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Simulation studies of concatenation as the simplest way of multi-phase inverter control

Jan Iwaszkiewicz[1], Adam Muc[1*], Agata Bielecka[1]

[1]Department of Ship Automation, Gdynia Maritime University, Poland Morska St. 83, 81-225 Gdynia, Poland; j.iwaszkiewicz@we.umg.edu.pl, a.muc@we.umg.edu.pl, a.bielecka@we.umg.edu.pl

Abstract. The paper presents simulation studies of potentially thinkable method of multi-phase inverter control. The method consists in concatenation of consecutive voltage space vectors. Useful mathematical tools, suitable to study the inverter control as well as selected results of simulation studies are also included.

Key words. Multi-phase inverter, concatenation, polar space vector.

1. Introduction

Novel requirements and expectations in electric energy conversion have a great influence on development of electric machines and converters as well as their performance and level of power. Due to this continuous process and innovative technology there has been an expansion of new solutions in power electronics and in electric machines. Although conventional three-phase machines are still widely used in variable-speed AC drives, they have numerous disadvantages and limits. Among them, one can distinguish their relatively poor operation reliability as the lack of power even in only one-phase makes their further operation impossible. High pulsations of the electromagnetic torque during the frequency control is another example [1÷5].
The need to address these issues caused the researchers have taken deep interest in multi-phase machines: five phase [5, 6], six phase [7] or even nine-phase electric machines [8]. They are characterized by potentially higher efficiency, improved fault tolerance ability, reduced torque ripple and lower per phase power handling requirement. They have also improved the system reliability because of their redundant structure. In addition, dividing the system power into more than three phases results in diminishing the rating of semiconductor devices of the power electronics converter, which is an additional important feature. Generally it seems to be evident that a good way to improve and develop electric drives lies in higher number of machine phases and multi-level inverter control. The most effective control strategies using such methods as PWM and SPPVM have been developed in a number of varieties [9÷15].
A simple and precise mathematical model of the multi-level inverter is a very good tool making possible the development of control strategies. More precise model means better and easer inverter control. Usually, the inverter mathematical model can be described by use of three mathematical tools: analytic expressions, the voltage state and space vectors [16]. The analytic formulas determine the inverter phase current and voltage, whereas the state voltage vectors define phase voltage distribution in all the states of the inverter. Also polar voltage space vectors are a very valuable and well recognized instrument in inverters' control. They constitute a simple and basic tool that can be applied in the space vector method - the most widespread contemporary control method of AC drives. The paper presents a few examples of voltage and current waveforms illustrating the control process of the six-phase inverter. The complete control process is restricted to the simplest concatenation of consecutive vectors. This way of control permits to limit to minimum the number of switching and zero vectors used as well as to avoid problems resulting in parity of phases. Moreover this control method seems to be especially suitable for inverters working in the range of relatively higher frequencies 40 ÷ 60 Hz, e.g. inverters interfacing a six-phase smart grid and a solar power plant.
The paper recommends polar voltage space vectors of the six-phase and two-level inverter as a useful tool for vector control of the inverter. As far as mathematical tools are concerned the state voltage vectors make easier to define phase voltage distribution in every imaginable state of the inverter and voltage space vectors are the most important tool used for inverters' control. The space vectors are defined using the standard voltage space vector transformation whilst the state vectors are denoted by binary numbers and determine all voltage states of the inverter. The proposed notation system and vectors' marking have been used in [16] and proved their usefulness in specifying the inverter states. This system certificates a deep correlation between the space and state vectors as they are described using the same digits. Although it seemed there should be no problematic issues at first, an even number of phases greatly complicated the whole computational process since the choice of vectors in such a case was further limited by the symmetry of phases. It was not present in the case of an odd phase number. This is also a justification for why various methods have been used for 6-phase inverters to avoid phase symmetry. Among them, there are shifting the initial phase by 30 degrees or analyzing the 6-phase inverter as

two 3-phase inverters. Another encountered problem was that even though it was possible to find vector sequences that were optimal in terms of the number of switching, they were not implementable in the inverter due to the asymmetry of the voltage and current waveforms that were generated by the inverter. Based on the analysis in this paper as well as previous papers on multiphase inverters, it is easier to obtain vector sequences that meet control expectations for inverters with an odd number of phases than for inverters with an even number of phases.

