

# Multiphase Quad-Inverter System with Feedforward Synchronous PWM and Nonlinear Voltage Regulation

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**Abstract**—This manuscript presents modified scheme of synchronous space-vector modulation allowing providing nonlinear dependences between the fundamental voltage and fundamental frequency of dual three-phase open-winding ac drive with four modulated inverters. Behavior of the system with six control modes (characterized by different dc-voltages and switching frequencies of inverters) and two nonlinear Voltage/Frequency ratios has been analyzed and simulated by the means of MATLAB-software.

## I. INTRODUCTION

Multiphase and multi-inverter power conversion systems have been studied intensively during the last decade [1]-[3]. One of perspective topologies of such systems is presented in Fig. 1 structure of six-phase open-winding drive with asymmetrical induction motor, which has two sets of windings, spatially shifted by 30 el. degrees, supplied by four modulated inverters (INV1 – INV4) [4]-[9].

Standard scalar control of induction motor drives is based on the principle of constancy of ratio between the fundamental voltage and frequency. And realization of nonlinear Voltage/Frequency ( $V/F$ ) dependences of ac drives can be done by modification of scheme of synchronous space-vector PWM for control of inverters.

## II. FEATURES OF THE METHOD OF SYNCHRONIZED SPACE-VECTOR MODULATION

To insure continuous voltage symmetries and to avoid subharmonics in spectra of the output voltage of drive inverters, method of synchronized PWM has been proposed and elaborated for application in electric drives and in renewable energy systems [10]-[13]. Table I presents its basic peculiarities in comparison with conventional (classical) scheme of space-vector modulation.

In particular, the proposed scheme of synchronized PWM includes some additional control parameters (presented in the lower part of Table I). Also, special boundary frequencies  $F_i$  and  $F_{i-1}$  between control sub-zones, characterizing this PWM scheme, are calculating in accordance with (1)-(2) as function of duration of switching intervals (sub-cycles)  $\tau$ . Index  $i$  in (1)-(2) is equal in this case to number of notches inside a half of the 60°-clock-intervals, and is determined from (3), where fraction is rounded off to the nearest higher integer [10]. It has been shown in [6], that this PWM scheme can provide voltage waveform symmetries of inverters of six-phase open-winding drive with standard control modes for any magnitudes of voltages of dc sources and for different switching frequencies of inverters.

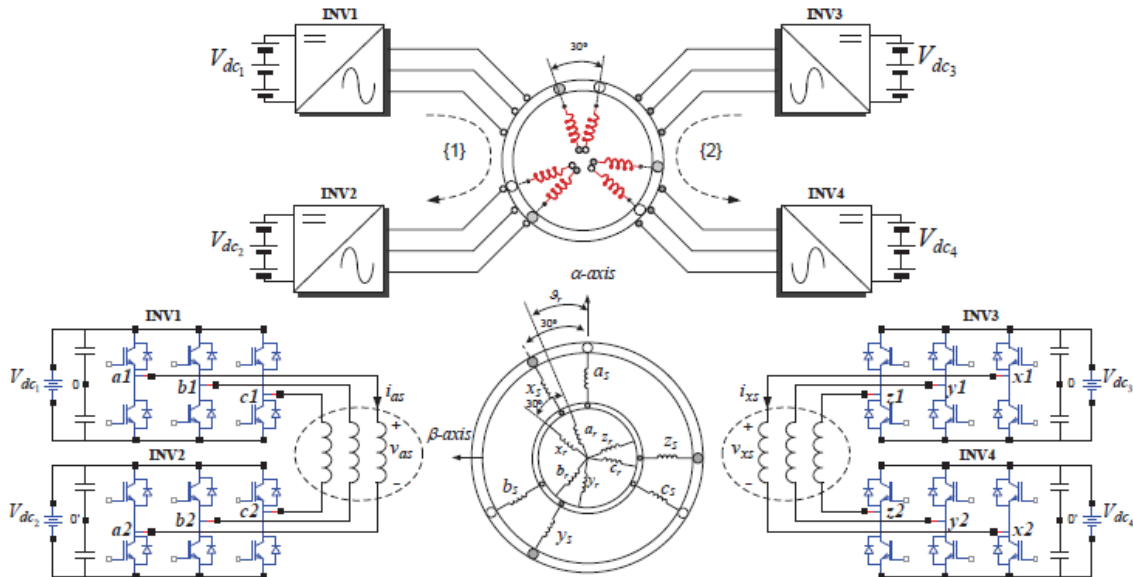


Fig. 1. Dual three-phase (six-phase) drive with open-end winding asymmetrical six-phase induction motor with two groups of two inverters (INV1+INV2, supplied by the  $V_{dc1}$  and  $V_{dc2}$  dc sources, as the first group, and INV3+INV4, supplied by the  $V_{dc3}$  and  $V_{dc4}$  dc sources, as the second group).

