

Simulation of a simple control strategy for a common 3x3 Matrix Converter

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Abstract

Simulation strategies for a classical three phase matrix converter are presented in this paper. A simple control method, which can be realized on the basis of the table functions and elementary calculation algorithms, is described. Both - MATLAB and more detailed schematic simulation in PSpice environment are covered. The simulation results have confirmed the validity of the proposed control method.

Keywords

Matrix converter, simulation, vector modulation, pulse width modulation.

Introduction

Matrix converters (MC) are well known for more than twenty years when M.G.B.Venturini and A.Alesina formed a mathematical matrix description of behavior of the MC, gave a possible control algorithm and defined the main restrictions of power conversion [1]. Interest about MCs has been rising ever since and there is rather large number of articles devoted to MCs ([2]-[5] to mention just few of them). In [6] a scalar representation of space vector modulation is given. These traditional control methods are reviewed in this paper and simplified two-level PWM control algorithm is presented and verified by means of algorithmic simulation in MATLAB and more detailed schematic simulation in PSpice.

1. Simple control of matrix converters

1.1 General assumptions

Some assumptions are taken into account during the analysis. First, power losses switching elements are negligible. That is why it is assumed that all power is transferred completely from one side of an MC to the other. Second, MCs operate with voltage sources on one side and current sources on the other. In this case, each phase of the second side must be connected to one phase of the first side. Commutation strategies are not discussed here. Third, MCs mostly act as symmetrical converters. It means that there is a symmetrical voltage set on the one side and symmetrical load on another. Consequently, at proper control all variables of a MC are sinusoidal and form symmetrical set.

1.2 Vector approach

Each input and output phase can be associated with a space axis of a definite direction. If variables

are in vector form, the resulting vector can be found. From practical point of view it is more efficient to use line voltage:

$$\bar{V}_{IN} = \begin{bmatrix} v_{AB}(t) \\ v_{BC}(t) \\ v_{CA}(t) \end{bmatrix} = \begin{bmatrix} V_{inM} \cdot \sqrt{3} \cdot \sin(\omega_{in} \cdot t) \\ V_{inM} \cdot \sqrt{3} \cdot \sin(\omega_{in} \cdot t - 2 \cdot \pi / 3) \\ V_{inM} \cdot \sqrt{3} \cdot \sin(\omega_{in} \cdot t + 2 \cdot \pi / 3) \end{bmatrix} \cdot (1)$$

If base vector is $\bar{D} = \begin{bmatrix} e^{j0} & e^{j\frac{2\pi}{3}} & e^{-j\frac{2\pi}{3}} \end{bmatrix}$ then the

resulting vector can be found:

$$\bar{V}_{IN0} = \bar{D} \cdot \bar{V}_{IN} = \sqrt{3} \cdot \frac{3}{2} \cdot V_{inM} \cdot e^{j(\frac{\pi}{2} - \omega_{in}t)} \quad (2)$$

As can be seen from (2), the input voltage vector rotates at the angular speed of ω_{in} . On the other hand, if the reference vector is known, then axial components can be found. For the output voltage and input current a reference vector can be set based on the power parameters of the system. This vector rotates at the angular speed ω_{OUT} with a discrete step $\Delta\theta_0$, which is defined by the desirable value of the switching frequency.

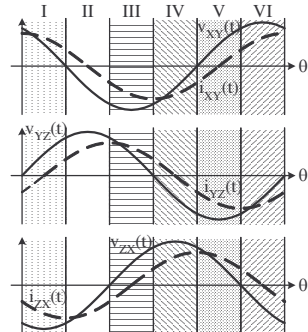
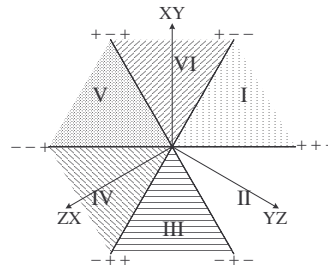


