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The active filtering of the inverter output voltage by use of orthogonal vectors' control strategy

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Abstract. The paper proposes a creative control method permitting to filter output voltage waveforms of the inverter. The main idea is based on the assumption that the total inverter output space vector is carefully chosen as a composition of two space vectors generated by 2 two-level inverters. The total built-up inverter is assembled of two standard three-phase inverters: a main inverter (MI) and an auxiliary one (AI) serving as an active filter. The output voltage space vector of the built-up inverter is composed of one or two space vectors generated by the respective inverters. The space vectors of the auxiliary inverter are orthogonal to the respective space vectors of the main inverter. The structure and its performance as well as the control method using specified vectors are discussed in the paper.

Key words. Control method, multilevel inverter, orthogonal space vector, voltage filtering.

1. Introduction

The features and performance of 2 level voltage source inverters (VSIs) have been largely documented and confirmed in practice. The disadvantages and limitations of the VSIs are well acknowledged. The most appropriate control method is based on using pulse width modulation - PWM. This control method implies a few drawbacks: reduction of modulation index, generated noise level, appearance of large voltage derivatives at motor clamps, high harmonic content of the output voltage. These features speed up the wearing out of the motor insulation and create new issues of electromagnetic compatibility.

The simplest way of VSI control limits to subsequent switching consecutive inverter states. Then the VSI produces a step changing phase voltage at the output. It means the inverter output voltage takes up a shape of a steeped waveform. The method has some advantages: simple control circuitry and negligible switching losses. The ratio: output frequency (of the voltage fundamental) to switching frequency, is relatively high as well as a modulation index. The greatest disadvantage of such a control method is a high harmonic content of the output voltage. For instance if every subsequent voltage state of the inverter is switched on 60º then the THD_U factor amounts to ≈31 %. Besides there is no possibility of output regulating in order to decrease the output voltage fundamental. In this case it would be necessary to adjust the DC voltage of the inverter or to switch on zero vectors. Therefore the method is rarely applied in practice.

Many control methods and inverter topologies permitting to increase the total output power and to improve the inverter performance have been developed. There are solutions of complex inverters composed e.g. with several standard inverters and a transformer [1]. These inverters could be destined to higher power applications and permit to limit the output voltage spectrum therefore generating better voltage waveforms.

Higher power and better performance- this is the field of multilevel inverters. They effect shape upgrading of the output voltage waveforms. The recommended control methods focus on attempt to limit the output voltage frequency spectrum. Thanks to their performance the multilevel inverters have been becoming more and more an alternative to conventional two level inverters [2-6]. There are a lot of examples of multilevel inverters including neutral point clamped (NPC) inverters.

Another main stream of power electronics development relates to multiphase electric machines and inverters. Although primary significant papers appeared in nineties of the 20th century but in recent times one can notice a great explosion of many scientific papers relating to multi-phase electric machines and inverters. The papers present and specifically describe novel solutions and constructions of electric machines such as permanent magnet and induction motors. At the same time control methods including space vector and field-oriented control are intensely developed [7-13].

However the possibilities of the inverter structure composed from two level inverters have not been exhausted. The paper presents a less known proposal of a complex inverter and its control method. The solution is based on an OVT (Orthogonal Vectors Theory) inverter defined in [14-17]. The OVT inverter in question is built from two standard inverters. Its performance and the way of control are presented in the next chapter. Although the

paper describes the control method of three phase inverters the offered theory is suitable to apply in multiphase systems. The paper presents some simulations results signifying possibilities of the OVT inverter control. That proposal seems to be a significant alternative to recently developed numerous multilevel inverters [18].

2. Basic idea of the OVT inverter

The block diagram and the idea of the OVT inverter control are outlined in Fig.1. The inverter consists of a mains rectifier (MR), a DC circuit, a main inverter (MI) and an auxiliary inverter (AI). The inverters are connected together by use of a summing nod (S), which can be set up in a number of ways.