TABLE I. BASIC CONTROL PARAMETERS OF METHODS OF PWM

Control (modulation) parameter	Conventional schemes of space-vector PWM	Proposed method of synchronized modulation	
Operating and max parameter	Operating & max voltage $V$ and $V_m$	Operating & maximum fundamental frequency $F$ and $F_m$	
Modulation index $m$	$V/V_m$	$F/F_m$	
Duration of sub-cycles	$T$	$\tau$	
Center of the $k$ -signal	$\alpha_k$ (angles/degr.)	$\tau(k-1)$ (sec)	
Switch-on durations	$T_{ak} = 1.1mT[\sin(60^\circ - \alpha_k) + \sin \alpha_k]$ $t_{ak} = 1.1mT \sin \alpha_k$ $t_{bk} = 1.1mT \times \sin(60^\circ - \alpha_k)$	Algebraic PWM	Trigonometric PWM
		$\beta_k = \beta_1[1 - A \times (k-1)\pi F K_{ov1}]$ $\gamma_k = \beta_{1-k+1}[0.5 - 6(i-k)\pi F]K_{ov2}$ $\beta_k - \gamma_k$	$\beta_k = \beta_1 \times \cos[(k-1)\pi K_{ov1}]$ $\gamma_k = \beta_{1-k+1}[0.5 - 0.9m(i-k)\tau]K_{ov2}$ $\beta_k - \gamma_k$
Switch-off states (zero voltage)	$t_{0k} = T - t_{ak} - t_{bk}$	$\lambda_k = \tau - \beta_k$	
Special parameters providing synchronization of the process of PWM		$\beta'' = \beta_1[1 - A \times (k-1)\pi F K_{ov1}]K_s$ $\lambda' = (\tau - \beta'') \times K_{ov1}K_s$	$\beta'' = \beta_1 \times \cos[(k-1)\pi K_{ov1}]K_s$ $\lambda' = (\tau - \beta'') \times K_{ov1}K_s$

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

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

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

where  $K_1=1$ ,  $K_2=3$  for continuous PWM,  $K_1=1.5$ ,  $K_2=3.5$  for discontinuous PWM.

Realization of nonlinear  $V/F$  dependences of systems controlled by algorithms of synchronized PWM should be based on the corresponding modification of function for determination of the  $\beta_1$ -parameter of PWM scheme. Table II presents these functions (and boundary overmodulation frequencies) for three control regimes of the system, including standard scalar  $V/F=const$  regime, and also  $V^2/F=const$  and  $V^{3/2}/F=const$  control regimes. Application of nonlinear control regimes can provide effective operation of ac drives with some specific motors and loads [14]-[15].

Fig. 2 illustrates adjustment of the fundamental voltage versus fundamental frequency (with the maximum fundamental frequency  $F_{max}=50\text{Hz}$ ) for converter with three control regimes presented in Table II. Also, any intermediate modes of motor drive can also be performed in this case, with other specific  $\beta_1$  functions. As an example, the dotted line in Fig. 2 illustrates voltage control under other nonlinear dependence  $V^{4/3}/F=const$  (in this case  $\beta_1 = 1.1\sqrt[4]{m^3} \tau$ ).

TABLE II. BASIC PARAMETERS FOR LINEAR AND NONLINEAR CONTROL REGIMES

Control regime	$\beta_1$	$F_{ov1}$	$F_{ov2}$
$V/F=const$	$1.1m\tau$	$0.907F_m$	$0.952F_m$
$V^2/F=const$	$1.1\sqrt{m}\tau$	$0.823F_m$	$0.907F_m$
$V^{3/2}/F=const$	$1.1\sqrt[3]{m^2}\tau$	$0.866F_m$	$0.931F_m$

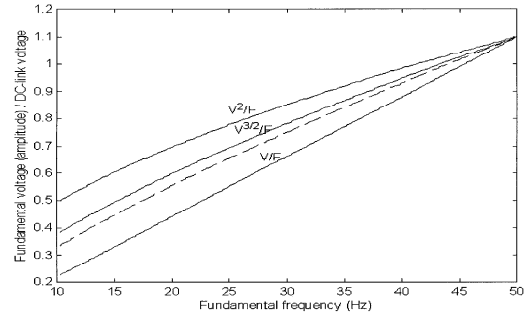


Fig. 2. Fundamental voltage as function of fundamental frequency for linear and nonlinear control of voltage source inverters.

