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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) τ. Index i in (1)-(2) is equal in this case to number of notches inside a half of the 60^0-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.

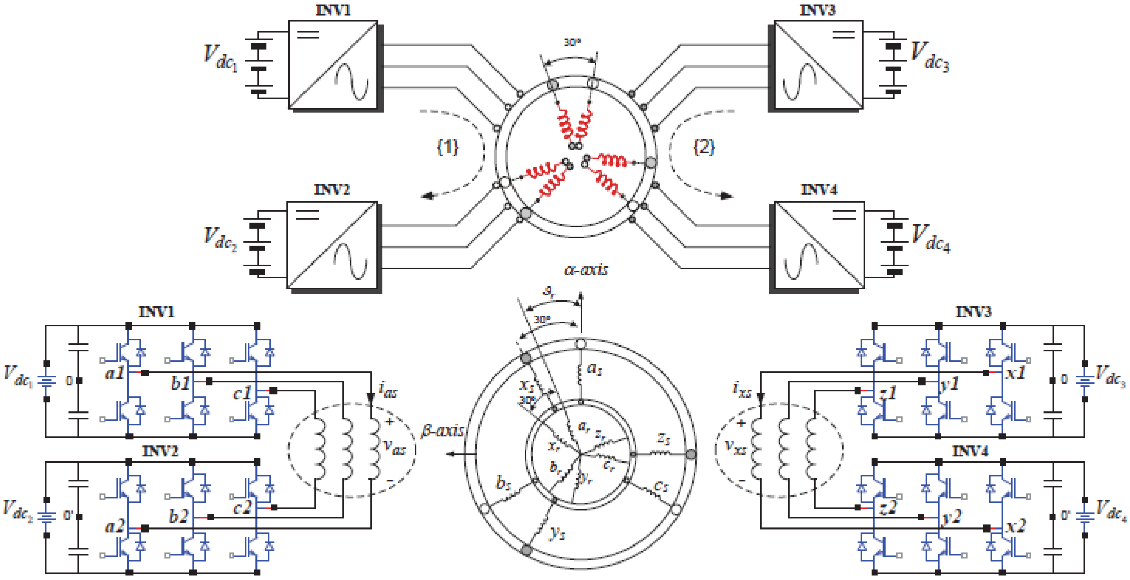

Fig. 1. Dual three-phase (six-phase) drive with open-end winding asymmetrical six-phase induction motor with two groups of two inverters (**INV1+INV2**, supplied by the V_{dc1} and V_{dc2} dc sources, as the first group, and **INV3+INV4**, supplied by the V_{dc3} and V_{dc4} dc sources, as the second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

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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	τ	
Center of the k-signal	α_k (angles/degr.)	$\tau(k-1)$ (sec)	
Switch-on durations	$T_{ak}=1.1mT[\sin(60^0-\alpha_k)+\sin\alpha_k]$ $t_{ak}=1.1mT\sin\alpha_k$ $t_{bk}=1.1mT\times\sin(60^0-\alpha_k)$	Algebraic PWM $\beta_k=\beta_1[1-A\times(k-1)\tau FK_{ov1}]$ $\gamma_k=\beta_{i-k+1}[0.5-6(i-k)\tau F]K_{ov2}$ $\beta_k-\gamma_k$	Trigonometric PWM $\beta_k=\beta_1\times\cos[(k-1)\tau K_{ov1}]$ $\gamma_k=\beta_{i-k+1}[0.5-0.9tn(i-k)\tau]K_{ov2}$ $\beta_k-\gamma_k$
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		$\beta''=\beta_1[1-A\times(k-1)\tau FK_{ov1}]K_s$ $\lambda'=(\tau-\beta'')\times K_{ov1}K_s$	$\beta''=\beta_1\times\cos[(k-1)\tau K_{ov1}]K_s$ $\lambda'=(\tau-\beta'')\times K_{ov1}K_s$