2. State and Space Vectors of a Six-Phase Two-Level Voltage Source Inverter

Figure 1 depicts a simplified diagram of the six-phase two-level converter. The proposed model consists of six two-state switches denoted as K_a, K_b, K_c, K_d, K_e, K_f that are connected to the U_D voltage source and associated with the corresponding phases.

According to the model in Figure 1, the six-phase two-level voltage source inverter (VSI) has 64 diverse switching states, denoted by decimal index k = 0, 1, ... 63 respectively. Particular k-states determine the six phase-to-phase voltages that appear at the output of the inverter. The 6-phase VSI state vector is defined as a matrix row composed of six elements:

(1) $V_k = \left[U_{abk}\ U_{bck}\ U_{cdk}\ U_{dek}\ U_{efk}\ U_{fak}\right]$

where k = 0, 1, 2, …, 63.

Assuming $U_{abk}+U_{bck}+U_{cdk}+U_{dek}+U_{efk}+U_{fak}=0$ the state vector V_k is determined by a set of five U_{xy} phase-to-phase voltages under the condition that x and y denote the neighbouring phases: x≠y and x,y=a,b,c,d,e,f.

The phase-to-phase voltage is formed by a difference between the particular phase outputs' potentials. The switch Ka,b,c,d,e,f attaches the related phase output to one pole of the voltage source U_D. The state of the Ka,b,c,d,e,f is determined by the selected vector V_k.

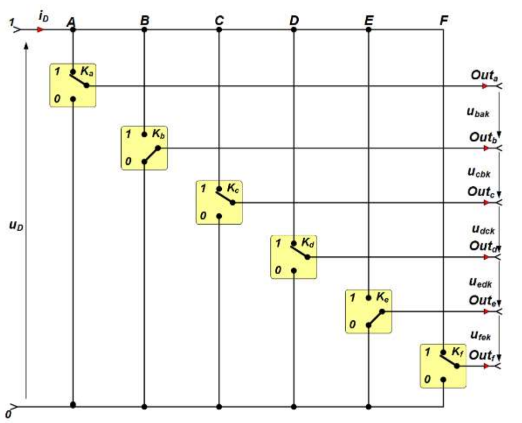

Fig. 1. Simplified diagram of the six-phase two-level inverter with six switches.

The decimal vector index k can be reconverted to the binary number system and written as a binary number

(2) $k = (a_k, b_k, c_k, d_k, e_k, f_k)_2$

where: $a_k,b_k,c_k,d_k,e_k,f_k=\{0,1\}$.

The phase output potentials related to the negative pole of the voltage source U_D are defined using the relevant binary symbol. So, the phase output polar voltages are:

$$(3)\ \begin{bmatrix} u_{a0_k} = a_k U_D \\ u_{b0_k} = b_k U_D \\ u_{c0_k} = c_k U_D \\ u_{d0_k} = d_k U_D \\ u_{e0_k} = e_k U_D \\ u_{f0_k} = f_k U_D \end{bmatrix}$$

It allows defining six-phase two-level VSI state vector using the binary symbols of the decimal index k. The transpose of the matrix V_k allows presenting in one column all six phase-to-phase voltages:

$$(4)\ V_k = \begin{bmatrix} u_{ab_k} \\ u_{bc_k} \\ u_{cd_k} \\ u_{de_k} \\ u_{ef_k} \\ u_{fa_k} \end{bmatrix} = \begin{bmatrix} u_{a0_k} - u_{b0_k} \\ u_{b0_k} - u_{c0_k} \\ u_{c0_k} - u_{d0_k} \\ u_{d0_k} - u_{e0_k} \\ u_{e0_k} - u_{f0_k} \\ u_{f0_k} - u_{a0_k} \end{bmatrix} = U_D \begin{bmatrix} (a_k - b_k)_2 \\ (b_k - c_k)_2 \\ (c_k - d_k)_2 \\ (d_k - e_k)_2 \\ (e_k - f_k)_2 \\ (f_k - a_k)_2 \end{bmatrix}$$

