IMPLEMENTATION OF MATRIX CONVERTER CONTROL CIRCUIT WITH DIRECT SPACE VECTOR MODULATION AND FOUR STEP COMMUTATION STRATEGY

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Abstract

In this paper a matrix converter control circuit with implemented vector modulation and four-step commutation strategy is described. The presented control circuit consists of two DSP processors and FPGA. The matrix converter is a device build with 9 bidirectional switches (18 IGBT transistors). The Control circuit in contest makes possible of the matrix converter output voltage amplitude and frequency change, in addition input power factor can be controlled. Some simulation and experimental tests results of the ca. 1 kVA matrix converter laboratory model controlled by described control circuit are shown.

1. Introduction

In recent years transformation and control of energy has been mostly realized with indirect AC-AC converters with DC link. An alternative for this solution is still searched for. One of the recently considered alternatives is Matrix Converter (MC). The MC is a direct energy converter (build with nine bidirectional switches) able to connect every output phase to every input phase and on this principle deliver output power with desired frequency.

The main advantages of the MC are: 1- lack of the DC link energy storage device, 2- generation of the load voltages with arbitrary amplitude and frequency, 3- sinusoidal input and output currents, 4- possibility to control input power factor, 5-regeneration capability. The basic disadvantages are: 1- maximum input/output voltage transfer ratio by sinusoidal current shape below 1 by most control strategies, 2- sensitivity to the disturbance of the input voltage systems.

There are two main concepts of MC control strategies: the first based on low frequency transfer matrix (for example: scalar [20] control strategy or control strategy proposed by Venturini [1], [2]) and the second based on currents and voltages space vector (SV) representations (for example direct [5]-[8] or indirect [3] space vector control strategy).

A direct space vector modulation (SVM) does not need fictitious DC link or addition of the third-harmonic as in other common MC control strategies.

Maximal voltage transfer ratio for this strategy is 0,866. Furthermore control of the input power factor is realized regardless of the output power factor [5]-[10]. Because of those advantages the strategy (after some modifications) will be implemented in Matrix Reactance Frequency Converters (MRFC). The converters have been studied by Professor Fedyczak’s team at the University of Zielona Góra. Implementation of the SVM for MRFC is going to be a part of the author’s PhD work. MRFC is based on a unipolar PWM AC matrix reactance choppers (MRC), description of the MRF family (9 topologies) is included in [15] and [16]. In MRFC both a frequency change and the buck-boost load voltage conversion are possible [12]-[19].

This paper presents project as well as simulation and experimental tests results of the MC control circuit with implemented direct (SVM) and four-step current commutation control strategy. Presented control circuit is going to be a part of the MRFC with modified direct SVM.

Next section contains description of the matrix converter and its control circuit. Basing on [5]-[8] and [11] implemented control and commutation strategy is described in section 3. In section 4 some simulation and experimental test results are shown. Conclusion follows in the last section.

2. Description of the MC

Schema of the main and control circuit of the three phase voltage MC with RL load is shown in fig. 1. Voltage and current relations of the MC are described by (1)-(2) [1]-[9].

\[
\begin{align*}
\begin{bmatrix}
    u_a(t) \\
    u_b(t) \\
    u_c(t)
\end{bmatrix} &=
\begin{bmatrix}
    s_{ab}(t) & s_{ac}(t) & s_{bc}(t) \\
    s_{ac}(t) & s_{bc}(t) & s_{ab}(t) \\
    s_{bc}(t) & s_{ab}(t) & s_{ac}(t)
\end{bmatrix}
\begin{bmatrix}
    i_a(t) \\
    i_b(t) \\
    i_c(t)
\end{bmatrix} = T \times i_t
\end{align*}
\]

