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A modified PWM three intervals control for a matrix converter in real time

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In this paper, the application of the proposed control strategy PWM three intervals with 3×5 matrix converter is presented and analyzed. This control strategy is developed for the control of the multi-phases matrix converter, where the main aim is to ensure the waveform quality of the output voltages and the input currents based on the THD evaluation. Simulation results and real time implementation on dSpace 1103 of 3×5 matrix converter under R-L load are presented for the validation of the proposed control strategy and to clarify the main related advantages.

Key words: matrix converter [3×5], THD, PWM three intervals, real time

1. Introduction

Variable speed electric drives predominately utilize the three-phase machine, however, since the variable speed AC drives require a power electronic converter for their supply, the number of machine phases is essentially unlimited. This has led to an increase interest in multiphase AC drive applications due to their inherent advantages in comparison of three-phase AC drives [1], such as reducing the current amplitude, decreasing the torque ripples, reducing the rotor harmonic current per phase without increasing the voltage per phase, lowering the DC-link current harmonics, higher reliability and high fault tolerance [2].

A matrix converter is a variable amplitude and frequency power supply which converts the three phase line voltages directly [5] [6], without intermediate voltage or current link into the five phase output voltage. However, the matrix converter has several advantages compared to the conventional inverters. It is obvious that this is an AC-AC converter without DC link connected to the input. On the other side the passive elements of the energy storage which form the intermediate circuit (generally capacitors) between

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the AC-DC conversion stage and the inverter are eliminated [3], [4]. It is therefore possible to reduce considerably the volume and the cost of the conversion stage. Moreover the symmetry structure of the matrix converter allows ensuring the energy recovery directly to the supply system [5], [6].

The main objective of the study of this converter is the replacement of conventional inverters with DC link intermediary circuit by a direct AC-AC converter, where new control algorithms are developed to ensure this conversion function. This study is based on the waveform quality of the output voltage and input current and their THD. Finally simulation and real time results are presented for the validation of the proposed control strategy.

2. Modeling of the matrix converter

2.1. Structure of the matrix converter

The matrix converter is a static frequency and voltage converter which presents the main characteristic of conventional conversion rectifier-inverter. It allows in the same time obtaining a multiphase output voltage system with variable magnitude and frequency from a three phase or a multiphase input voltage power supply. [7], [8].

This converter topology is characterized by a matrix of fifteen switches (matrix [3×5], Fig. 1); three phases of the network as input are connected to five output phases through bidirectional power switches. Each switch in the matrix converter can be modeled by two diodes, and two transistors to reduce greatly the number of possible configurations of the matrix converter. [7], [8]. Since the converter is an idealized coupling, the principle of causality leads to precise rules concerning the switches grouping that are forming the matrix converter [1], [9]:

- Sources located on both sides of the group are necessarily different in nature.
- Continuity requires energy to retain, among the possible configurations of the operative part, that are physically possible: a non-zero voltage source can be short-circuited, a voltage source to zero can be set open circuit.

Finally it is deduced that for each leg one and only one switch should be closed, therefore the number of possible configurations is reduced to 3^5.

2.2. One leg operation principle of a matrix converter

The five legs commutations present a symmetrical function, hence a symmetrical control is adapted for the five legs. Thus the study of the matrix converter control can be reduced to the study of the control commutation of one leg which is shown in Fig. 2. [10], [11].

The leg commutation has three possible configurations. Each of these configurations is characterized by the output voltage which is presented in Tab. 1.

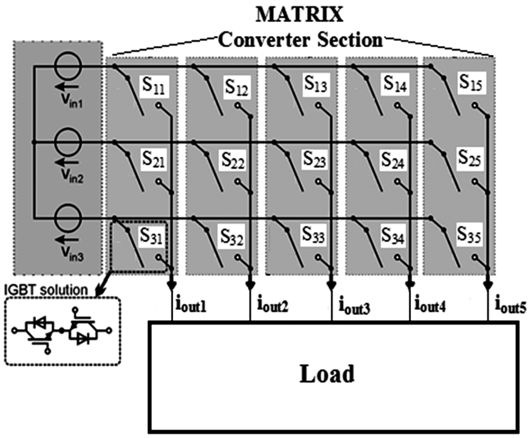


Figure 1. Schematic diagram of the matrix converter.