Fig.1. Output zones during vector modulation: a) vector diagram; b) time diagram at $\phi = \pi/6$

$$\Delta\theta_0 = \frac{2 \cdot \pi \cdot f_{OUT}}{f_{sw}} \quad (3)$$

where f_{out} – output frequency, f_{sw} – switching frequency. In this case the phase angle at the given time instant can be expressed as follows:

$$\theta_o = \omega_{OUT} \cdot t = \Delta k \cdot \quad (4)$$

There are sub-periods of the input and output cycle, when general representation of the voltage and current of the MC is similar. That is why it is convenient to divide the input and output periods into 6 zones. Input zones depend on the conversion method and there are several sets of input zones. Output subdivisions are presented in Fig.1 (both time and vector representations are given).

If MC has 3 input phases and 3 output phases, then there are 9 power switches. The number of possible states of the switch array is $2^9=512$. However, since each output phase should be connected to one of the input phases, there are $3^3 = 27$ valid combinations

Each state of the power matrix gives a certain vector. Equations like (2) can be written for all states of power array and resulting vectors can be found.

1.3 Two-level vector modulation

The simplest kind of vector modulation is one-level vector modulation - when axial components contain only one part, which is created by one modulation voltage. However this modulation algorithm is not described in this paper due to its main drawback – bad harmonic content of the input current. This feature may be improved only if each input phase is involved into the conversion process during the entire period. It is possible if two (or more) modulation voltages are used. It can be concluded that each reference vector must have more than 2 axial components or, if this number is 2, each of them must consist of at least two sub-vectors (axial parts). The simplest modification of the valid control algorithm, which is presented in the given section and also in [7] uses 2 axial components of the reference vector, and each of these components consists of 2 parts.

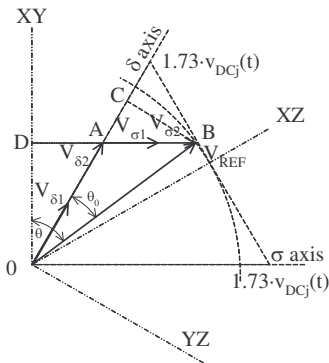


Fig.2. Vector diagram at the two-level control algorithm

The vector diagram for such control principle is given in Fig.2. There are two modulation voltages available at three-phase input system. While the input angle is $0 \dots \pi/3$ the first – falling modulation voltage is created by phase C(+) and B(-) (Fig.3-a). The second – rising modulation voltage is created by phase A(+) and B(-). Thus, there are two parts of each axial component: $v_{\delta\Sigma} = v_{\delta1} + v_{\delta2}$ and $v_{\sigma\Sigma} = v_{\sigma2} + v_{\sigma1}$. Then output phase to phase voltage of the converter has voltage pulses of two values during the same switching cycle (Fig.3-b).

Since all three input phases are always involved in the conversion, there are no long periods ($> T_{SW}$) when some of phase currents are zero, which improves the harmonic content of phase currents.

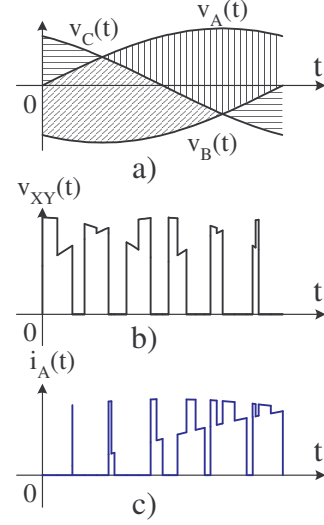


Fig. 3. Input and output variables of the MC at the two level control: a) input voltage set; b) output voltage $v_{XY}(t)$ ($f_{OUT}=23.8\text{Hz}$); c) input current $i_A(t)$ at $\phi=\pi/6$

