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BASIC SCHEMES OF SYNCHRONIZED PULSEWIDTH MODULATION FOR CASCADED INVERTERS OF DRIVE SYSTEM WITH TWO DC-SOURCES

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Continuous and discontinuous schemes of synchronized pulsewidth modulation (PWM) have been applied for control of an open-end winding motor drive fed by cascaded inverters supplied by two dc-sources with non-equal voltages. Simulations illustrate behavior of these systems with algorithms of synchronized PWM. Spectra of multilevel phase voltage of open-end winding motor drives with synchronized PWM do not contain even harmonics and sub-harmonics during the whole control range, which is especially important for the medium-power and high-power systems. References 10, figures 6.
Key words: motor drive, synchronized pulsewidth modulation, harmonics, sub-harmonics.

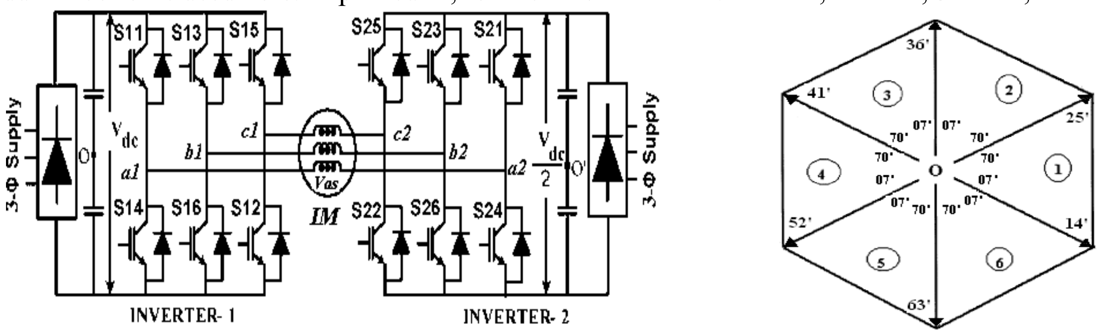
Introduction. Ones of the interesting and perspective topologies of power converters are now cascaded (dual) converters which utilize two standard three-phase voltage source inverters [1,8−10]. The structure of adjustable speed electric drives based on cascaded inverters is constructed by splitting the neutral connection of the induction motor and connecting both ends of each phase coil to a two-level inverter. In this case cascaded converters are capable of producing voltages which are identical to those of three-level and four-level converters [1,8]. Dual-inverter fed open-end winding motor drives have some advantages such as redundancy of the space-vector combinations and the absence of neutral point fluctuations.

It is known that for some topologies of power conversion systems, mainly for high-power systems, it is necessary to provide symmetry of the output voltage waveforms of converters for elimination of undesirable sub-harmonics of voltage and current [2−4]. In order to avoid asynchronous character of standard schemes of space-vector modulation, a novel method of synchronized PWM has been proposed and developed with application to different topologies of converters and electric drives [5−7].

In this paper, both continuous and discontinuous schemes of space-vector-based synchronized modulation have been applied for control of asymmetrical dual-inverter fed open-end winding drive supplied by two isolated dc-sources with non-equal voltages.

Basic topology of asymmetrical dual-inverter fed drive system. Fig. 1, *a* presents basic structure of a dual-inverter fed open-end winding induction motor drive, where the INVERTER-1 and INVERTER-2 are standard three-phase voltage source inverters. Two isolated dc-sources with different (asymmetrical) voltages (V_{dc} and $V_{dc}/2$) are used in this case, and this ratio of dc-voltages allows providing of four-level (multilevel) waveforms of the phase voltage in the system [8].