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

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

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

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 β_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 $F_{max}=50Hz$) 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 β_1 functions. As an example, the dotted line in Fig. 2 illustrates voltage control under other non-linear 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	β_1	F_{ov1}	F_{ov2}
$V/F=const$	$1.1m\tau$	$0.907F_m$	$0.952F_m$
$V^2/F=const$	$1.1\sqrt{m}\tau$	$0.823F_m$	$0.907F_m$
$V^{3/2}/F=const$	$1.1\sqrt[3]{m^2}\tau$.	$0.866F_m$	$0.931F_m$

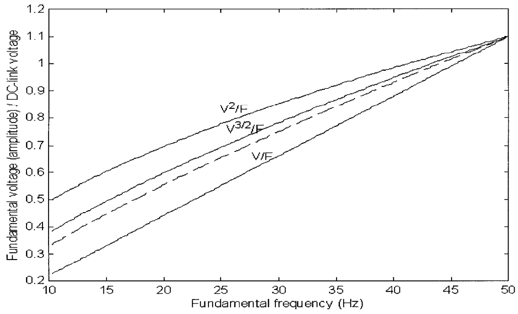

Fig. 2. Fundamental voltage as function of fundamental frequency for linear and nonlinear control of voltage source inverters.

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:

$$m_1V_{dc1}+m_2V_{dc2}=m_3V_{dc3}+m_4V_{dc4} \quad (8)$$

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 30^0-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*	Para-meter	INV1	INV2	INV3	INV4
1 (DPWM) *V^2/F=const*	*36*	V_{dc}	*1*	*1*	*1*	*1*
		F_s	*1kHz*	*1kHz*	*1kHz*	*1kHz*
2 (DPWM) *V^2/F=const*	*37*	V_{dc}	*0.5*	*1*	*0.5*	*1*
		F_s	*2kHz*	*1kH*	*2kHz*	*1kH*
3 (DPWM) *$V^{3/2}/F$=const*	*41*	V_{dc}	*1*	*1*	*1*	*1*
		F_s	*1kHz*	*1kHz*	*1kHz*	*1kH*
4 (DPWM) *$V^{3/2}/F$=const*	*39*	V_{dc}	*0.6*	*1*	*0.6*	*1*
		F_s	*1.7kHz*	*1kHz*	*1.7kHz*	*1kH*
5 (CPWM) *V^2/F=const*	*38*	V_{dc}	*1*	*1*	*1*	*1*
		F_s	*1kHz*	*1kHz*	*1kHz*	*1kHz*
6 (CPWM) *$V^{3/2}/F$=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.

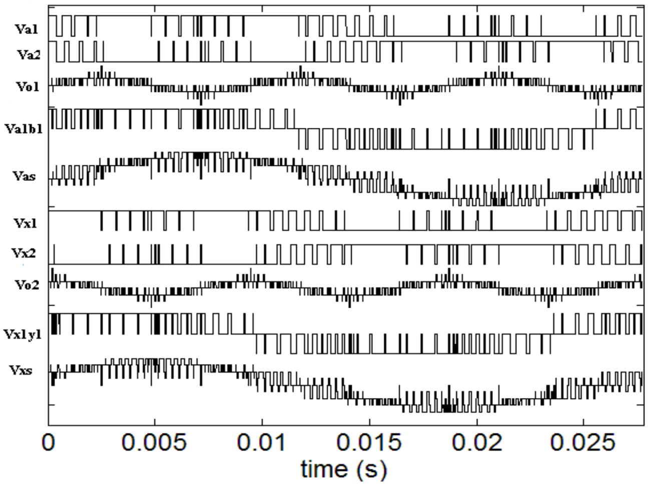

Fig. 3. Basic voltages of six-phase system with discontinuous synchronized PWM (**Mode 1**, *V^2/F=const, F=36Hz, F_s=1kHz*).

