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Transfer Ratio Improvement and Reduction of THD in the Matrix Converter based on the Novel Cascaded H-bridge Matrix Converter

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Abstract: The general function of a matrix converter is to convert AC supply to variable-voltage variable-frequency outputs. A new matrix is presented to reduce harmonic components in the output voltage. The transfer ratio has improved in the proposed converter. The structure of the proposed converter is identical to the cascaded H-bridge multilevel converter, but here the switches are bi-directional. A simple modulation method is described and utilized. In order to verify the theoretical issues, simulations based on MATLAB/SIMULINK are presented.

Keywords: Matrix converter, modulation method, harmonic components, H-bridge cascade.

1. Introduction

Matrix converters are direct power conversion systems that consist of an array of n×m bidirectional power switches. They convert three-phase AC supply to variable-voltage variable-frequency outputs [1-4].The main advantages of matrix converters are [4-10]:

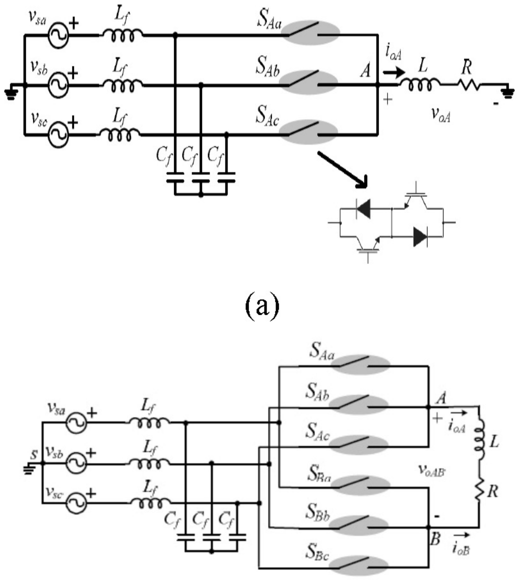
- direct AC-AC poly phase power conversion
- bidirectional power flow
- input/output sinusoidal waveforms
- variable output voltage amplitude and frequency
- input power factor control
- elimination of bulky reactive elements.

The matrix converters have some disadvantages such as [11-14]:

- a lower voltage modulation index
- higher sensitivity to power supply disturbances
- complexity control
- switching losses
- d*v*/d*t* stresses on the load
- higher harmonic components
- output voltage with high total harmonic distortion (THD)

Different topologies of matrix converters are used in industry. They can be classified according the number of input and output phases, for example, some of the most popular being 3-phase to single-phase, 3-phase to 2-phase, 3-phase to 3-phase matrix converters.

The 3-phase to single-phase matrix converter is one of the most popular and most important in the matrix converter family. It can be used in many industrial applications such as induction motor drives, induction heating systems, switching power supplies and so on [15-17]. Fig. 1 shows two circuit configurations of a 3-phase to single-phase matrix converter [18].



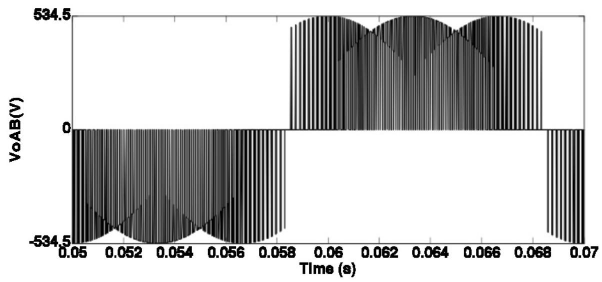
(a)

(b)

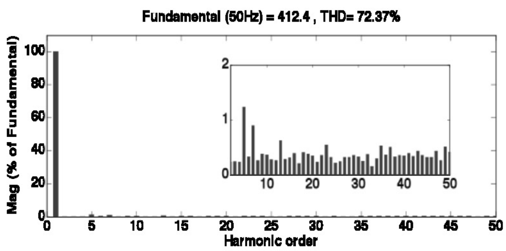
FIGURE 1. Circuit configuration of a 3-phase to single-phase matrix converter (a) with neutral connection and (b) with 2-leg.

