



IMPLEMENTATION OF SVPWM BASED ON dSPACE SYSTEM

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Abstract: In this paper, the theoretical basis of a space-vector pulse width modulation (SVPWM) technique is exposed. Also, a method for practical implementation of the SVPWM using the software package MATLAB / Simulink and the development system dSPACE ACE Kit 1104 is proposed. Processing time of presented SVPWM algorithm is minimized. Based on the experimental results obtained in available laboratory conditions, the proposed algorithm functionality is proved.

Key Words: SVPWM, switching pattern, PWM period

1. INTRODUCTION

In modern electric-motor drives different pulse width modulation (PWM) techniques are used: carrier-based PWM and the relatively new space-vector PWM (SVPWM). Application of particular method depends on the required performances such as: maximum utilization of the input voltage, voltage and current waveforms with a low content of higher harmonics, good dynamic response and simple implementation.

Space-vector pulse width modulation (SVPWM) technique has become a popular PWM technique for three-phase voltage-source inverters (VSI) in applications such as control of AC induction and permanent-magnet synchronous motors. SVPWM refers to a special way of determining the switching sequence of the upper three power transistors of a three-phase VSI. This PWM technique generates less harmonic distortion in the output voltages and currents and provides more efficient use of DC supply voltage, in comparison to carrier-based PWM [1].

Two different SVPWM symmetric switching patterns exist: software-implemented and hardware-implemented. Hardware-implemented switching pattern, in comparison with software-implemented switching pattern, has got less number of switching and less switching losses but amount of harmonics in the inverter line-to-line outputs is higher [1].

In this paper the theoretical basis of SVPWM is exposed and the method for its practical implementation using the software package MATLAB / Simulink and the development system dSPACE ACE Kit 1104 is proposed. Processing time of presented SVPWM algorithm is minimized. Also, based on the experimental

results obtained in available laboratory conditions, the proposed algorithm functionality is proved.

2. DSPACE'S TOOLBOX BLOCK FOR SVPWM

Development system dSPACE ACE Kit 1104 is equipped with a control card DS 1104 which, among other things, for VSI switching SVPWM is used. The control algorithm is made using the software package MATLAB / Simulink, while SVPWM implementation using dSPACE's *Toolbox* block shown in Fig. 1 is realized.

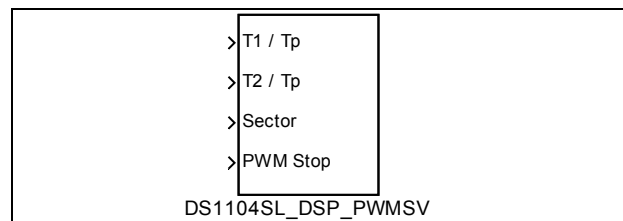


Fig. 1. Block for SVPWM implementation

In applying the block with Fig. 1, for the reference stator voltage vector, it is necessary to know the relative values of its projections at the nearest right (T_1/T_p) and the nearest left (T_2/T_p) inverter output voltage vector, as well as the sector in which it is located (*Sector*). Also, it is necessary to generate and a PWM work permission (*PWM Stop*). Values for the ratios T_1/T_p and T_2/T_p must remain within the range 0÷1, and the sum must be less or equal to 1. The *Sector* must be an integer value within the range 1÷6 [2, 3].

In the next section an method for the required values calculation is exposed. Processing time of presented calculation algorithm is minimized.

3. ANALYSIS AND IMPLEMENTATION

Reference stator voltage vector U_{sz} with angle displacement $\theta_{U_{sz}}$ in relation to the d reference axis of qd system is shown in Fig. 2. The reference vector U_{sz} is represented by its qd components, U_{qs} and U_{ds} . Also, U_{sz} projections at the nearest right and the nearest left inverter output voltage vector are represented by T_1 and

T_2 , respectively. Sectors between any two adjacent inverter output voltage vectors are marked with O_1 to O_6 .