Fig. 1, *b* shows the switching state vectors of two inverters, which provide avoidance of overcharging of the dc-link capacitors of the INVERTER-2 operating with lower dc-voltage [8]. The conventional definition for the switching state sequences (voltage vectors) for the switches of the phases of ***abc*** of each individual inverter is used here. In particular, for the INVERTER-1: **1** – 100; **2** – 110; **3** – 010; **4** –011;



a *b*

Fig. 1

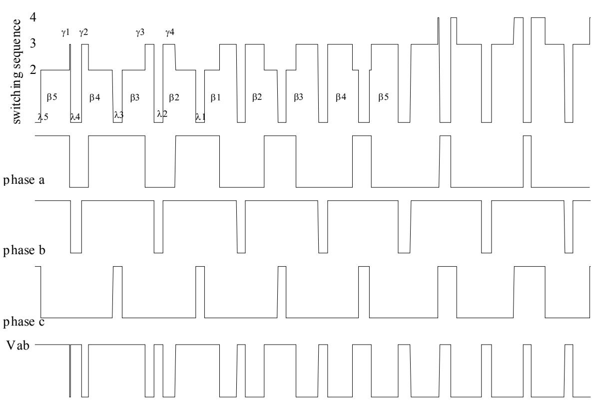
5 – 001; **6** – 101, **0** – 000, **7** - 111 (1 - switch-on state, 0 – switch-off state); and the same definition are used for the INVERTER-2: **1’** – 1’0’0’; **2’** – 1’1’0’; **3’** – 0’1’0’; **4’** –0’1’1’; **5’** – 0’0’1’; **6’** – 1’0’1’; **0’** – 0’0’0’; **7’**– 1’1’1’, where 1’ − switch-on state of switches, and 0’ – switch-off state.

Features of the method of synchronized space-vector modulation. Algorithms of synchronized space-vector-based PWM allow providing continuously symmetry of phase voltage waveforms of drive converters, and can be used successfully for control of each inverter in a dual-inverter system.

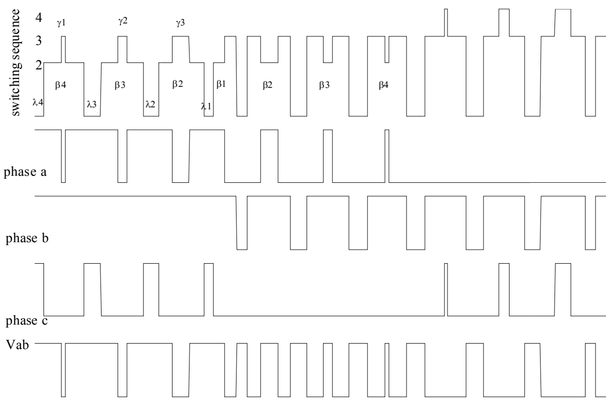
Fig. 2 presents switching state sequences of standard three-phase inverter inside the interval 0^0−90^0. It illustrates schematically two basic versions of space-vector PWM (Fig. 2, *a* – continuous PWM (CPWM), and Fig. 2, *b* – discontinuous PWM with the 30^0 − non-switching intervals (DPWM)) [5].

The upper traces in Figs. 2, *a* – 2, *b* are switching state sequences in accordance with conventional designation, then – the corresponding pole voltages of standard three-phase inverter. The lower traces in Figs. 2, *a* – 2, *b* show quarter-wave of the line-to-line output voltage of the inverter. Signals βj represent total switch-on durations during switching cycles τ, signals γ_k are generated at the boundaries (for CPWM) and in centers (for DPWM) of the corresponding β-signals. Widths of notches λ_k represent duration of zero states.

One of the basic ideas of the proposed PWM method is in continuous synchronization of positions of all central β_1-signals in the centers of the 60^0-clock-intervals (fixing of positions of the β_1-signals in the centers), with further symmetrical generation of other active β- and γ-signals, together with the corresponding notches λ, around the β_1-signals.



a



b

Fig. 2

Also, special signals λ' (λ_5 for CPWM, λ_4 for DPWM in Fig. 2) with the neighboring β'' (β_5 for CPWM, β_4 for DPWM) are formed in the clock-points (0^0,60^0,120^0..) of the output curve. They are reduced simultaneously until close to zero value at the boundary frequencies F_i, providing a continuous adjustment of voltage with smooth pulses ratio changing. F_i is calculated in a general form 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 determined from (3), where fraction is 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 K_1=1, K_2=3 for CPWM, K_1=1,5, K_2=3,5 for DPWM.