### III. OPERATION OF DRIVE SYSTEM WITH NONLINEAR $V/F$ RATIO

Phase voltages  $V_{as}$  and  $V_{xs}$  of the first and the second groups of voltage source inverters with four insulated dc-links (Fig. 1) are calculated in accordance with (4)-(7) [6]:

$$V_{01} = 1/3(V_{a1} + V_{b1} + V_{c1} + V_{a2} + V_{b2} + V_{c2}) \quad (4)$$

$$V_{as} = V_{a1} + V_{a2} - V_{01} \quad (5)$$

$$V_{02} = 1/3(V_{x1} + V_{y1} + V_{z1} + V_{x2} + V_{y2} + V_{z2}) \quad (6)$$

$$V_{xs} = V_{x1} + V_{x2} - V_{02}, \quad (7)$$

where  $V_{a1}$ ,  $V_{b1}$ ,  $V_{c1}$ ,  $V_{a2}$ ,  $V_{b2}$ ,  $V_{c2}$  and  $V_{x1}$ ,  $V_{y1}$ ,  $V_{z1}$ ,  $V_{x2}$ ,  $V_{y2}$ ,  $V_{z2}$  are the corresponding pole voltages of each section of inverters,  $V_{01}$  and  $V_{02}$  are the corresponding zero sequence voltages of the first and the second inverter sections.

To provide approximate equivalence of the phase fundamental voltages (and also power balancing) of two sections of inverters, it is necessary to assure correlations between modulation indices of four inverters and magnitudes of the corresponding dc-links:

$$m_1 V_{dc1} + m_2 V_{dc2} = m_3 V_{dc3} + m_4 V_{dc4} \quad (8)$$

To study operation of dual three-phase system with nonlinear control regimes, six modes of operation of the system with continuous (CPWM) and discontinuous PWM (DPWM, version with the  $30^\circ$ -non-switching intervals [6],[8],[10]) have been chosen for analysis of processes in four-inverter-based system (Table III, **Modes 1-6**). In this case **INV4** has been supplied by the maximum relative dc

TABLE III. NONLINEAR REGIMES OF OPERATION OF DUAL THREE-PHASE DRIVE

Mode	$F$ , Hz	Parameter	INV1	INV2	INV3	INV4
<b>1 (DPWM)</b> $V^2/F=const$	36	$V_{dc}$	1	1	1	1
		$F_s$	1kHz	1kHz	1kHz	1kHz
<b>2 (DPWM)</b> $V^2/F=const$	37	$V_{dc}$	0.5	1	0.5	1
		$F_s$	2kHz	1kHz	2kHz	1kHz
<b>3 (DPWM)</b> $V^{3/2}/F=const$	41	$V_{dc}$	1	1	1	1
		$F_s$	1kHz	1kHz	1kHz	1kHz
<b>4 (DPWM)</b> $V^{3/2}/F=const$	39	$V_{dc}$	0.6	1	0.6	1
		$F_s$	1.7kHz	1kHz	1.7kHz	1kHz
<b>5 (CPWM)</b> $V^2/F=const$	38	$V_{dc}$	1	1	1	1
		$F_s$	1kHz	1kHz	1kHz	1kHz
<b>6 (CPWM)</b> $V^{3/2}/F=const$	42	$V_{dc}$	1	1	1	1
		$F_s$	1kHz	1kHz	1kHz	1kHz

voltage  $V_{dc4}=1$ , and dc voltages of other inverters were equal or less of  $V_{dc4}$ . Correspondingly, switching frequency of **INV4** has been chosen equal to  $F_{s4}=1kHz$ , and switching frequencies of other inverters were equal or bigger of this frequency (as inverse relationship of dc-voltages of the corresponding dc-sources).

Fig. 3 – Fig. 16 present results of MATLAB-simulation of dual three-phase system operating under nonlinear control **Modes 1-6**, it show basic voltage waveforms (normalized voltages) of open-winding drive, together with spectral composition of the phase and line voltages of the system.

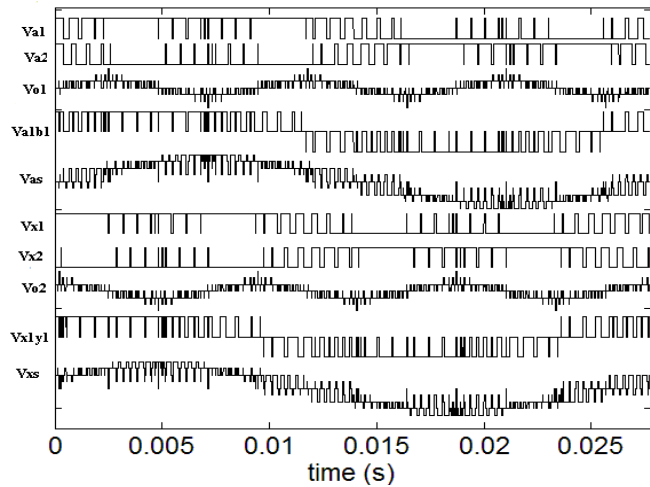


Fig. 3. Basic voltages of six-phase system with discontinuous synchronized PWM (**Mode 1**,  $V^2/F=const$ ,  $F=36Hz$ ,  $F_s=1kHz$ ).