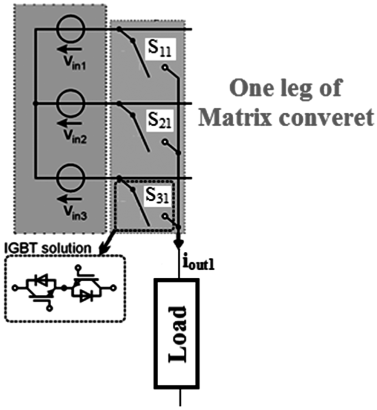


Figure 2. One leg of the matrix converter.

Table 1. Possible configuration of the matrix converter

Configuration	The output voltage of phase "1"
E_1	$U_{out1} = V_{in1}$
E_2	$U_{out1} = V_{in2}$
E_3	$U_{out1} = V_{in3}$

3. Principle of PWM three intervals control strategy

The control principle of the matrix converter is based on the analogy with the indirect converter with an intermediate circuit (rectifier/inverter) [1,9]. So to avoid the complexity of the matrix converter control, the advantage of simplicity of the conventional converter is adopted by introducing a virtual intermediate voltage Fig. 3. Based on the fact that at any given time, the power supply three phase input voltage system has at least one phase which is positive and at least another phase is negative relative to neutral power supply, the virtual intermediate voltage dependins on the chosen virtual potentials U^+ and U^- so that:

$$U_d = U^+ - U^- \tag{1}$$

where: U_d – intermediate virtual potential, U^+ – virtual positive potential, U^- – virtual negative potential.

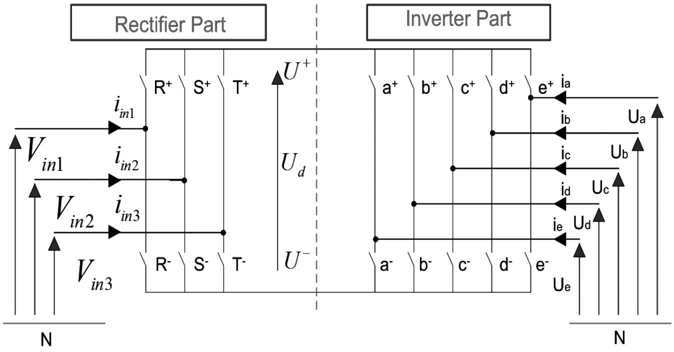


Figure 3. Model of the matrix converter with middle fictitious circuit.

3.1. Study of the rectifier part

The harmonic spectrum of the input current for this part is very important. Thus it is necessary to use a modulation function to provide the input a sinusoidal current, maintaining the same power transmitted via the intermediate circuit. This modulation function τ is defined as follows [17], [18]:

$$\tau = \frac{\cos\left(\Phi - 2\pi/3\right)}{\cos\left(\Phi\right)} + 1 \qquad 0 \leqslant \tau \leqslant 1 \tag{2}$$

where $\Phi = (\omega t)_{\text{mod}\,(\pi/3)} - (\pi/6)$. The connection between the input voltages and the virtual potential are represented follows [19]:

$$\begin{bmatrix} U^+ \\ U^- \end{bmatrix} = \begin{bmatrix} R^+ & S^+ & T^+ \\ R^- & S^- & T^- \end{bmatrix} \begin{bmatrix} V_{in1} \\ V_{in2} \\ V_{in3} \end{bmatrix}. \tag{3}$$

The value of the virtual DC-voltage $U_d = U^+ - U^-$ will be varying as function of the line phase angle and the rectifier control functions. For example, in the interval $\pi/3 < \omega t < 2\pi/3$, the switches can be taken the values ($R^+ = 1$, $S^+ = 0$, $T^+ = 0$) and ($R^- = 0$, $S^- = 1 - \tau$, $T^- = \tau$). The potential $U^+ = R^+ V_{in1} + S^+ V_{in2} + T^+ V_{in3}$, and the potential $U^- = R^- V_{in1} + S^- V_{in2} + T^- V_{in3}$, the parameters of the connection matrix are given in Tab. 2. Considering the symmetry founded in during a recovery period, six intervals can be determined as in Fig 4.

