Algorithms of Synchronous Vector Modulation for Hybrid Multi-Converter Six-Phase System

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Abstract — **Topology of dual three-phase (six-phase) adjustable speed motor drives can be based on two standard inverters and two neutral-point-clamped converters. Control of these systems in accordance with specialized schemes and techniques of synchronized pulsewidth modulation (PWM) allows providing elimination of the common-mode voltage and continuous symmetry of the output voltage waveforms during entire control region for any operating conditions. MATLAB-simulations illustrate behavior of hybrid multi-inverter drive system with basic versions of synchronized PWM.**

Index Terms — **adjustable speed drive, control and modulation strategy, inverter, synchronization.**

I. INTRODUCTION

Multiphase power converters and adjustable speed drives, controlled by algorithms of PWM, are between the most perspective power conversion systems for the medium-voltage applications, which are characterized by low switching frequency of converters [1]-[6].

Focused to the medium-power and high-power application of ac drives, new multi-inverter topology of six-phase system has been investigated, based on four voltage source converters [7]-[10]. Fig. 1 shows structure of power circuits of this system, consisting of two sections (each with two converters), supplying asymmetrical six-phase induction motor with open-end windings [7]. Two sets of windings of ac machine are spatially shifted by 30 electrical degrees in this case.

Additional possibilities of dual three-phase multi-inverter drive allow using various system structures and various combinations of schemes of modulation for its control. In particular, it is possible to use two conventional three-phase inverters for the first converter section (**INV1 + INV2** in Fig. 1). Fig. 2 shows structure of power circuits of conventional voltage source inverter **INV1**. Also, it is possible to use two neutral-point-clamped converters for the second converter section (**INV3 + INV4** in Fig. 1). Fig. 3 presents structure of neutral-point-clamped (NPC) converter **INV3** (Fig. 3a), together with combination of its voltage space vectors (Fig. 3b) [12]. So, this paper presents results of investigation of operation of six-phase drive system on the basis of combined system topology (two conventional converters + two NPC converters), controlled by algorithms of synchronized space-vector modulation.

II. STRATEGY OF SYNCHRONIZED SPACE-VECTOR PWM

To provide voltage waveform symmetries of multi-inverter system (and elimination of undesirable sub-harmonics (of the fundamental frequency) from voltage spectra), specialized scheme of synchronized PWM [11] can be applied for adjustment of each converter of dual three-phase drive system.

Table I demonstrates generalized features and basic functional correlations for this scheme (method) of synchronized pulsewidth modulation [11], compared also with the corresponding parameters of classical versions of asynchronous space-vector PWM.

In accordance with basic features of specialized scheme of synchronized PWM, positions of all central active switch-on signals (β_1-signals in Table I) should be fixed in the centers of the 60^0-clock-intervals. And generation of other active β-and γ-signals (and also the corresponding notches, see Table I) should be done symmetrically around the β_1-signals [11].

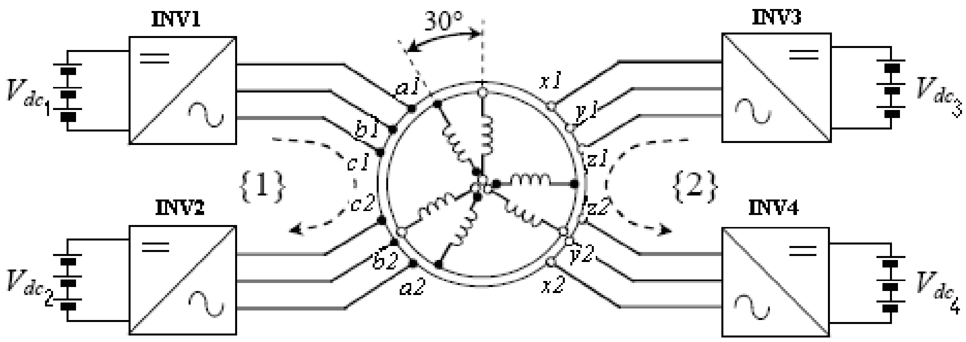


Fig. 1. Structure of six-phase drive with four converters (the first converter (inverter) section **INV1 + INV2**, and the second NPC converter section **INV3 + INV4**) feeding asymmetrical dual three-phase induction motor with open-end windings [7].

