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PWM methods providing phase voltage symmetry of dual-inverter fed drives: Systems modeling and simulation

***Abstract**. Algorithms of space-vector-based synchronized pulsewidth modulation (PWM) have been applied for control of dual-inverter fed open-end winding induction motor drives supplied by two isolated dc-sources with non-equal voltages. Results of modeling and simulation of these systems proved the fact, that techniques of synchronized PWM provide continuous phase voltage symmetry (quarter-wave symmetry, or half-wave symmetry) for any ratios (integral or fractional) between the switching and fundamental frequencies of dual-inverter systems on the base of either standard inverters or neutral-point-clamped inverters, and also for any ratios between voltages of two dc-sources of the system.*

***Streszczenie.** W artykule przedstawiono możliwość sterowania napędem silnika indukcyjnego zasilanego za pośrednictwem dwóch izolowanych źródeł napięcia stałego o nierównych napięciach. Do tego celu wykorzystano podwójny przekształtnik bazujący na algorytmie synchronizowanej modulacji szerokości impulsu PWM. (**Podwójny napęd przekształtnikowy wykorzystujący metodę PWM**)*

Keywords: voltage source inverter, dual-converter topology, modulation strategy, synchronization of the output voltage waveforms.
Słowa kluczowe: przekształtnik, napęd, silnik indukcyjny.

Introduction

Cascaded (dual) converters which utilize two three-phase inverters are now perspective topologies for the medium-power and high-power systems, allowing multilevel output voltage in systems [1]-[6]. The structure of adjustable speed 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 inverters (Fig.1).

It is known that for high-power/high-current drives (or for ultrahigh speed ac drives) it is necessary to provide elimination of undesirable sub-harmonics of voltage and current [7]-[9]. In order to avoid asynchronism of standard schemes of space-vector modulation, a novel method of synchronized PWM has been proposed, developed and disseminated for control of some topologies of power electronic converters, ac electric drives, and renewable energy systems [10]-[15].

In this paper, algorithms of space-vector-based synchronized PWM have been applied for control of asymmetrical dual-inverter fed open-end winding drive supplied by two isolated dc-sources with non-equal voltages. It had been analyzed two topologies of the system, based on either two standard inverters, or on two neutral-point-clamped inverters, controlled by specialized schemes of synchronized PWM, providing phase voltage symmetry for any operation conditions of the system.

Topology of asymmetrical dual-inverter fed motor drive

Fig. 1 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 waveforms of the phase voltage in the system [6].

Fig. 2 shows 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 [6]. 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 [10]. In particular, for the INVERTER-1: **1** – 100; **2** – 110; **3** – 010; **4** –011; **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.

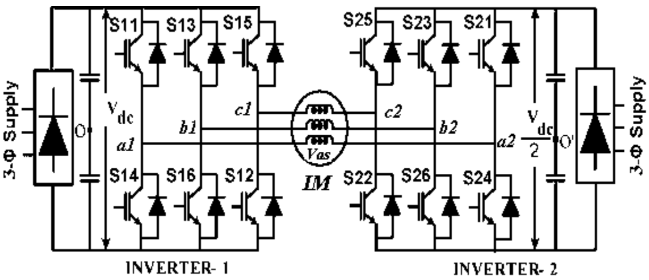

Fig. 1. Asymmetrical dual-inverter fed drive with two dc-sources

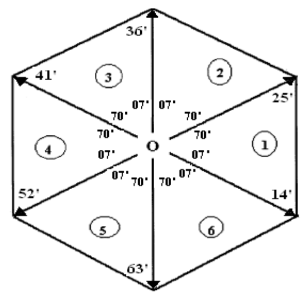

Fig. 2. Voltage space-vector combinations, providing avoidance of overcharging of the dc-source capacitors with lower voltage

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 for control of each inverter in a dual-inverter system.

Figs. 3 - 4 present switching state sequences of three-phase inverter inside the interval 0^0-90^0. They illustrate two basic versions of space-vector PWM (Fig. 3 – continuous PWM (CPWM), and Fig. 4 – discontinuous PWM with the 30^0-non-switching intervals (DPWM)) [10].

The upper traces in Figs. 3 – 4 are switching state sequences (in accordance with conventional designation [10]), then – the corresponding pole voltages of inverter. The lower traces in Figs. 3 - 4 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 in the centers of the corresponding β. Widths of notches λ_k represent duration of zero states.