The given control algorithm can be described by the following equations:

$$v_{\delta} = v_{\delta1} + v_{\delta2} = \frac{3}{2} \cdot \sqrt{3} \cdot V_{outM} \cdot \frac{\sin(\pi/3 - \theta_0^*)}{\sin(\pi/3)}, \quad (5)$$

$$v_{\sigma} = v_{\sigma1} + v_{\sigma2} = \frac{3}{2} \cdot \sqrt{3} \cdot V_{outM} \cdot \frac{\sin \theta_0^*}{\sin(\pi/3)}, \quad (6)$$

$$i_{\delta} \cdot \gamma_{\delta1} + i_{\sigma} \cdot \gamma_{\sigma1} = i_{MOD1} = i_{input1}, \quad (7)$$

$$i_{\delta} \cdot \gamma_{\delta2} + i_{\sigma} \cdot \gamma_{\sigma2} = i_{MOD2} = i_{input2}, \quad (8)$$

where v_{MOD1} , v_{MOD2} , i_{input1} and i_{input2} may be found from the following formulas:

$$v_{MOD1} = \sqrt{3} \cdot V_{inM} \cdot \sin(\theta_{in}^* + \pi/2), \quad (9)$$

$$v_{MOD2} = \sqrt{3} \cdot V_{inM} \cdot \sin(\theta_{in}^* + \pi/6), \quad (10)$$

$$i_{input1} = I_{inM} \cdot \sin(\theta_{in}^* + 2\pi/3), \quad (11)$$

$$i_{input2} = I_{inM} \cdot \sin \theta_{in}^*. \quad (12)$$

In fact (5)...(12) describe two separate systems of equations. Each system contains four unknown variables and only two equations. A simple solution requires an additional condition. This condition expresses the relationship between relative times that corresponds to the parts of the same axial component. It may be a constant, but it is better to compose this relationship as a ratio of the desirable current values of the phases that form the corresponding modulation voltage. If $\phi = 0$, then:

$$\frac{\gamma_{\delta1}}{\gamma_{\delta2}} = \frac{\gamma_{\sigma1}}{\gamma_{\sigma2}} = \frac{i_{input1}}{i_{input2}} = \frac{I_{inM} \cdot \sin(\theta_{in}^* + 2\pi/3)}{I_{inM} \cdot \sin \theta_{in}^*} = \frac{\sin(\theta_{in}^* + 2\pi/3)}{\sin \theta_{in}^*}. \quad (13)$$

(13) can be converted, for example into the following:

$$\gamma_{\delta2} = \frac{\sin \theta_{in}^*}{\sin(\theta_{in}^* + 2\pi/3)} \cdot \gamma_{\delta1}. \quad (14)$$

The last one and (5), (11), (12) can be converted to a single equation and $\gamma_{\delta 1}$ can be extracted:

$$\gamma_{\delta 1} = \frac{2}{\sqrt{3}} \cdot K_V \cdot \sin(\pi/3 - \theta_0^*) \cdot \sin(\theta_{in}^* + 2\pi/3) \quad (15)$$

Another equation can be composed based on (6), (11), (12) and (14) with respect to $\gamma_{\delta 2}$. Then the following equation can be written:

$$\gamma_{\delta 2} = \frac{2}{\sqrt{3}} \cdot K_V \cdot \sin(\pi/3 - \theta_0^*) \cdot \sin \theta_{in}^* \quad (16)$$

In similar manner (5)...(8), and (11)...(13) can give formulas for $\gamma_{\sigma 1}$ and $\gamma_{\sigma 2}$:

$$\gamma_{\sigma 1} = \frac{2}{\sqrt{3}} \cdot K_V \cdot \sin \theta_0^* \cdot \sin(\theta_{in}^* + 2\pi/3), \quad (17)$$

$$\gamma_{\sigma 2} = \frac{2}{\sqrt{3}} \cdot K_V \cdot \sin \theta_0^* \cdot \sin \theta_{in}^* \quad (18)$$

