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A NOVEL MODULATION METHOD FOR DC/AC MATRIX CONVERTERS UNDER DISTORTED DC SUPPLY VOLTAGE

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Abstract: The aim of this paper is to investigate the performance of a novel modulation algorithm for DC to AC direct matrix converters, with an alternative PWM strategy. By suitable toggling the matrix switches, this novel modulation provides independent control of the magnitude and frequency of the generated output voltages. This new modulation method for matrix converter based on forming the switches matrix. Using this control method in such a converter, ensures that the switches do not short-circuit the voltage source, and do not open-circuit the current sources, thus we have the continuous currents at output and input terminals. It is shown that, it is possible to operate the converter with undistorted output voltages, even when input voltage is distorted. Also the accordance of the simulation results with the mathematical investigation are pointed out.

Key words: Matrix Converter, Bi-directional Switches.

1. Introduction

The most practical power processors utilize more than one converter whose instantaneous operation is de-coupled by an energy element (an inductor or capacitor). Theoretically it is possible to replace the multiple conversion stages and the intermediate energy storage element by a single power conversion stage called "*Matrix Converter*". Such a converter uses a matrix of semiconductor or bi-directional switches, with a switch connected between each input terminal to each output terminal. With this general arrangement of switches, the power flow through the converter can be reversed [1][2][3][4]. Also, the waveform and the frequency at the two sides are independent. For example, the input may be three-phase AC and the output DC, or both may be DC or both may be AC. The matrix converter is very simple in structure and powerful controllability. In this paper we introduce a new method for inverters. Here we have studied this converter in two cases, DC to single-phase AC matrix converter and DC to three-phase AC matrix converter.

2. DC to Single-Phase AC Matrix Converter

The DC to single-phase AC matrix converter is presented schematically in Figure 1(a). Its input voltage is V_{in} and its output voltage is $v_o(t)$. It comprises four ideal bi-directional switches S_1, S_2, S_3, S_4. The matrix converter will be designed and controlled in such a manner that the fundamental of the output voltage is[4] :

$$v_o(t) = V_o \cos(\omega_o t) \tag{1}$$

where V_o denotes a peak value of desired output voltage, ω_o denotes an angular frequency of output voltage.

In this new strategy, the sampling time, T_s, will be divided 2-time intervals t_1 (Mode 1) and t_2 (Mode 2). (Figure 1 (b)).

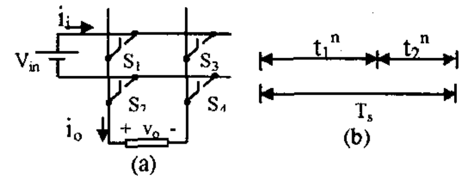

Figure 1 : (a) DC to single-phase AC matrix converter circuit configuration (b) The sampling time T_s

From Ref. [5] we have:

$$\frac{t_1}{T_s} = \frac{1 + \frac{V_o}{V_{dc}}\cos(\omega_o t)}{2} \quad ; \quad \left|\frac{V_o}{V_{dc}}\right| \le 1 \qquad \frac{t_2}{T_s} = \frac{1 - \frac{V_o}{V_{dc}}\cos(\omega_o t)}{2} \tag{2}$$

and for distorted conditions as follows:

$$v_{in}(t) = V_{dc} + V_r \cos(\omega_r t) \quad , \forall t : \; v_{in}(t) > 0 \tag{3}$$

the equations in eqn. (2) is expressed as :

$$\frac{t_1}{T_s} = \frac{1 + \frac{V_o \cos(\omega_o t)}{V_{dc} + V_r \cos(\omega_r t)}}{2} \quad ; \quad \frac{|V_o|}{|V_{dc}| + |V_r|} \le 1 \qquad \frac{t_2}{T_s} = \frac{1 - \frac{V_o \cos(\omega_o t)}{V_{dc} + V_r \cos(\omega_r t)}}{2} \tag{4}$$

In DC to single-phase AC matrix converter (Figure 2) the relation between the output voltage and the output current for the passive $R-L$ load is given by:

$$v_o(t) = R i_o(t) + L\frac{di_o(t)}{dt} \tag{5}$$

From eqns. (1) and (5), the fundamental of the output current is:

$$i_o(t) = \frac{Vo}{\sqrt{(L\omega_o)^2 + R^2}} \cos(\omega_o t - \tan^{-1}(\frac{R}{L})) \tag{6}$$

The relation between the output and input current is given by:

$$i_i(t) = \begin{cases} +i_o(t) & Mode \;\; 1 \\ -i_o(t) & Mode \;\; 2 \end{cases} \tag{7}$$