The performance of matrix converters is dependent on the modulation strategy. Various modulation strategies have been proposed for matrix converters [18-23]. First, Alesina and Venturini proposed the matrix converter control method using a mathematical approach to generate the desired output waveform [19]. The space vector pulse width modulation (SVPWM) method for a matrix converter is another method [20-22]. The algorithms based on SVPWM require complex calculations. A different concept of

PWM for the matrix converter has been introduced. In [18], a carrier-based modulation technique, which is mathematically proven to be identical with SVPWM is presented. Fig. 2 shows the output voltage and FFT analysis of a conventional 3-phase to single-phase matrix converter that is shown in Fig. 1. This figure shows that the output fundamental harmonic is 412.4 V and the total harmonic distortion (THD) is 72.37%. In this simulation, V_{LL}=380 V, frequency=50 Hz and the modulation index is 0.9. The load is the RL load with R=55 Ω and L= 100mH. As shown in this figure, the load voltage changes between zero and the line-to-line voltage, so dv/dt stress on the load is high and the THD has a high value.



(a)



(b)

FIGURE 2. 3-phase to single-phase matrix converter (a) output phase voltage and (b) harmonic spectrum of load voltage.

A novel matrix converter is presented in the paper. This converter is called a CMAT (cascaded matrix converter). The structure of the CMAT is the same as the cascaded H-bridge multilevel converter. This converter generates a desired output voltage and current. The voltage transfer ratio is increased in the CMAT while a low transfer ratio is the physical limitation of the matrix converter. A simplified modulation for the proposed converter is also presented. Simulation results are provided to validate the operation of the proposed converter.

2. Novel Matrix Converter

The H-bridge topology with bi-directional switches shown in Fig. 3 is used to synthesize a three-level output voltage. The switches of the H-bridge converter must block voltage and conduct current in both directions similarly to other matrix converters [24]. As can be seen, three unique output voltages are possible in the converter. These levels are: V_1, $-V_1$ and 0.

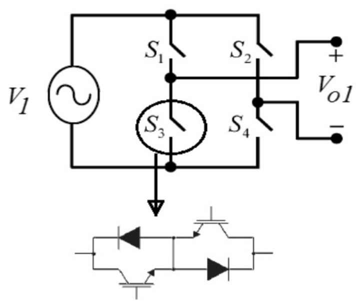


FIGURE 3. The H-bridge topology with bi-directional switches.

The basic H-bridge converter shown in Fig. 3 can be cascaded as shown in Fig. 4. Fig. 4 shows a single-phase topology of the CMAT with isolated AC voltage sources. This converter is an m×1 matrix converter. This topology has m H-bridge converters and m AC voltage sources. The AC voltage sources are given as Eq. 1.

$$V_i = V_p \sin\left(\omega t + (i-1)\frac{360}{m}\right) \qquad i = 1,2,\dots,m \tag{1}$$

where V_p is the peak value of the input voltage and ω is the angular frequency of the input voltages.

An output phase voltage is obtained by summing the output voltages of the H-bridges:

$$V_o = V_{o1} + V_{o2} + \dots + V_{om} \tag{2}$$

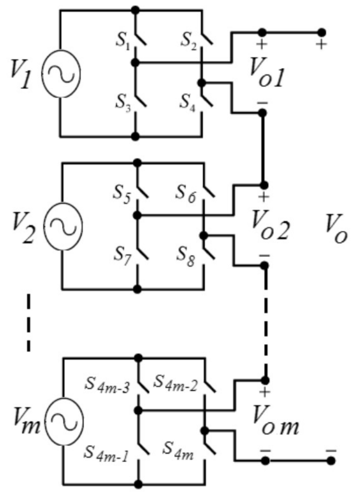


FIGURE 4. A single-phase topology of the CMAT with isolated AC voltage sources.

