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COMPUTER MODELING OF THREE-PHASE TO SINGLE-PHASE MATRIX CONVERTER USING MATLAB

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Abstract*: A three-phase to single-phase matrix converter is modeled and investigated in the MATLAB environment in the present paper. Based on the state matrix vector, a mathematical analysis of the converter is performed giving the relation between the sinusoidal line voltage (current) and the output voltage (current). The results of the investigation are confirmed using computer simulation of the converter by the program product MATLAB.*

Key Words: ***Power Electronics/ Matrix Converter/ MATLAB simulation***

1. INTRODUCTION

The development of new methods and circuits for electrical energy conversion with improved characteristics is a basic way for increasing of the energy efficiency of power electronic converters with respect to mains network. The matrix converters realize a direct conversion of alternating current to alternating current [1,2]. The basic principles of operation of the matrix converters are proposed by Venturini in the early 1980's [1]. Subsequently the bases were put of their investigation [2,3]. The matrix converter theory is based on direct conversion of alternating current to alternating current. Their main application is in the three phase motor drives where the frequency of the output voltage is lower than the frequency of the mains network voltage. The matrix converters had been developed in the last years with the appearance of AC/DC converters with direct conversion of the three-phase mains network voltage in high-frequency single phase voltage [4,5,6]. The main application of the direct AC/DC matrix converters is in the power supply for the needs of the telecommunications (for example the company Rectifier Technologies). From the recent publivations [7,8] it can be concluded that the application of three-to-single phase converters is extended in the energetics and industry. This fact is a result of their main advantages: decreased gabarits, weight and price due to the lack of reactance elements (filter inductor amd capacitor), a high efficiency and high power factor.

The aim of the present paper is the investigation of the three-phase to single-phase matrix converter with a series resonant circuit load. The frequency of the single-phase output voltage is higher than the frequency of the mains network voltage. Based on the state matrix vector, a mathematical analysis of the converter is performed. The obtained equations in matrix form are solved using the program MATLAB. The results of the investigation are confirmed using computer simulation of the converter by the program SIMULINK.

2. PRINCIPLE OF OPERATION AND MATHEMATICAL DESCRIPTION

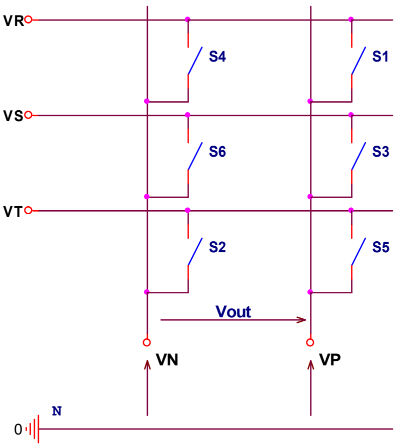
The equivalent circuit of the three-phase to single-phase matrix converter is presented in Fig. 1. *S*1 – *S*6 are bidirectional switches, realised as shown in Fig. 1b. The converter is supplied directly by the mains network. The three-phase line input voltages are described by the vector V_{in}:

$$V_{in} = \begin{bmatrix} V_R \\ V_S \\ V_T \end{bmatrix} = \begin{bmatrix} V_m \sin \omega t \\ V_m \sin(\omega t - \frac{2\pi}{3}) \\ V_m \sin(\omega t + \frac{2\pi}{3}) \end{bmatrix}. \quad (1)$$

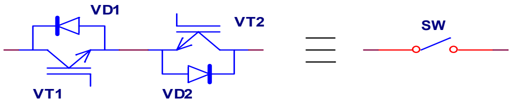
The considered matrix converter combines the functions of the three-phase rectifier and single-phase inverter. The possibilities for operation of the rectifier are demonstrated in Table 1. For the presented six intervals one of the phases is the most positive ($V_{p\max}$) and one – the most negative ($V_{n\max}$). In the column *GP*, the working pairs of semiconductor devices are presented for the six intervals, for the case when the odd switches (*S*1, *S*3, *S*5) are diodes with common cathodes connected to *VP*, and the even switches (*S*4, *S*6, *S*2) are diodes with common anodes connected to *VN* (Fig. 1a). In this case the output voltage

$$V_{out} = V_P - V_N \quad (2)$$

is positive.