\[
\begin{align*}
\begin{bmatrix}
    i_a(t) \\
    i_b(t) \\
    i_c(t)
\end{bmatrix} &=
\begin{bmatrix}
    s_{ab}(t) & s_{ac}(t) & s_{bc}(t) \\
    s_{ac}(t) & s_{bc}(t) & s_{ab}(t) \\
    s_{bc}(t) & s_{ab}(t) & s_{ac}(t)
\end{bmatrix}
\begin{bmatrix}
    I_a(t) \\
    I_b(t) \\
    I_c(t)
\end{bmatrix} = T^T \times I_t
\end{align*}
\]

where \( s_{jk} = \begin{cases} 1, & \text{switch is on} \\ 0, & \text{switch is off} \end{cases} \) \( j=\{a, b, c\}, k=\{A, B, C\} \)
MC can theoretically assume 512 (2^9) switching configurations (SC) but because of commutation lows there are only 27 SC permitted among which 21 SC (18 active and 3 zero), are engaged in direct SVM [3]-[8]. Geometrical interpretations of those 21 SC are shown in fig. 3.

Using transformation (3) input and output voltages and currents of the MC can be represented as space vectors:

\[ x = \frac{2}{3} (x_1 + x_2 e^{j(2\pi/3)} + x_3 e^{j(4\pi/3)}) \]

Where \( x, x_1, x_2, x_3 \) – instantaneous values of the transformed signals.

The geometrical interpretations of the space-vector representations of the line to neutral load voltages \((u_{an}, u_{bn}, u_{cn})\) and input line currents \((i_a, i_b, i_c)\), created for all active and zero SC (fig. 2) according to (3) are shown in fig. 3. Furthermore numbers of the sectors \((S_o, S_i)\) between those vectors are introduced [7].

Because of MC complexity its control and commutation strategy is complicated and demands advanced hardware solutions. That is why presented control circuit consists of two DSP processors (ADSP 21368), three A/D converters and a FPGA circuit (fig. 1). Basic specifications data for those components are collected in table 1. Using this control circuit instantaneous space-vector representations of the source currents are calculated.

Based on those calculations proper switching sequence can be found to form desired load voltage vector. This process will be described in detail in the next section.

### 3. Control and commutation strategy

Functional schema of the implemented control and commutation strategy and tasks division for control circuit components are shown in fig. 4. Because of MC source currents distortion their space vector representation \( i_j \) is determined basing on measured source phase voltages. The way in with
source currents vector position is defined, based upon source voltages vector position (calculated according to (3)) is shown in fig. 6b. Load voltages space vector $\mathbf{u}_{n}$ with desired amplitude and angular velocity $\omega_{\text{out}}$ is also calculated according to (3). In the next step according to fig. 3 previously calculated $\mathbf{i}_{q}$ and $\mathbf{u}_{n}$ positions allows sectors numbers $S_{n}$, $S_{i}$ and phase angles $\alpha_{q}$, $\beta_{i}$ to be identified. It has to be mentioned that phase angles $\alpha_{q}$, $\beta_{i}$ are defined with respect to bisecting line of suitable sector, limited according to (4) and differ then $\alpha_{0}$, $\beta_{i}$ (fig. 3, fig. 6) [7].

$$-\pi/6 < \alpha_{q} < \pi/6 \quad -\pi/6 < \beta_{i} < \pi/6$$

**Table 2. Summary of the active configurations assigned to sectors and on-time ratios.**

<table>
<thead>
<tr>
<th>Sector</th>
<th>$S_{n}$</th>
<th>$\delta_{n}$</th>
<th>$\delta_{i}$</th>
<th>$\delta_{0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 or 4</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>2 or 5</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>3 or 6</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

**Table 3. Summary of the zero configurations assigned to sectors and on-time ratios.**

<table>
<thead>
<tr>
<th>Sector</th>
<th>$S_{n}$</th>
<th>$\delta_{n}$</th>
<th>$\delta_{i}$</th>
<th>$\delta_{0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 or 4</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>2 or 5</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>3 or 6</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Selected switching configurations (vectors) are turned on according to the sequence described by (11), where for example $\delta_{0}/2\delta_{i}$ means that SC selected according to above described principles and assigned in table 2 to $\delta_{0}$ must be switched on as the first one for the time $\delta_{0}/2\delta_{i}$. This switching pattern was achieved by comparison of the modulation waves with saw wave as it is shown in fig. 5. As a result of this comparison during every switching period $T_{\text{seq}}$ local duty cycles $d_{0}$ for individual transistors are worked out.