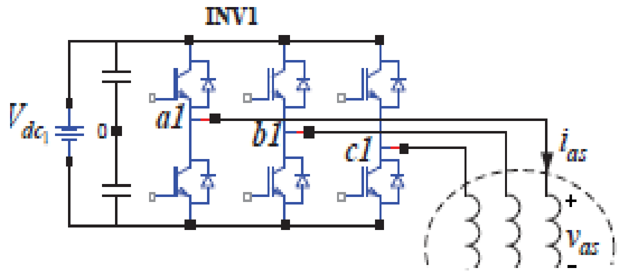
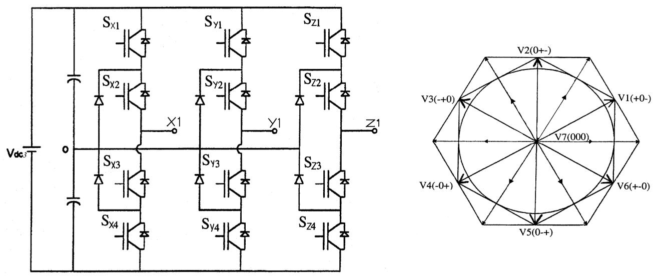


Fig. 2. The first inverter **INV1** of the first **INV1 + INV2** section in Fig. 1.



A) B)

Fig. 3. Neutral-point-clamped converter **INV3** of the second converter section **INV3 + INV4** in Fig. 1 (A), and its voltage space vectors (B).

TABLE I
BASIC FEATURES OF METHODS OF VECTOR MODULATION

Basic parameters and functions	**Classical schemes of space-vector PWM**	**Method of synchronized space-vector modulation**	
Operating and max parameter	Operating & max voltage V and V_m	Operating & maximum fundamental frequencies F and F_m	
Modulation index m	V/V_m	F/F_m	
Duration of sub-cycles	A. T	τ	
Center of the k-signal	α_k (angles/degr.)	$\tau(k-1)$ (sec)	
Switch-on durations		Algebraic PWM	Trigonomet-ric PWM
	$T_{ak}=1.1mT[\sin(60^0-\alpha_k)+\sin\alpha_k]$	$\beta_k=\beta_1[1-A\times(k-1)\tau F K_{ov1}]$	$\beta_k=\beta_1\times\cos[(k-1)\tau K_{ov1}]$
	$t_{ak}=1.1mT\sin\alpha_k$	$\gamma_k=\beta_{i-k+1}[0.5-6(i-k)\tau F]K_{ov2}$	$\gamma_k=\beta_{i-k+1}[0.5-0.9tn(i-k)\tau]K_{ov2}$
	$t_{bk}=1.1mT\times\sin(60^0-\alpha_k)$	$\beta_k-\gamma_k$	$\beta_k-\gamma_k$
Switch-off durations	$t_{0k}=T-t_{ak}-t_{bk}$	$\lambda_k=\tau-\beta_k$	
Durations of pulses and notches at the boundaries of clock-intervals		$\beta''=\beta_1[1-A\times(k-1)\tau F K_{ov1}]K_s$ $\lambda'=(\tau-\beta'')\times K_{ov1}K_s$	$\beta''=\beta_1\times\cos[(k-1)\tau K_{ov1}]K_s$ $\lambda'=(\tau-\beta'')\times K_{ov1}K_s$

In accordance with other specific peculiarity of this specialized scheme of space-vector PWM, special notch-signals λ' together with the neighboring active β''-signals (see Table I) are generated near the clock-points (0^0, 60^0, 120^0..) of the period of the fundamental frequency. Its widths are reduced simultaneously until close to zero value at the boundary frequencies F_i between control sub-zones. It allows providing voltage waveform symmetries and smooth pulses ratio changing during adjustment of the system. Each boundary frequency F_i is determined as a function of duration of sub-cycles τ in accordance with (1), and the neighboring F_{i-1} - from (2). Index i is equal here to number of notches inside a half of the 60^0-clock-intervals and is calculated from (3), where fraction should be rounded off to the nearest higher integer:

$$F_i = 1/[6(2i-K_1)\tau] \quad (1)$$

$$F_{i-1} = 1/[6(2i-K_2)\tau] \quad (2)$$

$$i = (1/6F + K_1\tau)/2\tau, \quad (3)$$

where (for conventional three-phase converter): $K_1=1$, $K_2=3$ for continuous synchronized PWM, $K_1=1.5$, $K_2=3.5$ for discontinuous synchronized modulation [11].

For NPC converters (Fig. 3) it is rational to use specialized control scheme, based on the use of only seven voltage vectors marked by the big arrows in Fig. 3, and it can provide elimination of undesirable common-mode voltages in drive system [12]. In particular, in this case it is possible to use one dc-source (instead of two separated dc-sources) for the second converter section **INV3 + INV4** of six-phase system.

III. SYNCHRONOUS OPERATION OF HYBRID FOUR-INVERTER-BASED DRIVE SYSTEM

Four converters of dual three-phase drive system (Fig. 1) are grouped into two sections with two cascaded converters in each section. Each converter section is connected with the corresponding open-end windings of dual three-phase ac machine. Symmetrical adjustment of the output voltage of each converter of each converter section by algorithms of synchronized modulation insures synchronized symmetrical regulation of voltage in open-end phase windings of six-phase induction motor. It is necessary also to provide the corresponding phase shift between voltage waveforms of two converters in each converter section, which should be equal to ½ of the switching sub-cycle τ [13].