The symbols a_k, b_k, c_k, d_k, e_k, f_k may be equal only to 0 or 1, so any phase-to-phase voltage may assume one of these voltages: 0, $+U_D$, $-U_D$.

In the considered load circuit, the phase voltage can be evaluated by the binary symbols of the decimal vector index k in the way presented in [16]. The phase voltages: u_{ak}, u_{bk}, u_{ck}, u_{dk}, u_{ek}, u_{fk} of the two-level six-phase VSI are:

$$(5)\ \begin{bmatrix} u_{a_k} \\ u_{b_k} \\ u_{c_k} \\ u_{d_k} \\ u_{e_k} \\ u_{f_k} \end{bmatrix} = \frac{U_D}{6} \begin{bmatrix} 5a_k - b_k - c_k - d_k - e_k - f_k \\ 5b_k - a_k - c_k - d_k - e_k - f_k \\ 5c_k - a_k - b_k - d_k - e_k - f_k \\ 5d_k - a_k - b_k - c_k - e_k - f_k \\ 5e_k - a_k - b_k - c_k - d_k - f_k \\ 5f_k - a_k - b_k - c_k - d_k - e_k \end{bmatrix}$$

The considered six-phase VSI has 64 voltage states determined as state vectors. Each vector represents its own phase connection to the supply voltage U_D and resulting in particular polar phase voltage. Two examples illustrating in detail reliance between phase voltages and phase-to-phase voltages are presented in Fig. 2.

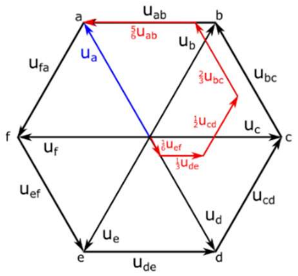

Fig. 2. The dependencies between voltages vectors V_a÷V_f and phase-to-phase voltage vectors.

Every polar phase voltage may be determined by a set of five phase-to-phase voltages U_{xy} according to the state vector definition (1): V_k = [U_{abk}, U_{bck}, U_{cdk}, U_{dek}, U_{efk}].Using the standard space voltage transformation it is possible to define the polar voltage space vector using symbols of the index k binary expansion:

$$(6)\ \bar{V}_k = \frac{5}{6} U_D \begin{pmatrix} a_k + b_k e^{j\frac{\pi}{3}} + c_k e^{j\frac{2\pi}{3}} \\ + d_k e^{j\pi} + e_k e^{j\frac{4\pi}{3}} + e_k e^{j\frac{5\pi}{3}} \end{pmatrix}$$

This definition confirms an evident correlation between the space and state vectors as they are described using the same digits.

Applying the Euler's formula and introducing interdependences among the angles as well as symbols a_k, b_k, c_k, d_k, e_k, f_k the space vector is given as follows:

$$(7)\ \bar{V}_k = \frac{5}{6} U_D \begin{bmatrix} a_k - d_k + \frac{1}{2}(b_k - c_k - e_k + f_k) \\ +j\frac{\sqrt{3}}{2}(b_k + c_k - e_k - f_k) \end{bmatrix}$$

After the transformation the space vector is situated as a complex number, therefore it may be represented by the modulus Mk and the argument φ_k. But in the case of the six-phase inverter the situation is more demanding in comparison to three-phase inverters due to a greater number of variables. The expression allowing calculation of the space vector modulus is the following:

$$(8)\ M_k = K\sqrt{\gamma_0 + \gamma_1 + \gamma_2 + \gamma_3 + \gamma_4 + \gamma_5}$$

where K denotes a constant of proportionality.