3.2. Study of the inverter part

The modulation functions U_{cmk} will be introduced to define the modulation matrix $[M_r(t)]$, where U_{cmk} takes continuous values between 0 and 1. This allows a link between

Table 2. Connections between input and virtual intermediate voltages

	Intervals		
	$0<\omega t<\frac{\pi}{3}$	$\frac{\pi}{3}<\omega t<\frac{2\pi}{3}$	$\frac{2\pi}{3}<\omega t<\pi$
$\begin{bmatrix} R^{+} & S^{+} & T^{+} \\ R^{-} & S^{-} & T^{-} \end{bmatrix}$	$\begin{bmatrix} \tau & 0 & 1-\tau \\ 0 & 1 & 0 \end{bmatrix}$	$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1-\tau & \tau \end{bmatrix}$	$\begin{bmatrix} 1-\tau & \tau & 0 \\ 0 & 0 & 1 \end{bmatrix}$

	Intervals cont.		
	$\pi<\omega t<\frac{4\pi}{3}$	$\frac{4\pi}{3}<\omega t<\frac{5\pi}{3}$	$\frac{5\pi}{3}<\omega t<2\pi$
$\begin{bmatrix} R^{+} & S^{+} & T^{+} \\ R^{-} & S^{-} & T^{-} \end{bmatrix}$	$\begin{bmatrix} 0 & 1 & 0 \\ \tau & 0 & 1-\tau \end{bmatrix}$	$\begin{bmatrix} 0 & 1-\tau & \tau \\ 1 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 1 \\ 1-\tau & \tau & 0 \end{bmatrix}$

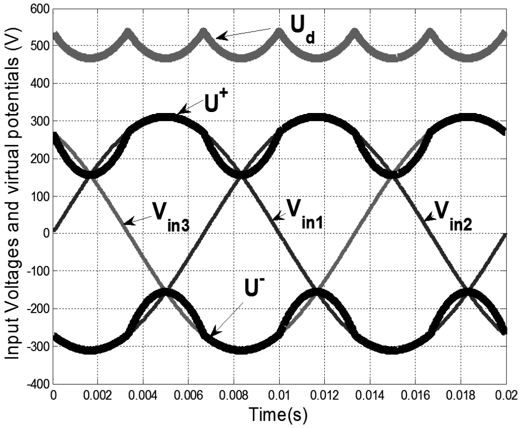


Figure 4. Curve of the input voltages and virtual potentials.

the middle potential and the output voltages of the matrix converter following to the expression:

$$\begin{bmatrix} U_a \\ U_b \\ U_c \\ U_d \\ U_e \end{bmatrix} = \underbrace{\begin{bmatrix} U_{cm1} & 1-U_{cm1} \\ U_{cm2} & 1-U_{cm2} \\ U_{cm3} & 1-U_{cm3} \\ U_{cm4} & 1-U_{cm4} \\ U_{cm5} & 1-U_{cm5} \end{bmatrix}}_{[M_r(t)]} \begin{bmatrix} U^+ \\ U^- \end{bmatrix}. \tag{4}$$

Taking into account the two blocks rectifier-inverter, the matrix $[M_r(t)]$ which allows to define the complete algorithm function of frequency conversion can be presented as follows:

$$\begin{bmatrix} U_a \\ U_b \\ U_c \\ U_d \\ U_e \end{bmatrix} = \underbrace{\begin{bmatrix} U_{cm1} & 1-U_{cm1} \\ U_{cm2} & 1-U_{cm2} \\ U_{cm3} & 1-U_{cm3} \\ U_{cm4} & 1-U_{cm4} \\ U_{cm5} & 1-U_{cm5} \end{bmatrix} \begin{bmatrix} R^+ & S^+ & T^+ \\ R^- & S^- & T^- \end{bmatrix}}_{[M(t)]} \begin{bmatrix} V_{in1} \\ V_{in2} \\ V_{in3} \end{bmatrix}. \tag{5}$$

The output reference voltage phases are defined as follows:

$$U_{ref\_k} = 220\sqrt{2}\sin\left(\omega_0 t - \frac{2\pi}{5}(k-1)\right) \tag{6}$$

where: $\omega_0 = 2\pi f_0$, $k = 1,2,\ldots,5$.