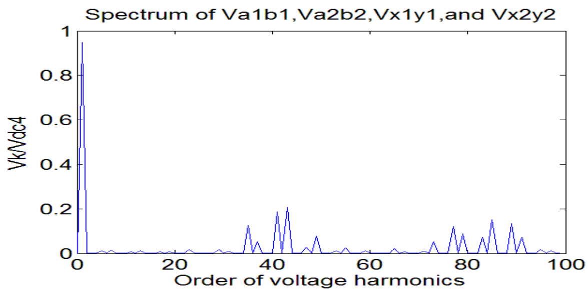

Fig. 4. Spectrum of the line voltages (**Mode 1**, DPWM, *V^2/F=const*).

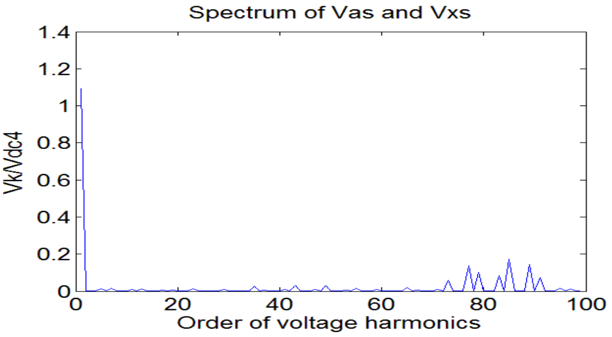

Fig. 5. Spectrum of the phase voltages (**Mode 1**, DPWM, *V^2/F=const*).

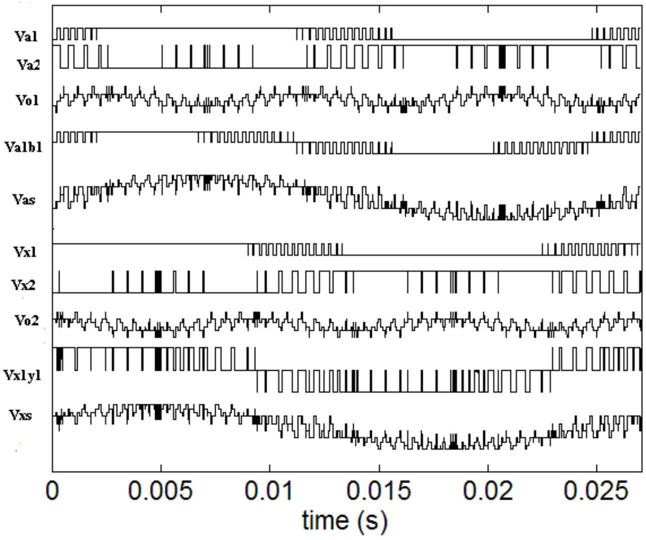

Fig. 6. Basic voltages of six-phase system with discontinuous synchronized PWM (**Mode 2**, *V^2/F=const*, *F=37Hz*).

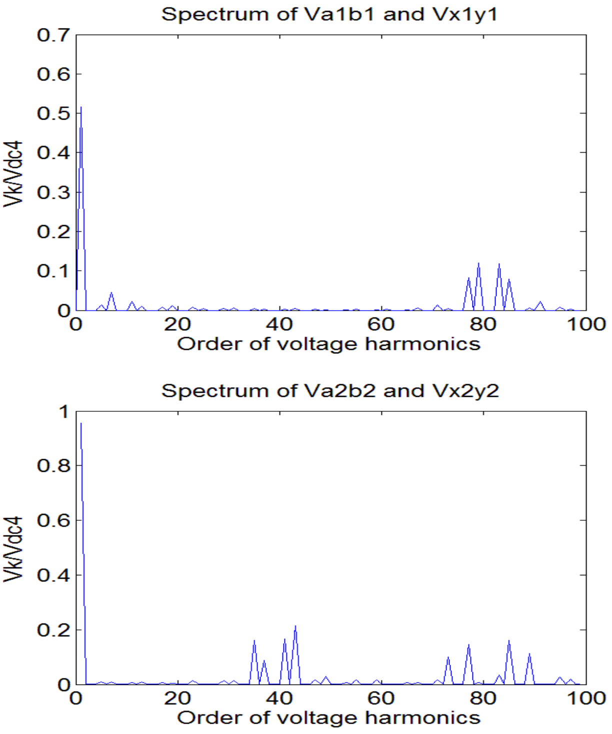

Fig. 7. Spectrum of the line voltages (**Mode 2**, DPWM, *V^2/F=const*).