For the first converter section **INV1 + INV2,** which includes two voltage source converters (Figs. 1 and 2), with two insulated dc-links V_{dc1} and V_{dc2}, the phase voltage V_{as} is determined by (4)-(5) [14]:

$$V_{01} = 1/3(V_{a10} - V_{a20} + V_{b10} - V_{b20} + V_{c10} - V_{c20}) \quad (4)$$

$$V_{as} = V_{a10} - V_{a20} - V_{01} \quad (5)$$

where V_{a10}, V_{b10}, V_{c10}, V_{a20}, V_{b20}, V_{c20} are pole voltages of the first converter section, V_{01} is zero sequence voltage.

For the second converter section **INV3 + INV4**, which includes two neutral-point-clamped converters adjusted by specialized algorithm allowing cancellation of zero sequence voltage (Figs. 1 and 3, it is necessary to mention, that the use of this control strategy insures two-level operation of NPC converters), the phase voltage V_{xs} is determined by (6) [12]:

$$V_{xs}=V_{x10} - V_{x20} \qquad (6)$$

where V_{x10} and V_{x20}, (and also V_{y10}, V_{z10}, V_{y20}, V_{z20}) are pole voltages of the second neutral-point-clamped converter section (Fig. 1).

A. Synchronized PWM for System with Four DC-Sources

To illustrate operation of combined topology of six-phase drive on the base of two standard converters and two NPC converters with four dc-links with non-equal dc-voltages ($V_{dc2}=0.5V_{dc1}$, $V_{dc4}= 0.5V_{dc3}$, $V_{dc1}=2V_{dc3}=V_{dc}=1$), controlled by various techniques of synchronized PWM [11],[12], Figs. 4 – 11 show, as a result of MATLAB-simulation, basic voltage waveforms (pole voltages V_{a10}, V_{a20}, V_{x10}, V_{x20},, common-mode voltage V_0, and the phase voltages V_{as} and V_{xs} (with harmonic composition of the V_{as} and V_{xs} voltages)) of two sections of converters (**INV1 + INV2** and **INV3 + INV4**) controlled by algorithms of synchronized PWM.

The fundamental and average switching frequencies of each converter are equal to $F=40Hz$ and $F_s=1kHz$, modulation indices of all converters are equal to $m_1=m_2=m_3=m_4=0.8$ ($V_{dc}=V_{dc1}= 2V_{dc3}=1$ in Figs. 4-11).

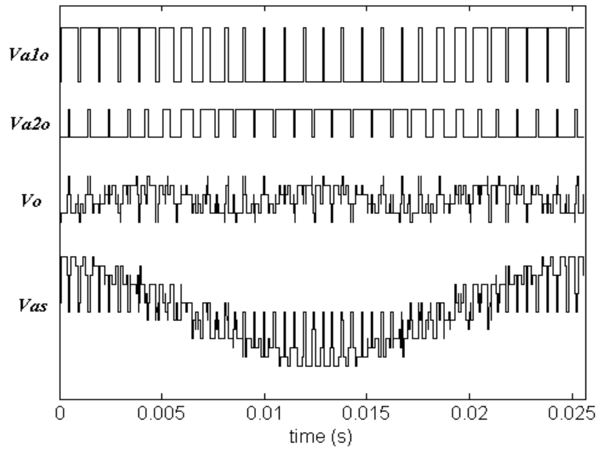


Fig. 4. Basic voltage waveforms of the first **INV1 + INV2** converter section with continuous synchronized PWM ($F=40Hz$, $F_s=1kHz$, $V_{dc2}=0.5V_{dc1}$, $m_1=m_2=0.8$).

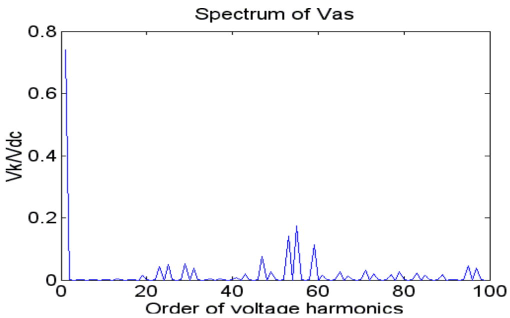


Fig. 5. Harmonic composition of the V_{as} voltage of the first **INV1 + NV2** converter section with continuous synchronized PWM ($F=40Hz$, $F_s=1kHz$).