a) Equivalent circuit



b) Bidirectional power switch

Fig. 1. *Circuit for investigation*

Table 1. *Possibilities for operation of the rectifier*

interval	$V_{p\max}$	$V_{n\max}$	*GP*	*GN*
π/6 — 3π/6	V_R	V_S	S1 — S6	S4 — S3
3π/6 — 5π/6		V_T	S1 — S2	S4 — S5
5π/6 — 7π/6	V_S		S3 — S2	S6 — S5
7π/6 — 9π/6		V_R	S3 — S4	S6 — S1
9π/6 — 11/6	V_T		S5 — S4	S2 — S1
11π/6 — 13π/6		V_S	S5 — S6	S2 — S3

The column *GN* is related to the case of an opposite (inverse) connection of the diodes, when V_{out} becomes negative. If *S*1-*S*6 are bidirectional switches, it follows that we can change the polarity of V_{out} within each of the six intervals, commutating the switches *GN*-*GP*. It can be seen from the Table 1 that the work of the matrix converter within one period 360° (2π rad) can be considered independently for each of the six intervals. It can be considered as single-phase bridge inverter for each interval [9].

The waveforms which characterise the first two intervals, are shown in Fig. 2. The origin of the coordinate system cioncides with the start of a positive halfperiod for the phase *R*.

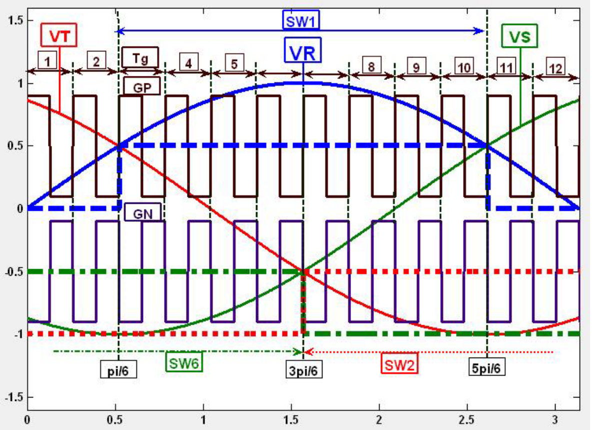


Fig.2. *Illustration of the operation in first two intervals*

Fig.3.a.

Fig.3.b.

Fig.3.c.

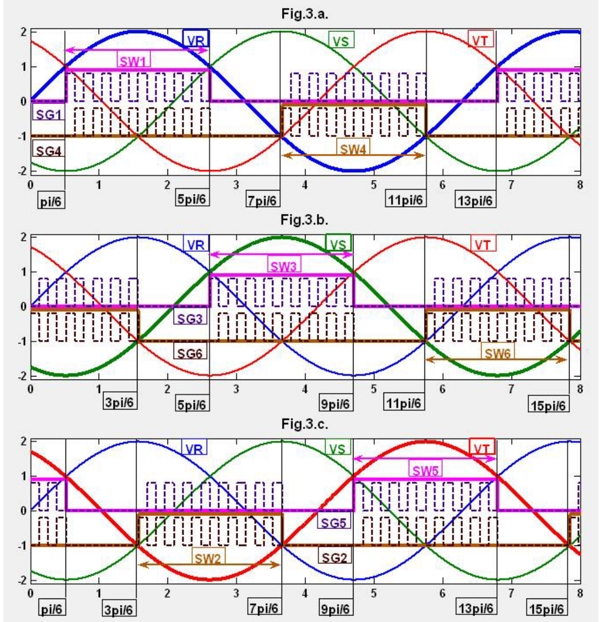


Fig.3. *Control pulses for the bidirectional switches*

In the interval ($\pi/6-3\pi/6$) the most positive is the phase V_R. This state is marked by the rectangle pulse *SW*1 = 1. In the same time, the most negative is the phase V_S , which is marked by *SW*6 = 1. In this interval, the equivalent circuit of the single-phase bridge inverter consists of the switches *S*1-*S*6, *S*4-*S*3. They are commutated by the opposite pulses *GP* and *GN* (Fig. 2). In the next interval ($3\pi/6-5\pi/6$) the most negative becomes the phase V_T where the ulse is *SW*2 = 1 (*SW*1 = 1). Here the equivalent circuit of the single-phase bridge inverter consists of the switches *S*1-*S*6, *S*4-*S*3. They are commutated by the opposite pulses *GP* and *GN* (Fig. 2).

