

A NOVEL FIVE-PHASE MATRIX-CONVERTER USING SPACE VECTOR MODULATION CONTROL ALGORITHM

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ABSTRACT

In this paper the control algorithm for a novel five-phase matrix converter under balanced input voltage conditions is proposed. This algorithm is essentially based on the indirect space vector modulation. The complete algorithm, analysis and the model of the proposed matrix converter are introduced. The model has been applied for the case of inductive loads. The simulation results of input-output voltages and current waveforms are presented. Finally, the results show that five-phase matrix converter based on space vector modulation can be implemented.

يقترح هذا البحث خوارزميات التحكم في محول المصفوفة خماسي الأوجة الجديد تحت ظروف جهد دخل متزن. تعتمد أساساً هذه الخوارزميات على طريقة تعديل فضاء المتجة الغير مباشرة. ويقدم البحث الخوارزمية كاملة وتحليلها ونموذج لمحول المصفوفة المقترح. هذا النموذج تم تطبيقه على حمل حثي. نتائج المحاكاة لجهود والتيارات الدخل و الخرج تم تقديمها. وتوضح النتائج إمكانية تنفيذ محول المصفوفة خماسي الأوجة الجديد.

Keywords: AC-AC power conversion, five-phase matrix converter, Indirect Space Vector Modulation

1. INTRODUCTION

AC-AC power converters transform a constant voltage constant frequency supply into a variable voltage with variable frequency output required for many applications, as the adjustable speed drives. There are two kinds of AC-AC converter topologies, as shown in Fig.1:

- DC-Link converters (AC-DC-AC)
- Direct AC-AC converters

DC link converters have the disadvantage of large capacitor for the voltage source inverters or large inductor for the current source inverters. These disadvantages are overcome by direct AC-AC converters.

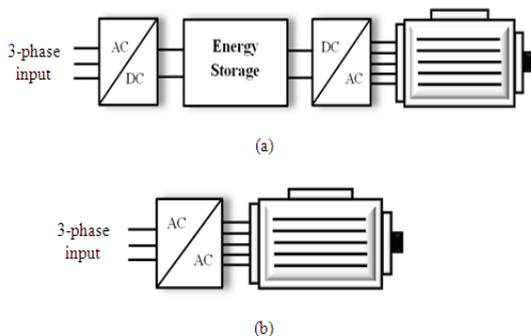


Fig.1 Ac/ac converter (a) indirect, (b) direct

Now the matrix converter is the superior of direct AC-AC converters. Was firstly introduced in 1976 and it steadily growth, pushed by the progress of the power electronics device technology. In recent years the matrix converter has received an increased amount of interest and has been studied intensely as an alternative to conventional AC-DC-AC power converter systems.

This paper proposes a new matrix converter which converts the ac power from three-phase to five-phase when supplying inductive loads.

2. FIVE-PHASE MATRIX CONVERTER TOPOLOGY

The analysis of the proposed system can be achieved using either of two strategies:

- Direct Matrix Converter (DMC), and
- Indirect Matrix Converter (IMC).

Direct Five-Phase Matrix Converter

The direct five-phase matrix converter is a direct three-phase to five-phase through one stage; it utilizes fifteen switches, as shown in Fig.2. Each of the fifteen switches depicted is a bidirectional switch, which are connected so that any of the input phases (A, B, and C) can be connected to any of the

output phases; (a, b, c, d, and e) for a given switching.

With the fifteen bi-directional switches, the Matrix Converter has 2^{15} different switching states. Some of the basic rules or constrains must be regarded when applying different switching states to the Matrix Converter at any switching time. These rules are:

- The input phases must never be shorted, and
- The output phases must not be left open, due to the inductive nature of the load.

Due to the above constraints, the switching states reduce to 3^5 different switching combinations for connecting output phases to input phases.

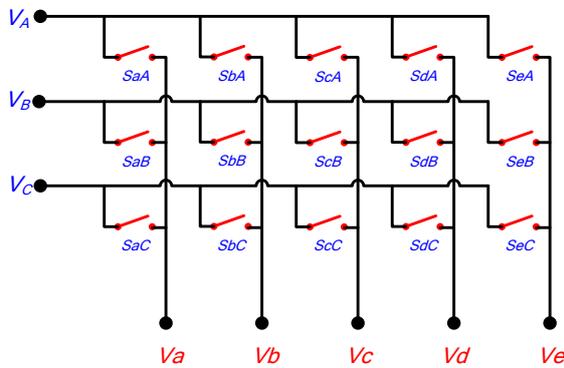


Fig.2 Direct Five-phase Matrix converter topology.