Phase currents consist of two current pulses per switching cycle. That is way the following expressions can be written (see also (7) and (8)):

$$i_{input1} = i_{\delta} \cdot \gamma_{\delta 1} + i_{\sigma} \cdot \gamma_{\sigma 1}, \quad (19)$$

$$i_{input2} = i_{\delta} \cdot \gamma_{\delta 2} + i_{\sigma} \cdot \gamma_{\sigma 2}. \quad (20)$$

Currents that correspond to the axial vectors can be expressed as follows (as is seen in Fig.3.1):

$$i_{\delta} = I_{outM} \cdot \sin(\theta_0^* + \pi/2 - \phi), \quad (21)$$

$$i_{\sigma} = I_{outM} \cdot \sin(\theta_0^* + \pi/6 - \phi). \quad (22)$$

Equations (21) and (22) may substitute currents, but (15)...(18) may be used to express relative times $\gamma_{\delta 1}$, $\gamma_{\delta 2}$, $\gamma_{\sigma 1}$ and $\gamma_{\sigma 2}$ in the last two formulas, after simplifications, the input current can be written as:

$$i_{input1} = K_V \cdot I_{outM} \cdot \cos \phi \cdot \sin(\theta_{in}^* + 2\pi/3). \quad (23)$$

In case of symmetrical system the active power equilibrium is:

$$I_{inM} = K_V \cdot I_{outM} \cdot \cos \phi. \quad (24)$$

Taking into account the latest expression, a formula of the desired input current can be obtained from (23):

$$i_{input1} = I_{inM} \cdot \sin(\theta_{in}^* + 2\pi/3). \quad (25)$$

Similar conversions are done for second current:

$$i_{input2} = K_V \cdot I_{outM} \cdot \cos \phi \cdot \sin \theta_{in}^* = I_{inM} \cdot \sin \theta_{in}^*. \quad (26)$$

Since the third phase is used in the process of generating both modulation voltages, the current of the given phase is a sum of two other currents:

$$i_{input3} = i_{input1} + i_{input2} = I_{inM} \cdot \sin(\theta_{in}^* - 2\pi/3). \quad (27)$$

Equations (25)...(27) show that there are no other harmonics in the input current, except main frequency (as can be seen from the formulas) and switching frequency (since these equations are obtained for the variables averaged on the switching period). Besides that these equations correspond to a symmetric 3-phase system.

In order to estimate maximal voltage transfer rate K_V the sum of relative times $\gamma_{\delta 1}$, $\gamma_{\delta 2}$, $\gamma_{\sigma 1}$ and $\gamma_{\sigma 2}$ should be found. Since these times are known from (15)...(18), then the sum also can be found:

$$\begin{aligned} & \gamma_{\delta 1} + \gamma_{\delta 2} + \gamma_{\sigma 1} + \gamma_{\sigma 2} = \\ & = \frac{2}{\sqrt{3}} \cdot K_V \cdot \cos(\theta_0^* - \pi/6) \cdot \sin(\theta_{in}^* + \pi/3) \leq 1. \end{aligned} \quad (28)$$

After simple transformation, the following rule can be found:

$$K_V \leq \frac{\sqrt{3}/2}{\cos(\theta_0^* - \pi/6) \cdot \sin(\theta_{in}^* + \pi/3)}. \quad (29)$$

Therefore, like at one-level control mode, maximal value of K_V is 0.866.

In general any input phase shift from the range can be programmed in a similar way. However, it is not necessary, since the desirable input angle is 0. In some specific application the reactive power of the input must be controllable, but in that case a completely different control algorithm should be used.

2. Simulation and testing of 3x3 matrix converter

In order to check validity of the proposed control method simulations were carried out. First, general statements of the elaborated method were tested through algorithmic simulation in MATLAB environment. After that, some details of the conversion principles were explored by means of real circuit modelling, using PSpice.