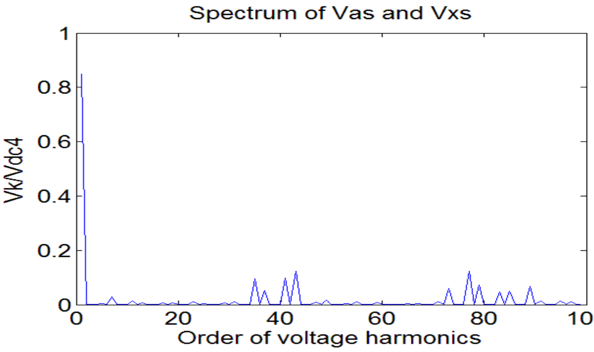

Fig. 8. Spectrum of the phase voltages (**Mode 2**, DPWM, $V^2/F=const$).

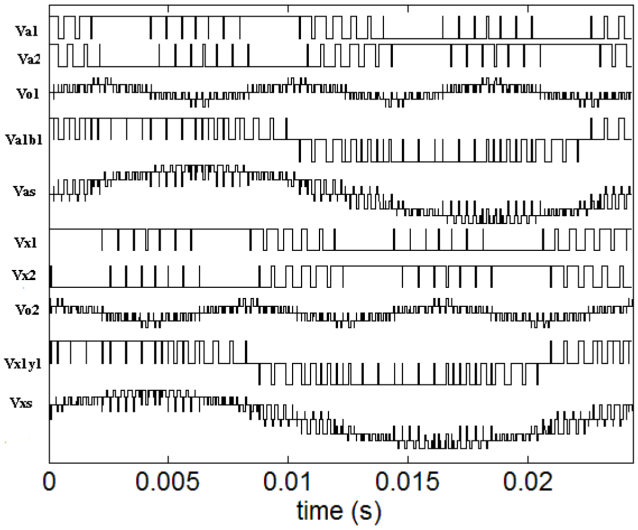

Fig. 9. Basic voltages of six-phase system with discontinuous synchronized PWM (**Mode 3**, $V^{3/2}/F=const$, $F=41Hz$, $F_s=1kHz$).

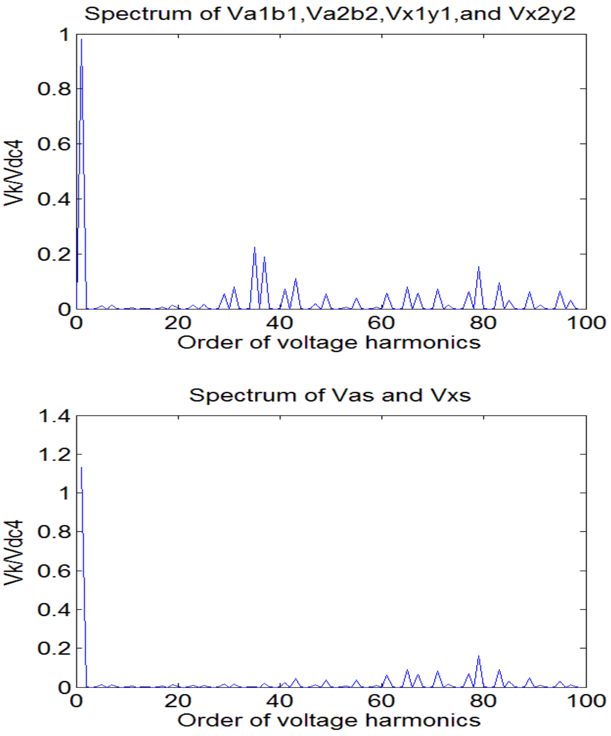

Fig. 10. Spectra of the basic voltages (**Mode 3**, DPWM, $V^{3/2}/F=const$).