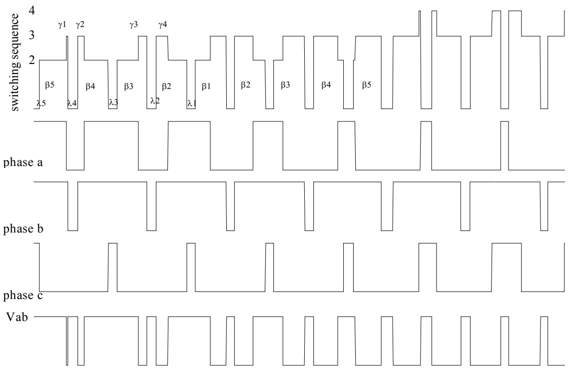

Fig. 3. Switching state sequence, pole voltages V_a, V_b, V_c, and line voltage V_{ab} of inverter with continuous PWM (CPWM)

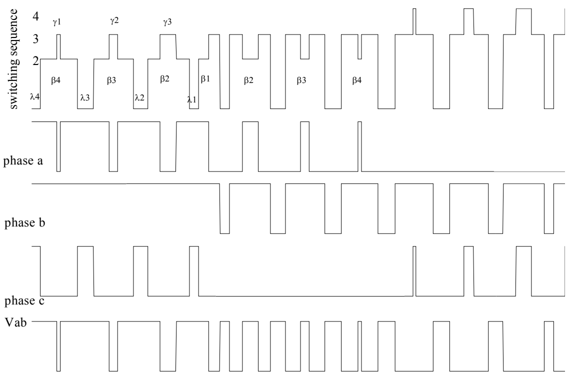

Fig. 4. Switching state sequence, pole voltages V_a, V_b, V_c, and line voltage V_{ab} of inverter with discontinuous PWM with the 30^0-non-switching intervals (DPWM)

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, around the β_1 - signals.

Also, special signals λ' (λ_5 for CPWM, λ_4 for DPWM in Figs. 3-4) 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 [10]:

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

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

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

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

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 for scalar *V/F* control mode [8]:

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

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

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

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

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

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

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

where: $\beta_1 = 1.1\tau m$ (*m=F/F_{max}* – modulation index) if *m<0.907*, and $\beta_1 = \tau$ 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 $K_{ov1} = [1 - (F - F_{ov1})/(F_{ov2} - F_{ov1})]$ in the zone 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 asymmetrical 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. 2, 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 0.5τ) [1].

The phase voltage V_{as} of the system on the basis of dual inverters (Fig. 1) is calculated in accordance with (10)-(11) [6]:

(10) $$V_0 = 1/3(V_{a1o} - V_{a2o} + V_{b1o} - V_{b2o} + V_{c1o} - V_{c2o})$$

(11) $$V_{as} = V_{a1o} - V_{a2o} - V_0$$

where V_{a1o}, V_{b1o}, V_{c1o}, V_{a2o}, V_{b2o}, and V_{c2o} are the corresponding pole voltages of each inverter, V_0 is zero sequence (triplen harmonic components) voltage in the system.

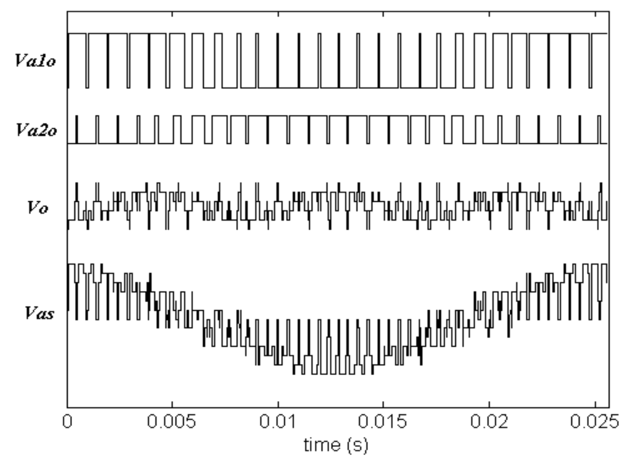

Fig. 5. Pole voltages V_{a1o}, V_{a2o}, zero sequence voltage V_0, and phase voltage V_{as} of dual-inverter fed system with continuous synchronized PWM (*F=39Hz*, F_s*=1kHz*, $m_1=m_2=0.78$)