Determining the functions of undulation (standard reference functions) that are modulating the virtual middle voltage afore mentioned:

$$U_{cmk} = r\cos(\Phi)\sin\left(\omega_0 t - \frac{2\pi}{5}(k-1)\right) + \frac{1}{2} \tag{7}$$

where: U_{cmk} – modulation function, r – rate of modulation, $k = 1,2\ldots,5$.

It is well known that the control of the matrix converter ensures each output phase to be switched to each input phase during specified pulses duration within the period of the output voltage. Therefore the pulse period has to be divided into five intervals (number of output phases). Furthermore, a control method can be proposed for 3×5 matrix converters similar to the conventional control techniques that have been used for 3×3 matrix converter [14], [15], [17]. The obtained control signals by phase have binary values indicating the state of power switches. Fig. 5 shows the time sequence of the switches of one leg during one period of the output voltage. It is clear that the PWM strategy is characterized by two parameters, the modulation index m and the rate of modulation r.

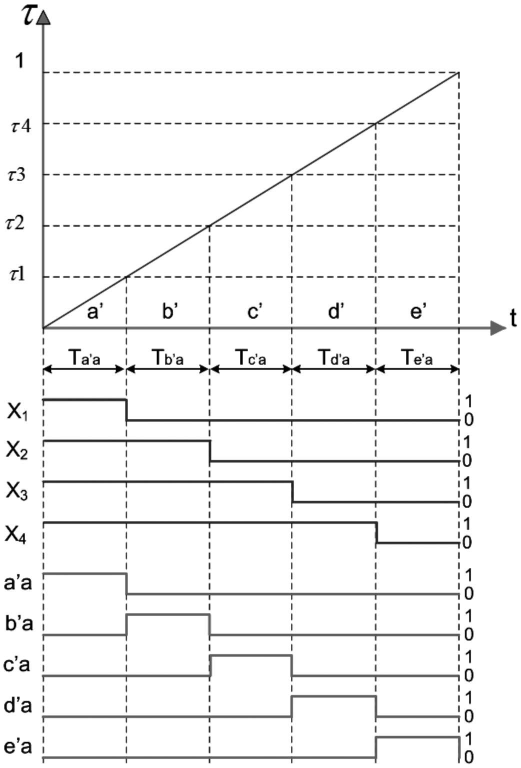


Figure 5. PWM five intervals that control output phase.

The equation of the carrier is defined as follows:

$$U_p = \frac{t}{T}, \quad 0 < t < T_p. \tag{8}$$

The output binary signals X_i of PWM modulator are defined as follow [18]:

$$X_i = \begin{cases} 1 & \tau_{xi} > U_p \\ 0 & \text{if not.} \end{cases} \tag{9}$$

The control signals of the switches of the matrix converter are obtained using a simple logic as:

$$\begin{cases} T_{a1} = X_1 \\ T_{b1} = \overline{X_1} \& X_2 \\ T_{c1} = \overline{X_2} \& X_3 \\ T_{d1} = \overline{X_3} \& X_4 \\ T_{e1} = X_4. \end{cases} \tag{10}$$

The previous equations are taken into account, so that the reference signals τ_x are defined as follows:

$$\begin{cases} \tau_{\mathrm{x1k}} = R^{+}U_{cmk} + R^{-}(1 - U_{cmk}) \\ \tau_{\mathrm{x2k}} = S^{+}U_{cmk} + S^{-}(1 - U_{cmk}) \end{cases} \tag{11}$$

where $k = 1, 2, \ldots 5$.

