

2 Matrix Converter

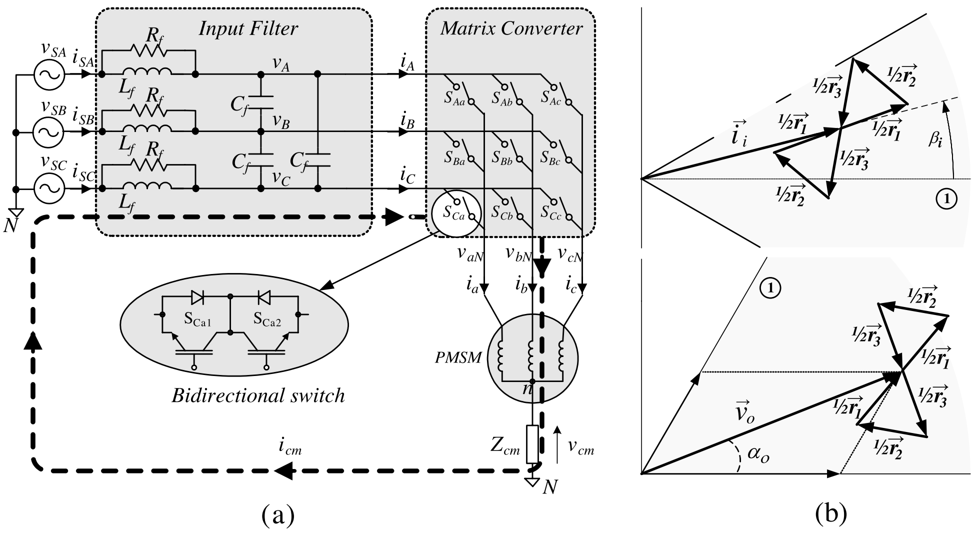

Fig. 1. (a) Matrix Converter scheme driving a PMSM with the leakage current path. (b) Composition of the output voltage and input current direction references using rotating vectors instead of zero ones.

MCs are direct AC-AC four quadrant converters, which connects a multiphase load with a multiphase AC power supply, where the most used topology is the three phase to three phase illustrated on Fig. 1. The lack of an intermediate reactive element is considered one of its main advantages, as well as less weight, compact size, low cost, power density and bidirectional power flow [10]. These advantages make MCs attractive for special applications such as compact drives, drives in hostile environments, including aerospace applications, and renewable energy.

From Fig. 1 (a), it can be noted that the MC allows any output phase to be connected to any input phase [11]. Only two restrictions must be considered: input phases should never be short circuited and output phases should never be unconnected. Therefore, just 27 switching configurations are possible in a

DOI: 10.1587/elex.7.281
Received December 29, 2009
Accepted January 20, 2010
Published February 25, 2010

ELectronics EXpress

Table I. MC Output Voltage & Input current vectors.

	abc	$\lvert\vec{v}_o\rvert$	α_o	$\lvert\vec{i}_i\rvert$	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	A B A	$-2/3 v_{AB}$	$2\pi/3$	$-2/\sqrt{3}\, i_b$	$11\pi/6$
-5	B C B	$-2/3 v_{BC}$	$2\pi/3$	$-2/\sqrt{3}\, i_b$	$\pi/2$
-6	C A C	$-2/3 v_{CA}$	$2\pi/3$	$-2/\sqrt{3}\, i_b$	$7\pi/6$
-7	A A B	$-2/3 v_{AB}$	$4\pi/3$	$-2/\sqrt{3}\, i_c$	$11\pi/6$
-8	B C 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	$1/\sqrt{3}\, v_{ijMAX}$	$[v_{ijMAX}]$	i_{oMAX}	$[i_{oMAX}]$
$+r_2$	C A B	$1/\sqrt{3}\, v_{ijMAX}$	$[v_{ijMAX}+2\pi/3]$	i_{oMAX}	$[i_{oMAX}+2\pi/3]$
$+r_3$	B C A	$1/\sqrt{3}\, v_{ijMAX}$	$[v_{ijMAX}+4\pi/3]$	i_{oMAX}	$[i_{oMAX}+4\pi/3]$
$-r_1$	A C B	$1/\sqrt{3}\, v_{ijMAX}$	$[-v_{ijMAX}]$	i_{oMAX}	$[-i_{oMAX}]$
$-r_2$	B A C	$1/\sqrt{3}\, v_{ijMAX}$	$[-v_{ijMAX}+2\pi/3]$	i_{oMAX}	$[-i_{oMAX}+2\pi/3]$
$-r_3$	C B A	$1/\sqrt{3}\, v_{iiMAX}$	$[-v_{iiMAX}+4\pi/3]$	i_{oMAX}	$[-i_{oMAX}+4\pi/3]$