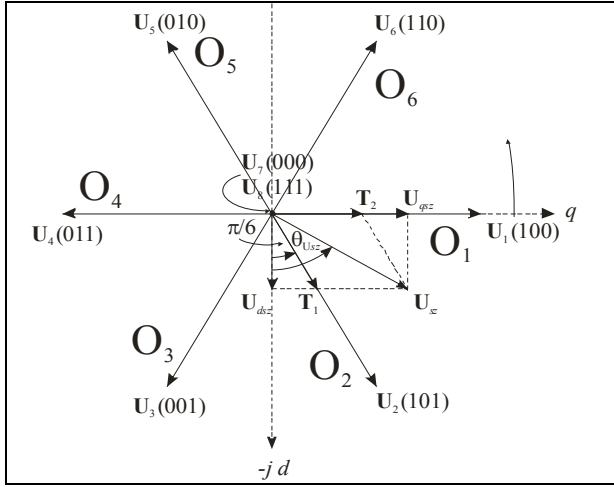


Fig. 2. Reference stator voltage vector U_{sz}

Reference stator voltage vector qd components, U_{qsZ} and U_{dsZ} , can be written as the functions of vector magnitudes T_1 and T_2 :

$$U_{qsZ} = T_2 + T_1 \cdot \sin\left(\frac{\pi}{6}\right) \quad (1)$$

$$U_{dsZ} = T_1 \cdot \cos\left(\frac{\pi}{6}\right) \quad (2)$$

From the last two equations we can calculate T_1 and T_2 as:

$$T_1 = \frac{2}{\sqrt{3}} \cdot U_{dsZ} \quad (3)$$

$$T_2 = \frac{2}{\sqrt{3}} \cdot \left(\frac{\sqrt{3}}{2} \cdot U_{qsZ} - \frac{1}{2} \cdot U_{dsZ} \right) \quad (4)$$

The Fig. 3 shows the reference vector U_{sz} , whose magnitude is equal to radius of the circle inscribed in the hexagon which forming "peaks" of inverter output voltage vector. It can be concluded that this is the maximum value of the reference stator voltage, which can have for each angle displacement θ_{Uisz} .

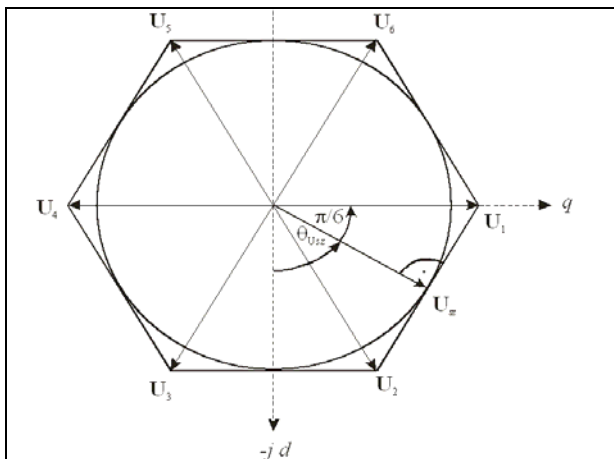


Fig. 3. Maximum value of U_{sz} for each θ_{Uisz}

As is known, the inverter output voltage vector magnitude (U_1 to U_6) is $\frac{2}{3}u_{dc}$, where u_{dc} is the dc link voltage. From Fig. 3 it can be concluded that the maximum value of the reference stator voltage, for any angle displacement θ_{Uisz} , is $\frac{2}{3}u_{dc} \cos\left(\frac{\pi}{6}\right)$ or $\frac{1}{\sqrt{3}}u_{dc}$. In order to normalize equation (3) and (4) for the base voltage can be adopted:

$$U_b = \frac{1}{\sqrt{3}} \cdot u_{dc} \quad (5)$$

Vector magnitudes T_1 and T_2 are proportional to the respective duration in time for which nearest right and nearest left inverter output voltage are applied within PWM period, respectively. If adopted that inverter time duration in relation to PWM period, which corresponds to the voltage $\frac{2}{3}u_{dc}$ is 1 p.u., for the T_1 and T_2 base values we can write:

$$T_b = \frac{2}{3} \cdot u_{dc} \quad (6)$$

When equations (3) and (4) are normalized with (5) and (6), for reference stator voltage vector we can calculate the time duration in p.u. of nearest right and nearest left inverter output voltage as:

$$t_1 = u_{dsZ} \quad (7)$$

$$t_2 = \frac{1}{2} \cdot \left(\sqrt{3} \cdot u_{qsZ} - u_{dsZ} \right) \quad (8)$$

In equations (7) and (8) u_{qsZ} and u_{dsZ} represent the normalized qd components with respect to the base voltage (5). These equations give per unit time durations for sector O_1 , with respect to the inverter PWM period.

In a similar manner t_1 and t_2 can be calculated for all sectors. For different sectors expressions for t_1 and t_2 are listed in Table 1.