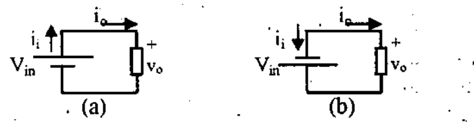

Figure 2 : Equivalent circuits for DC to single-phase converter at different modes, (a) Mode 1, (b) Mode2

3. DC to Three-Phase AC Matrix Converter

The DC to three-phase AC matrix converter is presented schematically in Figure 3. The matrix converter will be designed and controlled in such a manner that the fundamentals of the output voltages are :

$$\begin{aligned} v_{ab}(t) &= V_o\cos(\omega_o t) \\ v_{bc}(t) &= V_o\cos(\omega_o t - \frac{2\pi}{3}) \\ v_{ca}(t) &= V_o\cos(\omega_o t + \frac{2\pi}{3}) \end{aligned} \quad (8)$$

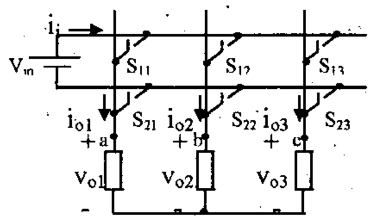

Figure 3 : DC to three-phase AC matrix converter circuit configuration

In this strategy, the sampling time, T_s, will be divided 3-time intervals t_1, t_2 and t_3. The sampling time, T_s, related with these time intervals as follows :

$$T_s = t_1 + t_2 + t_3 \quad (9)$$

If we form the switches matrix, then we have :

$$S = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \end{bmatrix} \quad (10)$$

As this is not a square matrix and this causes un-continuous currents available at output terminals, we repeat 1st row, as 3th row, then we have square matrix as follows :

$$S = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{11} & S_{12} & S_{13} \end{bmatrix} \quad (11)$$

We emphasis that this repetition does not cause short circuit in the input voltage source. In this approach, at t_1 time interval (Mode 1), the switches in the major-diagonal will be turned on and the remaining switches will be off, at t_2 time interval (Mode 2), the switches in the minor-diagonal (next to major diagonal) will be turned on and the remaining switches will be off, and this procedure is repeated for 3th minor-diagonal at t_3 time interval (Mode 3). As a result of high frequency of the converter, the average output voltages during any n^{th} sampling time, T_s, can be written as :

$$\begin{aligned} v_{ab}(t) &= \frac{1}{T_s}\{t_1 V_{dc} - t_3 V_{dc}\} \\ v_{bc}(t) &= \frac{1}{T_s}\{-t_1 V_{dc} + t_2 V_{dc}\} \\ v_{ca}(t) &= \frac{1}{T_s}\{-t_2 V_{dc} + t_3 V_{dc}\} \end{aligned} \quad (12)$$

In other words in matrix form as follows :

$$[V_o(t)] = \frac{1}{T_s}\,[V_i(t)]\begin{bmatrix} t_1 \\ t_2 \\ t_3 \end{bmatrix} \quad (13)$$

A unique solution of eqn. (13) exists when $\det[V_i(t)] \neq 0$, since $\det[V_i(t)] = 0$, infinite number of solutions for t_1, t_2 and t_3 existed, and this is obvious, because the equations in eqns. (12) are dependent. To solve this problem, we assume one of times, t_1, t_2 or t_3 and calculate others, here we assume :

$$t_1 = T_s - t_2 - t_3 \quad (14)$$

From eqns. (12) and (14), we have :

$$\begin{aligned} \frac{t_1}{T_s} &= \frac{1}{3} + \frac{\sqrt{3}}{3}\frac{V_o}{V_{dc}}\sin(\omega_o t + \frac{2\pi}{3}) \\ \frac{t_2}{T_s} &= \frac{1}{3} + \frac{\sqrt{3}}{3}\frac{V_o}{V_{dc}}\sin(\omega_o t) \\ \frac{t_3}{T_s} &= \frac{1}{3} + \frac{\sqrt{3}}{3}\frac{V_o}{V_{dc}}\sin(\omega_o t - \frac{2\pi}{3}) \end{aligned} \quad (15)$$

