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MULTIPHASE POWER CONVERTERS AND ELECTRIC DRIVES WITH SYNCHRONIZED PULSEWIDTH MODULATION

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Abstract – *The paper presents analysis of operation of five-phase and six-phase converters and drives, controlled by algorithms of synchronized pulsewidth modulation (PWM). Basic peculiarities of space-vector-based method of synchronized PWM have been described. It has been shown, that algorithms of synchronized modulation allow providing continuous output voltage synchronization for any operating conditions of multiphase power conversion systems.*

Keywords – *five-phase and six-phase inverters, modulation strategy, synchronization of the output voltage waveforms*

CONVERTOARE ŞI ACŢIONĂRI ELECTRICE MULTIFAZATE CU MODULAŢIE PRIN IMPULSURI DE DURATĂ VARIABILĂ DE TIP SINCRON

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Rezumat – *Această lucrarea reprezintă o analiză a funcţionării convertoarelor şi acţionări electrice cu cinci şi şase faze, dirijat în baza algoritmilor de modulaţie prin impulsuri de durata variabilă (MIDV) de tip sincron. S-au descris particularităţile de bază ale metodei MIDV vectoriale sincrone. S-a demonstrat, că algoritmii MIDV sincrone permite o sincronizare continuă a tensiunii de ieşire pentru orice condiţii de funcţionare a sistemelor de convertizoare electrice multifazate.*

Cuvinte cheie – *invertoare cu cinci şi şase faze, strategia de modulare, sincronizarea curbelor tensiunii de ieşire*

МНОГОФАЗНЫЕ ПРЕОБРАЗОВАТЕЛИ И ЭЛЕКТРОПРИВОДЫ С СИНХРОННОЙ ШИРОТНО-ИМПУЛЬСНОЙ МОДУЛЯЦИЕЙ

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Реферат – *Выполнен анализ функционирования пятифазных и шестифазных преобразователей и электроприводов, регулируемых на базе алгоритмов синхронной широтно-импульсной модуляции (ШИМ). Описаны основные особенности метода синхронной векторной ШИМ. Показано, что алгоритмы синхронной ШИМ позволяют обеспечить непрерывную синхронизацию выходного напряжения многофазных преобразовательных систем при различных режимах работы.*

Ключевые слова – *пятифазные и шестифазные инверторы, стратегия ШИМ, синхронизация выходного напряжения*

1. INTRODUCTION

Multiphase power electronic converters and ac drives are a subject of increasing interest in the last years due to some advantages compared with standard three-phase systems, especially in the field of high power/current applications. In particular, multiphase topologies of electric drives allow reduction of amplitude and increasing the frequency of torque pulsation, and also reduction of the rotor harmonic losses in electrical machines. Between different multiphase solutions the more interesting and addressed ones are the five-phase and six-phase power conversion systems [1]-[4].

In order to avoid asynchronism of standard space-vector PWM, novel space-vector-based method of synchronized PWM has been recently developed for control of five-phase inverters [5]-[6], and of symmetrical and asymmetrical six-phase converters and drives [7]-[13]. So, this paper presents analysis of operation of five-phase and six-phase power conversion systems controlled by algorithms of synchronized pulsewidth modulation.

2. STRATEGY OF CONTINUOUS OUTPUT VOLTAGE SYNCHRONIZATION IN INVERTER SYSTEMS

One of the basic ideas of the method of synchronized PWM for three-phase (and six-phase) inverters is in continuous synchronization of positions of all central control signals in the centres of the 60^0-clock-intervals, and in symmetrical generation of all other signals (together with the correspond-ding notches) around the centres of the 60^0-clock-intervals.

Correspondingly, for synchronization of the output voltage waveforms of five-phase inverters it is necessary to provide synchronization of the positions of all central active switching signals in the centres of the 36^0-clock-intervals. The schemes of synchronized PWM include also, as an important parameter, boundary frequencies F_i, transient between control sub-zones, which are situated on the axis of the fundamental frequency F of the system. Table I presents basic control functions for both three-phase (six-phase) and five-phase inverters with synchronized PWM, operated under standard *V/F* control, during linear modulation zone.

Table 1. – Basic Control Functions of Inverters with Synchronized PWM [6]