$$\delta_{0}/2 \delta_{i}/2 \delta_{0}/2 \delta_{i}/2 \delta_{0}/2 \delta_{i}/2 \delta_{0}/2 \delta_{i}/2$$

**Fig. 5. Switching pattern description.**

In fig. 6 there is an example how vector $\mathbf{u}_{n}$ which represents instantaneous values of the load phase voltages, and vector $\mathbf{i}_{q}$, which represents instantaneous values of the source currents is formed. Vector $\mathbf{u}_{n}$ is set up of two components $\mathbf{u}_{n}^{+}$ and $\mathbf{u}_{n}^{-}$, which are created by switching on earlier selected vectors (in ex. 7, 16, 21, 6, 1) through suitable times (9), (10) during the cycle period. Furthermore in Fig. 4b it is shown how the control
of $\varphi_i$ (input power factor) is achieved by controlling $\beta_i$. It has to be accounted that:

$$q_{\text{max}} = 0.866 \cdot \cos(\varphi_i)$$

4. Simulation and experimental test results

A photograph of the MC prototype for which the described control circuit was designed is shown in fig. 9. The MRFC are also researched with this prototype[19]. Simulation tests were obtained by Matlab Simulink. Simulation and experiment parameters are collected in table 4.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source amplitude and frequency</td>
<td>$U_s / f$</td>
<td>Simulation: 230 V/50 Hz, Experiment: 62 V/50 Hz</td>
</tr>
<tr>
<td>Switching time period</td>
<td>$T_{\text{seq}}$</td>
<td>2 ms</td>
</tr>
<tr>
<td>Inductivities</td>
<td>$L_p$</td>
<td>1.5 mH</td>
</tr>
<tr>
<td></td>
<td>$L_a$</td>
<td>10 mH</td>
</tr>
<tr>
<td>Capacitors</td>
<td>$C_p$</td>
<td>10 µF</td>
</tr>
<tr>
<td>Resistance</td>
<td>$R_s$</td>
<td>60 Ω</td>
</tr>
</tbody>
</table>

Table 4. Simulation and experiment parameters.

Fig. 6 Vector modulation principle a) for exemplary output voltage vector position, b) for exemplary input current vector position.

In fig. 7a a fragment of MC from fig. 1 is shown. Bidirectional switch $S_{B}$ ($T_{BA1}$, $T_{BA2}$) cannot be switched on in the same time when $S_{C}$ ($T_{CA1}$, $T_{CA2}$) is switched off because of the finite turn-on and turn-off times. In such switch state short-circuit or overvoltage can occur which can cause semiconductor damage. To avoid such switch states in presented control circuit a four step current commutation strategy is implemented. In fig. 7b an exemplary commutation diagram between $S_{B}$ and $S_{CB}$ is shown. In fig. 8a transition diagram which presents how this commutation strategy is realized in FPGA (fig. 1, fig. 4) is shown.

Fig. 7 Commutation in MC, a) fragment of MC- two bidirectional switches b) commutation diagram for $S_{B}$ and $S_{CB}$. $t_C$ - duration of commutation steps.

Rys. 9. Matrix converter prototype

1 - input filter; 2 - AC adapter; 3 - FPGA board (L19PLD); 4 - optical transmitters; 5 - load current measurement circuit; 6 - source voltage measurement circuit; 7 - optical receivers and transistor drivers; 8 - protection lamp circuit; 9 - load induction; 10 - load resistance; 11 - DSP board (ALS-G3-326CHPCI) 12 - A/D converters (ALS-G3-ACA1812-1); 13 - PC

Simulation and experimental tests results of the MC prototype controlled by the described control circuit are shown in fig. 10-18. In fig. 10 an example of the generated by FPGA transistors control signals (during commutation process) time waveforms are shown. Voltage and current time waveforms, for three desired first harmonic load voltage frequencies 25 Hz, 50 Hz, 75 Hz, are shown in fig. 11 and 12. It has to be mentioned that input power factor for those waveforms is corrected to value 1 thanks to proper control. In fig. 13-15 voltage and current time waveforms with desired displacement between source current and voltage (input power factor) with RL load (fig. 13, 14) and R load (fig. 15) are shown.
Fig 10. Example of the control signals (during commutation process) time waveforms.