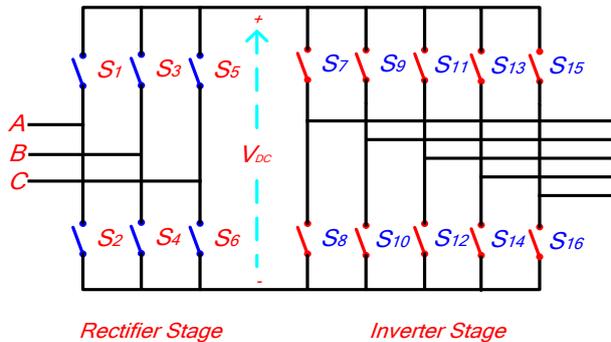


Fig.3 Indirect Five-phase Matrix converter topology

The output voltages v_o ($v_a v_b v_c v_d v_e$) and the input currents i_i ($i_A i_B i_C$) are therefore derived directly from the input voltages v_i ($v_A v_B v_C$), and the output currents i_o ($i_a i_b i_c i_d i_e$) as following.

$$[v_o] = [S]. [v_i] \tag{1}$$

$$[i_i] = [S]^T . [i_o] \tag{2}$$

where, S is the modulation matrix or the duty cycles of the switches.

$$S = \begin{bmatrix} S_{aA} & S_{aB} & S_{aC} \\ S_{bA} & S_{bB} & S_{bC} \\ S_{cA} & S_{cB} & S_{cC} \\ S_{dA} & S_{dB} & S_{dC} \\ S_{eA} & S_{eB} & S_{eC} \end{bmatrix} \tag{3}$$

Indirect Five-Phase Matrix Converter

This topology to model the matrix converter actually corresponds to regard the matrix converter as a double-PWM converter without any DC-Link energy storage, where matrix converter was described to an equivalent model combining current source rectifier and voltage source inverter connected through virtual dc link and it was first proposed by [6] for three phase to three-phase matrix converter, and by applying this algorithm on the direct five-phase matrix converter, the resulting indirect five-phase matrix converter is shown in Fig. 3.

The rectifier stage has the same topology of the three-phase rectifier with six switches, $S_1 \sim S_6$, and the Inverter stage has a standard five-phase voltage source inverter topology consisting of ten switches, $S_7 \sim S_{16}$. Both power stages are directly connected through virtual dc-link and inherently provide bidirectional power flow capability because of its symmetrical topology.

3. SPACE VECTOR MODULATION OF THE PROPOSED CONVERTER

The space vector modulation (SVM) technique constructs the desired sinusoidal output five-phase voltage by selecting the valid switching states of a matrix converter and calculating their corresponding on-time durations.

Basic idea of the indirect modulation is to decouple the control of the input current and the control of output voltage. This is done by splitting the modulation matrix S for the converter into the product of a rectifier transfer function R and an inverter transfer function I . The modulation matrix for the Matrix Converter is thus defined as following [3], [4]:

$$S = I . R \tag{4}$$

$$\text{Where } I = \begin{bmatrix} S_7 & S_8 \\ S_9 & S_{10} \\ S_{11} & S_{12} \\ S_{13} & S_{14} \\ S_{15} & S_{16} \end{bmatrix} \tag{5}$$

$$\text{And } R = \begin{bmatrix} S_1 & S_3 & S_5 \\ S_2 & S_4 & S_6 \end{bmatrix} \tag{6}$$

Therefore

$$S = \begin{bmatrix} S_7S_1 + S_8S_2 & S_7S_3 + S_8S_4 & S_7S_5 + S_8S_6 \\ S_9S_1 + S_{10}S_2 & S_9S_3 + S_{10}S_4 & S_9S_5 + S_{10}S_6 \\ S_{11}S_1 + S_{12}S_2 & S_{11}S_3 + S_{12}S_4 & S_{11}S_5 + S_{12}S_6 \\ S_{13}S_1 + S_{14}S_2 & S_{13}S_3 + S_{14}S_4 & S_{13}S_5 + S_{14}S_6 \\ S_{15}S_1 + S_{16}S_2 & S_{15}S_3 + S_{16}S_4 & S_{15}S_5 + S_{16}S_6 \end{bmatrix} \quad (7)$$