Control function	**Three-phase and six-phase inverters**	**Five-phase inverter**
Modulation index	$m = F / F_m$	
Boundary frequencies transient between control sub-zones	$F_i = \frac{1}{6(2i-1)\tau}$ $F_{i-1} = \frac{1}{6(2i-3)\tau}$	$F_i = \frac{1}{10(2i-1)\tau}$ $F_{i-1} = \frac{1}{10(2i-3)\tau}$
Coefficient of synchronization	$K_s = 1 - \frac{F - F_i}{F_{i-1} - F_i}$	
The central active switching state	$\beta_1 = 1.10 m\tau$	$\beta_1 = 1.21 m\tau$
Active switching states	$\beta_j = \beta_1 \times \cos[(j-1)\tau]$	$\beta_j = \gamma'_j + \gamma''_j + \delta'_j + \delta''_j = 1.618\beta_1 \cos[(j-1)\tau]$
Border active switching state	$\beta'' = \beta_1 \times \cos[(k-1)\tau] K_s$	$\beta'' = 1.618\beta_1 \times \cos[(k-1)\tau] K_s$
The minor part of active switching states	$\gamma_k = \beta_{i-k+1}[0.5 - 0.9\tan(i-k)\tau]$	$\delta_k' + \delta_k'' = 0.382\beta_{i-k+1}$
Switch-off states (zero voltages)	$\lambda_j = \tau - (\beta_j + \beta_{j+1})/2$	
Boundary switch-off state	$\lambda_i = \lambda' = (\tau - \beta'') K_s$	

3. FIVE-PHASE INVERTER WITH SYNCHRONIZED PWM

Basic topology of power circuit of a five-phase voltage source inverter with a star-connected load with the neutral point *n* is presented in Fig. 1 [3], [5]. In particular, in the case of a five-phase motor as a load, the five stator phases ***a***, ***b***, ***c***, ***d*** and ***e*** are distributed with a spacing of 72^0.

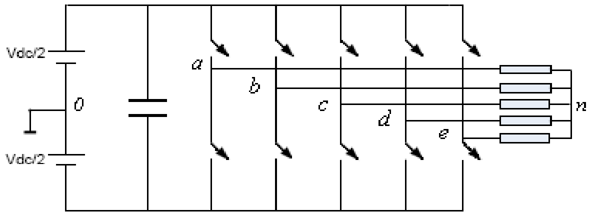


Fig. 1. Topology of a five-phase voltage source inverter [3]

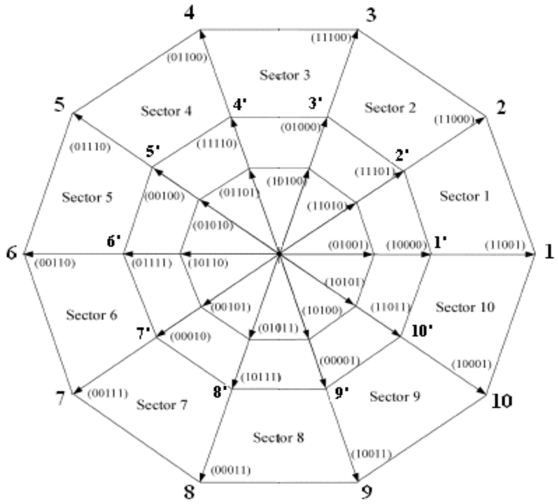


Fig. 2. Basic voltage vectors of five-phase system

Fig. 2 presents basic voltage vectors of five-phase system. In particular, Fig. 2 shows the basic ten large (**1, 2, 3, 4, 5, 6, 7, 8, 9, 10**) and ten medium (**1', 2', 3', 4', 5', 6', 7', 8', 9', 10'**) switching vectors for a five-phase inverter in accordance with conventional designation (in brackets) of switching state of every switch of the inverter, where "1" corresponds to the switch-on state of the corresponding switch of the upper group of switches of the phases ***a - e***. This control scheme includes also two zero switching states (**00000** and **11111**), providing zero voltage at the outputs of the inverter.

As an example of operation of five-phase inverter with synchronized PWM, Fig. 3 presents switching signals (pole voltages V_a - V_e) for the phases ***a – e***, line-to-line voltage V_{as} and phase-to-neutral voltage V_{an} on a period of the fundamental frequency F of inverter (*F=31Hz, m=0.62*) [5]. Fig. 4 presents spectra of the line and phase voltages. Both line-to-line and phase-to-neutral voltages of five-phase inverter with synchronized pulsewidth modulation have quarter-wave symmetry during the whole control range.

Fig. 5 and Fig. 6 show more in details switching state sequence and the pole and phase voltages of five-phase inverter for the 2nd and the 3rd control sectors [5].

In order to provide liner output voltage control of five-phase inverter in the zone of overmodulation, novel three-stage algorithm of synchronized PWM has been proposed and investigated [6]. It provides smooth transition from linear modulation range to the ten-step operation mode of five-phase system at the maximum fundamental frequency. In particular, Fig. 7 and Fig. 8 illustrate this algorithm and show basic voltage waveforms for the first (Fig. 7) and the second (Fig. 8) sub-zones of the overmodulation control.