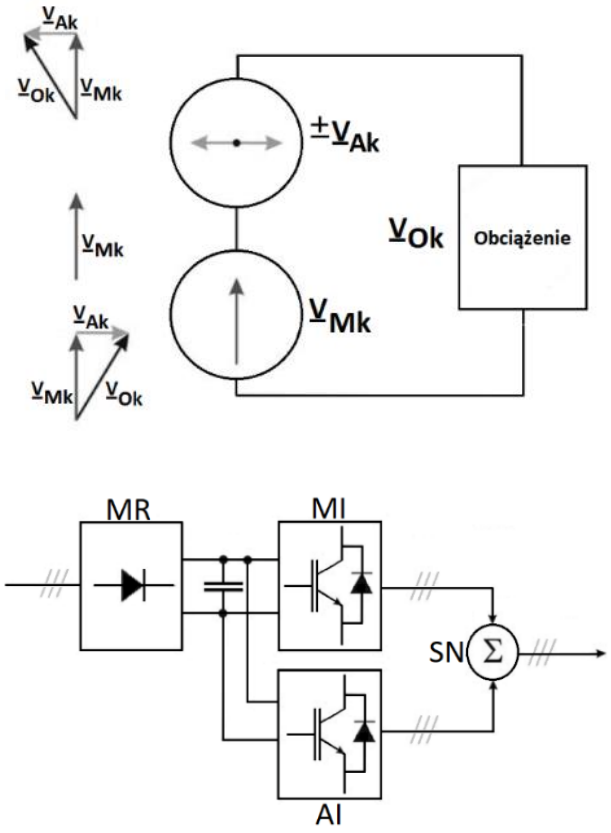


Figure.1. Idea and the block diagram of the OVT inverter: MR - mains rectifier, DC circuit, MI – main inverter, AI - auxiliary inverter, SN - summing nod.

The MI and AI units are two standard two level inverters. The main inverter MI produces space active vectors denoted as VMk while the auxiliary inverter generates space vectors VAk orthogonal to the interrelated MI vectors. The zero vectors VAk of the auxiliary inverter are used too. Output voltage vectors of the OVT inverter are composed according to the idea presented above. The resulting in output space vector of the complex inverter is composed as a combination (a sum or a difference) of orthogonal vectors generating by two inverters. While a zero vector of the AI inverter is added to the space vector of the main inverter that means practically the only active vector of the MI is connected to the load. Thus the MI produces generally active power to feed the load whereas the AI provides relatively small disturbance power in order to filter the output voltage. Active space vectors of both inverters are presented in Fig. 2. All active vectors are described by the following expressions:

$$\begin{cases} \underline{V}_{Mk} = |\underline{V}_{Mk}|e^{j\left[(k-1)\frac{\pi}{3}\pm 2\pi n\right]} \\ \underline{V}_{Ak} = \pm jm\underline{V}_{Mk} = \pm m\underline{V}_{Mk}e^{j\frac{\pi}{2}} \end{cases} \quad (1)$$

where k=1, 2, 3, 4, 5, 6; n=1, 2, 3...; m – the ratio of vectors' lengths. As it was mentioned earlier zero voltage space vectors of the AI are also utilized.

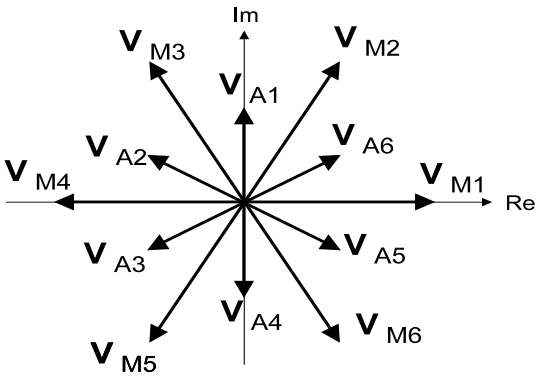


Figure.2. Active space vectors of both inverters.

The ratio m is defined as:

$$m = \frac{|\underline{V}_{Ak}|}{|\underline{V}_{Mk}|} = tg\left(\pi/9\right) = 0,364 \quad (2)$$

As a result of the proposed control method, the whole inverter is able to generate 42 output voltage space vectors assuming zero vectors of the MI are not considered. Among all these vectors there are 18 vectors similar in length.