4. Simulation results

To validate presented technique, simulation and real time implementation have been done. The same parameters for the load have been used in both experiments which was presented by R-L load (R=20 Ω, L=10 mH), on the other side, the input three-phase voltage of the matrix converter is a typical three-phase system which is characterized by a magnitude of 220 V and a frequency of 50 Hz, the switching frequency is chosen to be 1550 Hz with a modulation index $r = 0.8$. The output voltage obtained by the application of the proposed PWM three intervals strategy with simulation and real time implementation are presented in Fig. 6 and Fig. 7 respectively. The harmonics spectrum of the output voltage is represented in Fig. 8. Whereas in Fig. 9, Fig. 10, Fig. 11 and Fig. 12 the output/input currents of one phase are shown respectively, it is clear that the output current resulting has a sine waveform. In Fig. 13, Fig. 14, Fig. 15 and Fig. 16 a shift phases between the output voltage and the output current obtained with PWM three intervals strategy by simulation and real time implementation results are presented. It is obvious from the obtained results that there are great similarities between results obtained by simulation and from the real time implementation, thus the proposed method is a promising technique to be used for the three input to multiphase output matrix converter in several industrial applications.

In Tab. 3, the fundamental voltage and THD voltage are presented. It is clear that the calculated PWM algorithm gives the maximal magnitude compared to the typical three-phase without classical matrix converter control.

Table 3. Fundamental and THD voltages/crrents

	Output voltage	Output current	Input Current
Fundamental	324.2 V	16.01 A	20.83 A
THD	93.74 %	21.94 %	82.15 %

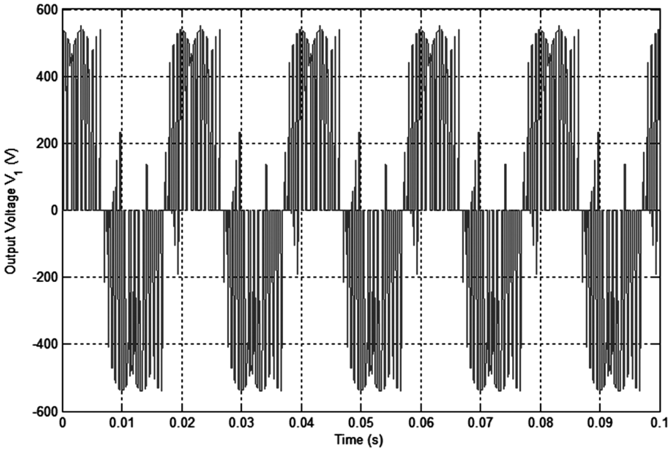


Figure 6. The output voltage obtained with PWM three intervals strategy – simulation.

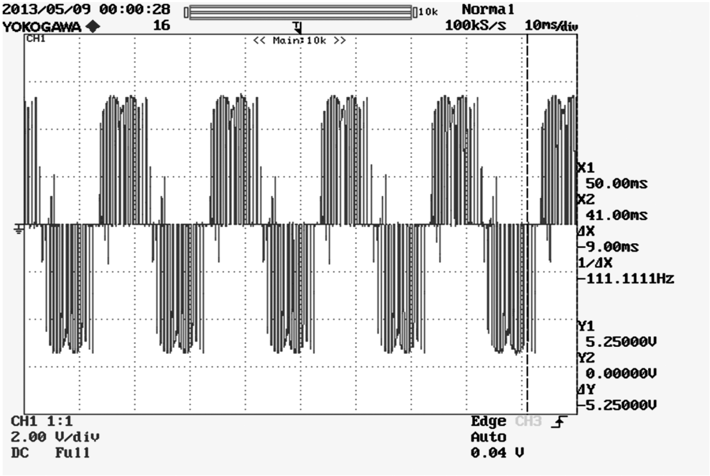


Figure 7. The output voltage obtained with PWM three intervals strategy – experimental results.