Table 1. Expressions for t_1 and t_2 in all sectors

sector	time duration t_1	time duration t_2
O_1	$t_1 = u_{dsZ}$	$t_2 = \frac{1}{2} \cdot \left(\sqrt{3} \cdot u_{qsZ} - u_{dsZ} \right)$
O_2	$t_1 = \frac{1}{2} \cdot \left(-\sqrt{3} \cdot u_{qsZ} + u_{dsZ} \right)$	$t_2 = \frac{1}{2} \cdot \left(\sqrt{3} \cdot u_{qsZ} + u_{dsZ} \right)$
O_3	$t_1 = \frac{1}{2} \cdot \left(-\sqrt{3} \cdot u_{qsZ} - u_{dsZ} \right)$	$t_2 = u_{dsZ}$
O_4	$t_1 = -u_{dsZ}$	$t_2 = \frac{1}{2} \cdot \left(-\sqrt{3} \cdot u_{qsZ} + u_{dsZ} \right)$
O_5	$t_1 = \frac{1}{2} \cdot \left(\sqrt{3} \cdot u_{qsZ} - u_{dsZ} \right)$	$t_2 = \frac{1}{2} \cdot \left(-\sqrt{3} \cdot u_{qsZ} - u_{dsZ} \right)$
O_6	$t_1 = \frac{1}{2} \cdot \left(\sqrt{3} \cdot u_{qsZ} + u_{dsZ} \right)$	$t_2 = -u_{dsZ}$

It is note that in Table 1 there are three different values for time durations t_1 and t_2 . If we define three variables:

$$x = u_{dsz} \quad (9)$$

$$y = \frac{1}{2} \cdot (\sqrt{3} \cdot u_{qsZ} - u_{dsz}) \quad (10)$$

$$z = \frac{1}{2} \cdot (\sqrt{3} \cdot u_{qsZ} + u_{dsz}) \quad (11)$$

Table 1 can be shown as:

Table 2. Time duration t_1 and t_2 in function of x, y, z

sector	time duration t_1	time duration t_2
O ₁	x	y
O ₂	$-y$	z
O ₃	$-z$	x
O ₄	$-x$	$-y$
O ₅	y	$-z$
O ₆	z	$-x$

For known reference stator voltage vector qd components, and using (9) to (11) and Table 2, can be determined the time durations of the nearest right and nearest left inverter output voltage vector, t_1 and t_2 , for each sector.

To Table 2 usage, the knowledge of the sector containing the reference stator voltage vector is needed. It should be noted that the sector in which is located reference stator voltage vector can be determined in several ways, and hereafter will be presented a method that requires a minimum of processing time.

Reference stator voltage vector qd components as function of angle displacement, in relation to the d reference axis of qd system is shown in Fig. 4. Reference vector sector location can be determined by comparing of qd components and the corresponding magnitude, u_{qsZ} , u_{dsz} and $\sqrt{u_{qsZ}^2 + u_{dsz}^2}$, by using simple arithmetic and logic operations.

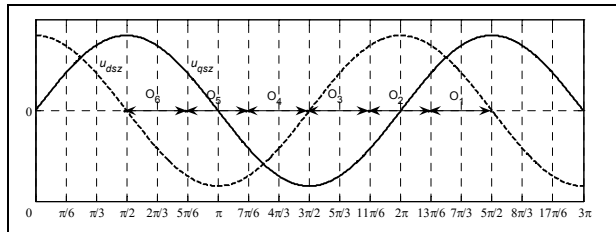


Fig. 4. Values of u_{qsZ} and u_{dsZ} in function of $\theta_{U_{sZ}}$

Also, sector in which the reference stator voltage vector is located can be determined by comparing the reference phase voltage values in the original (phase) domain.

For certain reference stator voltage vector qd components, u_{qsZ} and u_{dsZ} , by applying the appropriate inverse transformation, the reference stator voltage in three phase quantities, u_{asZ} , u_{bsZ} i u_{csZ} , can be calculated applying (12):

$$\mathbf{u}_{abcSz} = \mathbf{K}_s^{-1} \mathbf{u}_{qdsz} \quad (12)$$

where:

$$\mathbf{K}_s^{-1} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \quad (13)$$

According to (12) and (13) the following equations can be written:

$$u_{asZ} = u_{qsZ} \quad (14)$$

$$u_{bsZ} = -\frac{1}{2} \cdot (u_{qsZ} + \sqrt{3} \cdot u_{dsZ}) \quad (15)$$

$$u_{csZ} = -\frac{1}{2} \cdot (u_{qsZ} - \sqrt{3} \cdot u_{dsZ}) \quad (16)$$

Reference stator voltage in phase quantities as function of angle displacement, in relation to the d reference axis of qd system is shown in Fig. 5. The shown values are obtained by equations (14) to (16). Sector in which the reference stator voltage vector is located can be determined by comparing the reference phase voltage values u_{asZ} , u_{bsZ} and u_{csZ} , by using simple arithmetic and logic operations.