Its value depends on the voltage U_D supplying the inverter and may differ depending on the assumed canon. The coefficients $\gamma_0,\gamma_1,\gamma_2,\gamma_3,\gamma_4,\gamma_5$ are as follows:

$$(9)\ \gamma_0 = a_k^2 + b_k^2 + c_k^2 + d_k^2 + e_k^2 + f_k^2$$
$$(10)\gamma_1 = a_k(b_k - c_k - 2d_k - e_k + f_k)$$
$$(11)\gamma_2 = b_k(c_k - d_k - 2e_k - f_k)$$
$$(12)\gamma_3 = c_k(d_k - e_k - 2f_k)$$
$$(13)\gamma_4 = d_k(e_k - f_k)$$
$$(14)\gamma_5 = e_k f_k$$

If the constant K equals 5/6 U_D, as it was assumed in (6) then, according to (8), the modulus M_k may reach four diverse values: 0, 5/6 U_D, 5/3 U_D, 5/6√3 U_D.

The vectorial argument φ_k denotes an angle between vector and real axis and is determined using trigonometrical functions. In some cases it might be necessary to use both functions: arctg and arcsin due to diverse periodicity of sine and tangent. Then the argument is determined if $\varphi_k(\arcsin) = \varphi_k(\mathrm{arctg})$. The formulas (9) and (10) allow calculating the φ_k value:

$$(9)\ \phi_k = \arcsin\ \frac{\sqrt{3}(b_k + c_k - e_k - f_k)}{2M_k},$$
$$(10)\ \phi_k = \mathrm{arctg}\frac{\sqrt{3}(b_k + c_k - e_k - f_k)}{2(a_k - d_k) + b_k - c_k - e_k + f_k}$$

The denominator of the expressions (9) and (10) cannot equal zero. So, the results of φ_k is indeterminate for $a_k=b_k=c_k=d_k=e_k=0$ or $a_k=b_k=c_k=d_k=e_k=1$. The corresponding two vectors $V_{0(000000)}$ and $V_{63(111111)}$ are habitually termed zero vectors because they do not have any impact on the phase currents.

Figure 3 presents the polar voltage space vectors of the six-phase inverter. The constant K of the moduli used in this presentation was assumed K=5/6 U_D. The vectors are presented as points on the complex plane (α-jβ), where α denotes the real axis and β — the imaginary one. The diagram presents their position. Each marked point denotes at least one sense of a vector. According to the assumption K=5/6 U_D, the vector moduli reach only four values: 0,1,√3, 2.

3. Concatenation of vectors the way of control

Apart from two zero vectors in the middle of 62 vectors there are four groups of active vectors : six vectors with moduli 2, twelve with moduli √3, thirty six with 1 and also eight active vectors which formally have zero-dimensional moduli and indeterminate angles. The further down in tables 1 and 2, two sets of the binary expansions defining these relevant vectors are indicated. Among eight vectors two of them: V_{21} as well as V_{42} can be considered as representing two three-phase voltage systems (Table 1).

The first one could be determined by three voltages: V_b, V_d, V_f and the other - by voltages: V_a, V_c, V_e.

Table 1. The two vectors representing the three-phase voltage system.

V_k	*a*	*b*	*c*	*d*	*e*	*f*
V_{21}	0	1	0	1	0	1
V_{42}	1	0	1	0	1	0

Another possibility to reach two three-phase voltage systems is accessible using the next six active vectors which formally have zero-dimensional moduli, that is: V_9, V_{18}, V_{27}, V_{36}, V_{45}, V_{54}. These ones present the symmetry $a_k,b_k,c_k = d_k,e_k,f_k$ in the binary expansion of the vector number. The vectors are collected below in moderately different sequences. The sequences a_k,b_k,c_k and d_k,e_k,f_k are suitable to control three-phase system. So, following the order indicated in Table 2 it is possible to control two twin three-phase AC drives. Formally these vectors' angle φ_k is indeterminate but in Table 2 the angle φ_k was attributed in theory for application in standard α-β transformation used routinely to control three phase AC drives.