3×3 MC and are shown in Table I in which v_{ijMAX} is the maximum voltage between phase i and phase j, and i_{oMAX} is the maximum load current.

The permitted switching states of a 3×3 MC are shown in Table I, and have been classified in three groups. The first group contains the active states (± 1, ± 2, ± 3), (± 4, ± 5, ± 6), and (± 7, ± 8, ± 9), characterized by a variable amplitude, depending on the line-to-line voltage instant value, but stationary position (*pulsating vectors*). Zero vectors 0_A, 0_B and 0_C, correspond to the second group and connects all three outputs to the same input phase. The last group is composed by 6 rotating vectors which connects each output line to a different input line.

3 Common Mode Voltage

A PMSM fed by a MC is shown in Fig. 1 (a), where the impedance Z_{CM} represents the leakage current path between the machine's and the mains neutral points, (n) and (N) respectively. In this research, the CM voltage (v_{CM}) is defined as the voltage between these two points (v_{nN}). When a balanced system is considered [7], this CM voltage can be expressed as:

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

Where, v_{aN}, v_{bN} and v_{cN} are the MC output voltages with respect to mains neutral point (N).

DOI: 10.1587/elex.7.281
Received December 29, 2009
Accepted January 20, 2010
Published February 25, 2010

It is necessary to accurately determine the parasitic impedance Z_{CM} to correctly evaluate the leakage current, which is considered to be the main source of winding failure and bearing early deterioration. A variety of models considering the current path between windings and through bearings can be found in the literature [12] and a generalized agreement exists in considering this impedance mainly as a capacitance (C_{CM}). Therefore, high values of the leakage current will appear when fast and large changes in the CM voltage occurs, as shown in Eq. (2),

$$i_{CM} = C_{CM}\frac{dv_{CM}}{dt}. \tag{2}$$

In order to reduce the CM perturbations and consequently extend the machine's operational life [13], not only the CM voltage value but also its time derivative (dv_{CM}/dt) should be reduced.

4 CM perturbations reduction using MCs

The fundamental output voltage vector ($\vec{v}_o$) and the input current direction references (β_i) are full filled by the SVM using a double sided PWM sequence composed by four active vectors and the three zero vectors [6], where the active vectors determine the direction and the zero vectors the amplitude. In order to reduce the commutation switching frequency, zero vectors are usually placed in the beginning, center and end of the PWM period [6]. However, the CM voltage introduced by the zero vectors might be higher than any other MC vector [3, 7].

On the other hand, rotating vectors from Table I are normally not used in any SVM technique. However, since the application of rotating vectors implies a direct connection between the mains and the load, their CM voltage will be zero, provided that the input voltages are balanced.

The contribution presented in this paper relies on replacing the three zero vectors by either the three vectors rotating in clockwise direction ($-\vec{r}_1$, $-\vec{r}_2$, $-\vec{r}_3$) or the three rotating in anticlockwise direction, ($+\vec{r}_1$, $+\vec{r}_2$, $+\vec{r}_3$) maintaining the same duty cycles as for the zero vectors in the original SVM pattern. Since the addition of the three applied rotating vectors will always be zero, the fundamental output voltage and the direction of the input current will be kept unaltered as shown in Fig. 1 (b). The switching frequency and the output current distortion, although, will be slightly increased.