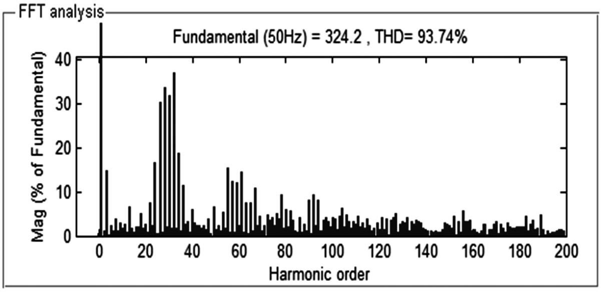


Figure 8. The harmonic spectrum of the output voltage obtained with PWM three intervals strategy.

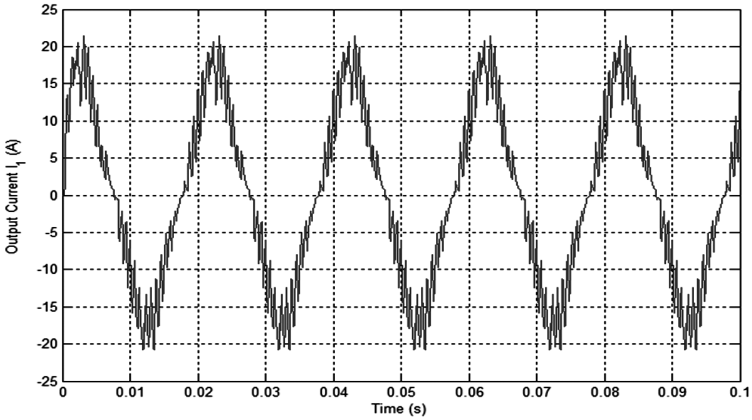


Figure 9. The output current obtained with PWM three intervals strategy – simulation.

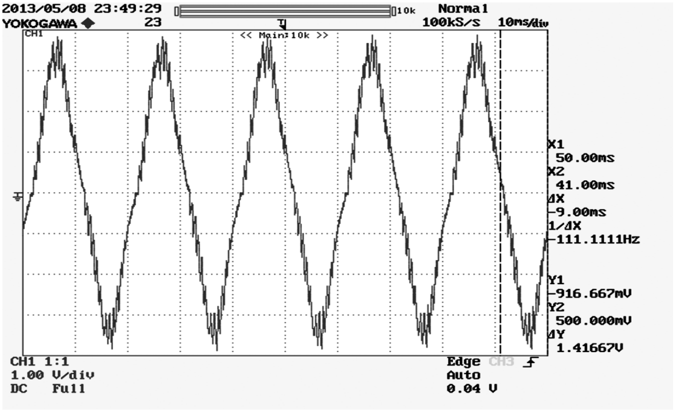


Figure 10. The output current obtained with PWM three intervals strategy – experimental results.