This paper focuses on a 3-phase to single-phase CMAT. The 3-phase to single-phase CMAT is schematically presented in Fig. 5. It consists of twelve bidirectional switches and three AC voltage sources. The input voltages are as follows:

$$\begin{aligned} V_a &= V_p \sin(\omega t) \\ V_b &= V_p \sin(\omega t + 120) \\ V_c &= V_p \sin(\omega t + 240) \end{aligned} \tag{3}$$

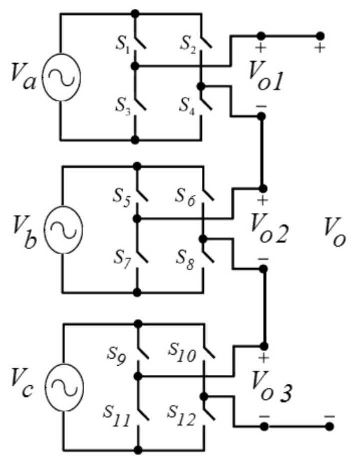


FIGURE 5. 3-phase to single-phase CMAT.

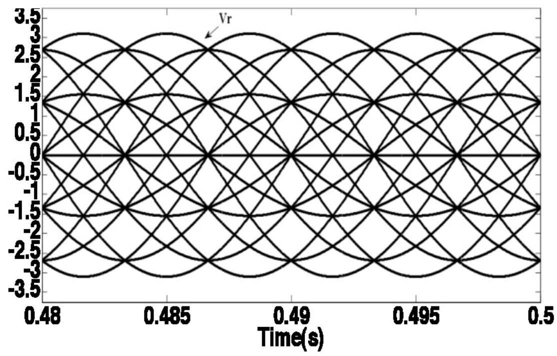
By using suitable switching, different values can be obtained for V_O. Table 1 indicates the values of V_O for states of switches $S_1, S_2, \ldots, S_{12}$. If the suitable values for AC voltage sources are selected as shown in Eq. 3, then an output voltage between $-2V_P$ and $+2V_P$ can be obtained. It is clear that the two switches that are put on in one leg of the H-bridges converters cannot be on at the same time since a short circuit across the voltage sources would be produced.

TABLE 1. Values of V_O for states of switches.

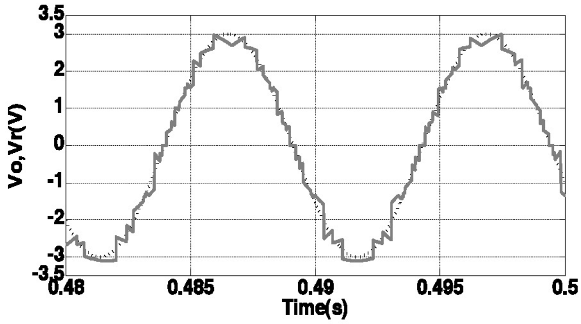
Switching state (SS)	On switches	Vo
SS1	1,4,5,6,9,10	V_a
SS2	2,3,7,8,11,12	$-V_a$
SS3	1,2,5,8,9,10	V_b
SS4	3,4,6,7,11,12	$-V_b$
SS5	1,2,5,6,9,12	V_c
SS6	3,4,7,8,10,11	$-V_c$
SS7	1,4, 6,7, 9,10	$V_a - V_b$
SS8	2,3,5,8,11,12	$V_b - V_a$
SS9	1,4,7,8,10,11	$V_a - V_c$
SS10	2,3,5,6,9,12	$V_c - V_a$
SS11	1,2,5,6,10,11	$V_b - V_c$
SS12	3,4,6,7,9,12	$V_c - V_b$
SS13	1,4,6,7,10,11	$V_a - V_b - V_c$
SS14	2,3,5,8,9,12	$-V_a + V_b + V_c$
SS15	2,3,5,8,10,11	$-V_a + V_b - V_c$
SS16	1,4,6,7,9,12	$V_a - V_b + V_c$
SS17	2,3,6,7,9,12	$-V_a - V_b + V_c$
SS18	1,4,5,8,10,11	$V_a + V_b - V_c$
SS19	1,4,5,8,9,12	$V_a + V_b + V_c$

3. Modulation Strategy

The principle of modulation strategy is based on a comparison of a sinusoidal reference waveform value with nineteen different voltage waveforms. The nineteen different voltage waveforms are created by using phase voltages. These waveforms are shown in the third column of Table 1. Fig. 6(a) shows the modulation waveforms. At each instant of time, from the comparison among nineteen different voltage waveforms and the reference wave one switching state is selected since the output has a minimum distance from the reference wave. Fig. 6(b) shows the output voltage and its reference. Fig. 7 shows a flowchart of the modulation strategy. This flowchart shows the Matlab function that is used to control the switches.