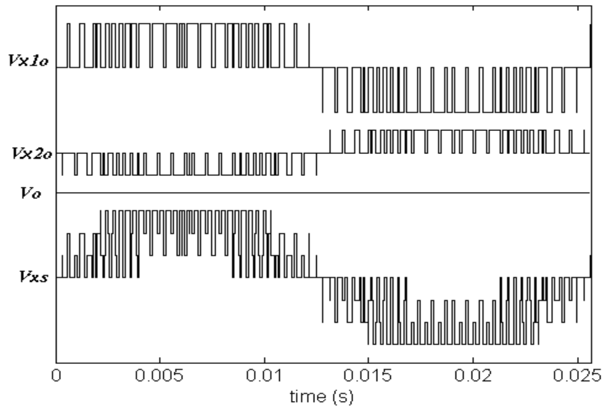


Fig. 6. Basic voltage waveforms of the second **INV3 + INV4** NPC converter section with discontinuous synchronized PWM ($F=40Hz$, $F_s=1kHz$, $V_{dc4}= 0.5V_{dc3}$, $m_3=m_4=0.8$).

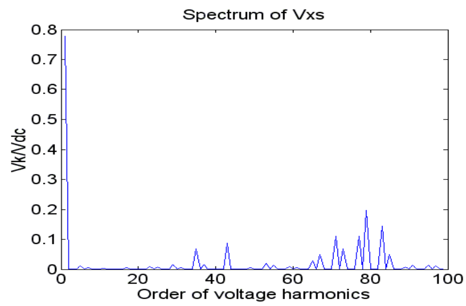


Fig. 7. Harmonic composition of the V_{xs} voltage of the second **INV3 + INV4** converter section with discontinuous synchronized PWM ($F=49Hz$, $F_s=1kHz$).

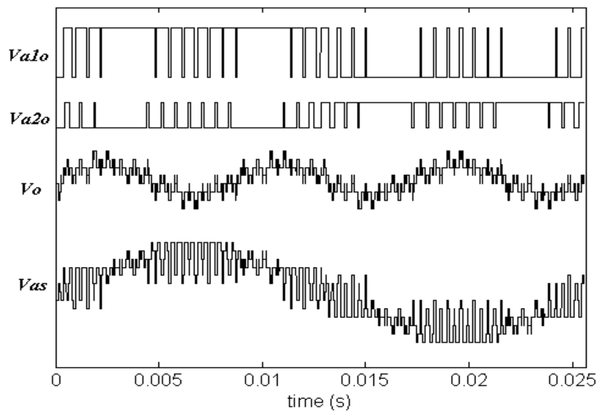


Fig. 8. Basic voltage waveforms of the first **INV1 + INV2** converter section with discontinuous synchronized PWM ($F=40Hz$, $F_s=1kHz$, $V_{dc2}= 0.5V_{dc1}$, $m_1=m_2=0.8$).

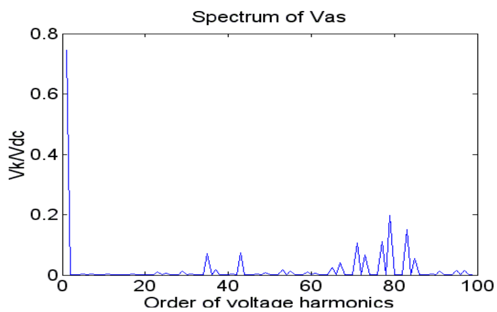


Fig. 9. Harmonic composition of the V_{as} voltage of the first **INV1 + INV2** converter section with discontinuous synchronized PWM ($F=40Hz$, $F_s=1kHz$).

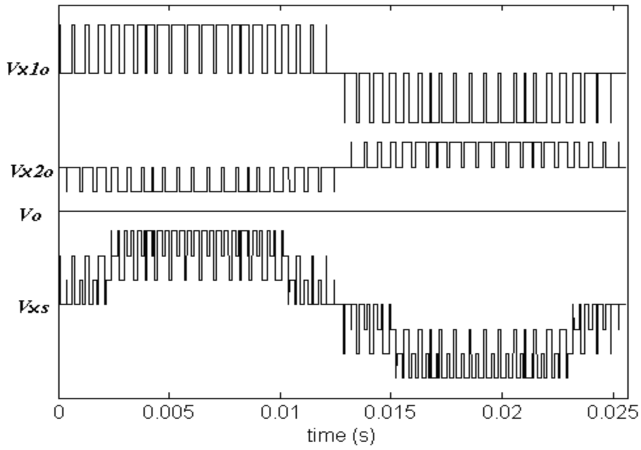


Fig. 10. Basic voltage waveforms of the second **INV3 + INV4** NPC converter section with continuous synchronized PWM (*F=40Hz*, F_s*=1kHz*, $V_{dc4}= 0.5V_{dc3}$, $m_3=m_4=0.8$).

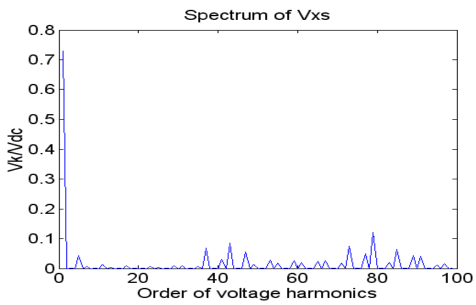


Fig. 11. Harmonic composition of the V_{xs} voltage of the second **INV3 + INV4** converter section with continuous synchronized PWM (*F=40Hz*, F_s*=1kHz*).