All combinations of the switches *S*1-*S*6 are presented in Table 1, for the six intervals corresponding to the respective equivalent circuits. The intervals in which operate the switches *S*1-*S*6, are defined by the switch pulses *SW*1-*SW*6 (Fig. 3), and their commutation – by the inverter pulses *GS*1-*GS*6.

It follows from Fig. 3 that the state of the bidirectional switches – open or closed – can be described in matrix form in the following way:

$$F_T = F_i\, F_S \qquad (3)$$

or

$$\begin{bmatrix} GS1 & GS3 & GS5 \\ GS4 & GS6 & GS2 \end{bmatrix} = \\ = \begin{bmatrix} GP & GN \\ GN & GP \end{bmatrix} \cdot \begin{bmatrix} SW1 & SW3 & SW5 \\ SW4 & SW6 & SW2 \end{bmatrix}, \qquad (4)$$

where F_T is the transfer function of the matrix converter, F_i is the inverter transfer function and F_S is the switching pulses transfer function.

It follows from (4) the pulses *GS*, switching *S*1-*S*6, are defined mathematically by the equations:

$$\begin{aligned} GS1 &= GP.SW1 + GN.SW4 \\ GS4 &= GN.SW1 + GP.SW4 \\ GS3 &= GP.SW3 + GN.SW6 \\ GS6 &= GN.SW3 + GP.SW6 \\ GS5 &= GP.SW5 + GN.SW2 \\ GS2 &= GN.SW5 + GP.SW2 \end{aligned} \tag{5}$$

The equations (5) correspond to the time intervals from Fig. 3. It is seen that

$$\begin{aligned} GS1 &= \overline{GS}4 \\ GS3 &= \overline{GS}6 \\ GS5 &= \overline{GS}2 \ . \end{aligned} \tag{6}$$

The state of the matrix converter can be described in the following way:

$$\begin{bmatrix} V_P \\ V_N \end{bmatrix} = F_T \, V_{in} \tag{7}$$

or

$$\begin{aligned} V_P &= VS1 + VS3 + VS5 \\ V_N &= VS4 + VS6 + VS2 \end{aligned} , \tag{8}$$

where

$$\begin{aligned} &VS1 = GS1.\, V_R \ ; \ VS3 = GS3.\, V_S \ ; \\ &VS5 = GS5.\, V_T \ ; \ VS4 = GS4.\, V_R \ ; \\ &VS6 = GS6.\, V_S \ ; \ VS2 = GS2.\, V_T \ . \end{aligned} \tag{9}$$

The single-phase output voltage (2) has the form:

$$\begin{aligned} V_{out}(t) = &\left(GS1 - GS4\right) V_R(t) + \left(GS3 - GS6\right) V_S(t) + \\ &+ \left(GS5 - GS2\right) V_T(t) \end{aligned} \tag{10}$$

$$\begin{aligned} SW1 - SW4 &= A_1.\sin(\omega_g t) + \sum_{n=3,5...}^{\infty} A_n.\sin(n\omega_g t), \\ SW3 - SW6 &= A_1.\sin(\omega_g t - \frac{2\pi}{3}) + \\ &+ \sum_{n=3,5...}^{\infty} A_n.\sin(n\omega_g t - \frac{2\pi}{3}) \\ SW5 - SW2 &= A_1.\sin(\omega_g t + \frac{2\pi}{3}) + \\ &+ \sum_{n=3,5...}^{\infty} A_n.\sin(n\omega_g t + \frac{2\pi}{3}) . \end{aligned} \tag{11}$$