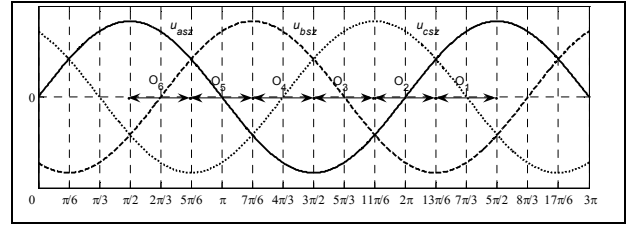


Fig. 5. Values of u_{asZ} , u_{bsZ} and u_{csZ} in function of $\theta_{U_{sZ}}$

Moreover, sector in which the reference stator voltage vector is located can be determined by using fictive stator phase voltages in the original domain, with respect to appropriate reference stator voltage qd components.

Fictive stator phase voltages in original domain can be calculated according to (12) and (13) by:

$$\mathbf{u}_{abcSf} = \mathbf{K}_s^{-1} \begin{bmatrix} u_{ds} \\ -u_{qs} \end{bmatrix} \quad (17)$$

After applying (17) we can write the followig:

$$u_{asf} = u_{dsz} \quad (18)$$

$$u_{bsf} = \frac{1}{2} \cdot (\sqrt{3} \cdot u_{qsZ} - u_{dsz}) \quad (19)$$

$$u_{csf} = -\frac{1}{2} \cdot (\sqrt{3} \cdot u_{qsZ} + u_{dsz}) \quad (20)$$

Comparing equations (18) to (20) with (9) to (11) the following can be concluded:

$$u_{asf} = x \quad (21)$$

$$u_{bsf} = y \quad (22)$$

$$u_{csf} = -z \quad (23)$$

It is clear that the fictive stator phase voltages in the original domain should not be calculated in particular because of their values are already calculated by (9) to (11).

Fictive stator phase voltages in the original domain as function of angle displacement, in relation to the d reference axis of qd system is shown in Fig. 6. The

shown values are obtained by equations (21) to (23) and (9) to (11).

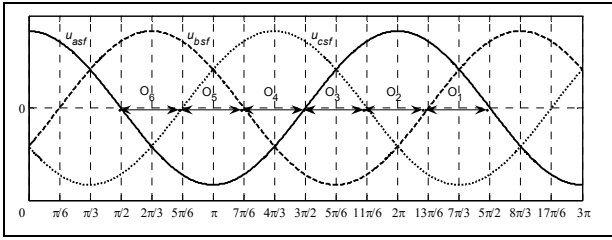


Fig. 6. Values of u_{asf} , u_{bsf} and u_{csf} in function of $\theta_{U_{sz}}$

Sector in which the reference stator voltage vector is located can be determined by comparing u_{asf} , u_{bsf} and u_{csf} with zero as shown in Table 3.

Table 3. Comparing u_{asf} , u_{bsf} and u_{csf} with zero

sector	u_{asf}	u_{bsf}	u_{csf}
O_1	> 0	> 0	< 0
O_2	> 0	< 0	< 0
O_3	> 0	< 0	> 0
O_4	< 0	< 0	> 0
O_5	< 0	> 0	> 0
O_6	< 0	> 0	< 0

Also, sector in which the reference stator voltage vector is located can be determined by fictive sector O_F [4].

Comparison of u_{asf} , u_{bsf} and u_{csf} with zero can be realized in the following way:

$$u_{asf} > 0 \Rightarrow a = 1, \text{ else } a = 0 \quad (24)$$

$$u_{bsf} > 0 \Rightarrow b = 1, \text{ else } b = 0 \quad (25)$$

$$u_{csf} > 0 \Rightarrow c = 1, \text{ else } c = 0 \quad (26)$$

Equations (24) to (26), with respect (21) to (23), we can write in form:

$$x > 0 \Rightarrow a = 1, \text{ else } a = 0 \quad (27)$$

$$y > 0 \Rightarrow b = 1, \text{ else } b = 0 \quad (28)$$

$$z < 0 \Rightarrow c = 1, \text{ else } c = 0 \quad (29)$$

In equations (24) to (29) values for a , b and c are the results of appropriate comparison. Sector O_F in which the reference stator voltage vector is located can be determined by the following equatin:

$$O_F = a + 2 \cdot b + 4 \cdot c \quad (30)$$

Based on O_F determined by (30), sector in which the reference stator voltage vector is located can be determined as shown in Table 4.