From eqes. (15) it is evident that :

$$\frac{V_o}{V_{dc}} \leq \frac{1}{\sqrt{3}} \quad or \quad \frac{V_o}{V_{dc}} \leq \frac{\sqrt{3}}{3} \quad (16)$$

and this means that the peak values of the input and output voltages must be satisfy in eqn. (16). If V_{in} is distorted (the input voltage is $v_{in}(t)$), then in eqns. (15) we replace constant input voltage, V_{dc}, with $v_{in}(t)$. For example, if we assume that, the input voltage has a ripple $V_r\cos(\omega_r t)$ as follows :

$$v_{in}(t) = V_{dc} + V_r\cos(\omega_r t) \quad ,\forall t : v_{in}(t) > 0 \quad (17)$$

then the equations in eqn. (15) will be as follows:

$$\begin{aligned} \frac{t_1}{T_s} &= \frac{1}{3} + \frac{\sqrt{3}}{3}\frac{V_o\sin(\omega_o t + \frac{2\pi}{3})}{V_{dc} + V_r\cos(\omega_r t)} \\ \frac{t_2}{T_s} &= \frac{1}{3} + \frac{\sqrt{3}}{3}\frac{V_o\sin(\omega_o t)}{V_{dc} + V_r\cos(\omega_r t)} \\ \frac{t_3}{T_s} &= \frac{1}{3} + \frac{\sqrt{3}}{3}\frac{V_o\sin(\omega_o t - \frac{2\pi}{3})}{V_{dc} + V_r\cos(\omega_r t)} \end{aligned} \quad (18)$$

From eqes (18) it is evident that :

$$\frac{|V_o|}{|V_{dc}| + |V_r|} \leq \frac{1}{\sqrt{3}} \quad or \quad \frac{|V_o|}{|V_{dc}| + |V_r|} \leq \frac{\sqrt{3}}{3} \quad (19)$$

It is obvious that the peak values of the input and output voltages must be satisfy in eqn. (19). The relations between the output voltages and the output currents for the three phase load ($R - L$) are given by:

$$
\begin{aligned}
v_{o1}(t) &= R\, i_{o1}(t) + L\frac{d\, i_{o1}(t)}{dt} \\
v_{o2}(t) &= R\, i_{o2}(t) + L\frac{d\, i_{o2}(t)}{dt} \\
v_{o3}(t) &= R\, i_{o3}(t) + L\frac{d\, i_{o3}(t)}{dt}
\end{aligned} \tag{20}
$$

and the fundamentals of the output voltages are :

$$
\begin{aligned}
v_{o1}(t) &= \frac{V_o}{\sqrt{3}}\cos(\omega_o t - \frac{\pi}{6}) \\
v_{o2}(t) &= \frac{V_o}{\sqrt{3}}\cos(\omega_o t - \frac{5\pi}{6}) \\
v_{o3}(t) &= \frac{V_o}{\sqrt{3}}\cos(\omega_o t + \frac{\pi}{2})
\end{aligned} \tag{21}
$$

From eqns. (20) and (21), the fundamentals of the output currents are given by (Figure(4)):

$$
\begin{aligned}
i_{o1}(t) &= \frac{V_o}{\sqrt{3}}\frac{1}{\sqrt{(L\omega_o)^2 + R^2}}\cos(\omega_o t - \tan^{-1}(\frac{R}{L}) - \frac{\pi}{6}) \\
i_{o2}(t) &= \frac{V_o}{\sqrt{3}}\frac{1}{\sqrt{(L\omega_o)^2 + R^2}}\cos(\omega_o t - \tan^{-1}(\frac{R}{L}) - \frac{5\pi}{6}) \\
i_{o3}(t) &= \frac{V_o}{\sqrt{3}}\frac{1}{\sqrt{(L\omega_o)^2 + R^2}}\cos(\omega_o t - \tan^{-1}(\frac{R}{L}) + \frac{\pi}{2})
\end{aligned} \tag{22}
$$

Also the relation between the input current and the output currents is given by:

$$
i_i(t) = \begin{cases} -i_{o2}(t) = i_{o1}(t) + i_{o3}(t) & Mode\ 1 \\ -i_{o3}(t) = i_{o1}(t) + i_{o2}(t) & Mode\ 2 \\ -i_{o1}(t) = i_{o2}(t) + i_{o3}(t) & Mode\ 3 \end{cases} \tag{23}
$$

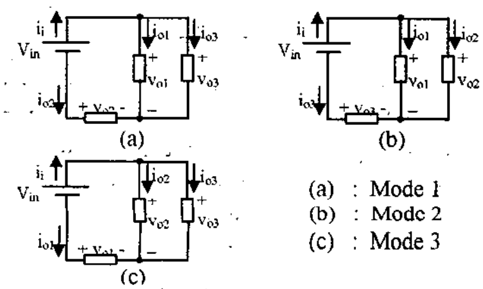

Figure 4: Equivalent circuits for DC to three-phase AC matrix converter at different modes