(a)



(b)

FIGURE 6. (a) Modulation waveforms and (b) output voltage and reference waveforms.

In the switching algorithm, there are two important parameters to define: the transfer ratio, or modulation index T_r, and the frequency modulation ratio T_f. Definitions are given by

$$T_r = \frac{V_{r\max}}{V_P} \tag{4}$$

$$T_f = \frac{f_r}{f_i} \tag{5}$$

where $V_{r\max}$ and V_P are the amplitudes of reference voltage and input phase voltage, respectively. In (5), f_i is the frequency of the main supply and f_r the frequency of the reference voltage (output voltage).

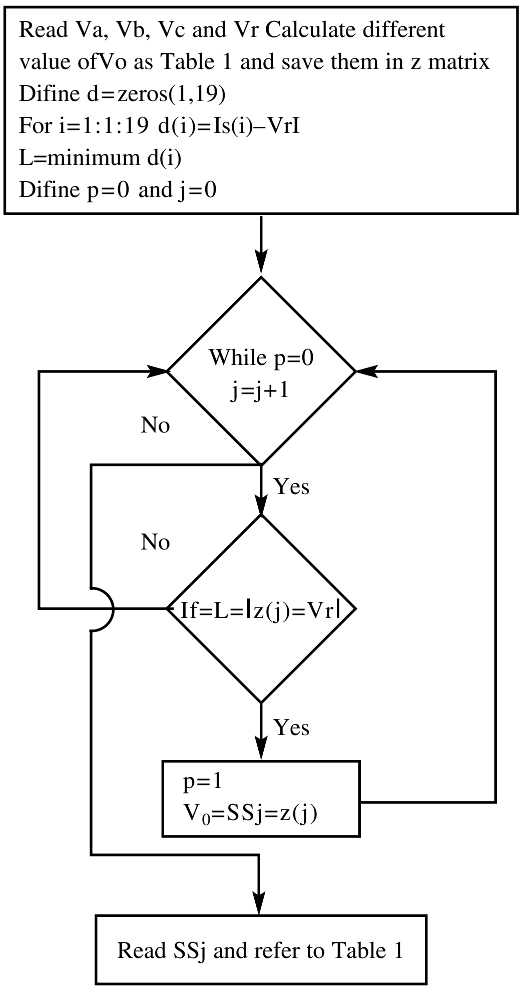


FIGURE 7. Flowchart of modulation strategy.

4. Comparison Study

The main purpose of this paper is the reduction of the disturbance harmonics and THD of the matrix converter. In comparison with traditional matrix converters, the CMAT has high power quality waveforms with lower disturbance harmonic components. The CMAT can produce a near sinusoidal output as shown in Fig. 6(b).

Another important problem in power electronic converters is the ratings of switches. The voltage and current ratings of switches in a power electronic converter affect the cost and realization of the converter. In traditional matrix converters, such as converters that are shown in Fig. 1, the peak inverse voltage (PIV) of all switches is represented by:

$$PIV_{sw} = V_{LL} = \sqrt{3}V_{ph} \tag{4}$$

where V_{LL} and V_{ph} respectively are line-to-line and phase voltage of input voltage power supply. In the proposed topology, the PIV of all switches are equal to the phase voltage. Therefore, the switches of the CMAT have lower voltage ratings than the switches of conventional matrix converters. In the CMAT, the currents of all switches are equal to the rated current of the load which is the same as the other converters.

In the first matrix converters publication, the control algorithms only allowed a voltage transfer ratio of 50%. The voltage transfer ratio was raised to 87% in some strategies. Next, an indirect modulation was proposed, which made it possible to use classical PWM modulation strategies with matrix converters [23]. The CMAT can generate an output voltage such that its amplitude is twice the phase voltage.