Equations (4)−(9) present set of control functions for determination of durations of all control signals of three-phase inverters with synchronized PWM in absolute values (seconds) for both undermodulation and overmodulation control regimes of inverters [5]:

For *j*=2,...*i*-1*:*

$$\beta_j = \beta_1 \cos[(j - 1 - K_3)\tau K_{ov1}] \quad (4)$$

$$\gamma_j = \beta_{i-j+1}\{0.5 - 0.87\tan[(i-j-0.25)\tau]\}K_{ov2} \tag{5}$$

$$\beta_i = \beta'' = \beta_1\cos[(i-1.25)\tau K_{ov1}]K_s \tag{6}$$

$$\gamma_1 = \beta''\{0.5 - 0.87\tan[(i-2.25)\tau + (\beta_{i-1}+\beta_i+\lambda_{i-1})/2]\}K_s K_{ov2} \tag{7}$$

$$\lambda_j = \tau - (\beta_j + \beta_{j+1})/2 \tag{8}$$

$$\lambda_i = \lambda' = \left(\tau - \beta''\right)K_{ov1}K_s, \tag{9}$$

where $\beta_1 = 1{,}1\tau m$ (m – modulation index), if $m<0{,}907$; $\beta_1 = \tau$, if $m>0{,}907$; $K_s = [1-(F-F_i)/(F_{i-1}-F_i)]$, $K_{ov1} = 1$ until $F_{ov1}=0.907F_m$ and $K_{ov1} = [1-(F-F_{ov1})/(F_{ov2}-F_{ov1})]$ between F_{ov1} and $F_{ov2} = 0{,}952F_m$; $K_{ov2} = 1$ until F_{ov2} and $K_{ov2} = [1-(F-F_{ov2})/(F_m-F_{ov2})]$ between F_{ov2} and F_m; K_3=0,25 for DPWM and K_3=0 for CPWM.

Algorithms of synchronized PWM for control of dual-inverter system. Control of each inverter of dual-inverter system on the base of algorithms of synchronized PWM and in accordance with the switching scheme, presented in Fig. 1, *b*, allows providing continuous symmetry of phase voltage waveforms during the whole control range of open-end winding motor drive. Output voltages of two inverters have opposite polarity in this case, with an additional phase shift between voltage waveforms, which is equal to one half of the switching interval (sub-cycle) τ (is equal to 0,5 τ) [9].

The phase voltage V_{as} of the system on the basis of dual inverters (Fig. 1) is calculated in accordance with (10)-(11) [8]

$$V_0 = 1/3(V_{a10} - V_{a20} + V_{b10} - V_{b20} + V_{c10} - V_{c20}) \tag{10}$$

$$V_{as} = V_{a10} - V_{a20} - V_0, \tag{11}$$

where V_{a10}, V_{b10}, V_{c10}, V_{a20}, V_{b20}, and V_{c20} are the correspondding pole voltages of each inverter, V_0 is zero sequence (triplen harmonic components) voltage in the system.

As an illustration of control of asymmetrical dual-inverter system with synchronized PWM and with non-equal voltages of dc-sources (V_{dc} and $V_{dc}/2$) Fig. 3 present the pole voltages V_{a10} and V_{a20}, zero sequence