4. Simulation results

We use the Simulink Matlab and Pspic softwares. They prove that we can obtain the expecting results. According to the operation principle, the input and output current and voltage waveforms may be determined by the digital simulation method. The matrix converters are constituted by ideal switches. The input terminals are connected to a DC voltage source, and the output terminals loaded by a $R-L$ load $(R = 20^{\Omega}, L = 40^{mH})$, which can be an induction motor as well as. In both matrix converters, the input voltage source is $V_{dc} = 100^{V}$ and the values of ripple voltage are $V_r = 5^{V}$ and $f_r = 60^{HZ}$. The peak value of the fundamental component of the output voltages is $V_o = 50^{V}$ and them frequency is $f_o = 50^{HZ}$. The DC to single-phase and DC to three-phase matrix converters operate with $f_s = 1^{KHZ}$ and $f_s = 0.8^{KHZ}$ switching frequency, respectively. Figures (5-8) show the simulation results for DC to AC matrix converters. In this Figures, the output currents, FFTs of the output currents, the output voltages, FFTs of the output voltages, the input currents, FFTs of the input currents and the input voltage are presented. Simulation results show that this method is able to produce the undistorted output voltages, even the input supply voltage is distorted. Let us summarize some results of this research:

- Based on the eqns. (2-4) and eqns. (15-19), one can conclude the switching patterns of DC to single-phase and DC to three-phase matrix converters. The switches of the these matrix converters will be controlled according to these switching patterns.
- The averaged output voltages follow the required voltages given in eqn. (1) and (8).
- The maximum value of output voltages are given by eqns. (2), (4), (16) and (19).
- The output voltages contain fundamental and additional high order harmonics located at well defined sampled frequencies.
- The output voltage and currents contain high order harmonics located at $m \times f_s \pm n \times f_o$ (m and n are integer numbers).
- Because of the load of the converters are almost always a low pass filter (R-L), the output currents contain loss high order harmonics than the output voltages.
- The FFTs of the output voltages and currents show that the fundamentals of them are 50^{HZ}, even when the input voltage is distorted.

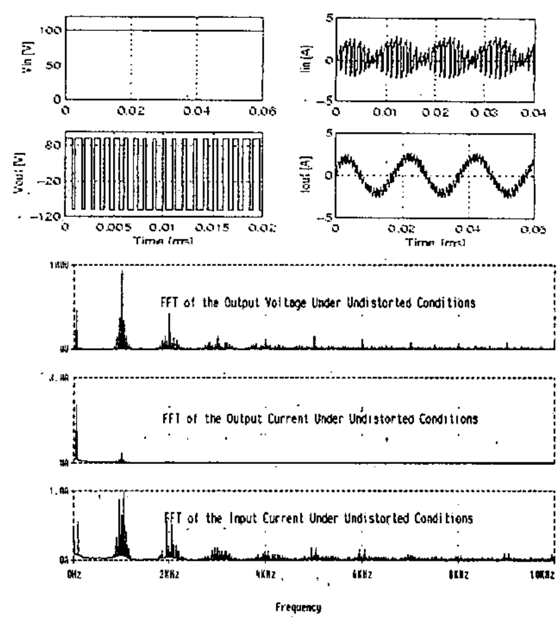

Figure (5): Simulation results for DC to single-phase AC matrix converter with constant input voltage.

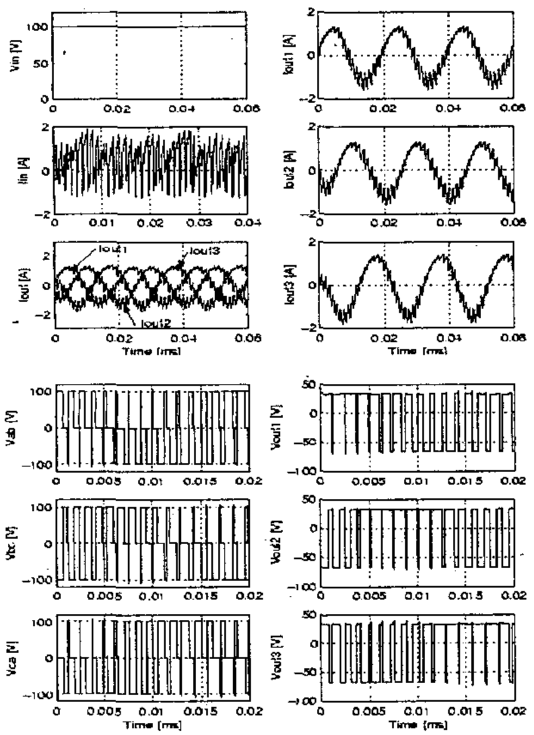

Figure (6): Simulation results for DC to three-phase AC matrix converter with constant input voltage.