As an illustration of control of dual-inverter system with synchronized PWM and with non-equal voltages of dc-sources (V_{dc} and $V_{dc}/2$), Figs. 5–8 present pole voltages V_{a1o} and V_{a2o}, zero sequence voltage V_0, and phase voltage V_{as} (with spectrum of the V_{as} voltage) of dual-inverter system with continuous (Figs. 5-6) and discontinuous (Figs. 7-8) synchronized PWM, for scalar control mode. The fundamental and switching frequencies of each inverter (averaged switching frequency for discontinuous PWM) are equal to $F=39Hz$ and $F_s=1kHz$, modulation indices of two inverters are equal to $m_1=m_2=0.78$, and ratio between the switching and fundamental frequencies is equal to $1000Hz/39Hz= 25.6$. Spectra of the presented voltage waveforms do not contain even harmonics and sub-harmonics.

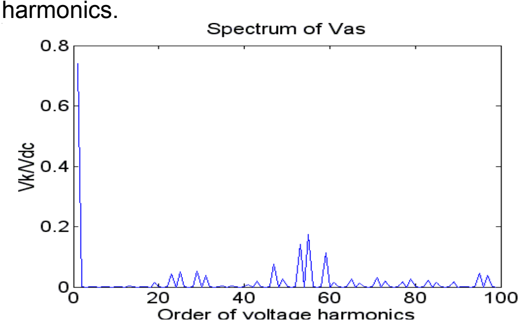

Fig. 6. Spectrum of the phase voltage V_{as} of the system with continuous synchronized PWM (*F=39Hz, F_s=1kHz*)

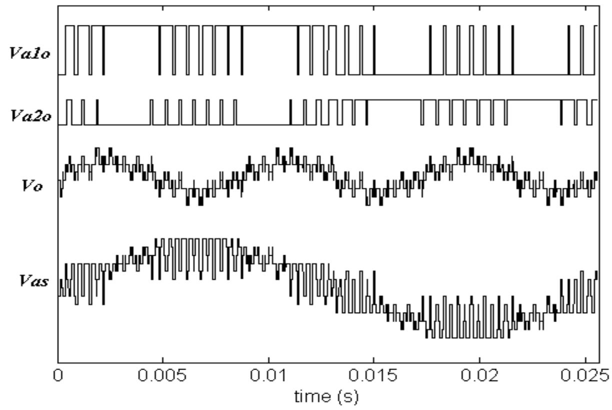

Fig. 7. Pole voltages V_{a1o}, V_{a2o}, zero sequence voltage V_0, and phase voltage V_{as} of dual-inverter fed system with discontinuous synchronized PWM (*F=39Hz, F_s=1kHz, $m_1=m_2=0.78$*)

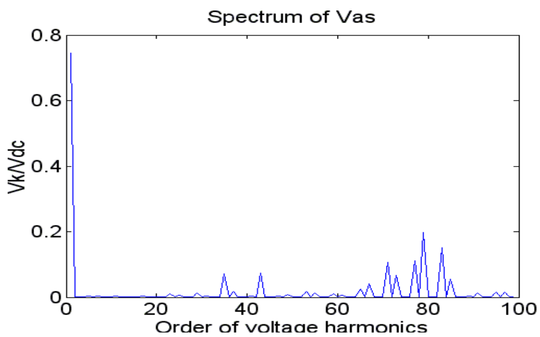

Fig. 8. Spectrum of the phase voltage V_{as} of the system with discontinuous synchronized PWM (*F=39Hz, F_s=1kHz*)

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 [6],[12]. In particular, for the analyzed asymmetrical open-end winding configuration of drive system, where lower dc-link voltage is one half of higher dc-link voltage, it is possible to increase correspondingly the switching frequency of the inverter supplied by lower dc-voltage. Figs. 9-10 present the corresponding basic voltage waveforms and spectra of the phase voltage for the system with discontinuous synchronized PWM with different switching frequencies of two inverters (*F_{s1}=1kHz, F_{s2}=2kHz*).