Fig 11. Simulation time waveforms of the source current and voltage \( (u_{SS}, i_a) \) and load current and voltages \( (u_{SL}, i_q) \) with corrected to value 1 input power factor and desired output frequency, a) \( f_s = 25 \) Hz, b) \( f_s = 50 \) Hz, c) \( f_s = 75 \) Hz.

Fig 12. Experimental time waveforms of the source current and voltage \( (u_{SS}, i_a) \) and load current and voltages \( (u_{SL}, i_q) \) with corrected to value 1 input power factor and desired output frequency, a) \( f_s = 25 \) Hz, b) \( f_s = 50 \) Hz, c) \( f_s = 75 \) Hz.

Fig 13. Simulation time waveforms of the source current and voltage \( (u_{SS}, i_a) \) and load current and voltages \( (u_{SL}, i_q) \) by RL load for a) \( f_s = 75 \) Hz, \( \varphi_s = 0,6 \) rad, \( q = 0,71 \), b) \( f_s = 75 \) Hz, \( \varphi_s = 0,6 \) rad, \( q = 0,71 \).

Fig 14. Experimental time waveforms of the source current and voltage \( (u_{SS}, i_a) \) and load current and voltages \( (u_{SL}, i_q) \) by RL load for a) \( f_s = 25 \) Hz, \( \varphi_s = 0,6 \) rad, \( q = 0,71 \), b) \( f_s = 25 \) Hz, \( \varphi_s = 0,6 \) rad, \( q = 0,71 \).

Fig 15. Experimental time waveforms of the source current and voltage \( (u_{SS}, i_a) \) and load current and voltages \( (u_{SL}, i_q) \) by R load for a) \( f_s = 50 \) Hz, \( \varphi_s = 0,7 \) rad, \( q = 0,66 \), b) \( f_s = 50 \) Hz, \( \varphi_s = 0 \) rad, \( q = 0,66 \), c) \( f_s = 50 \) Hz, \( \varphi_s = 0,7 \) rad, \( q = 0,66 \).

From fig. 10-14 it can be seen that control circuit in contest make possible the matrix converter output voltage amplitude and frequency change also input power factor (displacement between source currents and voltages) can be controlled. In fig 16-18 static characteristics of the controlled converter are shown. Maximum input/output voltage transfer ratio by
sinusoidal current shape is below 1 what is shown in fig. 16. In fig. 17 obtained range of input power factor changes is shown. Coefficient efficiency for presented MC is shown in fig. 18.

![Fig. 16. Input/output voltage ratio ($U_{out}/U_{in}$) as a function of desired in program Input/output voltage ($\phi$) for $f_{c}=25$, 50, 75 Hz](image1)

![Fig. 17. Input power factor changes as a function of input/output voltage transfer ratio $\rho$ dla for $f_{c}=25$, 50, 75 Hz](image2)

![Fig. 18. Experimental efficiency coefficient as a function of input/output voltage transfer ratio $\rho$ dla for $f_{c}=25$, 50, 75 Hz](image3)

5. Conclusions

In this paper the project of the control circuit of MC with implemented space vector modulation and four step commutation strategy has been presented. Simulation and experimental tests results have confirmed that the presented control technique exploits the MC’s possibility to control the input power factor regardless of the output power factor. In addition frequency and amplitude of the output voltage can be controlled. Implementation of the direct space vector modulation and four step current commutation strategies for Matrix-Reactance Frequency converter will be the subject of investigation in the near future.

6. References


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