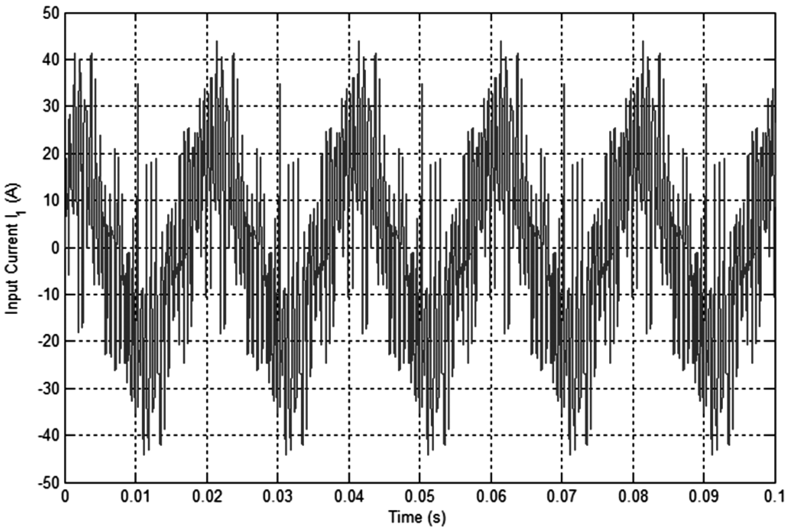
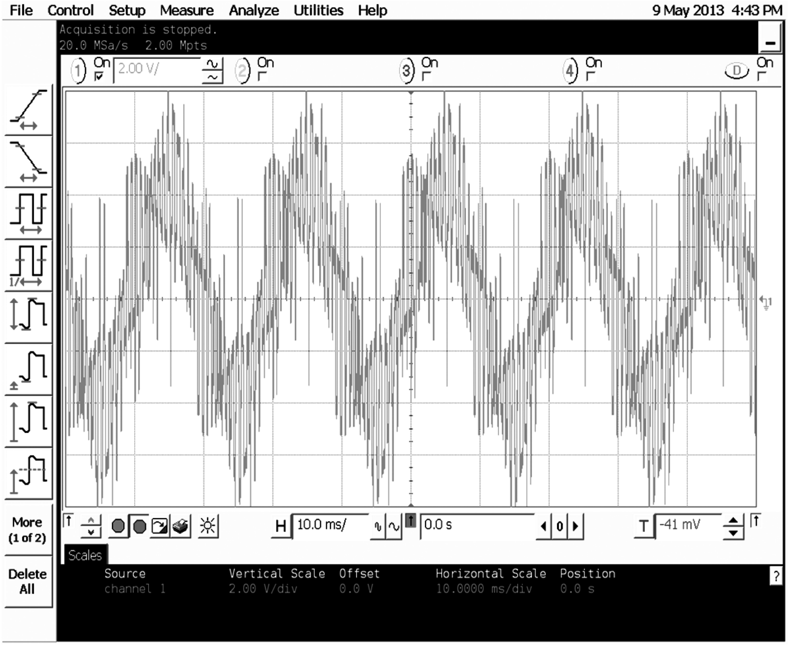


Figure 11. The input current obtained with PWM three intervals strategy – simulation.



Acquisition is stopped.
20.0 MSa/s 2.00 Mpts

2.00 V/

H 10.0 ms/ 0.0 s T -41 mV

Source	Vertical Scale	Offset	Horizontal Scale	Position
channel 1	2.00 V/div	0.0 V	10.0000 ms/div	0.0 s

Figure 12. The input current obtained with PWM three intervals strategy – experimental results.

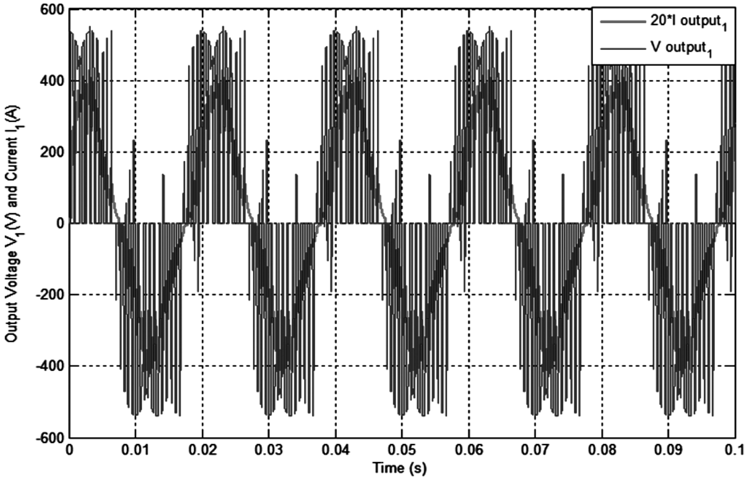
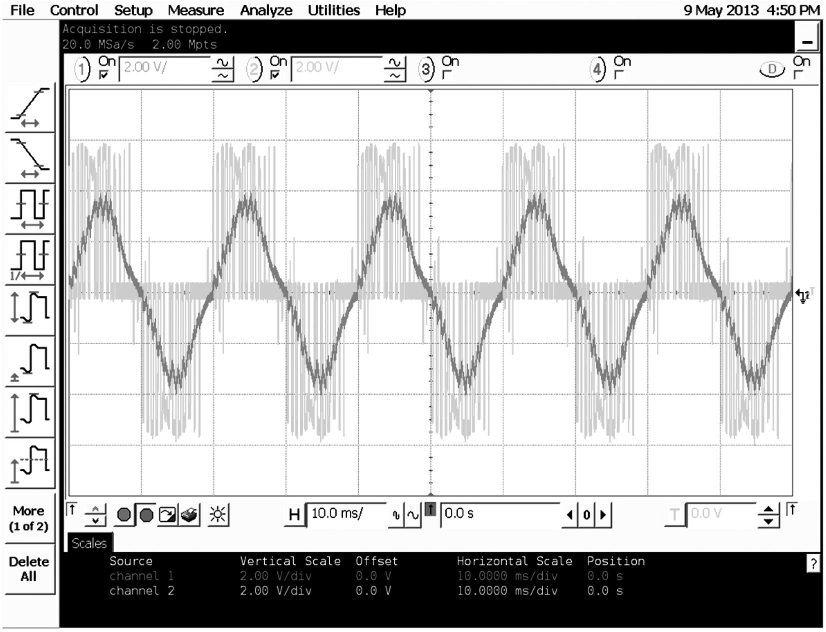