The above transfer matrix exhibits that the output phases are compounded by the product and sum of the input phases through rectifier switches S1~ S6 and inverter switches S7 ~ S16.

$$\begin{bmatrix} V_a \\ V_b \\ V_c \\ V_d \\ V_e \end{bmatrix} = \begin{bmatrix} S_{aA} & S_{aB} & S_{aC} \\ S_{bA} & S_{bB} & S_{bC} \\ S_{cA} & S_{cB} & S_{cC} \\ S_{dA} & S_{dB} & S_{dC} \\ S_{eA} & S_{eB} & S_{eC} \end{bmatrix} \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \quad (8)$$

The first row of the above matrix represents how output phase a is built from the input phase A, B and C for the direct MC using indirect topology and this mathematical expression can be interpreted again in the graphical viewpoint as shown in Fig. 4.

Based on the indirect modulation technique the following sections describe two independent space vector modulations for three-phase current source rectifier, and five-phase voltage source inverter stages and then the two modulation results are combined to modulate the five-phase matrix converter.

Space Vector Rectifier (SVR)

The rectifier converts the input three-phase voltage to DC-voltage. At the same time the rectifier algorithm assures the input currents to be sinusoidal. This section introduces a space vector PWM in the rectifier stage. The rectifier part of the equivalent model shown in Fig. 3 can be assumed to be a stand-alone current source rectifier (CSR) as shown in Fig. 5.

In the indirect space vector modulation, all quantities are referred to a virtual dc link which is obtained by chop of the input voltages.

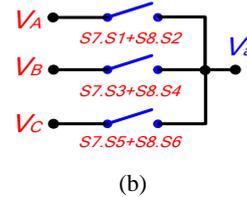
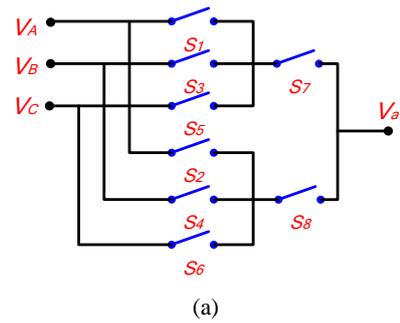


Fig. 4 Transformation from indirect model to direct matrix converter in phase a (a) Phase A of indirect model, and (b) Phase a of direct model

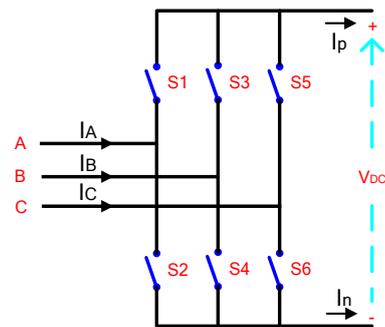


Fig.5 Rectifier stage topology

The input currents can be represented as the virtual dc-link current IDC multiplied by the switching states of rectifier transfer function R given by eq. (6) as following;

$$\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} = \begin{bmatrix} S_1 & S_2 \\ S_3 & S_4 \\ S_5 & S_6 \end{bmatrix} \cdot \begin{bmatrix} I_p \\ I_n \end{bmatrix} \quad (9)$$

Then the input current IIN is expressed as space vectors as following;

$$I_{IN} = \frac{2}{3}(I_A + a \cdot I_B + a^2 \cdot I_C) = |I_{IN}| e^{j\alpha_i} \quad (10)$$

The rectifier switches, S1 ~ S6 can have only possible nine allowed combinations to avoid an open circuit at the dc link rails. The nine combinations can be divided into six nonzero input currents which are active vector I1 ~ I6 and three zero input currents which are zero vector I7 ~ I9, as in Table 1, and Fig. 6 shows current space vector hexagon.