B. Synchronized PWM of Drive System with Two DC-Links

It is known, that in dual (cascaded) inverters with eliminated common-mode voltage (in particular, in dual NPC converters of the second converter section **INV3 + INV4** of six-phase drive (Figs. 1,3)) it is possible to use only one dc-source for supply of two inverters of cascaded system [12].

Also, special control strategy can insure elimination of the common-mode voltage in cascaded system on the base of two standard inverters. Fig. 12 shows the corresponding scheme (voltage vectors) applied for control of dual-inverter topology, standard definition of voltage vectors of each three-phase converter of this dual-inverter system has been used here [15].

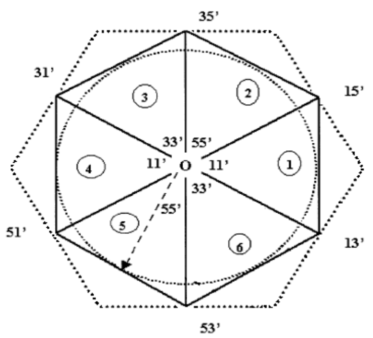


Fig. 12. Switching state sequences (voltage space-vectors) of the specific scheme of PWM control of dual inverters [15].

So, specific combinations of switching state sequences, presented in Fig. 12, allow preventing generation of common-mode voltages by the corresponding inverters. And this useful property of the presented control scheme can be used for PWM control of inverters of the first **INV1+ INV2** converter section of six-phase drive, presented in Fig. 1.

Fig. 13 shows switching state sequence, pole voltages V_{a1} and V_{a2} of the phase ***a*** of the inverters **INV1** and **INV2** (Fig. 1), and the phase voltage of the system $V_{as}=V_{a1}-V_{a2}$, controlled by continuous scheme of synchronized PWM. Fig. 14 presents the corresponding signals of dual inverters controlled by algorithms of discontinuous synchronized PWM (*F=40Hz* and F_s*=650Hz* in these cases).

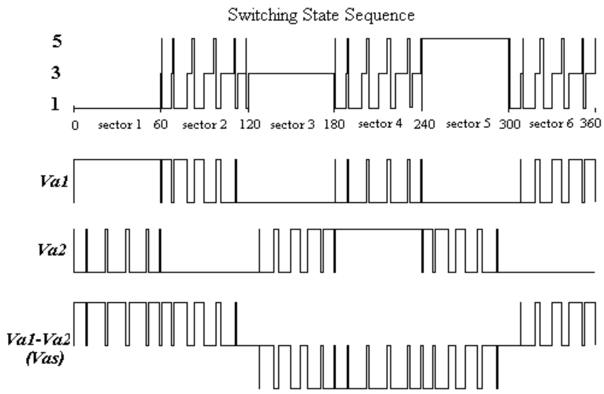


Fig. 13. Switching state sequence and basic voltage waveforms on the period of the fundamental frequency of the first **INV1 + INV2** converter section controlled by specialized algorithms of continuous synchronized PWM.

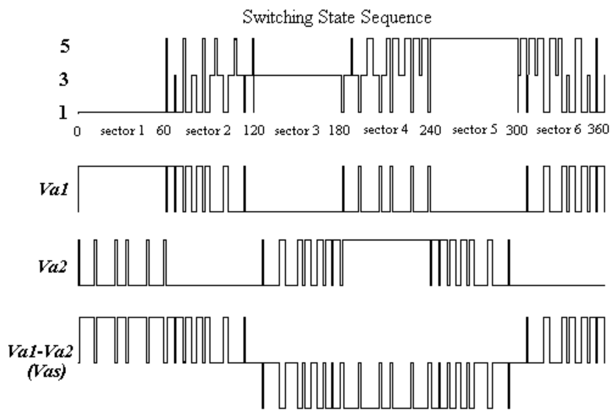


Fig. 14. Switching state sequence and basic voltage waveforms on the period of the fundamental frequency of the first **INV1 + INV2** converter section controlled by algorithms of discontinuous synchronized PWM.

Figs. 15-22 present, as a result of MATLAB-simulation, basic voltage waveforms (pole voltages V_{a1}, V_{a2}, V_{x1}, V_{x2},, common-mode voltage V_0, line voltage V_{a1b1}, and phase voltages V_{as} and V_{xs} (with spectral composition of the V_{as} and V_{xs} voltages)), of the corresponding sections of converters of six-phase drive with two dc-sources (**INV1 + INV2** section is supplied by V_{dc1}, and **INV3 + INV4** section is supplied by V_{dc3} (Fig. 1), $V_{dc}=V_{dc1}=V_{dc3}$), controlled by algorithms of specialized schemes of synchronized PWM, insuring elimination of the common-mode voltage.