Figure 13. The shift phase between the output voltage and the output current obtained with PWM three intervals strategy – simulation.



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Acquisition is stopped.
20.0 MSa/s   2.00 Mpts
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Source       Vertical Scale  Offset      Horizontal Scale  Position
channel 1    2.00 V/div      0.0 V       10.0000 ms/div    0.0 s
channel 2    2.00 V/div      0.0 V       10.0000 ms/div    0.0 s
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Figure 14. The shift phase between the output voltage and the output current obtained with PWM three intervals strategy – implementation results.

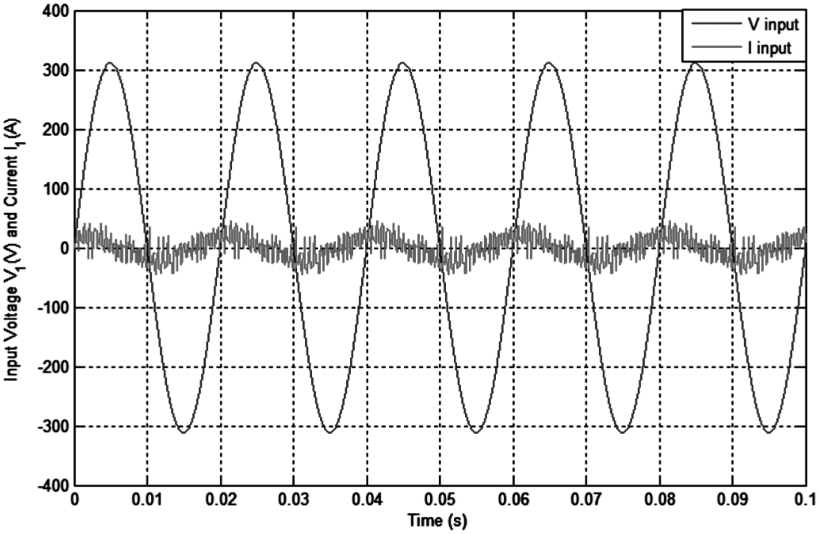

Figure 15. The shift phases between the input voltage and the input current obtained with PWM three intervals strategy – simulation.

5. Conclusion

This paper presents an approach to control matrix converter 3×5 with a modified strategy called PWM three intervals which is inspired by the conventional matrix converter 3×3 control method. The technique presented in this paper can be used for any number of output phases in a simplified way by changing only some parameters of the main proposed technique initially applied for matrix converter 3×3. Simulation and real time implementation results for 3×5 matrix converter are presented for the validation of the proposed method which has been developed analytically. It is clear that the obtained results are satisfactory. Hence, the proposed method can be used for the control of the three to multiphase matrix converter applications.

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