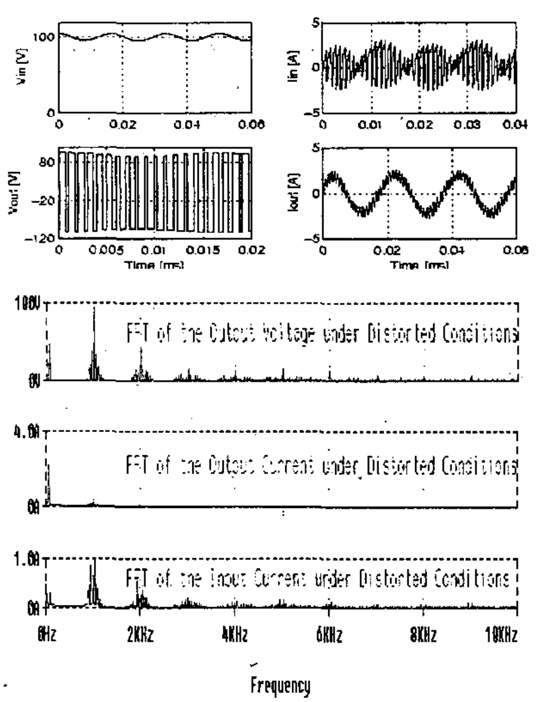

Figure (7): Simulation results for DC to single-phase AC matrix converter under distorted input voltage.

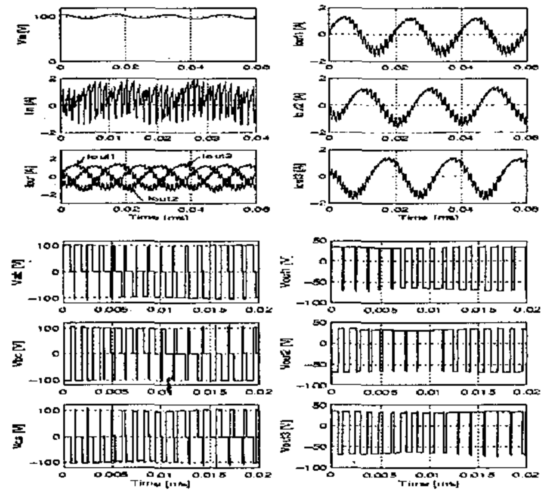

Figure (8): Simulation results for DC to three-phase AC matrix converter under distorted input voltage.

5. Conclusion

This paper presented a new switching strategy for DC to AC matrix converter, with an alternative PWM strategy, regardless of the number of output phases, also this novel modulation is very simple to implement. The derivation of the computational formulate has been described. The basic equations of the presented topologies were developed enabling the calculations of the ideal power switching patterns. The switching functions in such a converter, ensure that the switches do not short-circuit the voltage source, and do not open-circuit the current sources, thus we have the continuous currents at output and input terminals. Simulation results show that the new method is able to synthesize the desired reference voltages even when the supply voltage is distorted.

References

1. Der-Fa Chen, Tian-Hun Liu, *Implementation of a Novel Matrix Converter PMSM Drive*, IEEE Transaction on Aerospace and Electronic System, Vol.37, No. 3, pp. 863-875, July 2001.
2. L. Zhang, C. Watthanasarn, W. Shepherd, *Analysis and Comparison of Control techniques for AC-AC Matrix Converters*, IEE Proc. Elctr. Power Appl., July 1998, Vol. 145, No. 4, pp.284-294 .
3. Christian Klumpner, Peter Nielsen, Ion Boldea, Frede Bloabjerg, *New Steps towards a Low-Cost Power Electronic Building Block for Matrix Converters*, Proceeding of IAS'00, 2000, Vol. 3, pp. 1964-1971.
4. A. Zuckerberger, D. Weinstok , A. Alexandrovitz , *Single Phase Matrix Converter*, IEE Proc. Electr. Power App., July 1997, Vol. 144, No. 4, pp. 235-240.
5. S.H. Hosseini, E. Babaei, *A New Generalized Direct Matrix Converter*, 2001 IEEE International Symposium on Industrial Electronics Proceedings (ISIE2001) , PUSAN, KOREA, June 2001, Vol. 2, pp. 1071-1076.