Table 1, Switching states and switching vectors for the Rectifier side

Vectors	On switch	I_a	I_b	I_c	I_{IN}	α_i
I_1	S1S4	I_b	$-I_b$	0	$\frac{2}{\sqrt{3}}I_b$	$-\pi/6$
I_2	S1S6	I_b	0	$-I_b$	$\frac{2}{\sqrt{3}}I_b$	$\pi/6$
I_3	S3S6	0	I_b	$-I_b$	$\frac{2}{\sqrt{3}}I_b$	$\pi/2$
I_4	S2S3	$-I_b$	I_b	0	$\frac{2}{\sqrt{3}}I_b$	$5\pi/6$
I_5	S2S5	$-I_b$	0	I_b	$\frac{2}{\sqrt{3}}I_b$	$-\pi/6$
I_6	S4S5	0	$-I_b$	I_b	$\frac{2}{\sqrt{3}}I_b$	$-\pi/2$
I_7	S1S2	0	0	0	0	0
I_8	S3S4	0	0	0	0	0
I_9	S5S6	0	0	0	0	0

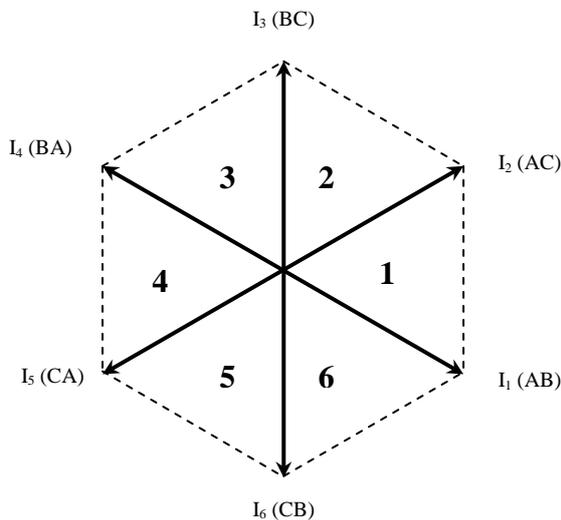


Fig. 6 Rectifier current hexagon

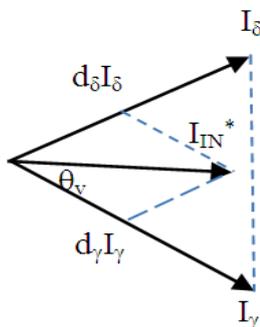


Fig.7 Synthesis of reference current vector ($m_c=1$)

Figure 7 shows the reference input current vector I_{IN}^* within a sector of the current hexagon. The I_{IN}^* is synthesized by impressing the adjacent switching vectors I_γ and I_δ with the duty cycles d_γ and d_δ , respectively.

If the input currents are considered constant during a short switching interval TS, the reference vector can be expressed by the current-time product sum of the adjacent active vectors as;

$$I_{IN}^* = d_\gamma \cdot I_\gamma + d_\delta \cdot I_\delta + d_o \cdot I_o \tag{11}$$

Thus, the duty cycle of the active vectors are written as;

$$d_\gamma = m_c \cdot \sin\left(\frac{\pi}{3} - \theta_c\right) \tag{12}$$

$$d_\delta = m_c \cdot \sin(\theta_c)$$

$$d_o = 1 - (d_\gamma + d_\delta)$$

where, θ_c indicates the angle of the reference current vector within the actual hexagon sector. The m_c is the current modulation index and defines the desired current transfer ratio such as

$$0 \leq m_c \leq 1$$

$$m_c = \frac{I_{IN}^*}{I_{DC}}$$

The current modulation index m_c is often fixed to unity and the voltage modulation index m_v is variable according to a required overall voltage transfer gain.

Space Vector Inverter (SVI)

This section introduces a space vector PWM in the inverter stage. Consider the inverter part of the equivalent model in Fig. 3 as a standalone VSI supplied by a dc voltage source, as shown in Fig.8. The power conversion is performed via the virtual dc-link of VDC.

where, $V_{DC} = V_p - V_n$

The output voltages can be obtained by multiplying the virtual dc-link voltage VDC by inverter transfer function I so that:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \\ V_d \\ V_e \end{bmatrix} = \begin{bmatrix} s_7 & s_8 \\ s_9 & s_{10} \\ s_{11} & s_{12} \\ s_{13} & s_{14} \\ s_{15} & s_{16} \end{bmatrix} \cdot \begin{bmatrix} \frac{V_{DC}}{2} \\ -\frac{V_{DC}}{2} \end{bmatrix} \tag{13}$$

The space vector scheme reviewed here considers the outer most and the intermediate decagons of space vectors in d-q plane as shown in Fig.10.