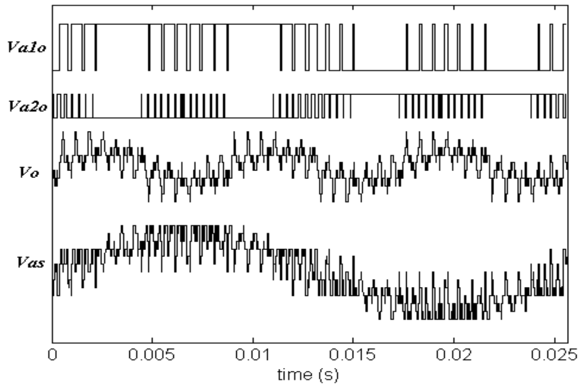

Fig. 9. Pole voltages V_{a1o}, V_{a2o}, zero sequence voltage V_0, and phase voltage V_{as} of dual-inverter fed system with discontinuous synchronized PWM (*F=39Hz, F_{s1}=1kHz, F_{s2}=2kHz , $m_1=m_2=0.78$*)

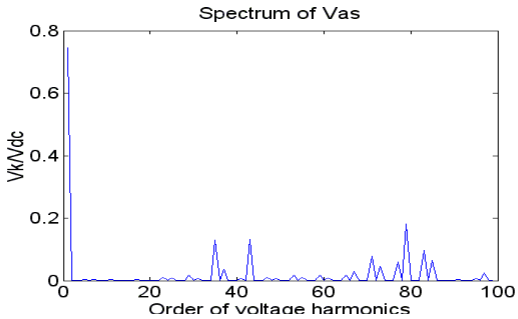

Fig. 10. Spectrum of the phase voltage V_{as} of the system with discontinuous synchronized PWM (*F=39Hz, F_{s1}=1kHz, F_{s2}=2kHz*)

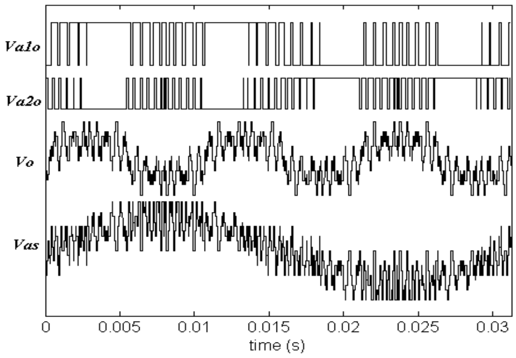

Fig. 11. Pole voltages V_{a1o}, V_{a2o}, zero sequence voltage V_0, and phase voltage V_{as} of dual-inverter fed system with discontinuous synchronized PWM (*F=32Hz, $V_{dc2}=0.7V_{dc1}$, F_{s1}=1kHz, F_{s2}=1.43kHz, $m_1=m_2=0.64$*)

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, Figs. 11-12 show basic voltage waveforms and spectra of the phase voltage for the system with two dc-voltages $V_{dc2}=0.7V_{dc1}$ with discontinuous synchronized PWM for scalar control mode. The fundamental frequency of inverters is equal to *F=32Hz* (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}=1kHz* and *F_{s2}=1.43kHz*.

In particular, spectra of the presented phase voltage waveforms (see Figs. 6, 8, 10, 12) do not contain even harmonics and sub-harmonics for any operating conditions of dual-inverter-based opened-end winding drive system. Method of synchronized space-vector modulation allows providing also high quality linear control of the fundamental voltage of dual-inverter system in the zone of overmodulation too [10],[12].

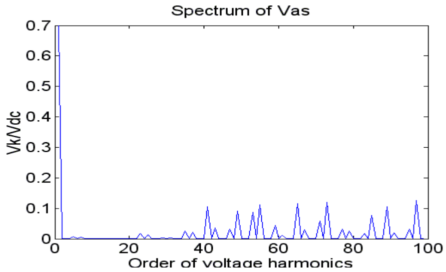

Fig. 12 Spectrum of the phase voltage V_{as} of the system with discontinuous synchronized PWM (*F=32Hz,*, $V_{dc2}=0.7V_{dc1}$, $F_{s1}=1kHz$, $F_{s2}=1.43kHz$

Dual-inverter system on the base of neutral-point-clamped inverters

In order to increase effectiveness of operation of asymmetrical dual-inverter fed open-end winding motor drive, it is possible also to use dual neutral-point-clamped inverters as basic components of dual-inverter topology. In particular, specialized control scheme allows to provide elimination of zero sequence voltages in dual-inverter system on the base of neutral-clamped inverters [11], [13], [15]. Fig. 13 presents basic topology of a neutral-clamped inverter. Each of the three legs of the inverter consists of four power switches, four freewheeling diodes and two clamping diodes.