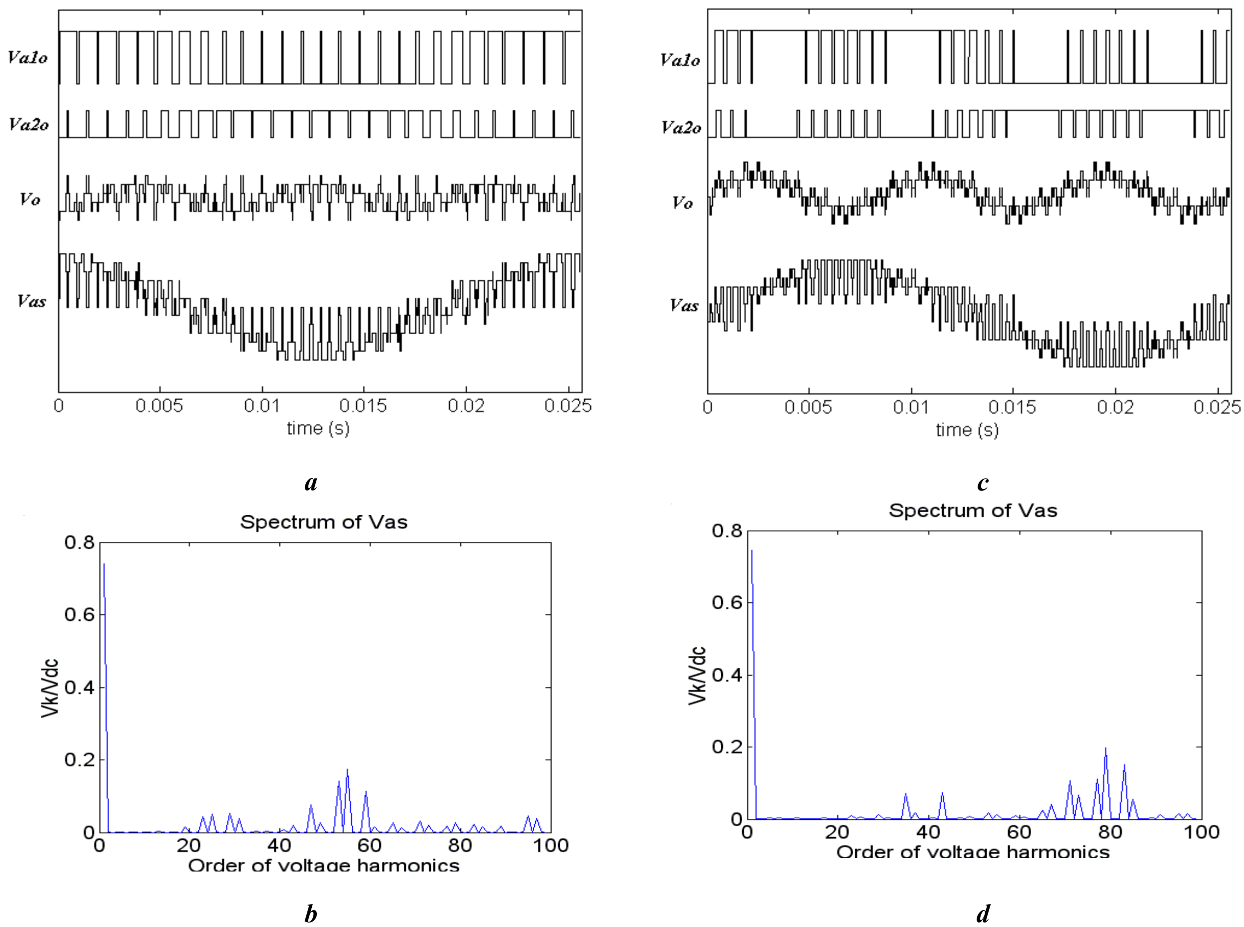


Fig. 3

voltage V_0, and phase voltage V_{as} (with spectrum of the V_{as} voltage in Figs. 3, *b* and 3, *d*) of dual-inverter system with continuous (Figs. 3, *a* and 3, *b*) and discontinuous (Figs. 3, *c* and 3, *d*) synchronized PWM, for scalar *V/F*=const control mode. The fundamental and switching frequencies of each inverter (averaged switching frequency for discontinuous PWM) are equal correspondingly to F=39 Hz and F_s=1 kHz, modulation indices of two inverters are equal to $m_1=m_2$=0,78, and ratio between the switching frequency and fundamental frequency is equal to 1000Hz/39Hz=25,6 in this case. In particular, the spectra of the presented voltage waveforms do not contain even harmonics and sub-harmonics.

An increased effectiveness of operation of power conversion systems on the base of dual inverters for some control modes can be provided by the corresponding control of switching frequencies of two inverters [8]. In particular, for the analyzed asymmetrical open-end winding configuration of drive system, where lower dc-link voltage is one half of the higher dc-link voltage, it is possible to increase correspondingly the switching frequency of the inverter supplied by lower dc-voltage. Fig. 4 presents the corresponding basic voltage waveforms and spectra of the phase voltage for the system with continuous (Figs. 4, *a* and 4, *b*) and discontinuous (Figs. 4, *c* and 4, *d*) synchronized PWM with different switching frequencies of two inverters (F_{s1}=1 kHz, F_{s2}=2 kHz).