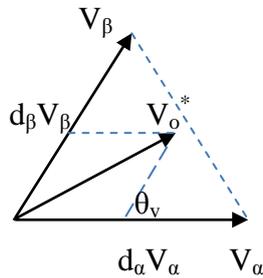


Fig.10 Synthesis of reference voltage vector

Figure 10 shows the outermost decagon of the input reference voltage vector V_{o^*} within a sector of the voltage decagon. The V_{o^*} is synthesized by impressing the adjacent voltage vectors V_{α} and V_{β} with the duty cycles d_{α} and d_{β} , respectively.

$$d_{\alpha} = m_v \cdot \sin(\pi/5 - \theta_v) \quad (15)$$

$$d_{\beta} = m_v \cdot \sin(\theta_v) \quad (16)$$

where

$$m_v = \frac{V_o^*}{V_l \sin(4\pi/5)}$$

$$V_l = 0.6472V_{DC}$$

Therefore maximum fundamental peak output voltage V_{max} is given by:

$$\begin{aligned} V_{max} &= 0.6472V_{DC} \cos\left(\frac{\pi}{10}\right) \\ &= 0.6155 V_{DC} \end{aligned}$$

Space vector modulation with large and medium vectors is based on the proportional sub-division of the time of application of each vector from outer and intermediate sectors. The times obtained are sub-divided according to the ratio of medium and large vector lengths, so that the duty ratios are given by:

$$\begin{aligned} d_{\alpha l} &= d_{\alpha} \frac{V_l}{V_l + V_m} \\ d_{\alpha m} &= d_{\alpha} \frac{V_m}{V_l + V_m} \\ d_{\beta l} &= d_{\beta} \frac{V_l}{V_l + V_m} \end{aligned} \quad (17)$$

$$d_{\beta m} = d_{\beta} \frac{V_m}{V_l + V_m}$$

where, $V_m = 0.4V_{DC}$

The time of zero space vectors application can be obtained so that its duty ratio d_o is given by:

$$d_o = 1 - (d_{\alpha l} + d_{\alpha m} + d_{\beta l} + d_{\beta m}) \quad (18)$$

To minimize the number of the inverter-switching, the sequence of the impressed voltage vectors is given by:

$$V_{\alpha m} \rightarrow V_{\beta l} \rightarrow V_{\alpha l} \rightarrow V_{\beta m} \rightarrow V_o$$

4. SIMULATION RESULT

Simulation of the five-phase matrix converter has been performed with a passive RL load. The load parameters are 10Ω and $0.12H$. The converter is fed by a three-phase sinusoidal supply which has line voltage and frequency of $380V$ and $50Hz$, respectively. The switches are controlled using the indirect space vector modulation method described above at switching frequency of $6-kHz$. Three values of output frequencies have been considered, namely 30 , 50 , and $70-Hz$.

Figures 11, 12, and 13 describe the output line voltage and load currents of the MC for the above mentioned conditions. This figure shows very clearly the validity of the proposed model of the MC.

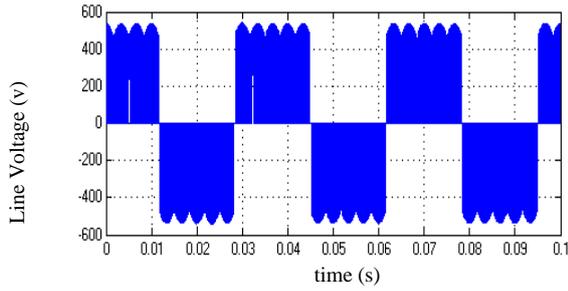
The RL load currents are near sinusoidal currents. In addition, it can be observed that the matrix converter can generate output frequencies that are not restricted by the source frequency.

Figure 14 shows that the input current generated by the MC has the form of several pulses with a high di/dt, making it necessary to introduce an input filter to avoid the generation of over-voltages. This figure shows very clearly zero input current displacement angle i.e. unity input power factor of the MC. While Fig. 15 shows the virtual dc-link voltage.

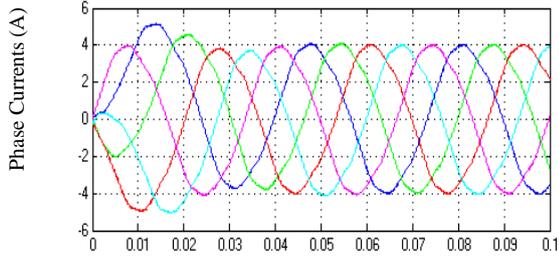
Table 3 list the change in THD of the output current with the change of the output frequency.