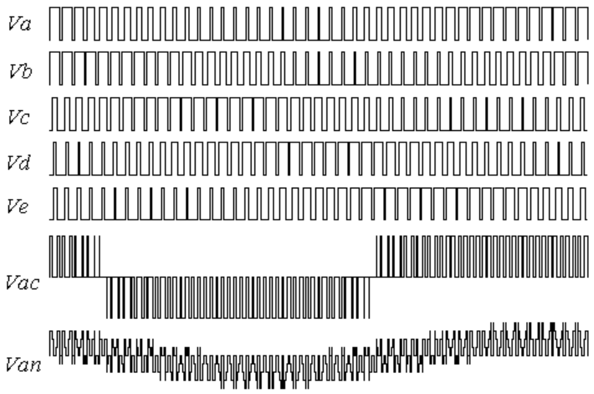


Fig. 3. Basic voltages of five-phase inverter (*F=31Hz, m=0.62*)

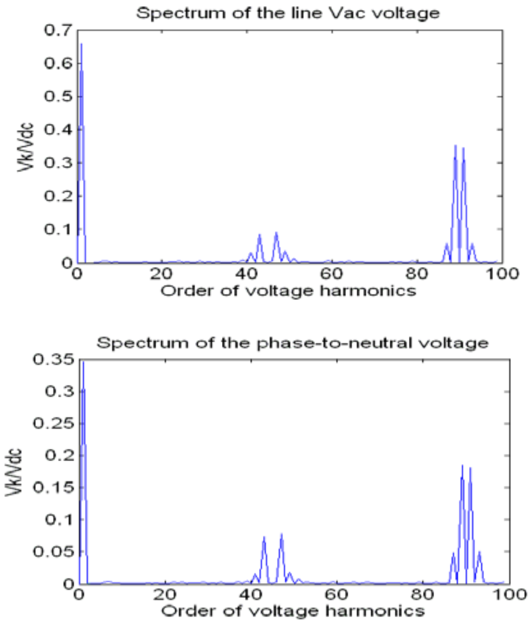


Fig. 4. Spectra of the line and phase voltages of five-phase system at linear modulation region (*F=31Hz, m=0.62*).

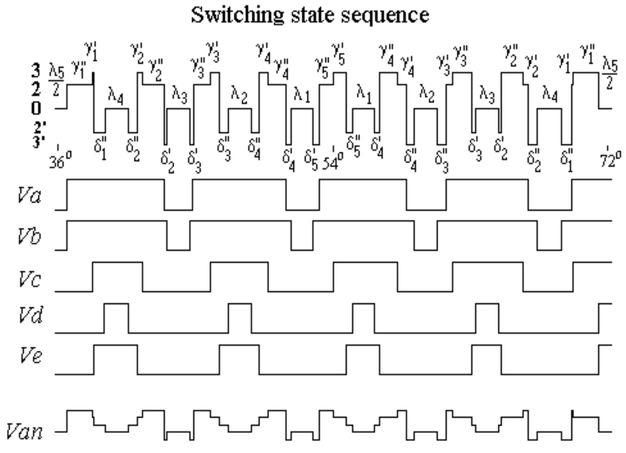


Fig. 5. Switching state sequence and basic voltage waveforms of five-phase inverter with synchronized PWM in the second control sector

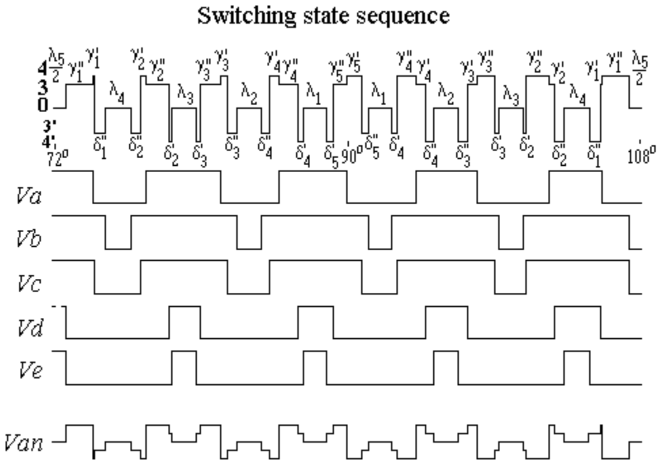


Fig. 6. Switching state sequence and basic voltage waveforms of five-phase inverter with synchronized PWM in the third control sector

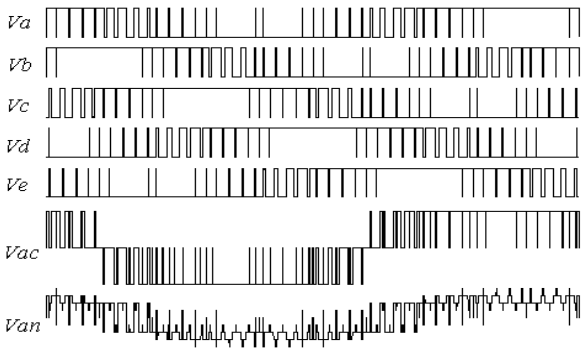


Fig. 7. Pole voltages $V_a - V_c$, line and phase voltages V_{ac} and V_{an} of the system during overmodulation (the first stage, *F=46Hz, m=0.92*)