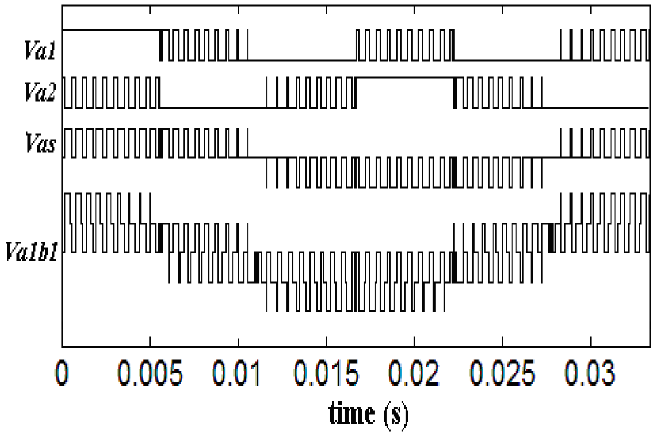


Fig. 15. Basic voltage waveforms of the first **INV1 + INV2** converter section controlled by specialized scheme of continuous synchronized PWM (*F=30Hz*, $V_{dc1}=V_{dc2}$, $m_1=m_2=0.6$, $F_s=1kHz$).

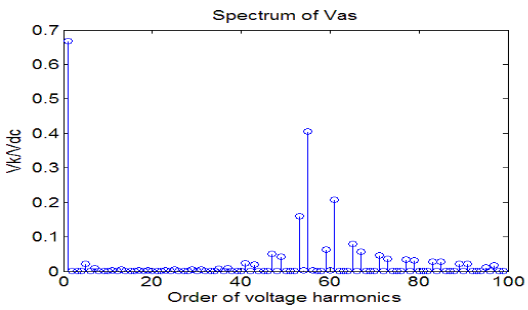


Fig. 16. Spectral composition of the V_{as} voltage of the first **INV1+INV2** sec-tion controlled by specialized scheme of continuous PWM (*F=30Hz*, *m=0.6*).

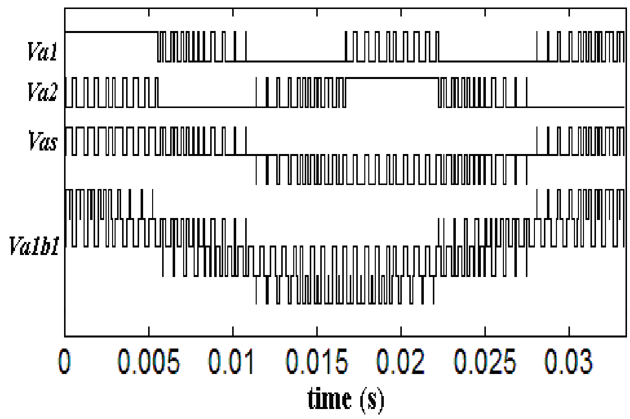


Fig. 17. Basic voltage waveforms of the first **INV1 + INV2** converter section controlled by specialized scheme of discontinuous synchronized PWM (*F=30Hz*, $V_{dc1}=V_{dc2}$, $m_1=m_2=0.6$, $F_s=1kHz$).

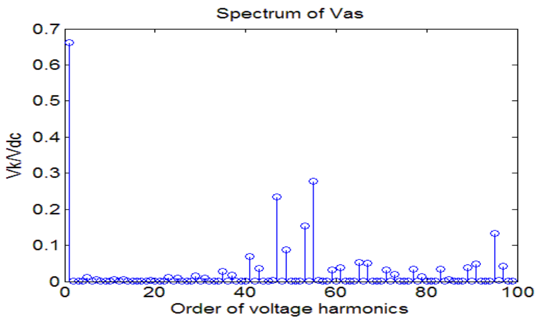


Fig. 18. Spectral composition of the V_{as} voltage of the first **INV1+INV2** converter section controlled by specialized scheme of discontinuous PWM (*F=30Hz*, *m=0.6*).

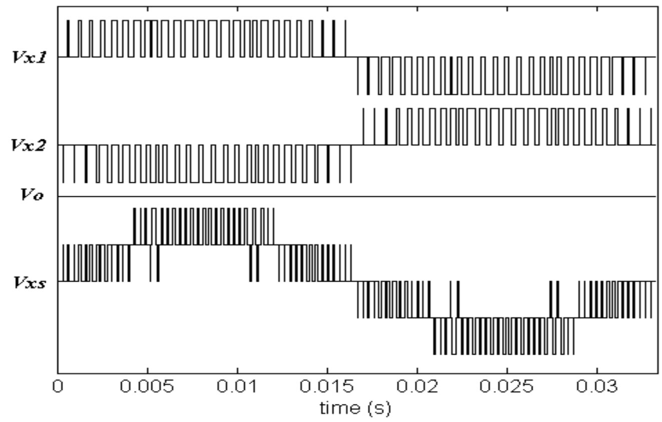


Fig. 19. Basic voltage waveforms of the second **INV3 + INV4** NPC converter section controlled by specialized scheme of continuous synchronized PWM (*F=30Hz*, $V_{dc3}=V_{dc4}$, $m_3=m_4=0.6$, $F_s=1kHz$).