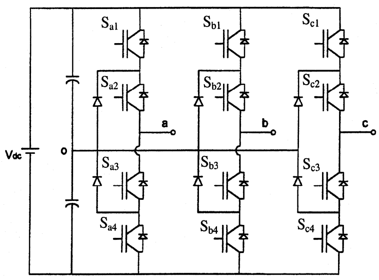

Fig. 13. Topology of three-phase neutral-point-clamped inverter

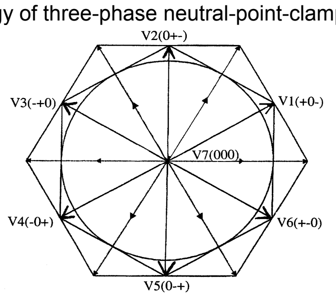

Fig. 14. Switching state vectors providing elimination of zero sequence voltage in inverter system

Fig. 14 shows the switching state vectors of the inverter. It is known, that the use of only seven of the vectors, ***V_1* - *V_7*,** marked in Fig. 14 by the big arrows with the corresponding number of vector, can provide elimination of zero sequence voltages in system [11]. Two basic schemes of synchronized PWM have been elaborated for control of neutral-clamped inverters with elimination of zero sequence voltage, which can be applied for control of dual inverters.

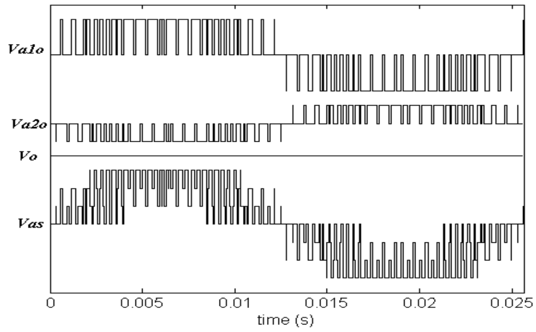

Fig. 15. Pole voltages V_{a1o}, V_{a2o}, zero sequence voltage V_0, and phase voltage V_{as} of dual-neutral-clamped-inverter system with discontinuous PWM (*F=39Hz*, $F_s=1kHz$, $m_1=m_2=0.78$)

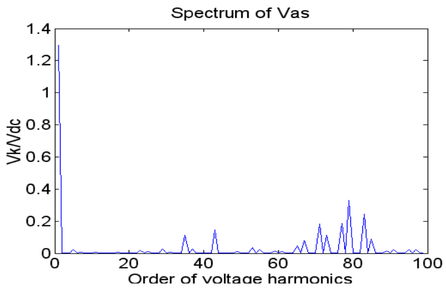

Fig. 16. Spectrum of the phase voltage V_{as} of system with neutral-clamped inverters with discontinuous PWM (*F=39Hz*, $F_s=1kHz$)

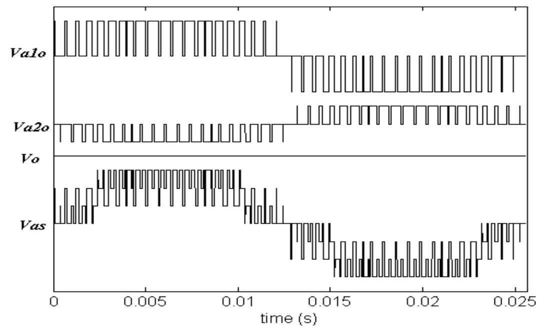

Fig. 17. Basic voltages of dual-inverter fed system with neutral-clamped inverters with "direct-direct" synchronized PWM (*F=39Hz*, $F_s=1kHz$, $m_1=m_2=0.78$)