In addition to the contribution of null CM voltage, the application of rotating vectors will introduce, in the worse case, a CM voltage derivative of [7]:

$$\frac{dv_{CM}}{dt}|_{\max} = \frac{V_{pN}}{\sqrt{3}t_{sw}} \approx 0.58\frac{V_{pN}}{t_{sw}}. \tag{3}$$

in contrast to the maximum derivative value obtained when zero vectors are used:

$$\frac{dv_{CM}}{dt}|_{\max} = \frac{2V_{pN}}{3t_{sw}} \approx 0.67\frac{V_{pN}}{t_{sw}}. \tag{4}$$

Where $V_{pN}$is the peak value of the input phase involved and t_{sw} is the time needed to perform the transition from a rotating vector to an active one.

DOI: 10.1587/elex.7.281
Received December 29, 2009
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IEICE Electronics Express, Vol.7, No.4, 281–287

Since the input voltage amplitude is time varying, the CM voltage amplitude will depend on the position in which the input voltage vector lies. The time derivative of the CM voltage between nN is reduced from a minimum value of 11% to a maximum value of 33% when rotating vectors are employed instead of zero ones.

5 Results

In this section, the proposed SVM pattern is analyzed and compared to the standard doubled-sided SVM pattern described in [6]. In both cases, a 7.5 kW MC has been used to feed a PMSM with the following parameters: 4 pole pairs, 200 W, 0.64 Nm, and 3000 rpm. Field Oriented Control (FOC) with a Space Vector PWM (SVPWM) period of 80 μs has been employed to control the PMSM.

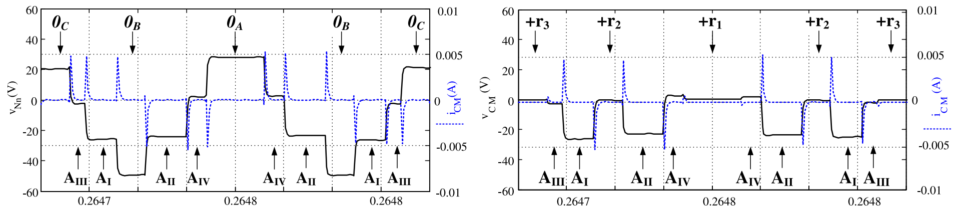

Fig. 2. SV PWM switching pattern and vNn and iCM when zero vectors (a) and rotating vectors are used (b).

Figure 2 shows, (for both, input and output sectors 1), the CM voltage and the leakage current when the conventional (a) and rotating vector (b) based SVPWM patterns are used respectively. Comparing both SVPWM patterns, it can be concluded how the CM voltage time derivatives are much lower in the proposed method, leading to lower values of leakage current.

6 Conclusion

An alternative SVPWM pattern strategy which reduces the CM perturbations (voltage amplitude, its time derivative and leakage current) has been presented in this work. The contribution is based on the replacement of the MC zero vectors used in the conventional double-sided SVPWM by MC rotating vectors without increasing the system complexity. CM voltage amplitude, its time derivative and leakage current have been reduced; where the reduction varies from a minimum value of 11% to a maximum value of 33% at the expense of introducing 2 more switching commutation per PWM period. Such alternative SVPWM pattern not only does not increase the system complexity at all but also it does keep the same modulation index and input power factor control capability and has the potential benefit of contributing to extend the machine operational life.

DOI: 10.1587/elex.7.281
Received December 29, 2009
Accepted January 20, 2010
Published February 25, 2010

Acknowledgments

The authors would like to acknowledge the economic support received from the "Ministerio de Ciencia y Tecnología de España" for realising this work under the *ENE2007-67033-C03-01* and *TEC2007-61582-MIC* Research Projects.

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Received December 29, 2009
Accepted January 20, 2010
Published February 25, 2010