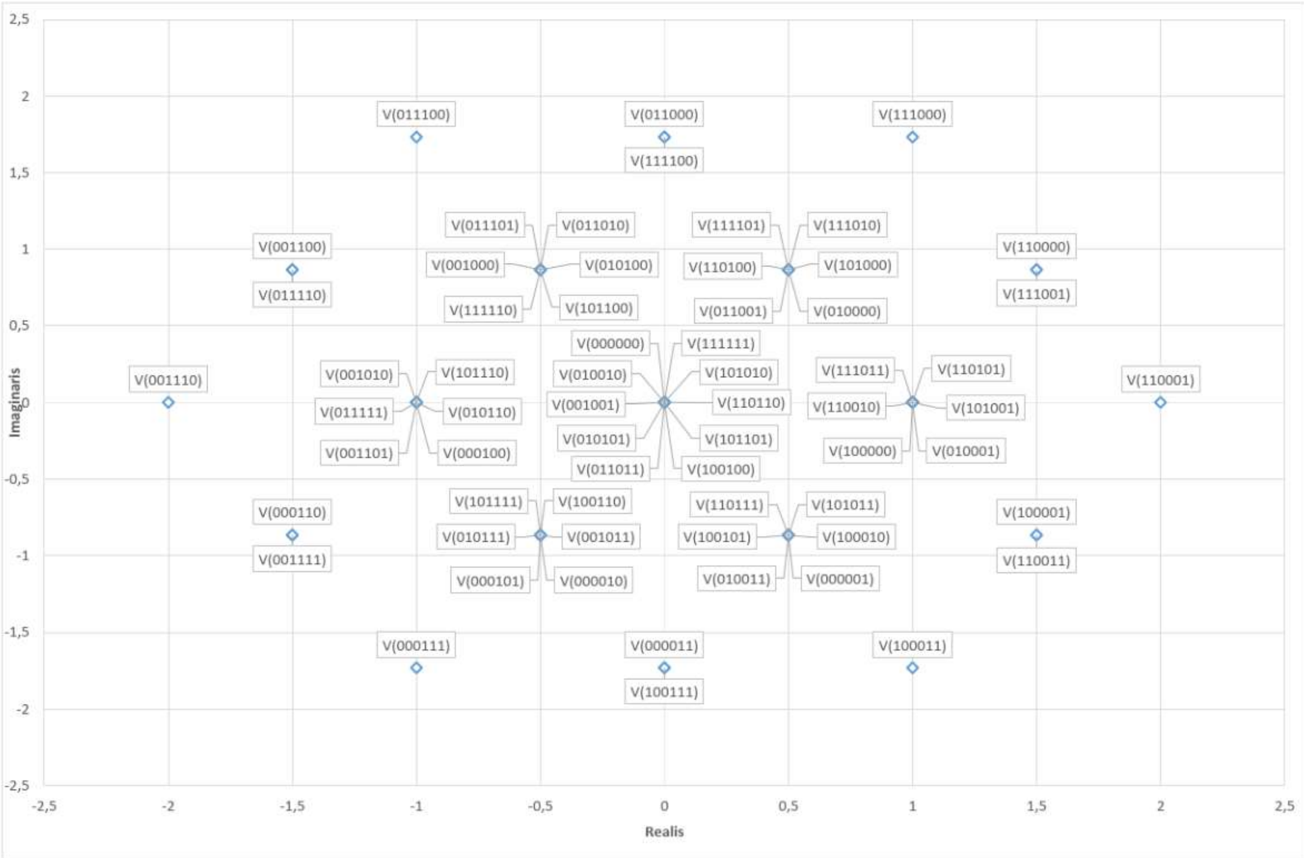

Fig. 3. The polar voltage space vectors of the two-level six-phase VSI.