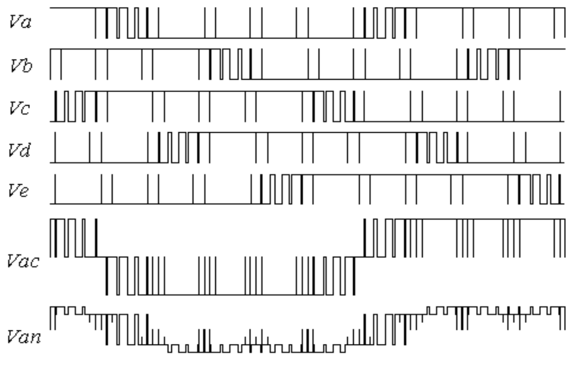


Fig. 8. Pole voltages $V_a - V_c$, line and phase voltages V_{ac} and V_{an} of the system during overmodulation (the second stage, *F=48.7Hz, m=0.97*)

4. SYMMETRICAL SIX-PHASE SYSTEMS WITH ALGORITHMS OF SYNCHRONIZED PWM

The method of synchronized PWM can be used effectively for control of a drive system based on a six-phase inverter and a symmetrical six-phase machine, providing phase voltage synchronization during the whole control range, including the zone of overmodulation.

Basic topology of a six-phase inverter feeding a symmetrical six-phase induction motor with two neutral points is presented in Fig. 9 [4],[7]. The induction motor is characterized in this case by two sets of three-phase windings that are spatially shifted by 60 electrical degrees. In order to provide synchronous generation of phase voltage waveforms of symmetrical six-phase drive, separate control of two parts of the six-phase inverter, correspondingly with the legs (phases) ***a, b, c*** and ***x, y, z***, has to be performed in accordance with basic algorithm of synchronized PWM. The corresponding phase shift between control signals of these two parts of six-phase inverter is equal to 60^0 in this case.

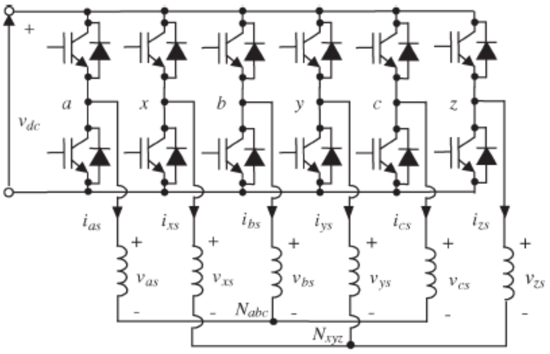


Fig. 9. Six-phase inverter feeding symmetrical six-phase motor with two neutral points

Fig. 10 – Fig. 13 present basic voltage waveforms (with spectra of the V_{sa} voltage) during period of the fundamental frequency of the symmetrical six-phase system controlled in accordance with two basic schemes of synchronized PWM: 1) continuous synchronized PWM (CPWM, Figs. 10-11), and 2) discontinuous PWM with the 30^0-nonswitching intervals (DPWM3, Figs. 12-13). The average switching and fundamental frequencies of each inverter of dual three-phase system are, respectively, equal to *900 Hz* and *35 Hz* (modulation index $m=0.7$). Figs. 10 and 12 present the pole voltages in the system, and the corresponding useful V_{sa} (V_{sa} = V_{as}) and loss-producing V_{m1} components of the phase voltage [7],[8]. The V_{m1} voltage is equal to zero in these cases. The common-mode voltage V_0 relatively mid-point of the DC-source (the signal V_0–$V_{dc}/2$) is equal to zero too. Figs. 11 and 13 show spectra of the V_{sa} voltage, which include only odd non-triplen harmonics.

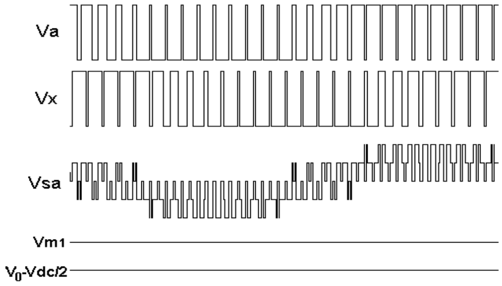


Fig. 10. Pole voltages V_a and V_x, useful V_{sa} and loss-producing V_{m1} components of the phase voltage, and common-mode voltage V_0, for the system with continuous synchronized PWM (CPWM)