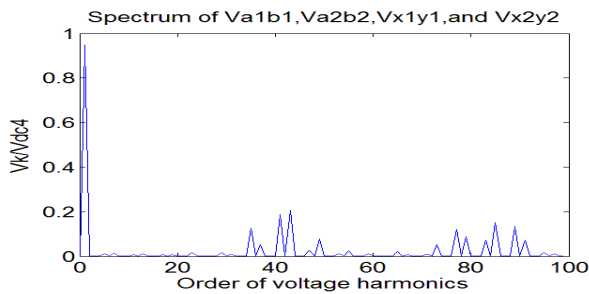


Fig. 4. Spectrum of the line voltages (**Mode 1**, DPWM,  $V^2/F=const$ ).

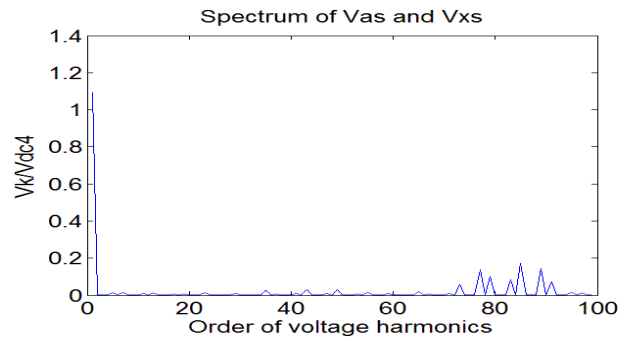


Fig. 5. Spectrum of the phase voltages (**Mode 1**, DPWM,  $V^2/F=const$ ).

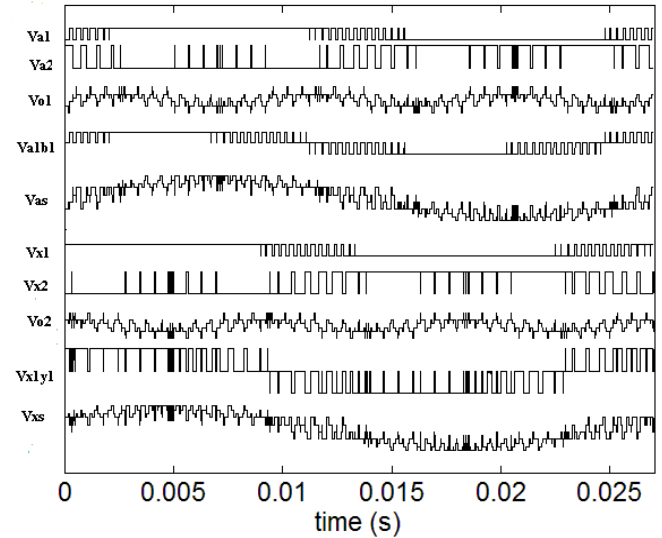


Fig. 6. Basic voltages of six-phase system with discontinuous synchronized PWM (**Mode 2**,  $V^2/F=const$ ,  $F=37Hz$ ).

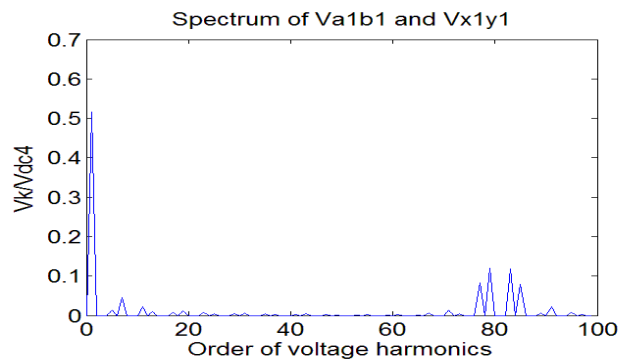


Fig. 7. Spectrum of the line voltages (**Mode 2**, DPWM,  $V^2/F=const$ ).