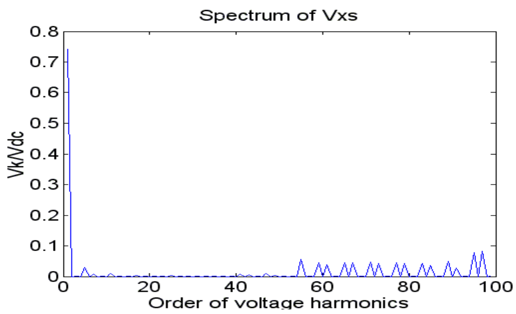


Fig. 20. Spectral composition of the V_{xs} voltage of the second **INV3 + INV4** NPC converter section controlled by specialized scheme of continuous PWM (*F=30Hz*, *m=0.6*).

The presented spectrograms illustrate the fact, that spectra of the phase voltages of dual three-phase system contain only odd (non-triplen) harmonics. So, even voltage harmonics and sub-harmonics are eliminated in spectra of the phase voltage of six-phase drives with synchronized PWM.

As an illustration of synchronous control of six-phase system at higher fundamental frequencies, Fig. 23 shows symmetrical voltage waveforms of the first converter section **INV1 + INV2,** controlled by algorithms of discontinuous synchronized PWM, operating in the overmodulation zone (*F=48Hz*, *m=0.96*).

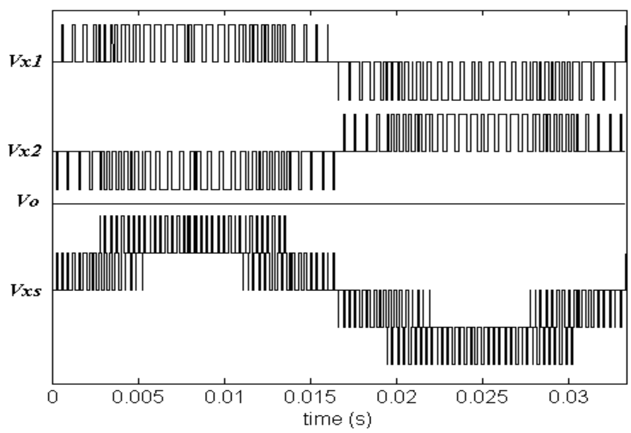


Fig. 21. Basic voltage waveforms of the second **INV3 + INV4** NPC converter section controlled by specialized scheme of discontinuous synchronized PWM (*F=30Hz*, $V_{dc3}=V_{dc4}$, $m_3=m_4=0.6$, $F_s=1kHz$).

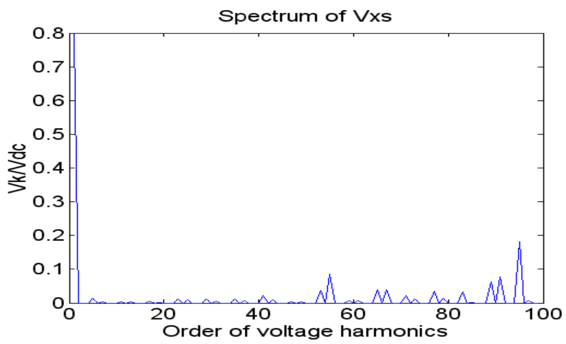


Fig. 22. Spectral composition of the V_{xs} voltage of the second **INV3 + INV4** NPC converter section controlled by specialized scheme of discontinuous PWM (*F=30Hz, m=0.6*).

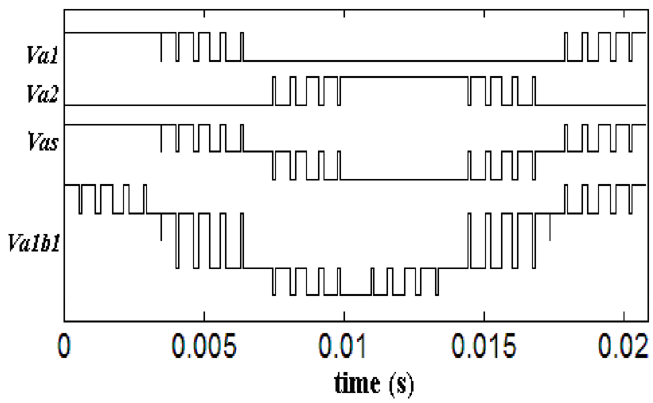


Fig. 23. Basic voltage waveforms of the first **INV1 + INV2** converter section controlled by specialized scheme of discontinuous synchronized PWM in the overmodulation zone (*F=48Hz*, $V_{dc1}=V_{dc2}$, $m_1=m_2=0.96$, $F_s=1kHz$).