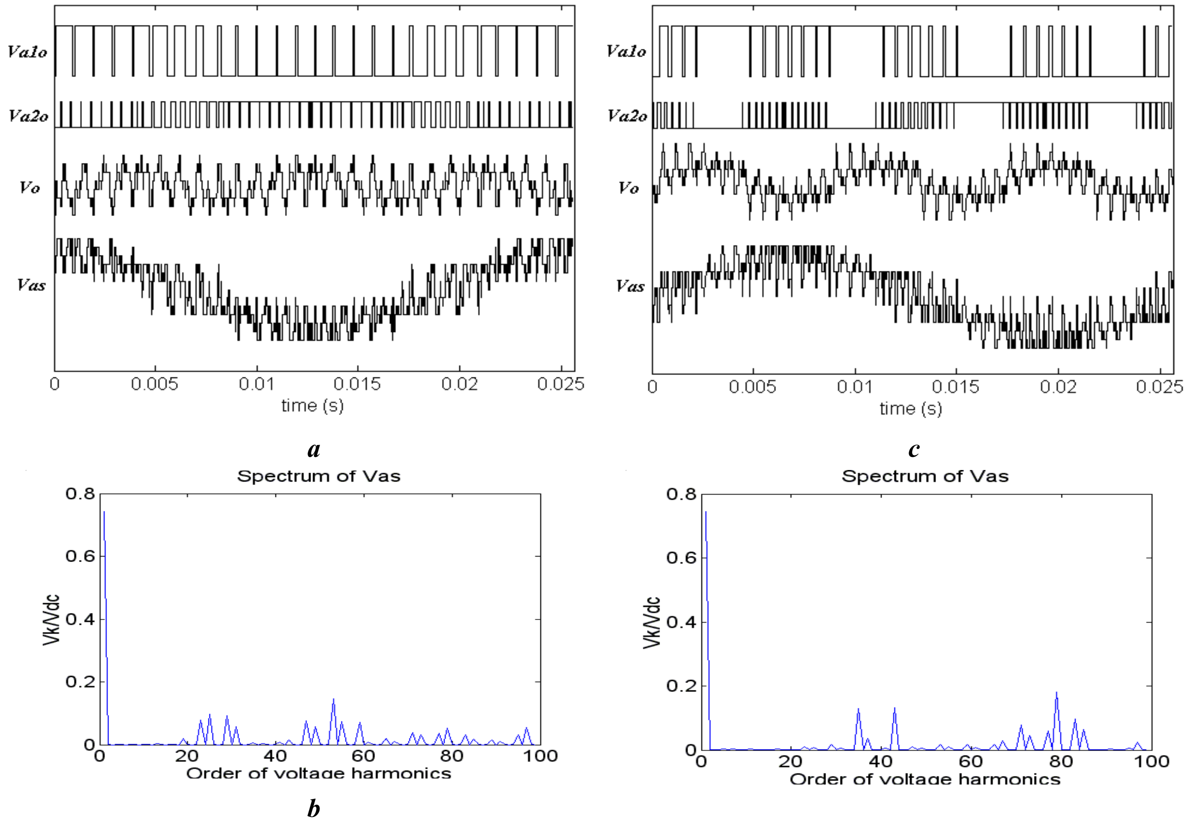
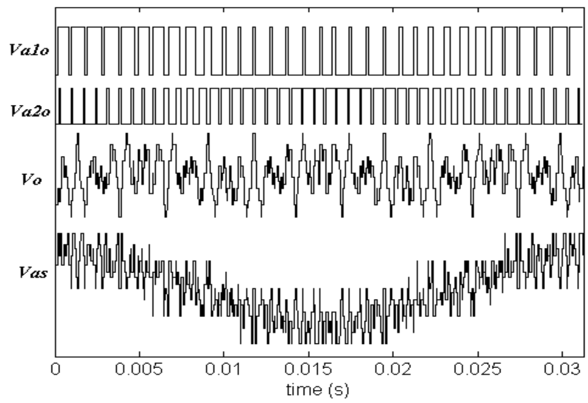