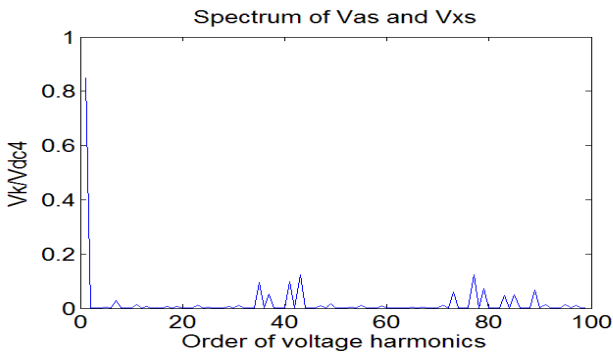


Fig. 8. Spectrum of the phase voltages (Mode 2, DPWM,  $V^2/F=const$ ).

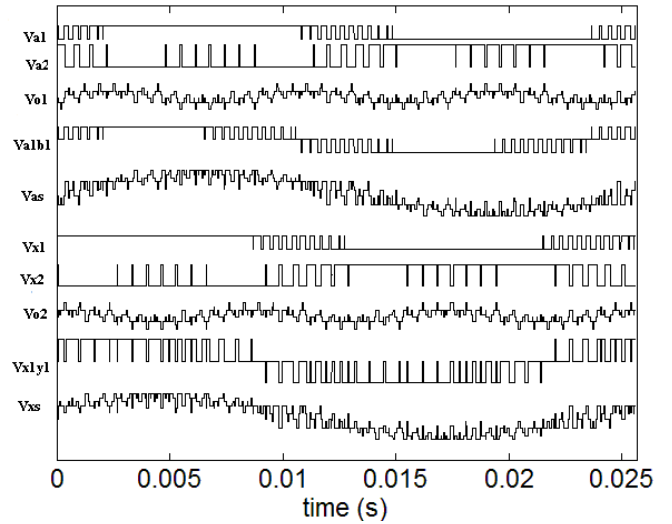


Fig. 11. Basic voltages of six-phase system with discontinuous synchronized PWM (Mode 4,  $V^{3/2}/F=const$ ,  $F=39Hz$ ).

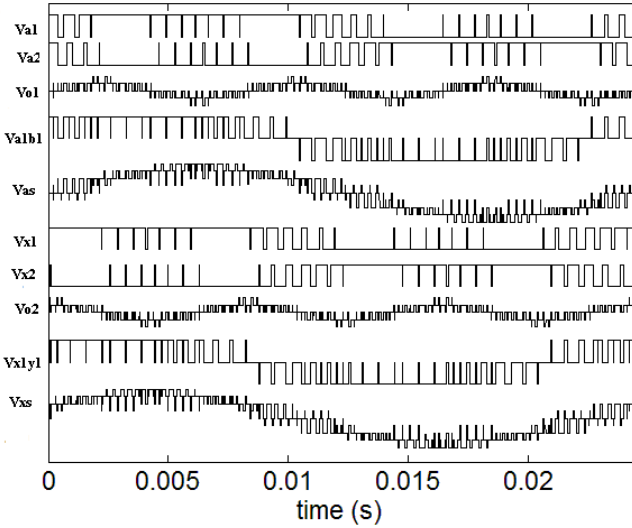


Fig. 9. Basic voltages of six-phase system with discontinuous synchronized PWM (Mode 3,  $V^{3/2}/F=const$ ,  $F=41Hz$ ,  $F_s=1kHz$ ).