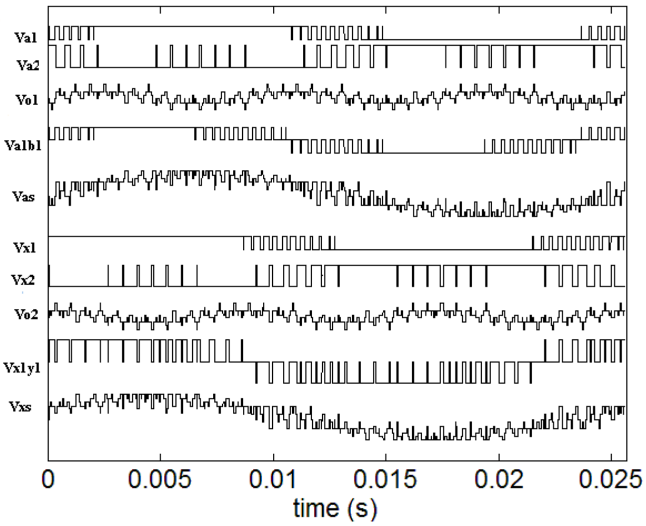

Fig. 11. Basic voltages of six-phase system with discontinuous synchronized PWM (**Mode 4**, $V^{3/2}/F=const$, $F=39Hz$).

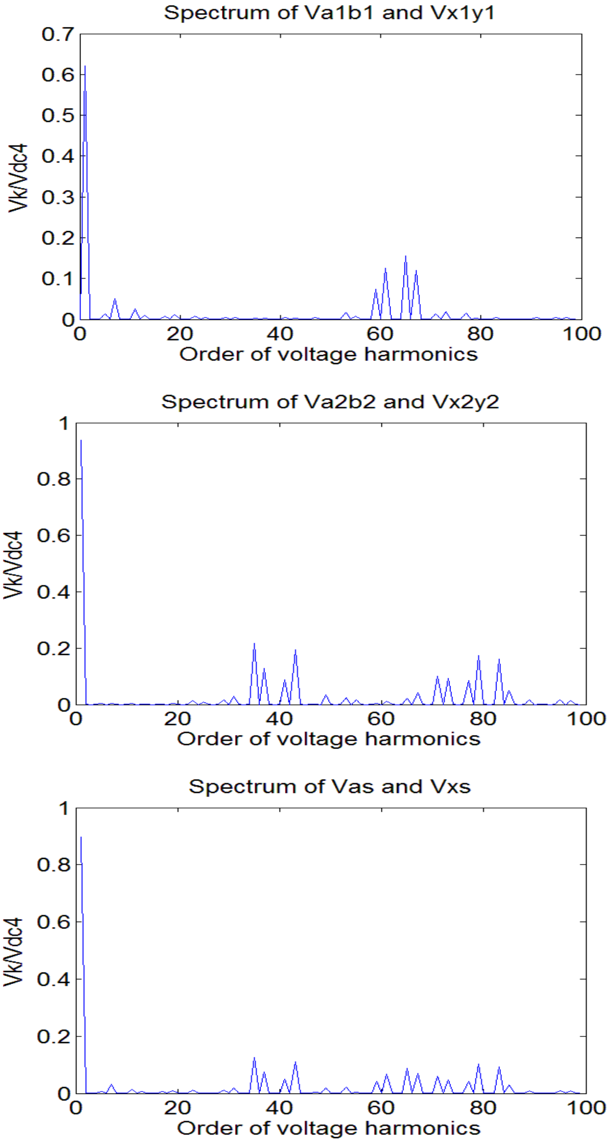

Fig. 12. Spectra of the basic voltages (**Mode 4**, DPWM, $V^{3/2}/F=const$).