Table 2. The active vectors guaranteeing the symmetry a_k, b_k, $c_k = d_k$, e_k, f_k.

	3-phase AC drive			*3-phase AC drive*			
V_k	*a*	*b*	*c*	*d*	*e*	*f*	φ_k
V_{36}	1	0	0	1	0	0	0
V_{54}	1	1	0	1	1	0	60°
V_{18}	0	1	0	0	1	0	120°
V_{27}	0	1	1	0	1	1	180°
V_9	0	0	1	0	0	1	240°
V_{45}	1	0	1	1	0	1	300°

The control process of twin AC drives consists in switching of the successive vectors starting from vector V_{36}. The sequence of vectors is evident according to the attributed angle φ_k. The pairs of vectors V_{36}-V_{54},V_{54}-V_{18},V_{18}-V_{27},V_{27}-V_9,V_9-V_{45},V_{45}-V_{36} relate to the consecutive sectors of the stationary coordinate system on the complex plane α-jβ.

4. Simulation experiment

The described methodology of using polar voltage space vectors was compared with other strategies during simulation study. The simulations were made in the PLECS program and the RT Box1 device. The adopted simulation test scenario was based on the fact that four control strategies were applied for RL load connected to a six-phase VSI (R = 2 Ω, L = 20 mH). The first strategy is based on the use of PWM modulation (marked as pwm), the second is based on the use of vector control described in Table 2 (marked as 1), the third is based on the use of vector sequences presented in the form of a vector map in Figure 4 (marked as 2), the fourth is based on a simple concatenation of successive vectors for the sequence presented in Figure 4 and its repetition (marked as 3).

Figure 4 shows in a graphic form a vector map for the adopted vector control strategy. This sequence is the basis for the next modification in which the presented vector sequence concept was repeated twice (Fig. 5). It should also be noted that the graphical representations of the vectors in each sector shown in Figure 4 and 5 were achieved by mirroring. The vector sequences were selected according to the one switch per phase principle above.

	Nr	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
	sectors	1												2											
	vectors	32	48	49	50	59	63	59	50	49	48	32	0	16	24	56	60	61	63	61	60	56	24	16	0
p	a	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	0	0	0
h	b	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	0
a	c	0	0	0	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0
s	d	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0
e	e	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
s	f	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0

	Nr	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
	sectors	3												4											
	vectors	8	12	28	30	62	63	62	30	28	12	8	0	4	6	14	15	31	63	31	15	14	6	4	0
p	a	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
h	b	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0
a	c	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	0	0	0
s	d	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	0
e	e	0	0	0	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0
s	f	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0

	Nr	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72
	sectors	5												6											
	vectors	2	3	7	39	47	63	47	39	7	3	2	0	1	33	35	51	55	63	55	51	35	33	1	0
p	a	0	0	0	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0
h	b	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0
a	c	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
s	d	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0
e	e	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	0	0	0
s	f	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	0

Fig. 4. The polar voltage space vectors of the two-level six-phase VSI and their binary expansions

Nr		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
sectors		1																								2																							
vectors		32	48	49	50	59	63	59	50	49	48	32	0	32	48	49	50	59	63	59	50	49	48	32	0	16	24	56	60	61	63	61	60	56	24	16	0	16	24	56	60	61	63	61	60	56	24	16	0
p	a	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0
h	b	0	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	0
a	c	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	0	0
s	d	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0
e	e	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
s	f	0	0	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0

Nr		49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96
sectors		3																								4																							
vectors		8	12	28	30	62	63	62	30	28	12	8	0	8	12	28	30	62	63	62	30	28	12	8	0	4	6	14	15	31	63	31	15	14	6	4	0	4	6	14	15	31	63	31	15	14	6	4	0
p	a	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
h	b	0	0	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0
a	c	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0
s	d	0	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	0
e	e	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	0	0
s	f	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0

Nr		97	98	99	##	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144
sectors		5																								6																							
vectors		2	3	7	39	47	63	47	39	7	3	2	0	2	3	7	39	47	63	47	39	7	3	2	0	1	33	35	51	55	63	55	51	35	33	1	0	1	33	35	51	55	63	55	51	35	33	1	0
p	a	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	0	0
h	b	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0
a	c	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
s	d	0	0	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0
e	e	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0
s	f	0	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	0

Fig. 5. The polar voltage space vectors of the two-level six-phase VSI with double repetition.