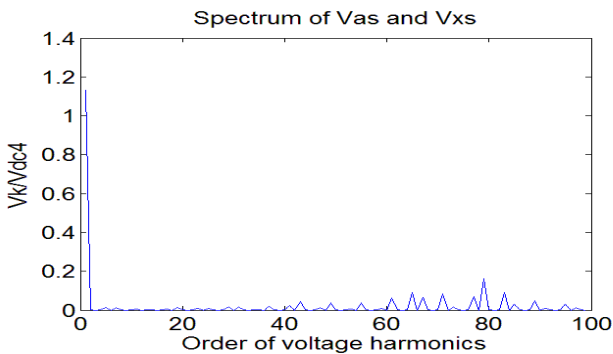
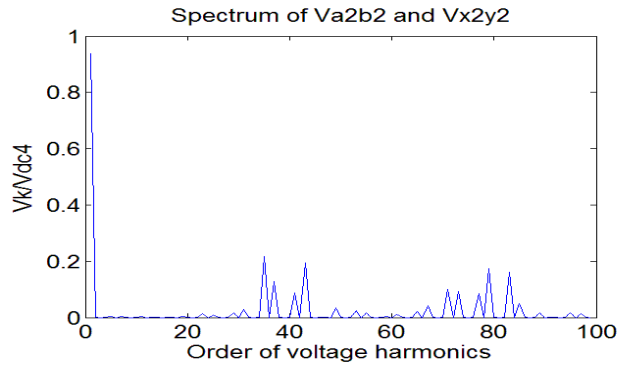
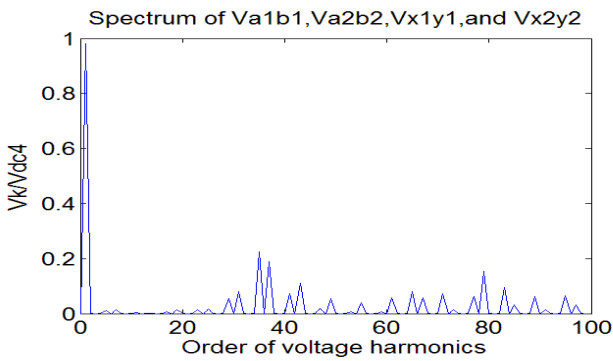
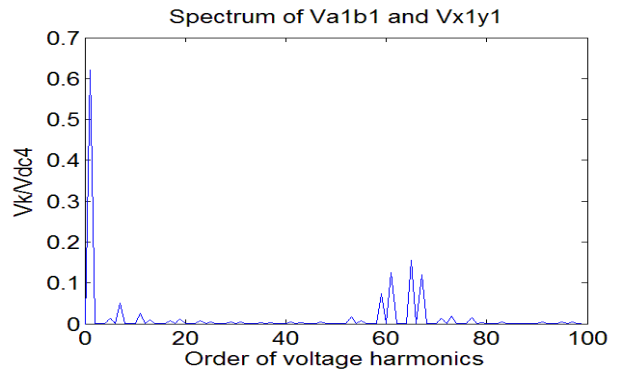


Fig. 10. Spectra of the basic voltages (Mode 3, DPWM,  $V^{3/2}/F=const$ ).

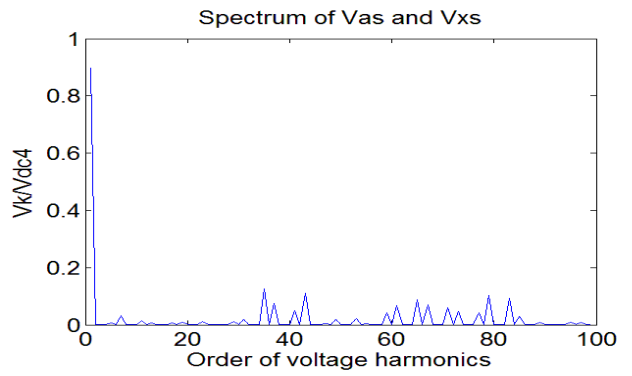


Fig. 12. Spectra of the basic voltages (Mode 4, DPWM,  $V^{3/2}/F=const$ ).

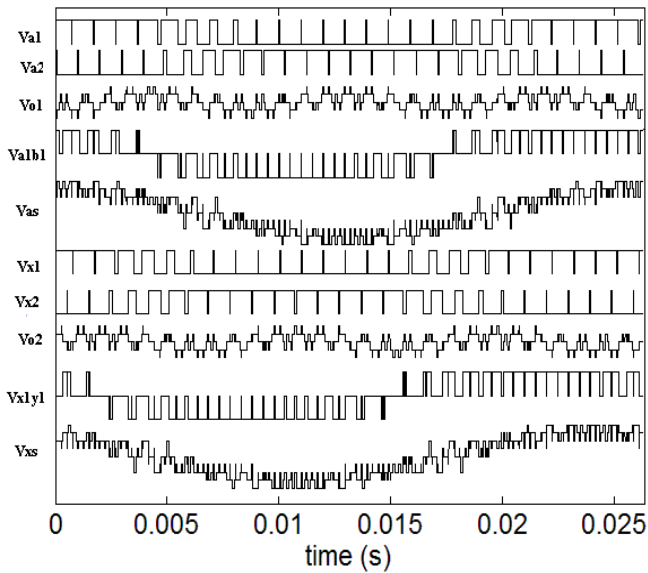


Fig. 13. Basic voltages of six-phase system with continuous synchronized PWM (Mode 5,  $V^2/F=const$ ,  $F=38Hz$ ,  $F_s=1kHz$ ).