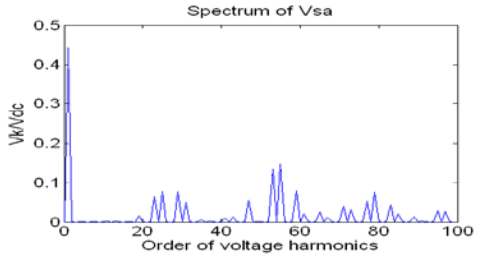


Fig. 11. Spectrum of the V_{sa} voltage of system with CPWM

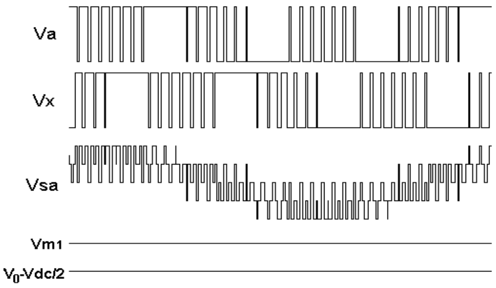


Fig. 12. Pole voltages V_a and V_x, useful V_{sa} and loss-producing V_{m1} components of the phase voltage, and common-mode voltage V_0, for the system with discontinuous synchronized PWM (DPWM3)

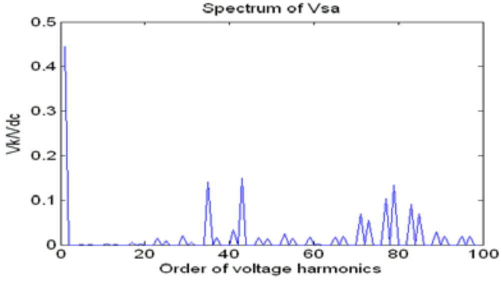


Fig.13. Spectrum of the V_{sa} voltage of system with DPWM3

Fig. 14 presents calculation results of Weighted Total Harmonic Distortion factor (WTHD) for the Vsa voltage (averaged values of $WTHD = (1/V_{sa1})\sqrt{\sum_{i=2}^{1000}(V_{sa_k}/k)^2}$) of symmetrical dual three-phase system with control algorithms, providing common-mode voltages elimination, which are based on continuous (CPWM) and two discontinuous (DPWM1 and DPWM3), versions of synchronized space-vector PWM. The average switching frequency of inverters is equal to 900 Hz during standard scalar V/F control [7].

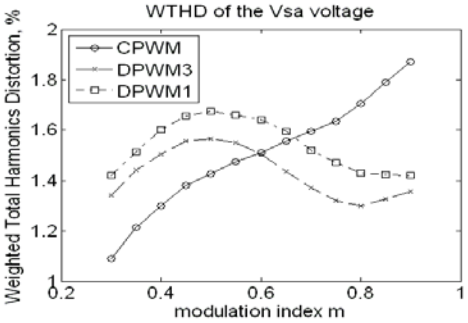


Fig. 14. Averaged *WTHD* factor of the V_{sa} voltage versus modulation index *m*

Presented in Fig. 14 characteristics show some advantage of continuous synchronized PWM at low modulation indices. At higher modulation indices, the discontinuous scheme with the 30^0-nonswitching intervals (DPWM3) provides slightly better *WTHD* factor of the V_{sa} voltage in comparison with the use of other versions of synchronized PWM.

5. ASYMMETRICAL SIX-PHASE DRIVE FED BY INVERTER WITH SYNCHRONIZED PWM

Ones of the interesting and perspective topologies of multiphase drives are now asymmetrical six-phase (dual-three phase) induction machine drives [2],[9]-[12]. The machine has in this case two sets of winding spatially shifted by 30 electr. degrees with isolated neutral points (Fig. 15 [2]).

Control of asymmetrical six-phase induction machine drives is based on the 30^0-phase-shift of control and output signals of two three-phase inverters with the phases ***a, b, c*** and ***x, y, z*** [9]-[10]. Both continuous and discontinuous schemes of synchronized PWM can be applied for synchronous phase voltage control in asymmetrical six-phase drives.

Fig. 16 – Fig. 17 present basic pole and phase voltages and phase current I_{as} waveforms of the drive with the 10 kW asymmetrical dual three-phase induction machine controlled in accordance with two basic schemes of synchronized PWM: 1) Continuous synchronized PWM (CPWM, Fig. 16); and 2) Discontinuous PWM with the 30^0-non-switching intervals (DPWM3, Fig. 17). The switching and fundamental frequencies of each inverter are equal to *1 kHz* and *40 Hz*, respectively (modulation index *m=0.8*) [9].