Taking into account only similar in length vectors the output space vector of the inverter is created in the way described below. In every surface sector of the stationary coordinates system (α-β), corresponding to the one of MI active vectors, the output vectors of the OVT inverter are generated as a sequence of three vectors: $\underline{V}_{Ok-}, \underline{V}_{Ok}, \underline{V}_{Ok+}$. They are given as:

$$\begin{cases} \underline{V}_{Ok-} = \underline{V}_{Ak\oplus 3} + \underline{V}_{Mk} \\ \underline{V}_{Ok} = \underline{V}_{Mk} \\ \underline{V}_{Ok-} = \underline{V}_{Ak} + \underline{V}_{Mk} \end{cases} \quad (3)$$

The symbol $k \oplus 3$ denotes the modulo-6 sum of the index k and 3. The expression (3) describes the method of control based on the developed orthogonal vectors' strategy. When the $\underline{V}_{Ok}$ vector is equal to a $\underline{V}_{Mk}$ vector of the main inverter then the auxiliary inverter generates a zero voltage vector. According to the rule (3) the inverter output vectors are expressed as:

$$\begin{cases} \underline{V}_{Ok-} = (1-jm)\underline{V}_{Mk} = \sqrt{1+m^2}\,\underline{V}_{Mk}\,e^{-j\arctan m} \\ \underline{V}_{Ok} = \underline{V}_{Mk} = |\underline{V}_{Mk}|\,e^{j\left[(k-1)\frac{\pi}{3}\pm 2\pi n\right]} \\ \underline{V}_{Ok+} = (1+jm)\underline{V}_{Mk} = \sqrt{1+m^2}\,\underline{V}_{Mk}\,e^{j\arctan m} \end{cases} \quad (4)$$

While vectors are composed according to the principle described, it is possible to obtain 18 non-zero vectors, that is three times as many as in case of using conventional inverters. Having repeated the operation for any other vector $\underline{V}_{Mk}$ one arrives at 18 non-zero voltage space vectors. The length of twelve vectors, composed as a sum of active vectors of both inverters, is identical. And it is about 6 % more than the length of remaining six vectors, which are generating by the main inverter. Fig.3 presents all vectors, which have been described directly above.

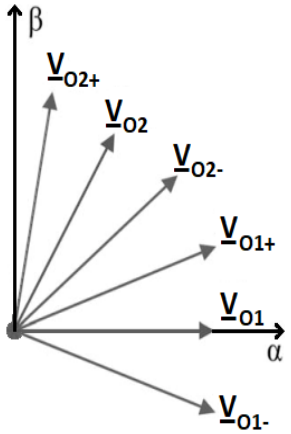
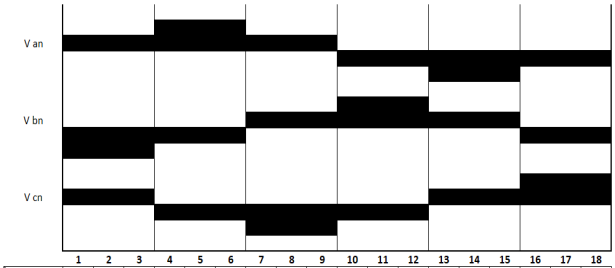


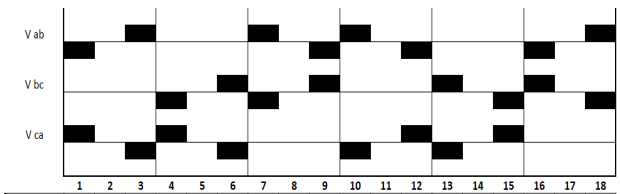
Figure.3. A few selected output space vectors of the inverter.