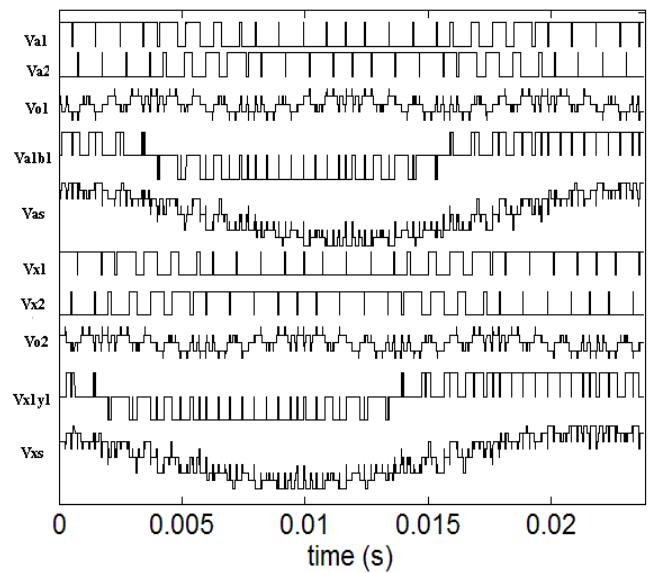


Fig. 15. Basic voltages of six-phase system with continuous synchronized PWM (Mode 6,  $V^{3/2}/F=const$ ,  $F=42Hz$ ,  $F_s=1kHz$ ).

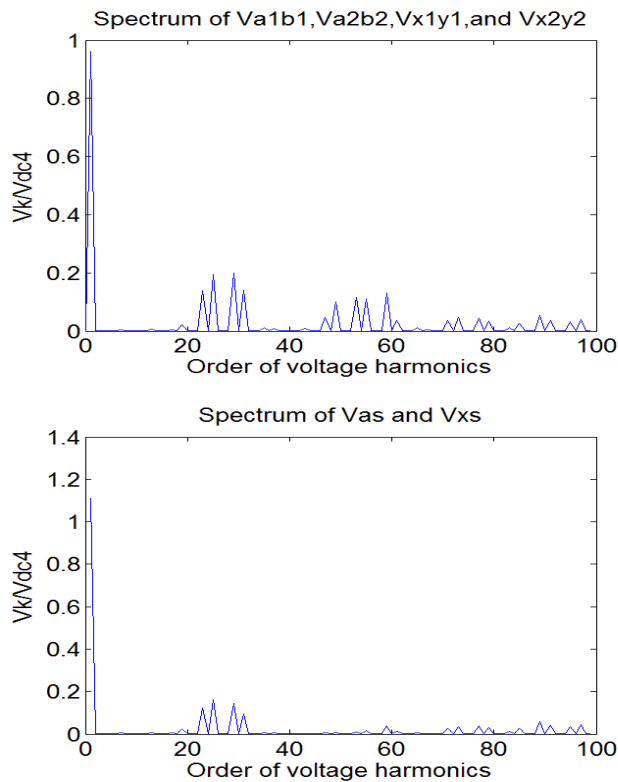


Fig. 14. Spectra of the basic voltages (Mode 5, CPWM,  $V^2/F=const$ ).

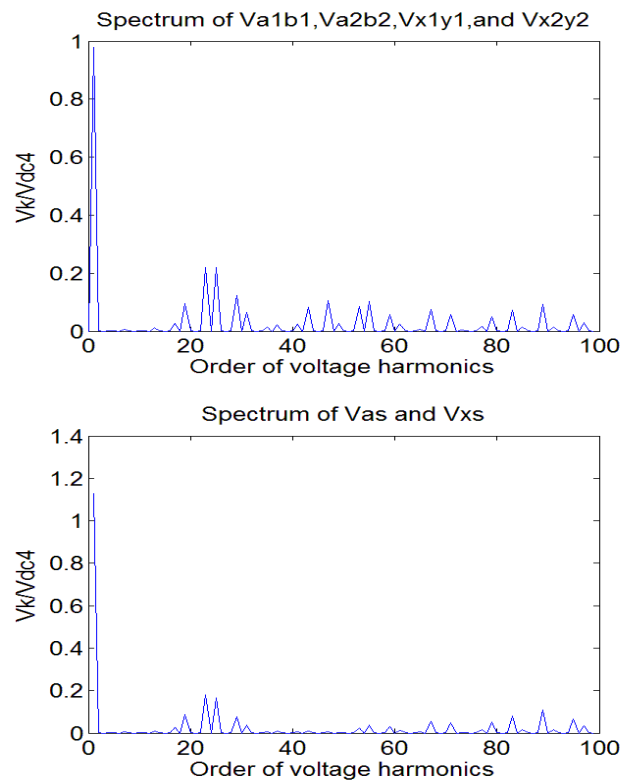


Fig. 16. Spectra of the basic voltages (Mode 6, CPWM,  $V^{3/2}/F=const$ ).