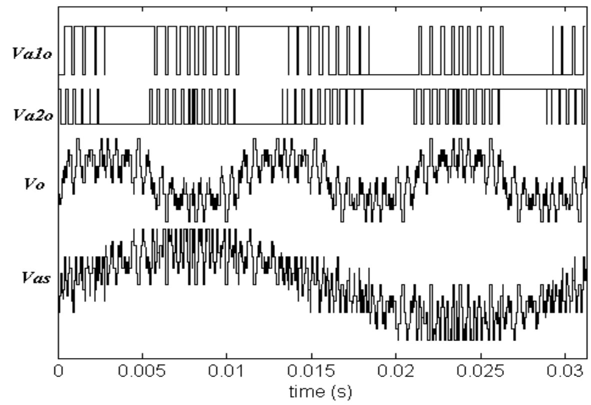
Fig. 4

It is necessary to mention, that algorithms of synchronized modulation allow providing symmetry of phase voltage waveforms of dual-inverter system for any ratio between dc-voltages of two isolated dc-sources (and also for any switching frequencies of two inverters). As an illustration of this fact, Fig. 5 shows basic voltage waveforms and spectra of the phase voltage for the system with two dc-voltages $V_{dc2}=0{,}7V_{dc1}$ with continuous (Figs. 5, *a* and 5, *b*) and discontinuous (Figs. 5, *c* and 5, *d*) synchronized PWM for scalar *V/F* control mode. The fundamental frequency of inverters is equal to F=32 Hz (modulation indices of two inverters $m_1=m_2$=0,64 in this case), and switching frequencies of two inverters are equal correspondingly to F_{s1}=1 kHz and F_{s2}=1,43 kHz.

In particular, spectra of the presented phase voltage waveforms (see Figs. 3, *b*, 3, *d*, 4, *b*, 4, *d*, 5, *b*, 5,) do not contain even harmonics and sub-harmonics for any operating conditions of dual-inverter fed opened-end winding motor drive system.



a



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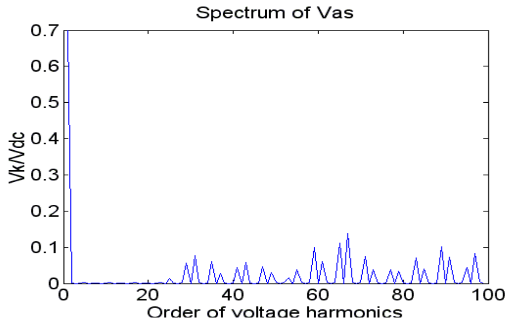

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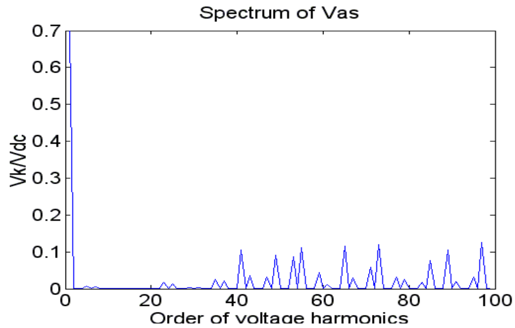

d

Fig. 5

Spectral assessment of phase voltage quality of dual-inverter systems with synchronized PWM. Weighted Total Harmonic Distortion (*WTHD*) factor of output voltage is one of the most suitable criteria for analysis of power quality in adjustable speed drive systems. Fig. 6 presents the calculation results of Weighted Total Harmonic Distortion factor ($WTHD = (1/V_{as_1})(\sum_{k=2}^{1000}(V_{as_k}/k)^2)^{0.5}$) for the phase voltage V_{as} as function of modulation index $m=m_1=m_2$ of two inverters of asymmetrical dual-inverter open-end winding drive system ($V_{dc2}=0{,}5V_{dc1}$) on the base of two two-level inverters (with algorithms of continuous (CPWM) and discontinuous (DPWM) synchronized PWM), and also on the base of two neutral-point-clamped inverters (NPC inverters), controlled by algorithms of the "direct-direct" (DDPWM-NPC) and discontinuous (DPWM-NPC) schemes of synchronized modulation (see [7] regarding NPC inverters with synchronized PWM). Control mode of the drive system corresponds to standard scalar *V/F*=const control (linear modulation zone), and the average switching frequency of each inverter of dual-inverter system is equal to F_s=1 kHz.