2.1 MATLAB algorithmic simulation

The simulation utilizes only basic instructions and functions of MATLAB and is based on the "zone" principle, which is applied mostly to constructing the instantaneous switch matrix. The input period is divided into six time (or angle) zones (or sub-periods) with the phase voltages that are used during the modulation. The zonal set depends on the modulation mode used. For the one-level PWM the first zone is $[\pi/6... \pi/2]$, the second is $[\pi/2... 5\pi/6]$ etc. At one-level PWM during these sub-periods the same phases have maximal and minimal voltage. For the two-level PWM zone boundaries are shifted by $\pi/6$ so that the first zone is $[0... \pi/3]$, the second is $[\pi/3... 2\pi/3]$ etc. The phase function is the same within the given zone. For instance, when zone number is one, input phase B is always used as minus, phase C is used as plus for one modulation voltage, but phase A as plus – for another.

The output period is also divided into six zones, but the criterion of this subdivision is instantaneous state of the space vector. Output zonal content depends on the output vector pattern. Since the two-axial representation of the output vector is used, only one set of the output zones is discussed. At the two-axis pattern output zone boundaries and the base axis set (axes XY, YZ and ZX) have shift angle of $\pi/6$ (or time shift of $T_{IN}/12$, which is 1.667ms at 50Hz). In other words, the time instant when $v_{XY}(t)$ is maximal and the closest time boundary of the output zone has time displacement of 1.667ms.

The input zone defines the column, but the output zone defines the row of matrix cell whose value is 1 for each state of the power matrix. Other cells of the row have value 0. For example, at the one-level PWM, when both input and output zones have value 1 input zone defines column A (or 1) for pluses and column B (or 2) for minuses. Output zone 1 determines two possible axial states. One of them requires X to be positive, but Y and Z - negative. Hence, for this axial state elements of the instantaneous matrix $s_{AX}(t_i)$, $s_{BY}(t_i)$ and $s_{BZ}(t_i)$ have

value 1, all other cells have value 0. Implementing of the zone principle into the real system is possible only at symmetrical and sinusoidal set of input voltages, but at the same time, it allows using voltage synchronization instead of continuous input voltage measuring. In the case of mathematical simulation it allows to use simple algorithms for constructing the instantaneous matrix.

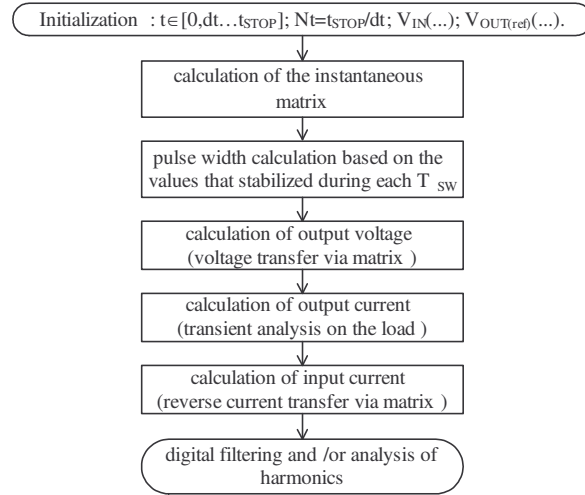


Fig.4. The algorithm of the MATLAB program for the simulation of 3x3 MFC

The input/output zone approach allows estimating the behavior of the power matrix on all switching intervals. The general algorithm of the MATLAB simulation program is given in Fig.4.

A significant part of the simulation is calculation of the switching times or width of pulses. The main goal of this part is variable discretization. In order to find appropriate values, the time, angle and input voltage variables are fixed during each switching interval (which is 556 μ s corresponding to switching frequency 1800Hz) to their average values. Stabilized values allow the calculation of strict switching time points.

As soon as switching times are determined, the instantaneous states of the power matrix in all the time points (during the given simulation time step between these points was set to 6.25 μ s) can be found. Since input voltage is known, but the state of the power matrix is determined for any time point, the output voltages can also be found over the whole calculation time period. It gives the possibility to perform transient analysis in the load of the MC and to find the output currents. At this stage pulsing input currents can be found. Note that reverse matrix analysis is performed for currents.