The parameter ω_g in (11) is the commutation frequency of the bidirectional switches. The coefficient A_1 is the magnitude of the commutation function, which is assumed to be 1. The first harmonic of the Fourier expansion of A_1 is of the value $4/\pi$. The higher harmonics A_n have significantly lower magnitudes and for the purposes of the performed consideration are neglected. Replacing (11) in (10), the following dependence is obtained for $V_{out}(t)$:

$$\begin{aligned} V_{out}(t) = &\frac{4}{\pi} V_m \sin \omega t . \sin \omega_g t + \\ &+ \frac{4}{\pi} V_m \sin(\omega t - \frac{2\pi}{3}) . \sin(\omega_g t - \frac{2\pi}{3}) + \\ &+ \frac{4}{\pi} V_m \sin(\omega t - \frac{2\pi}{3}) . \sin(\omega_g t - \frac{2\pi}{3}) \end{aligned} \tag{12}$$

The obtained mathematical dependencies $(1) \div (10)$ are solved using the program MATLAB. The input voltage vector V_{in} is shown in Table 2.

Table 2. *M-files vr, vs, vt*

File function *vr*	File function *vs*	File function *vt*

function y=vr(x)
lx=length(x);
y=zeros(size(x))
for i=1:lx
y(i)=sin(x(i));
end
	function y=vs(x)
	lx=length(x);
	y=zeros(size(x));
	for i=1:lx
	y(i)=sin(x(i)+
	+4*pi/3);
	end
		function y=vt(x)
		lx=length(x);
		y=zeros(size(x))
		for i=1:lx
		y(i)=sin(x(i)+
		+2*pi/3);
		end

The M-files defining the inverter transfer function F_i (*GP* and *GN*) are given in Table 3, where: h_p is the number of the half-periods of the vector V_{in}; n – number of commutations of the switches $S1$-$S6$ in one half-period (n=12 – Fig. 2); N – number of points (for instance 100) for one commutation period T_g.

Table 3. *M-files gp, gn*

File function *gp*	File function *gn*

function y=gp(x)
lx=length(x);
y=zeros(size(x));
i=0;
for k=1:12*4
for j=1:100
i=100*(k-1)+j;
if j<=50
y(i)=1.0;
else
y(i)=0.0;
end
end
end
	function y=gn(x)
	lx=length(x);
	y=zeros(size(x));
	i=0;
	for k=1:12*4
	for j=1:100
	i=100*(k-1)+j;
	if j<=50
	y(i)=0.0;
	else
	y(i)=1.0;
	end
	end
	end

The computational calculation step along the X axis is: *dx=pi*/(*n.N*), where $0 \le x \le (h_p.pi)$. The dimension of the vector X=x[lx] in MATLAB is defined in the main program using the command line:

```
x = 0: dx: (hp*pi);lx = length(x);
```

The M-files *sw1* and *sw2* are given in Table 4. The rest elements of the switching transfer function F_S are described similarly.

Table 4. *M-files sw1, sw2*

File function *sw1*	File function *sw2*

function y=sw1(x)
lx=length(x);
y=zeros(size(x));
for i=1:lx
if (vr(x(i))>vs(x(i)))
&(vr(x(i))>vt(x(i)))
y(i)=1.0;
else
y(i)=0.0;
end
end
	function y=sw2(x)
	lx=length(x);
	y=zeros(size(x));
	for i=1:lx
	if (vt(x(i))<vr(x(i)))
	&(vt(x(i))<vs(x(i)))
	y(i)=1.0;
	else
	y(i)=0.0;
	end
	end

The solution of equation (9) is shown in Fig. 4 and the solution of equations (8) and (2) is presented in Fig. 5.

3. SIMULINK SIMULATION

The electrical circuit for the computer simulation of the matrix converter is shown in Fig. 6. The simulation of the circuit is performed for a load series resonant circuit. The signals *SW*1-*SW*6, included in the switching transfer function F_S, are created in the block Subsystem1. Its electrical circuit is shown in Fig. 7.