Furthermore, the reduction of $\frac{dv}{dt}$ stresses on the load is given by using the CMAT. In the CMAT, the output voltage is created by using different voltage values (nineteen states) while in the conventional converters the number of voltage values to create the output voltage is less than the CMAT.

The main disadvantage associated with the CMAT is the requirement of a great number of semiconductor switches.

5. Simulation Results

In order to verify the validity of the CMAT in the generation of a desired output voltage, a prototype is simulated based on the suggested topology according to that shown in Fig. 4. The MATLAB software has been used for the simulation. The system parameters in the simulation are listed in Table 2.

TABLE 2. Simulation study parameters.

	Input voltage (V_{L-L})	Phase voltage magnitude (V_m)	Nominal frequency (f_i)	R-L Load
Values	380 V	310.2687 V	50 HZ	20 Ω, 50 mH

The simulation is divided into two groups. The first group is that simulation is done on a 3 to single phase matrix converter to create reference wave by this equation:

$$V_r = V_m * T_r * \sin(2 * T_f * f_i * \pi * t) \tag{5}$$

In this simulation, suppose $T_r = T_f = 2$. Fig. 8 reveals the output voltage and reference waveforms. This figure shows that the CMAT creates a voltage which has a near form to the reference wave. Fig. 9 respectively reveals the output waveform and harmonic spectrum of the load voltage. Fig. 9(a) shows the output voltage and current waveform. The harmonic spectrum of the load voltage is shown in Fig. 9(b). This figure shows that the output fundamental harmonic is 618.2 V and the THD is 7.1% so the proposed converter can produce a voltage with twice the phase voltage magnitude.

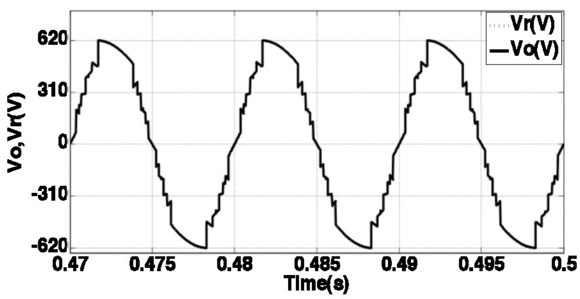


FIGURE 8. Output voltage and reference waveforms.