For known reference stator voltage vector qd components and by using (27) to (30) and Table 4 we can determine sector where reference stator voltage vector is located. This method requires a minimum of CPU processing time in comparison with other methods.

It can be concluded that equations (9) to (11), (27) to (30), Table 2 and Table 4 are sufficient for the realization of space-vector pulse width modulation (SVPWM). In this way, the SVPWM can be implemented only by using

simple arithmetic and logic operations, while the trigonometric functions are avoided.

Table 4. Sector determining by using O_F

sector	O_F
O_1	3
O_2	1
O_3	5
O_4	4
O_5	6
O_6	2

4. EXPERIMENTAL RESULTS

In order to SVPWM practical implementation using the theoretical results obtained in the previous section, *MATLAB / Simulink* block "PWMSV dSPACE", shown in Fig. 7, is formed. The structure of this block is shown in Fig. 8. Block "PWMSV dSPACE", for a given reference stator voltage vector qd components in volts, calculates the relative values of the reference stator voltage vector projections at the nearest right and the nearest left inverter output voltage vector, as well as the sector in which it is located. Calculated values, with the PWM work permission, represent a sufficient condition for application of the block shown in Fig. 1.

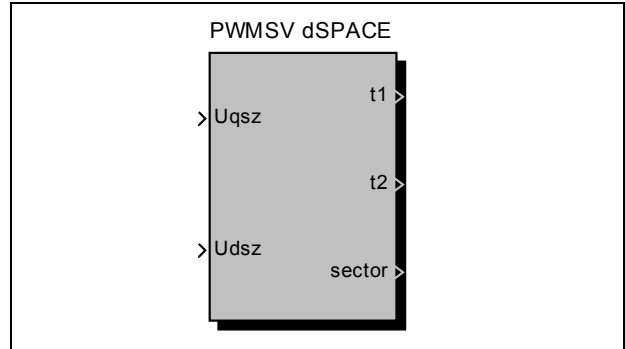


Fig. 7. *MATLAB / Simulink* block "PWMSV dSPACE"

By detailed testing and implementation in several three-phase induction motor control methods, the functionality of the proposed SVPWM algorithm was confirmed.

In this paper, one of the typical cases will be presented, where $|U_{sz}| = \frac{1}{2} \cdot \frac{1}{\sqrt{3}} \cdot u_{dc}$ and $\theta_{U_{sz}} = \frac{\pi}{3}$. Block "PWMSV dSPACE" calculated output values are: $t_1 = 0.25$, $t_2 = 0.25$ and $sector = 1$. Based on the obtained results, in accordance with Fig. 2, we should expect to be active inverter output voltage vectors U_1 and U_2 per 25 % of PWM period. The remaining 50 % of PWM period will be active zero voltage U_7 and/or U_8 . Whereas control card DS 1104 has built processor with hardware-implemented SVPWM and block "DS1104SL_DSP_PWMSV" generates symmetric PWM without the possibility of defining the direction of rotation vector, expected VSI switching sequence is: $U_2 - U_1 - U_7 - U_1 - U_2$.