The basic results of MATLAB algorithmic simulation of the MC with are given in Fig.5. The voltage set on the input is sinusoidal and symmetrical and one of the corresponding input phase currents is given in chart (a) and its harmonic content in (b). Output phase to phase voltage of the converter is shown in chart (c), but the output currents in (d). As can be seen, output current is sinusoidal. Output voltage has only main output (33.33Hz) and switching frequency (1800Hz and its sub-harmonics) in the harmonic content, so it can be said to be modulated very close to the sinusoidal reference. The digitally filtered curve (black) in diagrams (c) confirms this proposition. From Fig.4-c and d it is

obvious that at the two-level PWM input current has only two components of the main and switching frequency (exactly like the output voltage), as it was earlier demonstrated in (25)...(27). In general, MATLAB simulation has confirmed the validity of the proposed two-level PWM control method.

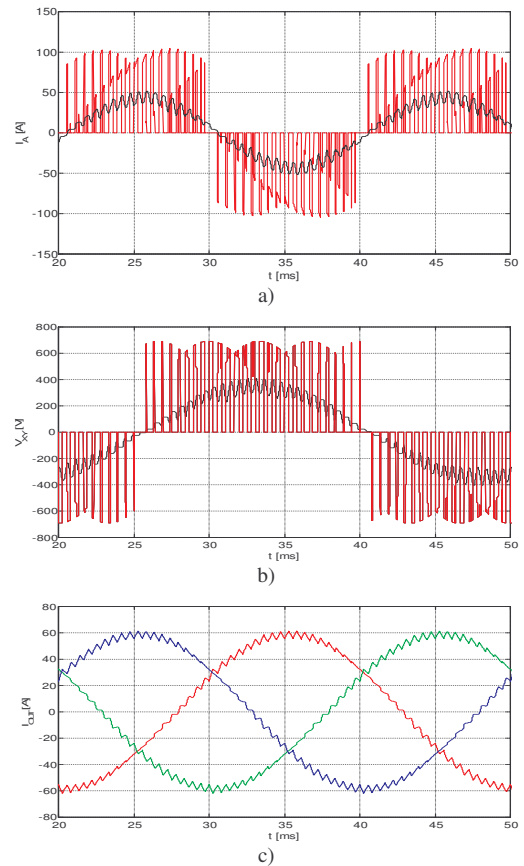


Fig.5. Results of the MATLAB simulation of the MC in the two-level modulation mode: a) input current (black – after digital filtering); b) output voltage between X and Y output terminals of the MC (black – after digital filtering); c) output currents

2.2 PSPICE schematic simulation

Like the MATLAB program the PSPICE simulation source utilizes the zone or supply network synchronization principle. Since it is not convenient to simulate the control logic [Reference 4.2] together with the electrical power circuit in PSpice environment, the algorithm is not described in a direct way. For this reason zone subdivision is realized on the basis of independent voltage sources that have a functional meaning. Since at the two-level PWM mode input may be used as plus or minus of two modulation voltages, the number of “non-zero” functional signals is 15.

In a similar manner each output phase may be used as positive or as negative potential for constructing one of the two - axial components (with the two axes pattern). Since there are 3 output phases, the number of output functional sources is 12. These signals and the output space zones are given in Fig.6. The described signals are the first significant part of the control circuit.

Another significant part is the input and the output local angle (θ_{in}^* and θ_{out}^*) generators and generator of switching frequency (f_{sw}). The first two signals

are passed through the sample and hold units, where sampling happens at switching frequency. In this way correct, temporary fixed signals ($\theta_{in,d}^*$ and $\theta_{out,d}^*$) for calculations are generated. Switching frequency is integrated and the resulting triangular signal may be used in the traditional comparator unit of the PWM controller. Corrected local angles are input variables for a simple mathematical unit that calculates pulse widths ($t1\sigma$, $t1\delta$, $t2\sigma$, $t2\delta$ and t_z) taking into account the switching period T_{sw} in correspondence with the equations (15)...(18). The signals that are obtained in this way can't be transferred to the comparators directly, since they overlap. That is why they first are added one to another in different combinations and then passed through the comparator. Proportional pulses with no overlap are obtained after the final reverse subtraction.