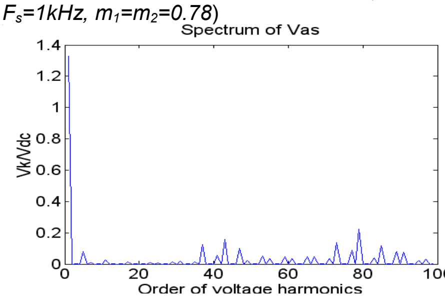

Fig. 18. Spectrum of the phase voltage V_{as} of system with neutral-clamped inverters with "direct-direct" PWM (*F=39Hz*, $F_s=1kHz$)

Figs. 15-18 present pole voltages V_{a1o} and V_{a2o}, zero sequence voltage V_0, and phase voltage V_{as} (with spectrum of the V_{as} voltage) of asymmetrical ($V_{dc2}=0.5V_{dc1}$) dual-inverter system on the base of neutral-clamped inverters with discontinuous (DPWM [13], Figs. 15-16), and "direct-direct" (DDPWM [13], Figs. 17-18) schemes of synchronized PWM, for scalar *V/F=const* control mode.

The fundamental and switching frequencies of each inverter are equal correspondingly to *F=39Hz* and $F_s=1kHz$, modulation indices of two neutral-clamped inverters are equal to $m_1=m_2=0.78$, and ratio between the switching and fundamental frequencies is equal to *1000Hz/39Hz=25.6* in this case. Spectra of the phase voltage of this topology of dual-inverter system with synchronized PWM do not contain undesirable even harmonics and sub-harmonics.

Spectral characteristics of the phase voltage

Fig. 19 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 drive ($V_{dc2} = 0.5V_{dc1}$) 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-clamped inverters, controlled by algorithms of the "direct-direct" (DDPWM-NPC) and discontinuous (DPWM-NPC) schemes of synchronized modulation. Control mode of the system corresponds to scalar *V/F* control (linear modulation zone), and the average switching frequency of each inverter of dual-inverter system is equal to $F_s=1kHz$.

The presented calculation results show, that dual-inverter systems on the base of neutral-clamped inverters with specialized algorithms of synchronized PWM have better spectral composition of the phase voltage (in comparison with the system on the base of standard inverters) in the zone of low and medium modulation indices of inverters. In the case of dual-inverter topology on the base of two-level inverters algorithms of discontinuous synchronized PWM allow better spectral composition of the phase voltage in the zone of higher fundamental frequencies.

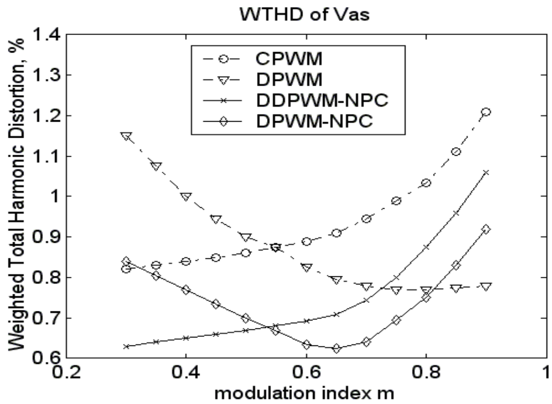

Fig. 19. Averaged *WTHD* factor of the phase voltage V_{as} versus modulation index $m=m_1=m_2$ for asymmetrical dual-inverter system ($V_{dc2}=0.5V_{dc1}$)

Conclusion

Algorithms of space-vector-based synchronized PWM, disseminated for control of asymmetrical dual-inverter fed open-end winding motor drive on the base of either two standard inverters or two neutral-point-clamped inverters with specialized scheme of modulation, supplied by two isolated dc-sources ($V_{dc2}=0.5V_{dc1}$), allow continuous symmetry (quarter-wave symmetry, or half-wave symmetry) of multilevel phase voltage waveforms during the whole control range and for any operating conditions.

Results of modeling and simulation proved the fact, that algorithms of synchronized PWM provide symmetry of multilevel phase voltage of dual-inverter systems:

- for any ratio (integral or fractional) between the switching frequency and fundamental frequency of each inverter of open-end winding motor drive;
- for the case of non-equal switching frequencies of two inverters of dual-inverter system;
- for any ratio of voltage magnitudes of two dc-sources.

Spectra of the phase voltage of dual-inverter-based drives controlled by algorithms of synchronized pulsewidth modulation do not contain even harmonics and sub-harmonics, which is especially important for the systems with an increased power rating.

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