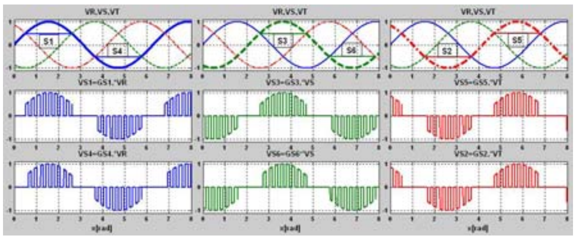


Fig.4. *Graphical representation of the solution of the equations (9)*

The signals *GS*1-*GS*6 included in the matrix transfer function F_T are created in the block Subsystem2. Its electrical circuit is shown in Fig. 8. The functional generators Pulse Generator – *GP* and Pulse Generator – *GN* create the signals of the inverter transfer function F_i. The simulation results for the three-phase supply voltages, the output voltage and the output current of the matrix converter are shown in Fig. 9.

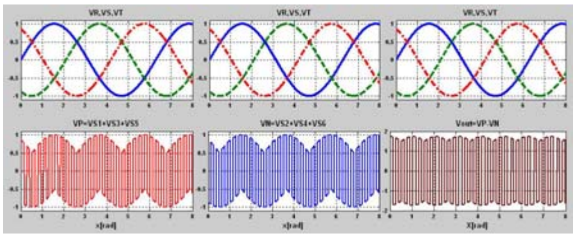


Fig.5. *Graphical representation of the solution of the equations (8) and (2)*

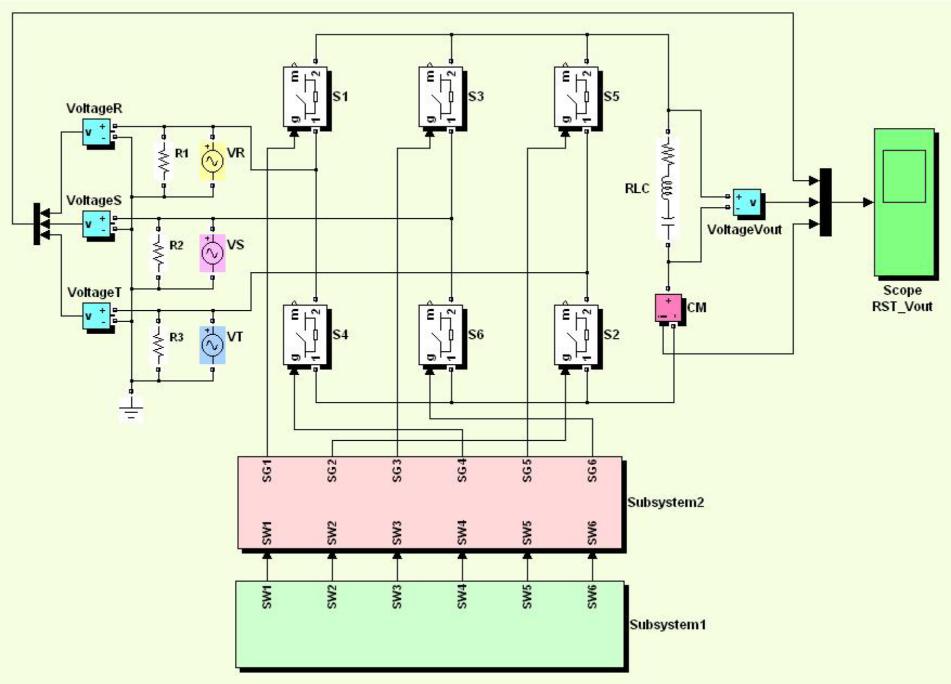


Fig.6. *Electrical circuit of the matrix converter represented in SIMULINK*

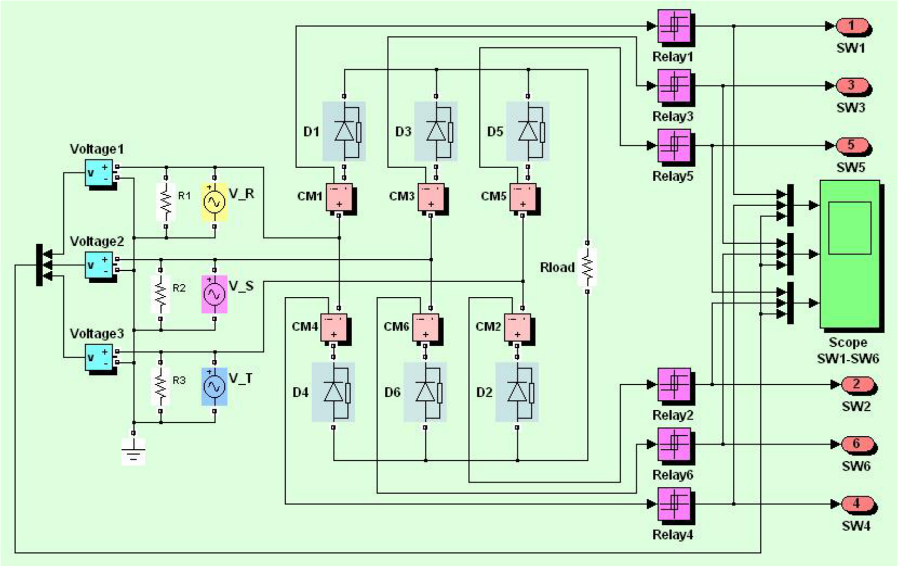


Fig.7. *Electrical circuit for creating the transfer function* F_S