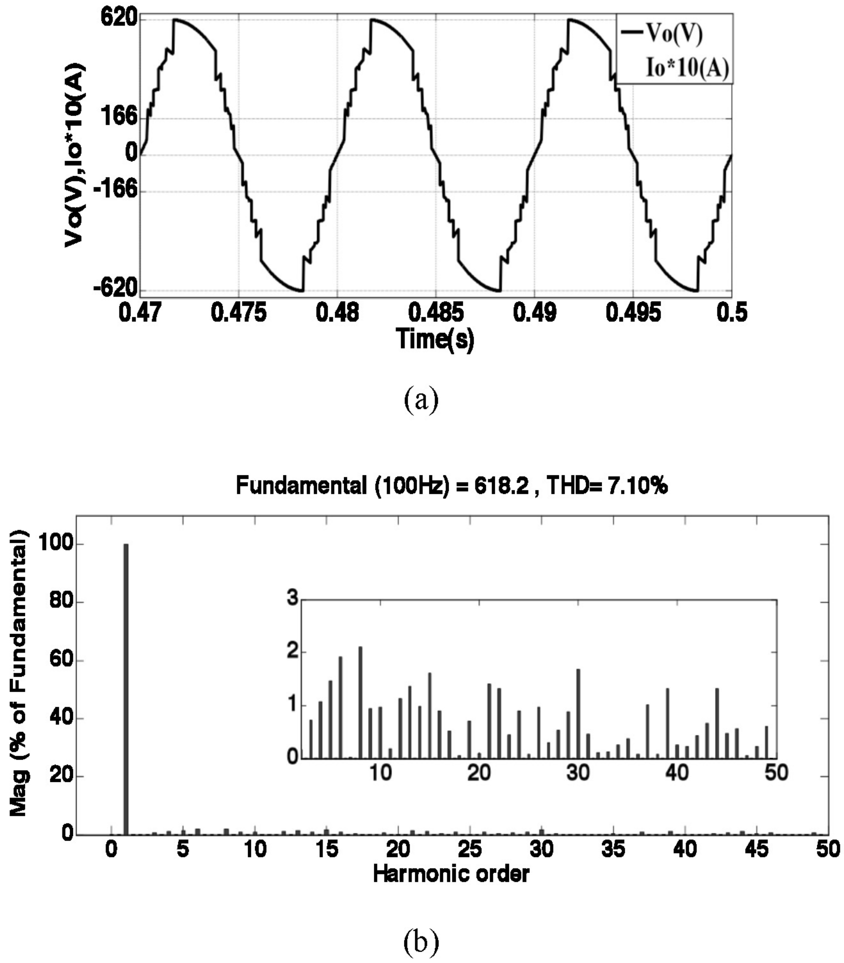


FIGURE 9. (a) output phase voltage and current and (b) harmonic spectrum of load voltage.

The second group is a simulation that is done on a 3 to single phase matrix converter with $T_r = T_f = 0.9$. In this state, the reference wave is shown by (6):

$$V_r = 310.2687 * 0.9 \sin(2 * 45 * \pi * t) \tag{6}$$

Fig. 10 shows the output voltage and reference waveforms. This figure shows that the CMAT creates a voltage which has a near form to the reference wave. Fig. 11 shows the output waveform and harmonic spectrum of the load voltage, respectively. Fig. 11(a) shows the output voltage and current waveform. The harmonic spectrum of the load voltage is shown in Fig. 11(b). This figure shows that the output fundamental harmonic is 287.4 V and the THD is 10.45%.

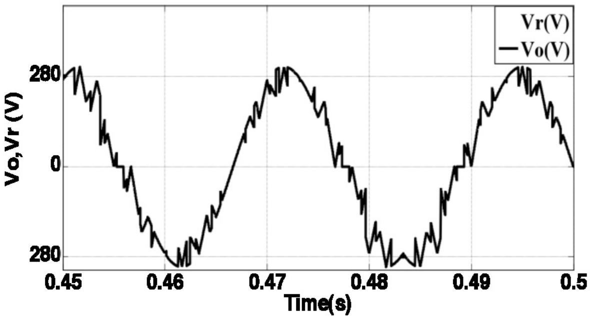
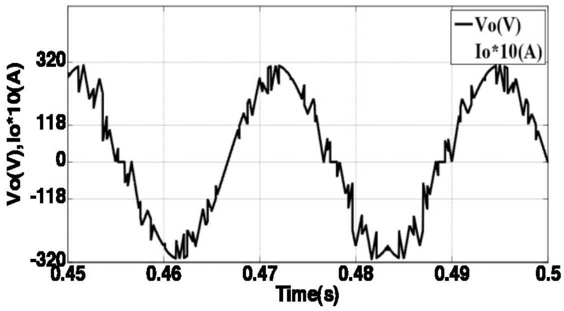
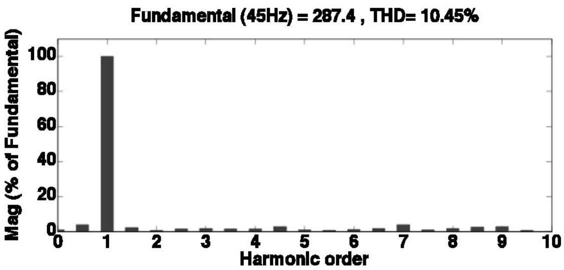


FIGURE 10. Output voltage and reference waveforms.



(a)



(b)

FIGURE 11. (a) output phase voltage and current and (b) harmonic spectrum of load voltage.

Matrix converters are very interesting for creating a variable voltage variable frequency voltage source. This paper has proposed a new topology of the matrix converter called CMAT. The main advantage of the CMAT are:

- improved output voltage quality
- improved transfer ratio
- reduction of switches PIV
- reduction of $\frac{dv}{dt}$ stresses on the load

Simulation results exhibit the good performance and feasibility of the proposed topology.

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