Figures 4 and 5 show the theoretical waveforms and vector distribution for the main and auxiliary inverter.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
vectors / phases	v5	v5	v5	v4	v4	v4	v6	v6	v6	v2	v2	v2	v3	v3	v3	v1	v1	v1
a	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0
b	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0
c	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1

Figure.4. Voltage waveforms and vectors for the main inverter



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
vectors / phases	v3	v7	v4	v1	v0	v6	v5	v7	v2	v4	v0	v3	v6	v0	v1	v2	v0	v5
a	0	1	1	0	0	1	1	1	0	1	0	0	1	1	0	0	0	1
b	1	1	0	0	0	1	0	1	1	0	0	1	1	1	0	1	0	0
c	1	1	0	1	0	0	1	1	0	0	0	1	0	1	1	0	0	1

Figure.5. Voltage waveforms and vectors for the auxiliary inverter

3. Simulation research

Simulation studies were performed using PLECS software. In the first test stage the OVT inverter was put under star-connected resistive load. The model of the orthogonal inverter equipped in the adder system in the form of transformer is shown in figure 6. The primary transformer windings are delta-connected to the AI auxiliary inverter output while the secondary windings are connected in series with the resistive load of the main inverter. Thus the AI phase-to-phase voltage is transformed to the respectively selected auxiliary voltage which is connected in series with the output voltage of the MI.

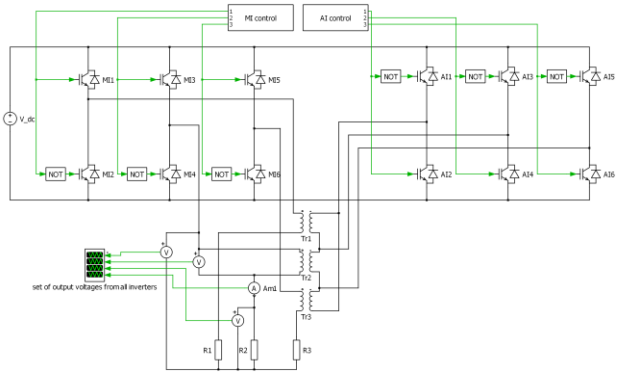


Figure.6. Model of the orthogonal inverter with a summation system in the form of transformer and resistance in the load.

Figure 7 shows the output voltage waveforms of the main inverter (MI), auxiliary inverter (AI), orthogonal inverter (OVT) and orthogonal inverter (OVT) output current and their spectra under resistive load.

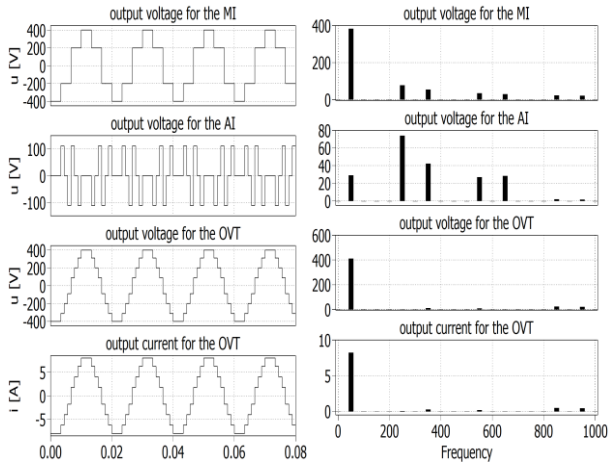


Figure.7. The waveforms of output voltages and current and their spectra at R = 50 Ω.

Figure 8 shows the schematic of the OVT inverter with RL load, while simulations were performed for two time constant loads. Figures 9 and 10 shows the output voltage waveforms of the main inverter, the auxiliary inverter, the orthogonal inverter and the output current of the orthogonal inverter and their spectra under resistive and inductive loads.

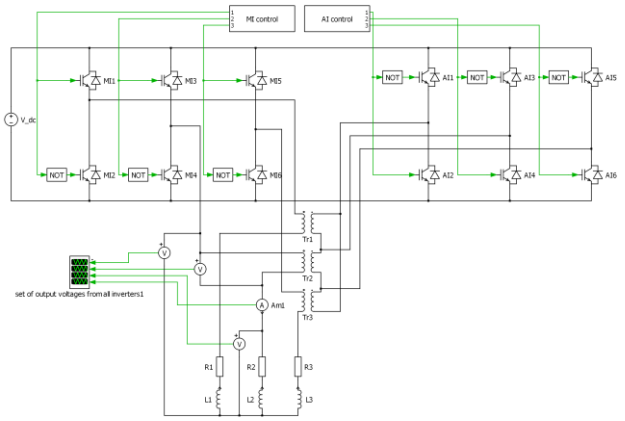


Figure.8. Model of an orthogonal inverter with a summation system in the form of transformers and resistance-inductance in the load.