Figure 6 shows the waveforms of the control signals corresponding to the individual control systems. The figures show the signals for phases a.

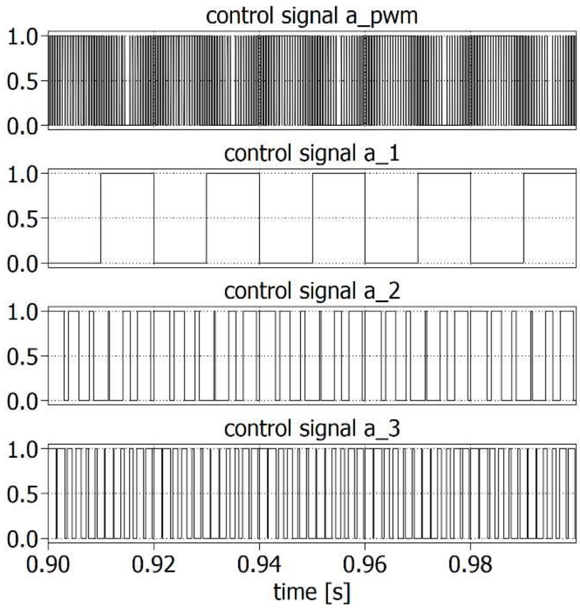

Fig. 6. The comparison of the control signal waveforms for various control strategy and for phase a.

Figure 7 shows the phase-to-phase voltage waveform u_{ba}.

Table 3 presents a summary of the most important parameters obtained during the simulation tests for currents.

Table 3. The vectors' parameters of the six-phase VSI inverter for currents.

Strategy	RMS [A]	THD [%]
1 (pwm)	32.17	2.32
2 (2 x 3 phase)	41.01	5.85
3 (vectors)	24.9	10.0
4 (vectors2)	25.01	6.42

Figure 8 and 9 shows the phase current i_a obtained for different control strategies.

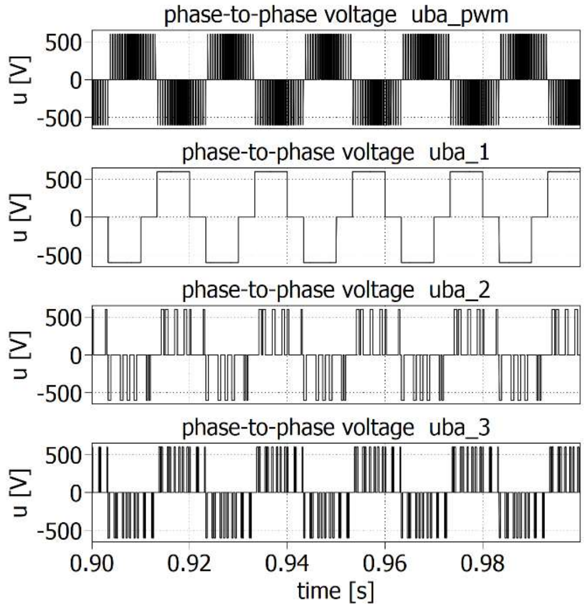

Fig. 7. The comparison of the phase-to-phase voltage waveforms for various control strategies.

