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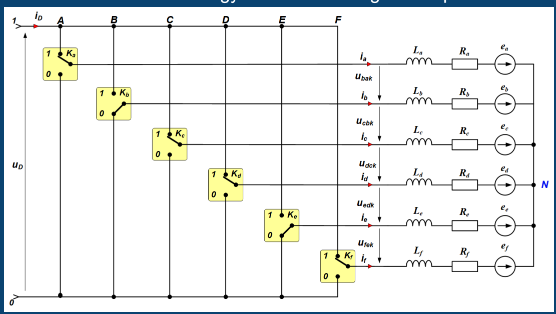
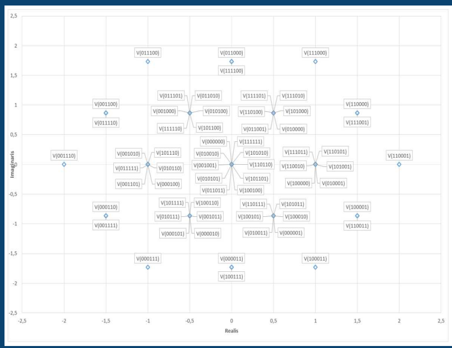
Simulation studies of concatenation as the simplest way of multi-phase inverter control

The paper recommends polar voltage space vectors of the six-phase two-level inverter as a useful mathematical tool for vector control of the inverter. The inverter model is described using two mathematical tools: voltage state vectors and voltage space vectors. The polar voltage space vectors are used for inverter control. They are defined using the standard voltage space vector transformation and are determined by the usage of the same binary digits as the numbers defining state vectors. The simulation experiment described in this paper shows the results of the assumed control strategy and its advantages compared to the PWM method.





$$V_k = [U_{abk}\ U_{bck}\ U_{cdk}\ U_{dek}\ U_{efk}\ U_{fak}]$$ where k = 0, 1, 2, …, 63

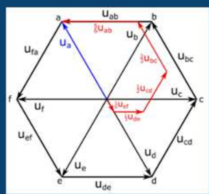
$$\begin{bmatrix} u_{a0_k} & = (\\ u_{b0_k} & = l \\ u_{c0_k} & = (\\ u_{d0_k} & = (\\ u_{e0_k} & = \epsilon \\ u_{f0_k} & = j \end{bmatrix}$$

$$V_k = \begin{bmatrix} u_{ab_k} \\ u_{bc_k} \\ u_{cd_k} \\ u_{de_k} \\ u_{ef_k} \\ u_{fa_k} \end{bmatrix} = \begin{bmatrix} u_{a0_k} - u_{b0_k} \\ u_{b0_k} - u_{c0_k} \\ u_{c0_k} - u_{d0_k} \\ u_{d0_k} - u_{e0_k} \\ u_{e0_k} - u_{f0_k} \\ u_{f0_k} - u_{a0_k} \end{bmatrix} = U_D \begin{bmatrix} (a_k - b_k)_2 \\ (b_k - c_k)_2 \\ (c_k - d_k)_2 \\ (d_k - e_k)_2 \\ (e_k - f_k)_2 \\ (f_k - a_k)_2 \end{bmatrix} \begin{bmatrix} u_{a_k} \\ u_{b_k} \\ u_{c_k} \\ u_{d_k} \\ u_{e_k} \\ u_{f_k} \end{bmatrix} = \frac{U_D}{6} \begin{bmatrix} 5a_k - b_k - c_k - d_k - e_k - f_k \\ 5b_k - a_k - c_k - d_k - e_k - f_k \\ 5c_k - a_k - b_k - d_k - e_k - f_k \\ 5d_k - a_k - b_k - c_k - e_k - f_k \\ 5e_k - a_k - b_k - c_k - d_k - f_k \\ 5f_k - a_k - b_k - c_k - d_k - e_k \end{bmatrix}$$

The 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

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



$$\gamma_0 = a_k^2 + b_k^2 + c_k^2 + d_k^2 + e_k^2 + f_k^2$$
$$\gamma_1 = a_k(b_k - c_k - 2d_k - e_k + f_k)$$
$$\gamma_2 = b_k(c_k - d_k - 2e_k - f_k)$$
$$\gamma_3 = c_k(d_k - e_k - 2f_k)$$
$$\gamma_4 = d_k(e_k - f_k)$$
$$\gamma_5 = e_k f_k$$

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

$$\phi_k = \arcsin\frac{\sqrt{3}(b_k + c_k - e_k - f_k)}{2M_k},$$

$$\phi_k = \operatorname{arctg}\frac{\sqrt{3}(b_k + c_k - e_k - f_k)}{2(a_k - d_k) + b_k - c_k - e_k + f_k}$$

Simulation experiment

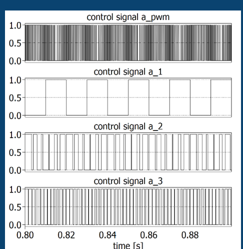
The adopted simulation test scenario was based on the fact that four control strategies were applied for two induction motors connected to a six-phase VSI. The first strategy is based on the use of PWM modulation (marked as pwm), the second is based on the use of vector control described in Table (marked as 1), the third is based on the use of vector sequences presented in the form of a vector map in Figure (marked as 2), the fourth is based on a simple concatenation of successive vectors for the sequence presented in Figure and its repetition (marked as 3).

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
phases	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
	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
	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
	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	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
	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

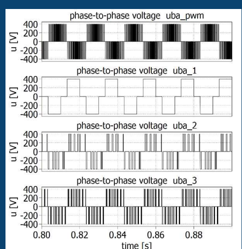
Nr		25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
sectors		3												4											
vectors		8	12	28	30	62	63	62	30	28	12	8	0	4	6	14	15	31	63	31	15	14	6	4	0
phases	a	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
	b	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0
	c	1	1	1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

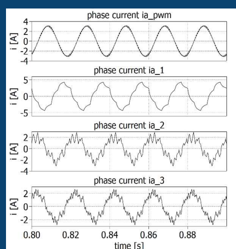
The polar voltage space vectors of the two-level six-phase VSI and their binary expansions



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



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



The comparison of the phase current waveforms 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, which can be seen from the THD values. 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 con-trol method described in the experiment over PWM 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.

Conclusions

The aim of the paper was to prove that state and polar voltage space vectors are a useful mathematical tool in the analysis and control of a six-phase inverter. The whole control process could be restricted to the simplest concatenation of successive vectors. This approach permits limiting to a minimum the amount of switching and the number of zero vectors used, as well as avoiding problems resulting in parity of phases.

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, which results also in higher efficiency of the inverter.

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.