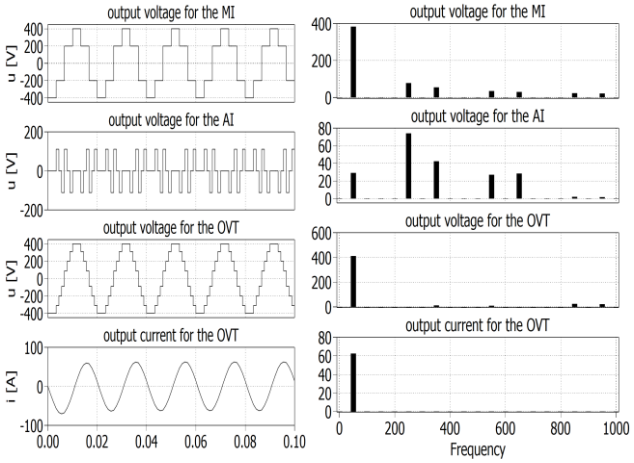


Figure.9. The output voltages waveforms: main inverter (MI), auxiliary inverter (AI), orthogonal inverter (OVT) and orthogonal inverter output current (OVT) and their spectra at R = 2 Ω, L = 20 mH.

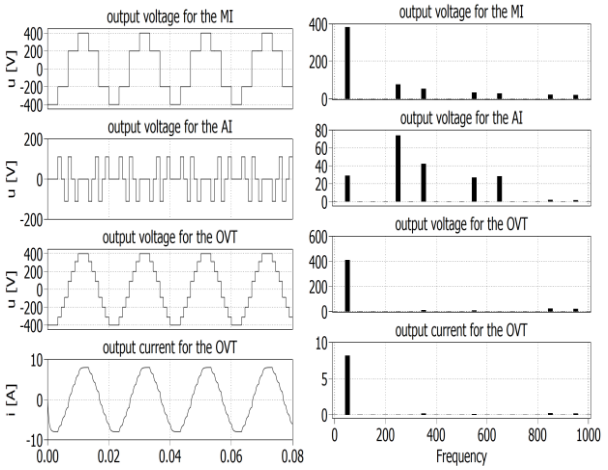


Figure.10. The output voltages waveforms: main inverter (MI), auxiliary inverter (AI), orthogonal inverter (OVT) and orthogonal inverter output current (OVT) and their spectra at R = 50 Ω, L = 20 mH.

The change of the time constant $\tau = L/R$ for two values τ = 10 ms and τ = 0.4 ms is not very evident in the waveforms and spectra shown in Figure 9 and 10, so in addition the relevant signal parameters are summarized in Table 1.

It is obvious that the RMS and THD for the MI and OVT inverter voltages are the same, but after changing the time constant, the change of RMS and THD values for the OVT inverter current can be seen. So, reducing relatively the time constant one can reduce the RMS value of the current and decreases its THD_I.

Table I. - List of selected parameters of output voltage and currents for MI and OVT

	R = 2 Ω, L = 20 mH	R = 50 Ω, L = 20 mH
u_{MI_RMS} [V]	282.8	282.8
THD_{MI-u} [%]	31.1	31.1
u_{OVT_RMS} [V]	298.9	298.9
THD_{OVT-u} [%]	10.6	10.6
i_{OVT_RMS} [V]	44.0	5.77
THD_{OVT_i} [%]	0.7	2.1

Figure 11 shows a schematic of an OVT inverter loaded with an induction motor, and Figure 12 shows voltage and current waveforms.