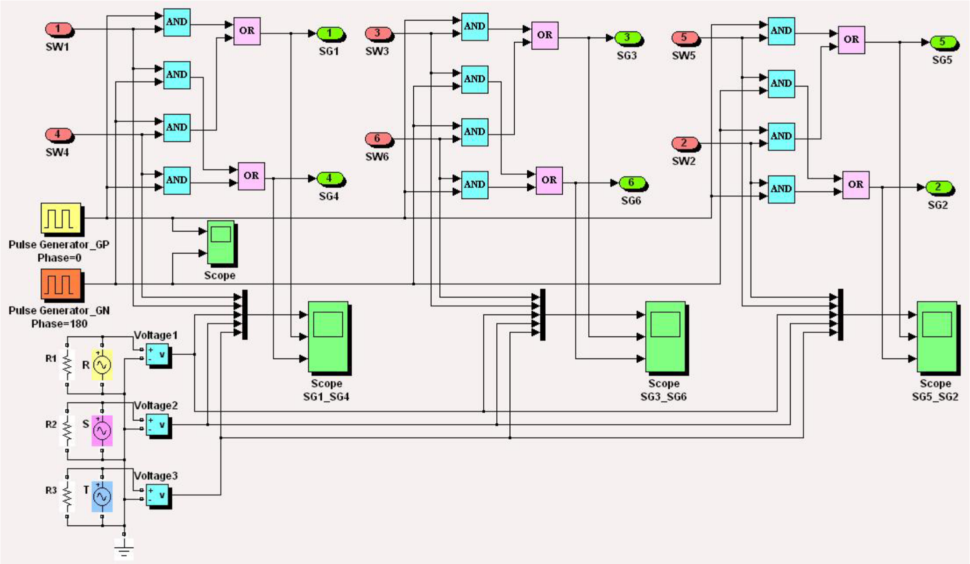


Fig.8. *Electrical circuit for creating the transfer function* F_T

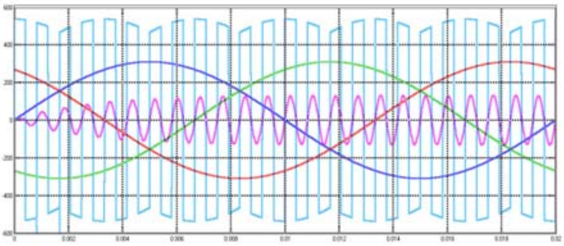


Fig.9. *Results from the computer simulation*

The sinusoidal character of the output current is represented for the so chosen *RLC* load. Fig. 9 illustrates a full confidence between the mathematical modeling using MATLAB and the SIMULINK simulation of the output voltage V_{out}.

4. CONCLUSION

Mathematical dependencies have been derived, describing the operation of three-phase to single-phase matrix converter with a hihger frequency. The expressions are suitable for computer simulation independently of the output load type. The simulation results using the program product MATLAB demonstrate the effective converter operation by the investigated load – series resonant circuit.

5. ACKNOWLEDGEMENT

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