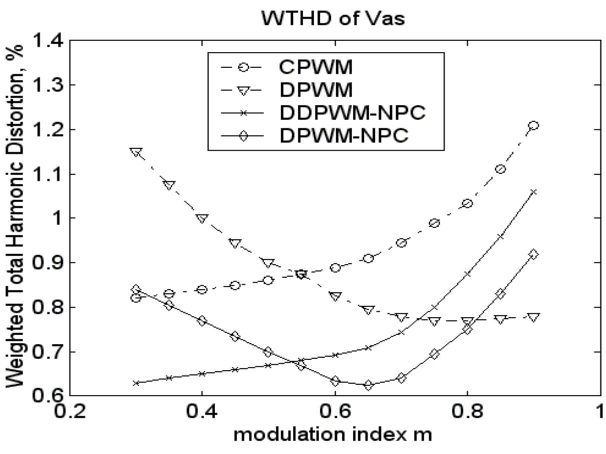

Fig. 6

The presented calculation results show, that dual-inverter system on the base of neutral-point-clamped inverters with specialized algorithms of synchronized PWM have better spectral composition of the phase voltage (in comparison with dual-inverter system on the base of two-level inverters) in the zone of low and medium modulation indices of two inverters. It is necessary to mark also, that in the case of dual-inverter topology on the base of two-level inverters algorithms of discontinuous synchronized PWM allow providing better spectral composition of the phase voltage in the zone of higher fundamental frequencies (including the zone of overmodulation).

Conclusion. Algorithms of space-vector-based synchronized pulsewidth modulation, disseminated for control of asymmetrical dual-inverter fed open-end winding motor system on the base of two voltage source inverters, supplied by two isolated dc-sources (V_{dc2}=0,5V_{dc1}), allow continuous symmetry of phase voltage waveforms during the whole control range and for any operating conditions. Spectra of the phase voltage of dual-inverter drives with algorithms of synchronized PWM do not contain even harmonics and sub-harmonics, which is especially important for the systems with increased power rating, including medium-power and high-power systems.

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ОСНОВНЫЕ СХЕМЫ СИНХРОНИЗИРОВАННОЙ ШИРОТНО-ИМПУЛЬСНОЙ МОДУЛЯЦИИ ДЛЯ РАСПОЛОЖЕННЫХ КАСКАДОМ ИНВЕРТОРОВ СИСТЕМЫ ПРИВОДА С ДВУМЯ ИСТОЧНИКАМИ ПОСТОЯННОГО ТОКА

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Представлены результаты исследования и моделирования режимов работы системы электропривода на базе асинхронного электродвигателя с разомкнутыми обмотками, подключенными к сдвоенным инверторам напряжения с синхронной модуляцией непрерывного и прерывистого типа, питающихся от двух изолированных источников постоянного напряжения. Показано, что в спектре многоуровневого фазного напряжения подобных систем с алгоритмами синхронной широтно-импульсной модуляции на всем диапазоне регулирования отсутствуют четные гармоники и субгармоники, что представляется особенно важным для преобразовательных систем повышенной мощности. Библ. 10, рис. 6.

Ключевые слова: электропривод, асинхронный двигатель, синхронная модуляция, гармоники, субгармоники.

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ОСНОВНІ СХЕМИ СИНХРОНІЗОВАНОЇ ШИРОТНО-ІМПУЛЬСНОЇ МОДУЛЯЦІЇ ДЛЯ РОЗТАШОВАНИХ КАСКАДОМ ІНВЕРТОРІВ СИСТЕМИ ПРИВОДУ З ДВОМА ДЖЕРЕЛАМИ ПОСТІЙНОГО СТРУМУ

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Представлено результати дослідження та моделювання режимів роботи системи електроприводу на базі асинхронного електродвигуна з розімкненими обмотками, які підключено до подвоєних інверторів напруги з синхронною модуляцією неперервного та переривчастого типу, що живляться від двох ізольованих джерел постійного струму. Показано, що у спектрі багаторівневої фазної напруги таких систем з алгоритмами синхронної широтно-імпульсної модуляції у всьому діапазоні регулювання відсутні парні гармоніки та субгармоніки, що є найважливішим для перетворювальних систем підвищеної потужності. Бібл. 10, рис. 6.

Ключові слова: електропривод, асинхронний двигун, синхронна модуляція, гармоніки, субгармоніки.

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