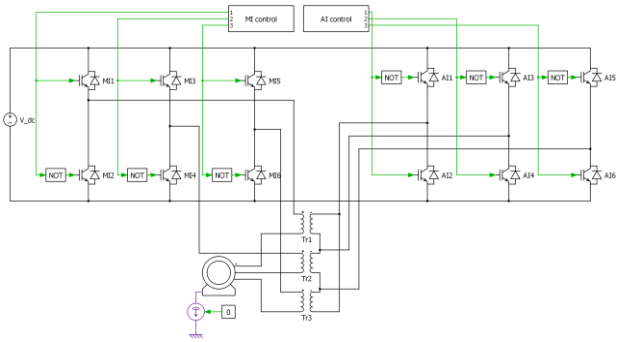


Figure.11. Model of an orthogonal inverter with a summing system in the form of transformers and an induction motor under load.

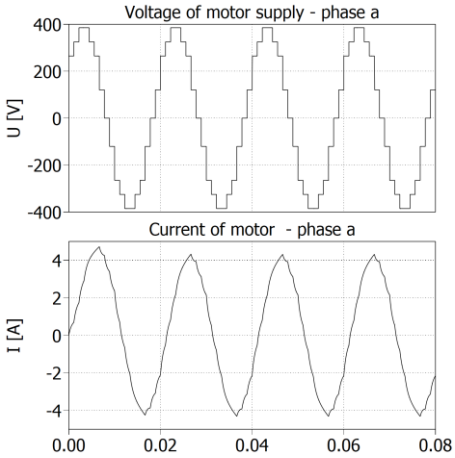


Figure.12. Waveforms of voltages and currents for a load in the form of an induction motor.

In the second stage of the simulation study, results are presented to show the effect of varying the transformer ratio between voltages generated by the main and orthogonal inverter. In addition the alterations of the voltage rms values related to MI, AI and OVT inverters have been presented as well as their voltages THD_U. All results are included in Table 2. The gearing of the transformers has been standardized to 100 turns. The winding on the main inverter side was designated N_{MI} and on the auxiliary inverter side it was designated N_{AI}.

Table II. - List of output voltage parameters for the main inverter, auxiliary and orthogonal inverter with different transformer winding ratios

N_{MI}:N_{AI}	$u_{MI_}$		$u_{AI_}$		$u_{OVT_}$	
	RMS [V]	THD [%]	RMS [V]	THD [%]	RMS [V]	THD [%]
45:100	282.8	31.1	181.8	345	336.2	31.6
33:100	282.8	31.1	133.3	345	312.7	19.1
26:100	282.8	31.1	105.2	345	301.8	12.8
22:100	**282.8**	**31.1**	**86.9**	**345**	**298.9**	**10.6**
18:100	282.8	31.1	74.1	345	292.3	10.8
16:100	282.8	31.1	64.5	345	290.1	12.1
14:100	282.8	31.1	57.1	345	288.5	13.4
12:100	282.8	31.1	51.3	245	287.4	14.8

where: N_{MI} - number of transformer windings on the main inverter side, N_{AI} - number of transformer windings on the auxiliary inverter side

The adjustment of the transformer ratio shows that it affects the change in auxiliary and orthogonal inverter voltages. The smaller the gear ratio, the smaller the rms voltage values of the mentioned inverters. However, the change of the ratio does not influence the voltage THD exchange of the auxiliary inverter but it influences the voltage THD alteration of the OVT inverter. The voltage THD variation of the OVT inverter is parabolic in nature, and its minimum appears at a gear ratio of 22:100.

4. Conclusions

The orthogonal vectors theory presents a very useful tool to design control strategy of the OVT inverter built from two standard three phase inverters. Such a solution is particularly suitable to produce a stepped output voltage characteristic to multilevel inverters. Thanks to the presented control method, the harmonic content of the output voltage is reduced. The THD_U factor reaches lower values thanks to filtering properties of the OVT inverter and output voltage waveforms are better similar to sine-waves. The power of the auxiliary inverter AI is significantly reduced in relation to thr main inverter MI. The switching frequency of both inverters is very low, so the power losses of the OVT inverter is maximally limited. The inverter in question seems to be a significant alternative to recently developed numerous multilevel inverters. Moreover the idea of the OVT inverter has the property of recurrence.