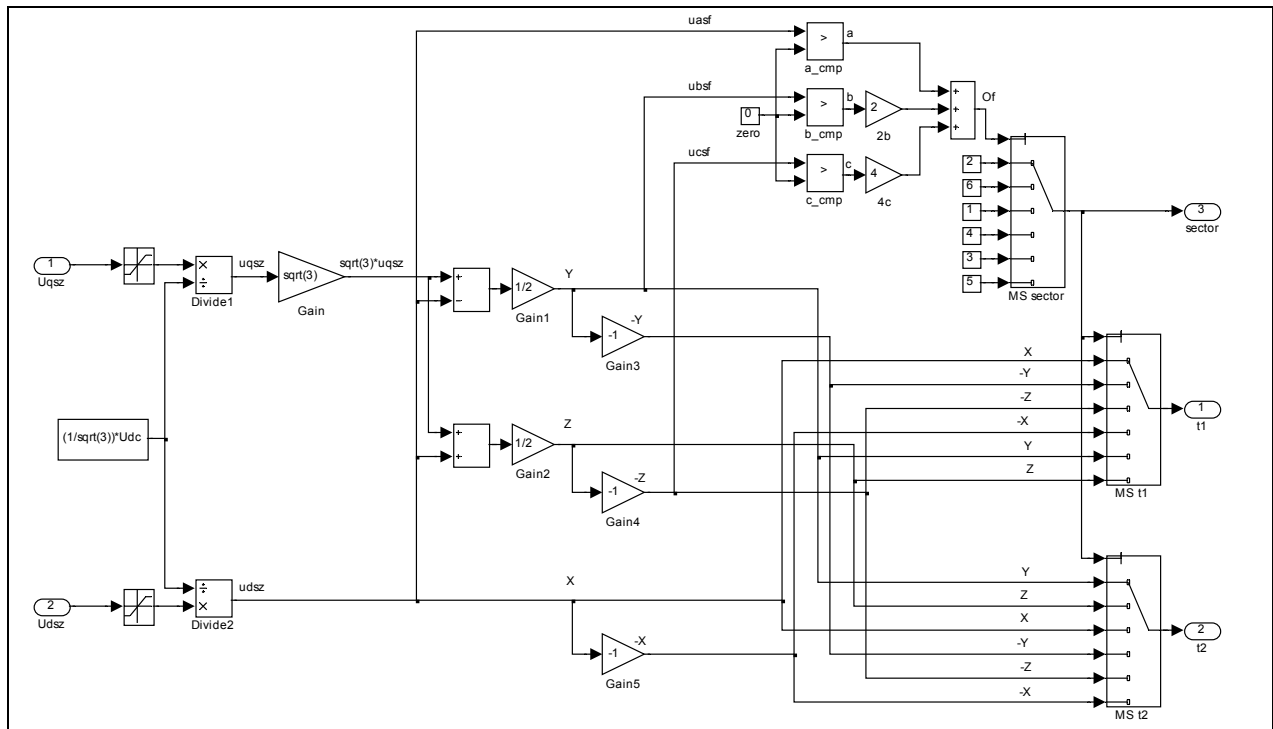


Fig. 8. The structure of MATLAB / Simulink block "PWMSV dSPACE"

Experimental results for the described case are shown in Fig. 9. Fig. 9 shows the signals from three non-inverted PWM output channels. SVPWM frequency is set to 5 kHz, and therefore duration of the PWM period is $T_p = 200 \mu s$. In the Fig. 9, vertical lines indicates one PWM period. Based on the analysis of results from Fig. 9 it can be concluded that the real VSI switching sequence corresponds to expected switching sequence. Also, each of inverter output voltages U_1 and U_2 are active two times per $25 \mu s$. This means that its total active time is $50 \mu s$, which is 25 % of PWM period. The inverter output zero voltage U_7 is active $100 \mu s$, which is 50 % of PWM period.

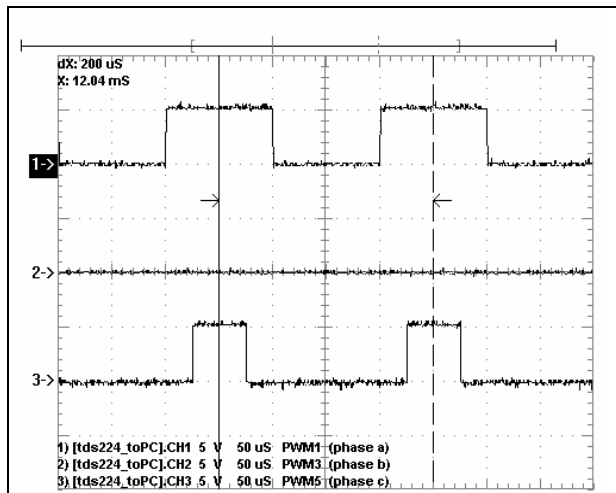


Fig. 9. Non-inverted PWM output channels

Whereas the experimental results correspond to the expected results, it can be concluded that the MATLAB / Simulink block "PWMSV dSPACE" is well designed. This block, in combination with block "DS1104SL_DSP_PWMSV" and control card DS 1104, for a given reference stator voltage vector $q d$ components in volts, generates VSI switching signals in accordance with the principles of symmetric hardware-implemented SVPWM.

5. CONCLUSION

In this paper the theoretical basis of SVPWM is exposed and the method for its practical implementation using the software package MATLAB / Simulink and the development system dSPACE ACE Kit 1104 is proposed. Processing time of presented SVPWM algorithm is minimized. Also, based on the experimental results obtained in available laboratory conditions, the proposed algorithm functionality is proved.

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