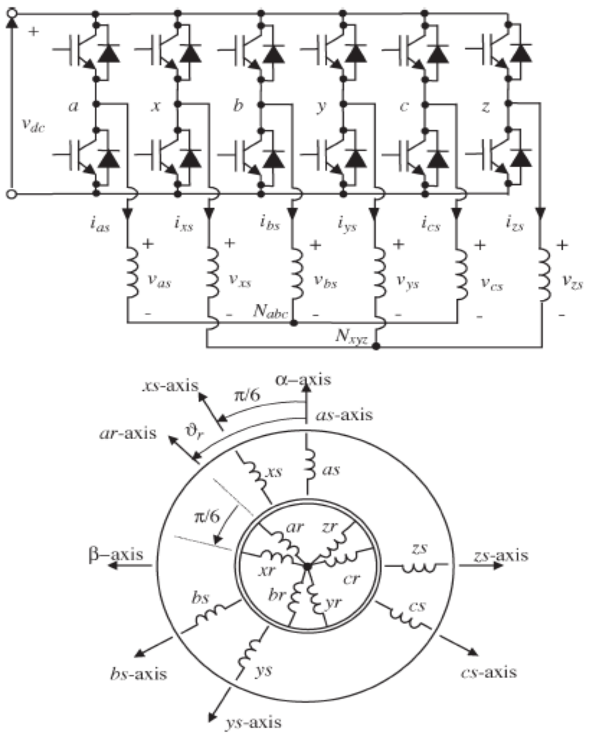
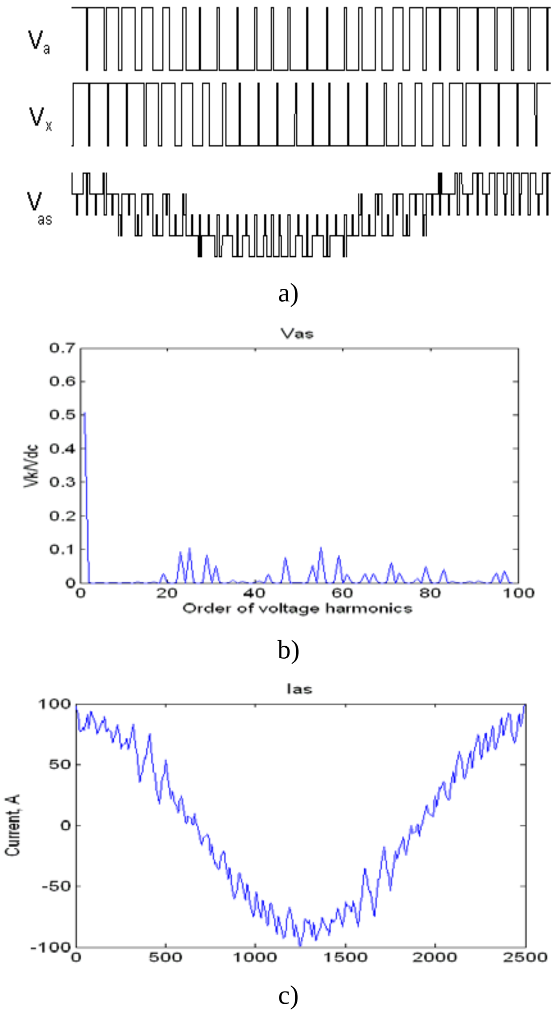


Fig. 15. Asymmetrical dual three-phase system with single DC source [2]

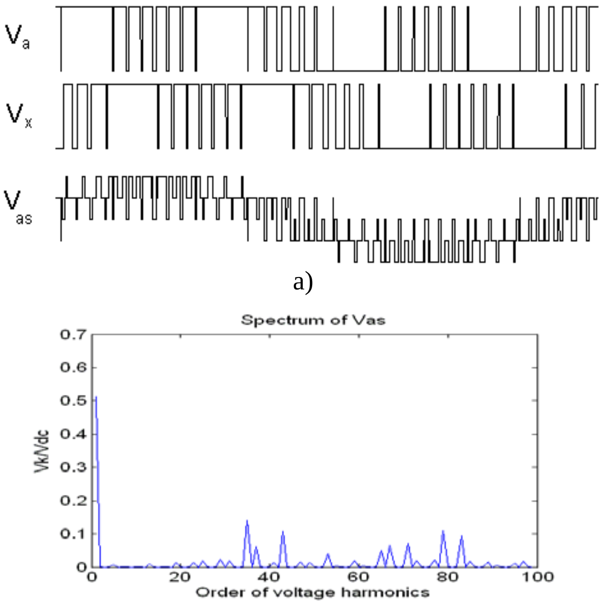


a)

b)

c)

Fig. 16. Pole voltages V_a and V_x, phase voltage V_{as} (a), and its spectrum (b), and the phase current I_{as} (c) for asymmetrical six-phase drive with continuous synchronized PWM



a)

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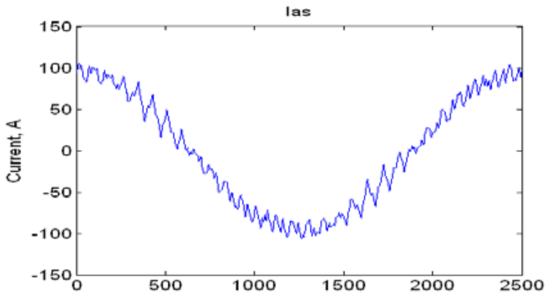

c)

Fig. 17. Pole voltages V_a and V_x, phase voltage V_{as} (a), and its spectrum (b), and the phase current I_{as} (c) for asymmetrical six-phase drive with discontinuous synchronized PWM

Fig. 18 presents calculation results of Total Harmonic Distortion factor (*THD*) of the phase current I_{as} ($THD = (1/I_{as})\sqrt{\sum_{k=2}^{1000} I_{as\,k}^{2}}$) of asymmetrical six-phase drive system with continuous (CPWM) and discontinuous (DPWM3) versions of synchronized modulation. The average switching frequency for each control regime is equal to *1 kHz*, control mode corresponds here to *V/F* control. The spectral characteristics of Fig. 18 show the advantage of the use of continuous synchronized PWM at low modulation indices *m* of inverters, meanwhile for *m>0.6*, the scheme of discontinuous PWM is the most suitable [9].