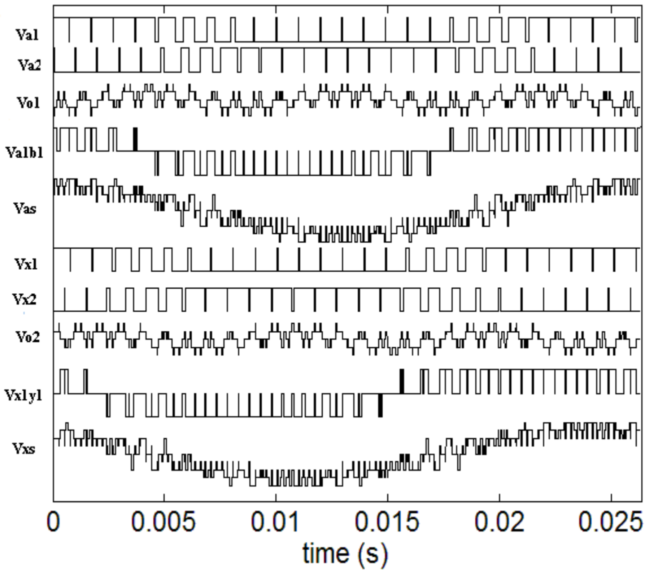

Fig. 13. Basic voltages of six-phase system with continuous synchronized PWM (**Mode 5**, $V^2/F=const$, $F=38Hz$, $F_s=1kHz$).

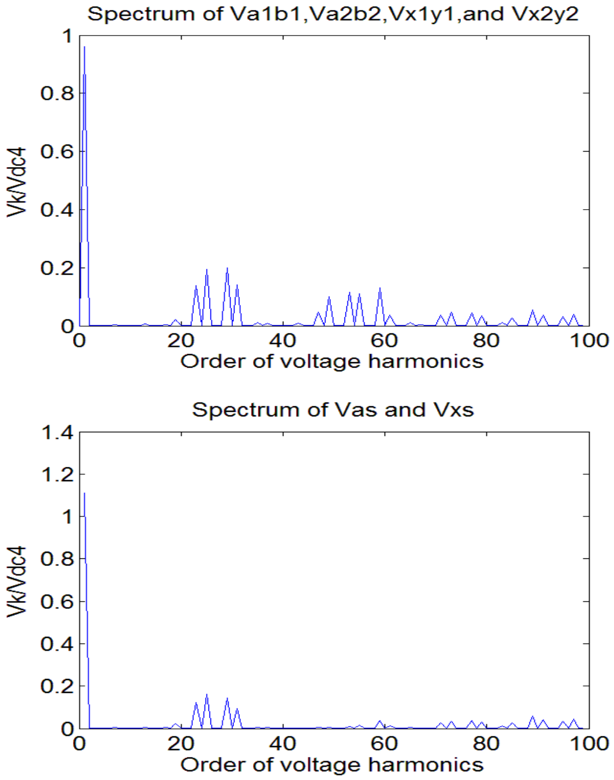

Fig. 14. Spectra of the basic voltages (**Mode 5**, CPWM, $V^2/F=const$).

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].