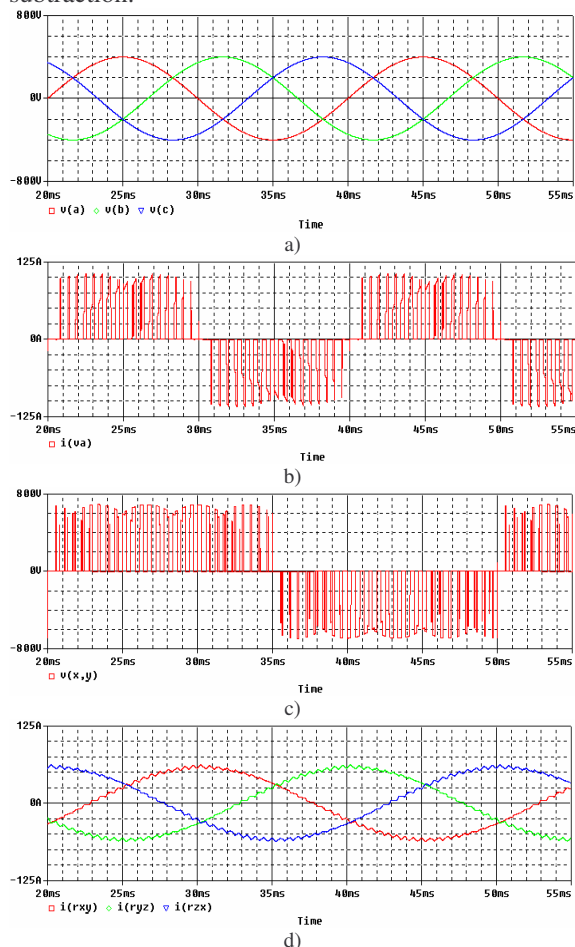


Fig.6. Results of the PSpice simulation of the MC in the two-level modulation mode: a) input voltage set; b) input current of phase A; c) output voltage between X and Y output terminals of the converter; d) output currents

Each element of the power matrix has a rather simple logic controller. It has AND_OR principle of operation. It means that control signals are first passed through AND elements and then through OR element. The final signal comes to the subject of control (power switch). Every power switch may connect positive or negative voltage from some input to some output during one of the four active time intervals ($t1\sigma$, $t1\delta$, $t2\sigma$ and $t2\delta$). It also may perform

electrical connection during zero interval (t_z). Thus there are 9 occasions when the switch of the power matrix may be in the "on" state. That is why the control signal of the switch comes from the disjunction element that has 9 inputs. These inputs accept signals from 9 three-input conjunction elements. Each such conjunction element is connected to one corresponding input functional signal, to one proper output functional signal and to a PWM signal from time calculation unit. An exception is "zero" conjunction, which takes only two signals – time and input zero-signal.

The described principle was realized in the Orcad PSPICE. Results of this simulation are given in Fig.6. In order to estimate the input displacement power factor, input voltage is also shown on these figures. As it can be seen, displacement angle is. It means that there is no reactive power circulation at the given control.

Conclusions

There are many control methods applicable in the MCs. However, PWM is most effective. A two-level PWM control method, which can be realized on the basis of the table functions and simple calculation algorithms, is described in this paper. It allows using very simple and cheap micro-controller units.

Simulation results show that at two-level PWM, input current has only two explicit harmonic components - at the main and switching frequencies (exactly like the output voltage). In general, MATLAB simulation has confirmed assumptions that were made while elaborating the control strategy. However, the implemented model describes only the basic principles of operation of the matrix converter. This is why the obtained results were confirmed by more detailed PSpice simulation.

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