Table 3, Total harmonic distortion for different output frequencies

Output frequency (Hz)	% THD
20	4.84
30	4.42
50	4.13
70	4.62
100	5.21



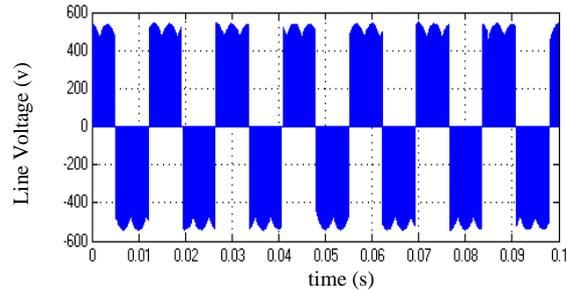
(a)



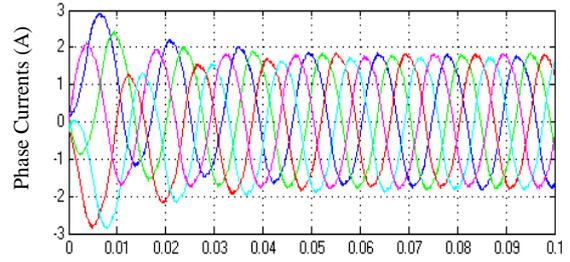
time (s)

(b)

Fig. 11 For output frequency 30Hz (a) output line voltage, (b) output five phase currents.



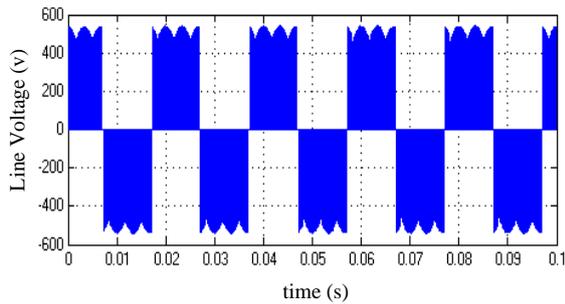
(a)



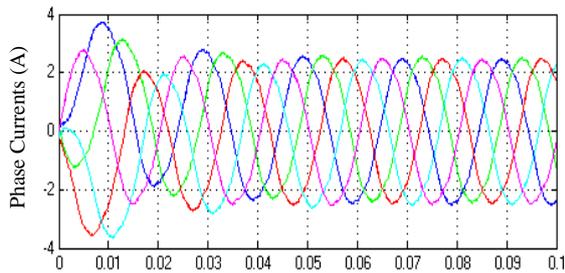
time (s)

(b)

Fig. 13 For output frequency 70 Hz (a) output line voltage, (b) output five phase currents.



(a)



time (s)

(b)

Fig.12 For output frequency 50Hz (a) output line voltage, (b) output five phase currents.

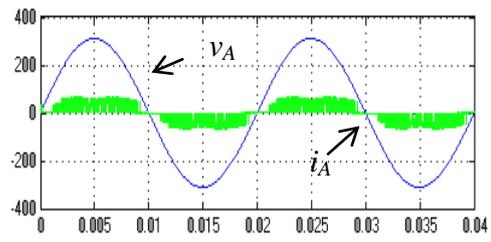


Fig.14 The input voltage v_A and current i_A

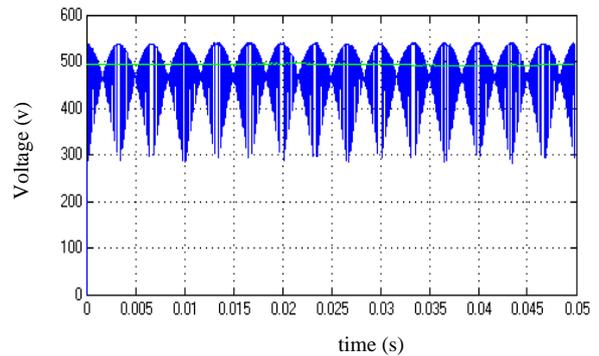


Fig.15 Virtual DC voltage at $m_c=1$, zero input current displacement angle, 220 v input voltage, and input frequency 50 Hz.

5. CONCLUSION

This paper presents a novel three-phase to five-phase matrix converter based on the indirect space vector modulation algorithm. The converter has been considered as a combination of three-phase rectifier and five-phase inverter. Both rectifier and inverter are space vector modulated. Simulation results are presented for five phase passive load. According to the results obtained, the control algorithm presented is advisable for the establishing in the industry. An experimental implementation of the proposed system will be considered in future work.

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