IV. CONCLUSION

Multi-inverter and multiphase power converters and drives have additional degrees of freedom for construction of system structure, and for the choice of modulation schemes and algorithms for control of converters of these systems. Combined (non-uniform) topologies of converter part of multiphase drives can be an interesting alternative of existing solutions. In particular, asymmetrical four-converter-based six-phase motor drive with open-end windings can be supplied by two conventional inverters and by two neutral-clamped converters, controlled correspondingly by different (hybrid) algorithms of synchronized space-vector modulation.

It has been shown, that in combined six-phase systems symbiosis of specialized control scheme with algorithms of synchronous space-vector PWM insures elimination of the common-mode voltage and continuous symmetry of voltage waveforms during entire control region for any operating conditions, and for any (integer or fractional) ratio between the switching and fundamental frequencies of converters.

REFERENCES

[1] E. Levi, R. Bojoi, F. Profumo, H.A. Toliyat, and S. Williamson, “Multiphase induction motor drives – a technology status review,” IET Electrical Power Applications, vol. 1, no. 4, 2007, pp. 489-516.

[2] R. Bojoi, F. Farina, F. Profumo, A. Tenconi, “Dual-three phase induction machine drive control – a survey,” IEEJ Trans. on Industry Applications, vol. 126, no. 4, 2006, pp. 420-429.

[3] G. Grandi, G. Serra, and A. Tani, “General analysis of multiphase systems based on space vector approach,” Proc. 2006 IEEE-EPE Power Electronics and Motion Control Conf. (EPE-PEMC’2006), pp. 834-840.

[4] E. Levi, “Multiphase electric machines for variable speed applications,” IEEE Trans. on Industrial Electronics, vol. 55, no. 5, 2008, pp. 1893-1909.

[5] V. Oleschuk, R. Bojoi, F. Profumo, A. Tenconi, and A.M. Stankovic, “Multifunctional six-phase motor drives with algorithms of synchronized PWM” Proc. 2006 IEEE Ind. Electronics Conf. (IECON’2006), pp. 1852-1859, 2006.

[6] G.K Singh, “Multi-phase induction machine drive research – a survey,” Electric Power System Research, vol. 61, 2002, pp. 139-147.

[7] G. Grandi, A. Tani, P. Sanjeevkumar, and D. Ostojic, “Multi-phase multi-level AC motor drive based on four three-phase two-level inverters,” Proc. 2010 IEEE Int’l Symp. on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM’ 2010), pp. 1768-1775.

[8] V. Oleschuk, G. Grandi, and P. Sanjeevikumar, “Simulation of processes in dual three-phase system on the base of four inverters with synchronized modulation,” Advances in Power Electronics, vol. 2011, 2011, 9 p.

[9] G. Grandi, P. Sanjeevkumar, and D. Casadei, “Preliminary hardware implementation of a six-phase quad-inverter induction motor drive,” Proc. 2011 European Power Electronics Conf. (EPE’2011), 9 p.

[10] V. Oleschuk, R. Gregor, and F. Barrero, “Multiphase multi-inverter drive with discontinuous synchronized modulation,” Proc. 2012 EPE Power Electronics and Motion Control Conf. (EPE-PEMC’2012), pp. DS2a.8-1 - DS2a.8-6.

[11] V. Oleschuk, F. Blaabjerg, and B.K. Bose, “Analysis and comparison of algebraic and trigonometric methods of synchronous PWM for inverter drives,” Proc. 2002 IEEE Power Electronics Specialists Conf. (PESC’2002), pp. 1439-1444.

[12] V. Oleschuk, F. Profumo, A. Tenconi, R. Bojoi, and A.M. Stankovic, “Cascaded three-level inverters with synchronized space-vector modulation,” Proc. 2006 IEEE Ind. Appl. Soc. Conf. (IAS’2006), pp. 595-602.

[13] H. Stemmler and P. Guggenbach, “Configurations of high power voltage source inverter drives,” Proc. 1993 European Power Electronics Conf. (EPE’93), pp. 7-12.

[14] B.V. Reddy, V.T. Somasekhar, and Y. Kalyan, “Decoupled space-vector PWM strategies for a four-level asymmetrical open-end winding induction motor drive with waveform symmetries,” IEEE Trans. on Industrial Electronics, vol. 58, no. 11, 2011, pp. 5130-5141.

[15] M.R. Baiju, K.K. Mohapatra, R.S. Kanchan, and K. Gopakumar, “A dual two-level inverter scheme with common mode voltage elimination for an induction motor drive”, IEEE Trans. on Power Electronics, vol. 19, no. 3, 2004, pp. 794-805.