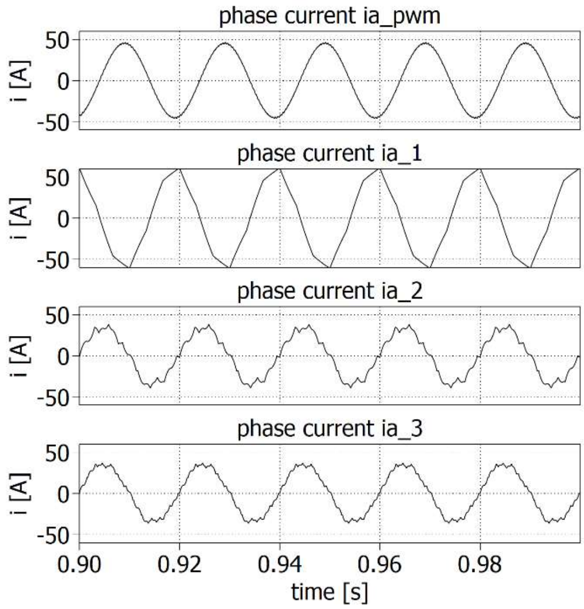

Fig. 8. The comparison of the phase current waveforms for different control strategies.

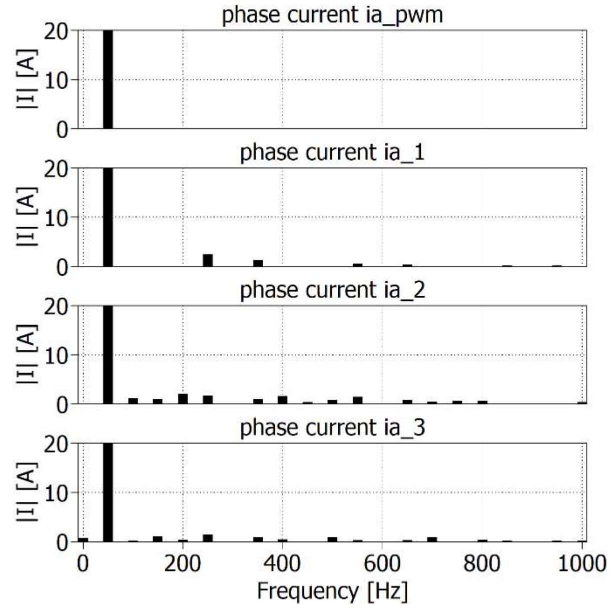

Fig. 9. The comparison of the phase current spectrums for different control strategies.

The control strategy number 3 has been chosen so that the switching of the keys in a given clock takes place only once. The control strategy 4 is a double repetition in a cycle of the control strategy 3. Using such a simple control method, very good results have been obtained for the content of higher harmonics. The THD values demonstrate this effect. At the same time, the adopted control also allows for maintaining a high rms value of the currents. Subsequent repetition of the adopted vector sequence would lead to results comparable to PWM control. However, the main advantage of the control method described in the experiment, in relation to the PWM method, is that it requires a much smaller amount of switching. However, the best results were obtained by selecting such vectors so that the six-phase inverter works as two three-phase inverters.

5. Conclusion

The conducted simulation tests have proved that the proposed solution might be indeed suitable in designing inverter control algorithms. The obtained results have shown that space vector method assures a significantly lower number of inverter switching in comparison to the PWM method, what results also in higher efficiency of the inverter. The presented in the paper mathematical tool may be in fact suitable in designing inverter control algorithms. The simulation experiment shows that the concatenation as the method of control strategy allows to significantly reduce the number of switching compared to PWM. At the same time, the adopted vector strategy allows to obtain a very favorable value of the current THD coefficient while maintaining the RMS values of the currents.

Both the notation and computational method described in this paper were used in previous works. However, only the inverters with an odd number of phases have been considered there. An even number of phases makes the computational process more complicated since the choice of vectors is limited by the phases' symmetry. Another problem is that even though some vector sequences are optimal in terms of the amount of switching, they are not implementable in the inverter due to the asymmetry of the output voltage and current waveforms. It can be stated that it is easier to obtain vector sequences which meet control expectations for inverters with an odd number of phases than for ones with an even number of phases.

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