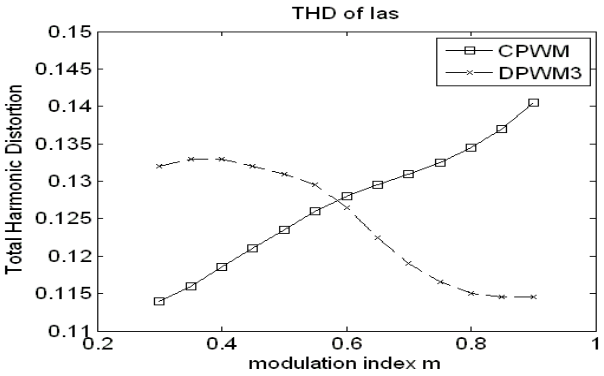

Fig. 18. *THD* factor of the phase current I_{as} versus modulation index *m*

An increased effectiveness of operation of dual three-phase systems on the base of two inverters supplied by isolated dc sources with different voltages can be provided by the corresponding control of switching frequency of each modulated inverter in the function of voltage magnitudes of the dc sources [12]. In particular, in order to provide similar switching losses in two inverters, the inverter supplied by the higher voltage V_{dc2} should be switched under lower frequency F_{s2}, and the inverter supplied by the lower voltage V_{dc1} should be operated at higher switching frequency F_{s1}:

$$F_{s1}\ V_{dc1} = F_{s2}\ V_{dc2} \qquad (1)$$

To illustrate processes in asymmetrical dual three-phase drive system on the base of two inverters with different switching frequencies, supplied by two isolated dc sources with different voltages ($V_{dc1} = 0.7V_{dc2}$), Fig. 19 – Fig. 21 present results of MATLAB/Simulink-based modeling and simulation of this system with standard scalar *V/F* control mode. The fundamental frequency is equal to *45 Hz* (modulation indices of two inverters are $m_1=0.9$ and $m_2=0.63$ in this case), the average switching frequency of the first inverter with lower dc voltage is equal to $F_{s1} = 1$ *kHz*, and the average switching frequency of the second inverter with a higher dc voltage is $F_{s2} = 700$ *Hz.* Fig. 21 shows the phase currents I_{as} and I_{xs} of the six-phase drive with synchronized PWM with a 10 kW asymmetrical dual three-phase induction machine.

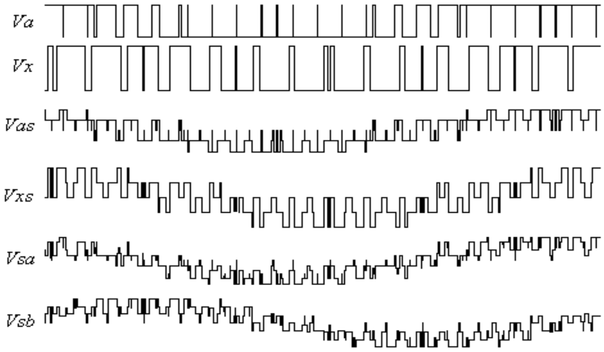

Fig. 19. Pole voltages V_a and V_x, phase voltages V_{as} and V_{xs}, and useful components V_{sa} and V_{sb} of the phase voltage of the system with continuous synchronized PWM ($F=45Hz$, $V_{dc1}=0.7V_{dc2}$, $m_1=0.9$, $m_2=0.63$, $F_{s1}=1kHz$, $F_{s2}=700Hz$)

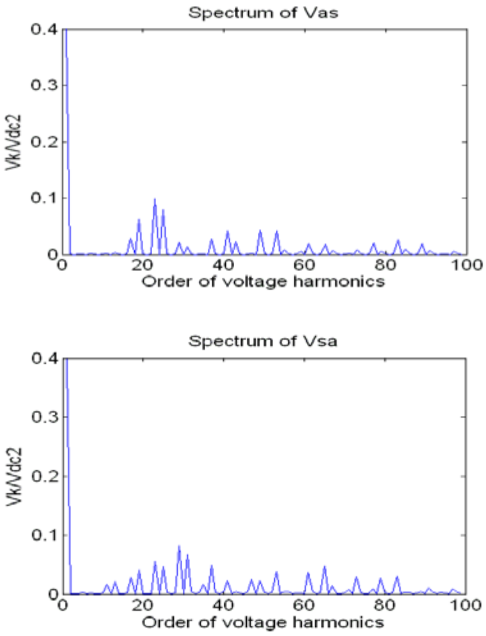

Fig. 20. Spectra of the V_{as} and V_{sa} voltages of the system with continuous synchronized PWM ($F=45Hz$, $F_{s1}=1kHz$, $F_{s2}=700Hz$)