References

[1] M.Malinowski, K.Gopakumar, J.Rodriguez, M.A.Perez, A Survey on Cascaded Multilevel Inverters. IEEE Trans. Ind. Electron. 2010, 57, pp. 2197–2206

[2] E.Cengeleci, U.Sulistijo, O.Woo, P.Enjeti, R.Teodorescu, Blaabjerg F., A New Medium-Voltage PWM Inverter Topology for Adjustable-Speed Drives, IEEE Transactions on Industry Applications, Vol. 35, No. 3, May/June 1999

[3] S.Iida, S.Masukawa, and Y. Kubota, Improved Voltage Source Inverter With 18-Step Output Waveforms, IEEE Industry Applications Magazine January/February 1998.

[4] C.Newton, M.Sumner, Multi-level convertors a real solution to medium/high-voltage drives? Mill Valley, CA: Power Engineering Journal, February 1998.

[5] G.Sinha, and T.Lipo, Four-Level Rectifier-Inverter System for Drive Applications. IEEE Industry Applications Magazine, January/February 1998

[6] S.Halasz, A.Hassan, and B.Huu, Optimal, Control of Three-Level PWM Inverters. IEEE Transaction on Industrial Electronics, vol. 44, no. 1, February 1997.

[7] B.Jakubiec, Multiphase Permanent Magnet Synchronous Motor Drive for Electric Vehicle. Przegląd Elektrotechniczny 2015, 91, pp. 125–128. ISSN 0033-2097

[8] Listwan, J., Pieńkowski, K. Field-oriented control of five-phase induction motor with open-end stator winding. Archives of Electrical Engineering, vol. 65, nr 3, 2016, pp. 395-410.

[9] Z.Liu, Z.Zheng, S. D.Sudhoff, C.Gu, Y.Li, Reduction of common-mode voltage in multiphase two-level inverters using SPWM with phase shifted carriers. IEEE Trans. Power Electron. 2016, 31, pp. 6631–6645.

[10] M.Ippisch, D.Gerling, Analytic Calculation of Space Vector Modulation Harmonic Content for Multiphase Inverters with Single Frequency Output. IECON 2019 - 45th Annual Conference of the IEEE Industrial Electronics Society. 2019, pp. 6187-6193.

[11] E.Levi, Multiphase electric machines for variable-speed applications. IEEE Transactions on Industrial Electronics. 2008, 55 (5), pp. 1893-1909.

[12] E.Koptjaew, E.Popkov, AC-multiphase Adjustable Electric Drive with Two-channel Conversion, International Conference on Industrial Engineering Applications and Manufacturing, ICIEAM, 2019.

[13] K.Oguchi, A.Kawaguchi, T.Kubota, N.Hoshi, A Novel Six-phase Inverter System with 60-Step Output Voltages for High Power Motor Drives. IEEE Transaction on Industry Applications, vol. 35, no. 5, September/October 1999.

[14] M.Hartman, M.Hashad, J.Iwaszkiewicz: *Developing Inverter Output Voltage Waveforms with the Help of Orthogonal Space Vectors*, IEE Conference Power Electronics and Variable Speed Drives PEVD'2000, London, United Kingdom, 18–19 IX 2000

[15] M.Hashad, J.Iwaszkiewicz: *A Novel Orthogonal–Vectors–Based Topology of Multilevel Inverters*, IEEE Transactions on Industrial Applications, vol. 49, no. 4, pp. 868–874, August 2002

[16] J.Iwaszkiewicz, M.Hashad, *Convertor Control with the Help of Orthogonal Space Vectors – Novel Control Strategy and Novel Topology*, Power Conversion Conference PCC OSAKA 2002, Japan, pp. 659–665

[17] J.Iwaszkiewicz, A Novel Recurrent Approach to the Output Voltage Filtering of the Inverter, Electrical Power Quality and Utilization EPQU PAN, Volume 9, No. 1, September 2003, pp. 59–65.

[18] Yuan Li, Wenwen Huang, Zhen Li, Yue Sun, Bi Liu, A Single Phase Transformerless Nine-Level Inverter, and Its Control Strategy, Energies 2022.

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