Presented in Figs. 4, 5, 7, 8, 10, 12, 14, 16 spectra of the line-to-line and phase voltages of six-phase system illustrate the fact, that in the case of nonlinear regulation of drive basic voltage waveforms are symmetrical for any operating conditions, and its spectra do not contain even harmonics and subharmonics. Factor of elimination of subharmonics from spectra of the output voltage and current is especially important for the medium-power and high-power drives [2],[16].

Calculation of Weighted Total Harmonic Distortion factor ( $WTHD = (1/V_{as1}) (\sum_{k=2}^{1000} (V_{as_k}/k)^2)^{0.5}$ ) of the phase voltage  $V_{as}$  as function of the fundamental frequency of the system ( $F_{max}=50Hz$ ) has been executed for the presented nonlinear regimes of operation of the system with average switching frequency equal to  $1kHz$ . Fig. 17 presents results

of this analysis of  $WTHD$  factor for the system with equal dc-voltages controlled by continuous (CPWM) and discontinuous (DPWM) versions of synchronous PWM, operating under  $V^2/F=const$  regimes (**Mode 1, Mode 5**), and under  $V^{3/2}/F=const$  control regimes (**Mode 3, Mode 6**).

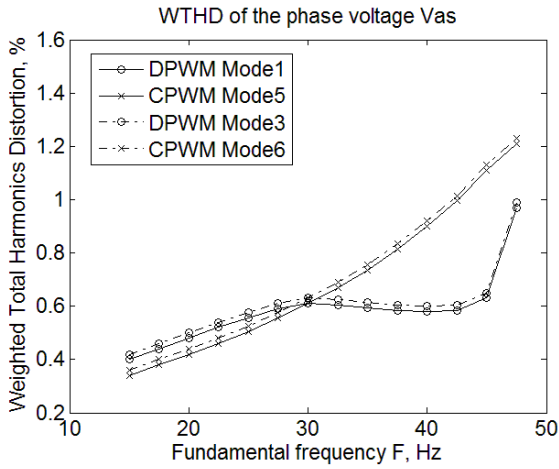


Fig. 17. WTHD factor of the phase voltage  $V_{as}$  of dual three-phase system with nonlinear regimes of operation.

#### IV. CONCLUSION

1. Method of synchronized space-vector modulation allows providing any nonlinear Voltage/Frequency dependency between the fundamental voltage and fundamental frequency of an open-loop six-phase system on the base of four PWM inverters. Required Voltage/Frequency ratio can be assured in this case by the corresponding modification of the  $\beta_1$ -parameter ( $\beta_1$ -duration of the central active switching state inside the  $60^\circ$ -clock-intervals) of the basic scheme of synchronized modulation.

2. Algorithms of both continuous and discontinuous synchronized modulation insure line and phase voltage symmetries of six-phase system with nonlinear control regimes for any ratio (integral or fractional) between the switching frequency and fundamental frequency of each inverter of the systems, supplied by equal dc-voltage (**Mode 1, Mode 3, Modes 5-6**, frequency ratios  $F_s/F$  are equal in these cases correspondingly to  $1000\text{Hz}/36\text{Hz}=27.8$ ,  $1000\text{Hz}/41\text{Hz}=24.4$ ,  $1000\text{Hz}/38\text{Hz}=26.3$ ,  $1000\text{Hz}/42\text{Hz}=23.8$ ).

3. Algorithms and schemes of synchronized space-vector modulation assure line and phase voltage symmetries of six-phase system with nonlinear control regimes for the case of different dc voltages of insulated dc-sources and different switching frequencies of inverters (**Modes 2 and 4** of operation, in this case  $V_{dc1}=0.5V_{dc4}$ ,  $F_{sINV1}=2F_{sINV4}$  (**Mode 2**), and  $V_{dc1}=0.6V_{dc4}$ ,  $F_{sINV1}=1.7F_{sINV4}$  (**Mode 4**), frequency ratios  $F_s/F$  of the first inverter are equal in these case correspondingly to  $2000\text{Hz}/37\text{Hz}=54.1$ ,  $1700\text{Hz}/39\text{Hz}=43.6$ ).

4. Presented in Figs. 4, 5, 7, 8, 10, 12, 14, 16 spectra of the line-to-line and phase voltages of six-phase system illustrate the fact, that in the case of nonlinear regulation of six-phase

drive system basic voltage waveforms are symmetrical for any operating conditions, and its spectra do not contain even harmonics and subharmonics. Factor of elimination of subharmonics from spectra of the output voltage and current is especially important for the medium-power and high-power conversion systems.

#### ACKNOWLEDGMENT

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