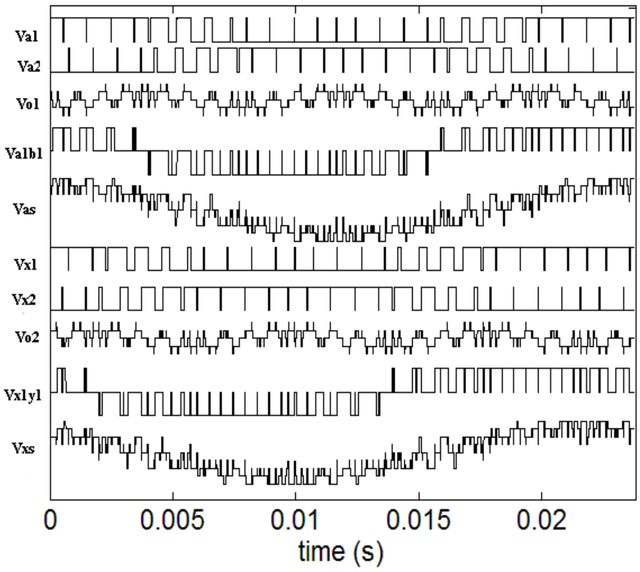

Fig. 15. Basic voltages of six-phase system with continuous synchronized PWM (**Mode 6**, $V^{3/2}/F=const$, $F=42Hz$, $F_s=1kHz$).

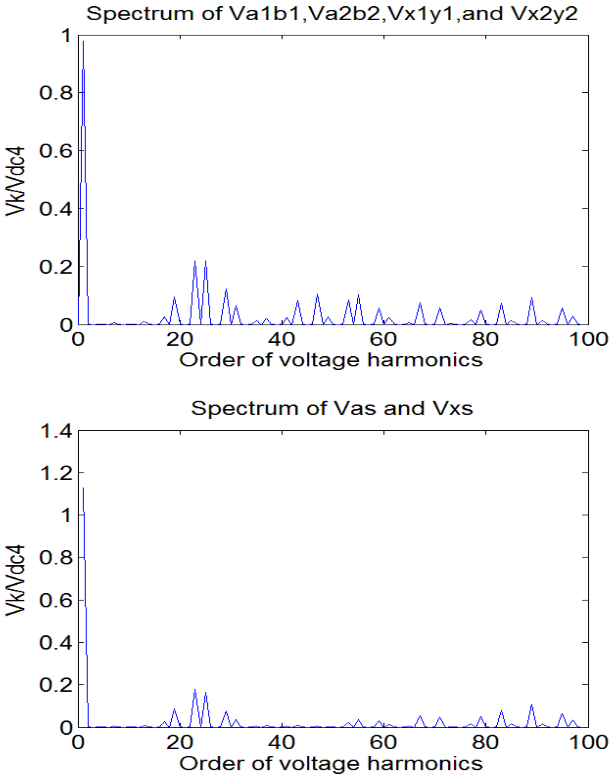

Fig. 16. Spectra of the basic voltages (**Mode 6**, CPWM, $V^{3/2}/F=const$).

Calculation of Weighted Total Harmonic Distortion factor ($WTHD=(1/V_{as_1})(\sum_{k=2}^{1000}(V_{as_k}/k)^2)^{0.5}$) 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**).

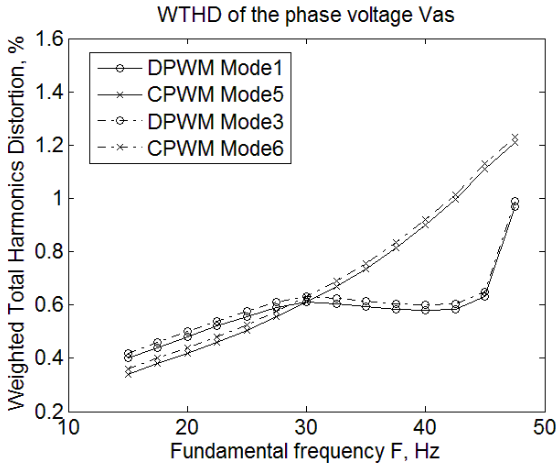

Fig. 17. WTHD factor of the phase voltage V_{as} of dual three-phase system with nonlinear regimes of operation.

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 β_1 -parameter (β_1 - duration of the central active switching state inside the 60^0-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 *1000Hz/36Hz=27.8, 1000Hz/41Hz=24.4, 1000Hz/38Hz=26.3, 1000Hz/42Hz=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 *2000Hz/37Hz=54.1, 1700Hz/39Hz=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.

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