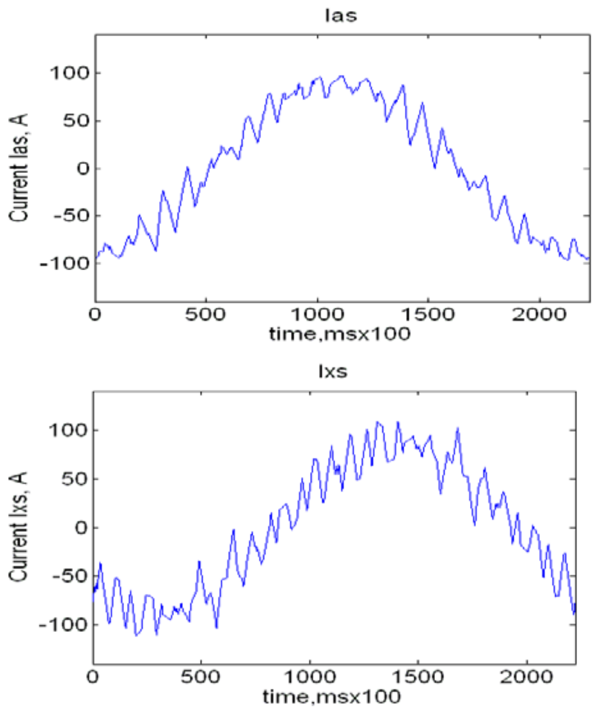

Fig. 21. Phase currents I_{as} and I_{xs} of the system with continuous synchronized PWM ($F=45Hz$, $V_{dc1}=0.7V_{dc2}$, $F_{s1}=1kHz$, $F_{s2}=700Hz$).

In order to compare characteristics of asymmetrical dual three-phase (six-phase) systems with both equal and different switching frequencies of two inverters, Fig. 22 presents calculation results of Weighted Total Harmonic Distortion factor (*WTHD*) versus modulation index m_1 for the useful component V_{sa} of the motor phase voltage for the six-phase drive with continuous (*CPWM*) and discontinuous (*DPWM*) schemes of synchronized PWM with equal switching frequency of two inverters ($F_{s1}=F_{s2}=700Hz$), and also for the system with different switching frequencies of inverters ($F_{s1}=1kHz$, $F_{s2}=700Hz$, curves *CPWMdiffFs* and *DPWMdiffFs* in Fig. 22) [12]. Control mode of the system corresponds here to scalar *V/F* control, and $V_{dc1}=0.7V_{dc2}$.

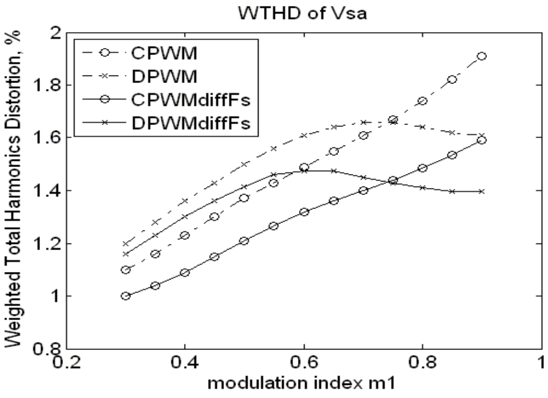

Fig. 22. Averaged *WTHD* factor of the V_{sa} voltage versus modulation index m_1 ($V_{dc1}=0.7V_{dc2}$)

The presented results show, that the control scheme with different switching frequencies of two inverters provides better spectral composition of the useful component V_{sa} of the phase voltage. Thus, in order to increase effectiveness of operation of asymmetrical six-phase dual-inverter system under condition of similar switching losses of two inverters, switching frequency of the inverter with lower DC-voltage can be increased correspondingly.

6. CONCLUSIONS

Novel method of synchronized space-vector-based PWM, developed and disseminated for control of five-phase and symmetrical and asymmetrical six-phase converters and drives, allows providing continuous synchronization of the phase voltages:

- for any ratio (integral or fractional) between the fundamental and switching frequencies of converters;
- for any ratio of voltage magnitudes of two dc-sources of asymmetrical six-phase drive systems;
- for dual-inverter based six-phase drives with separate control of switching frequencies of inverters.

Spectra of the phase voltages of multiphase systems with synchronized PWM do not contain even harmonics and sub-harmonics during the whole control range, which is especially important for high power/high current applications.

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