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Synchronous PWM Control of Symmetrical Split-Phase Induction Machines

Analysis of operation of symmetrical six-phase drives on the base of split-phase machine, supplied from the inverter with synchronized space-vector pulsewidth modulation (PWM), has been performed. Simulations give the behaviour of the systems with continuous and discontinuous versions of synchronized PWM.

Выполнено исследование систем шестифазного регулируемого электропривода на базе асинхронного электродвигателя с расщепленными обмотками, питающихся от инверторов напряжения с синхронной векторной широтно-импульсной модуляцией (ШИМ). Приведены результаты моделирования систем с непрерывной и прерывистой разновидностями синхронной ШИМ.

Introduction. Multilevel and multiphase topologies of converters and adjustable speed ac drives have an increasing interest in the last years due to some advantages compared with standard three-phase systems. Ones of the most frequently considered structures of multiphase drives are split-phase (six-phase) induction motor drives, which can be divided into two big groups — asymmetrical and symmetrical six-phase drives [1—6,8,10]. The most famous asymmetrical split-phase (dual-three phase) drives are based on two three-phase inverters feeding split-phase induction motor. The induction machine has in this case two sets of windings spatially shifted by 30 electrical degrees with isolated neutral points [1—3,5,6,8—10].

Less famous symmetrical split-phase (six-phase) drives are based on symmetrical split-phase electrical machines, which have two sets of three-phase windings that are spatially shifted by 60 electrical degrees [1,2,8]. Fig. 1 presents basic topology of symmetrical six-phase drive, which includes six-phase inverter feeding a symmetrical split-phase induction motor with single neutral point.

Multiphase, and, in particular, six-phase drives have several advantages over their three-phase counterparts, such as: reduction of torque pulsations, of the rotor harmonic losses, and of the rated current of power switches; improved reliability at system level; the possibility to supply more than one machine from a single inverter to get a multi-motor, multi-phase drive [6].

High power/high current drives (ship propulsion, locomotive, electrical vehicles, etc.) are perspective area of application of both asymmetrical and symmetrical six-phase drives. These power systems are characterized by low switching frequency of power switches of converters. It is known, that for high power drives it is necessary to synchronize the output voltage waveforms of modulated power converters for the minimization of undesirable sub-harmonics of voltage and current [4].

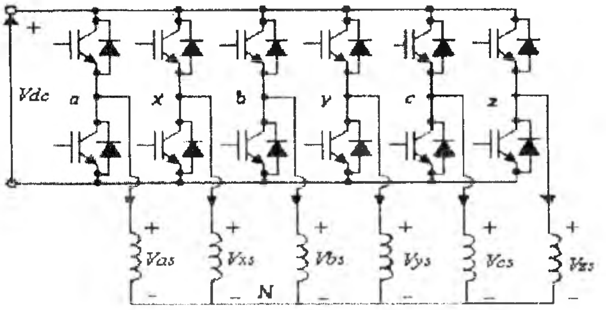
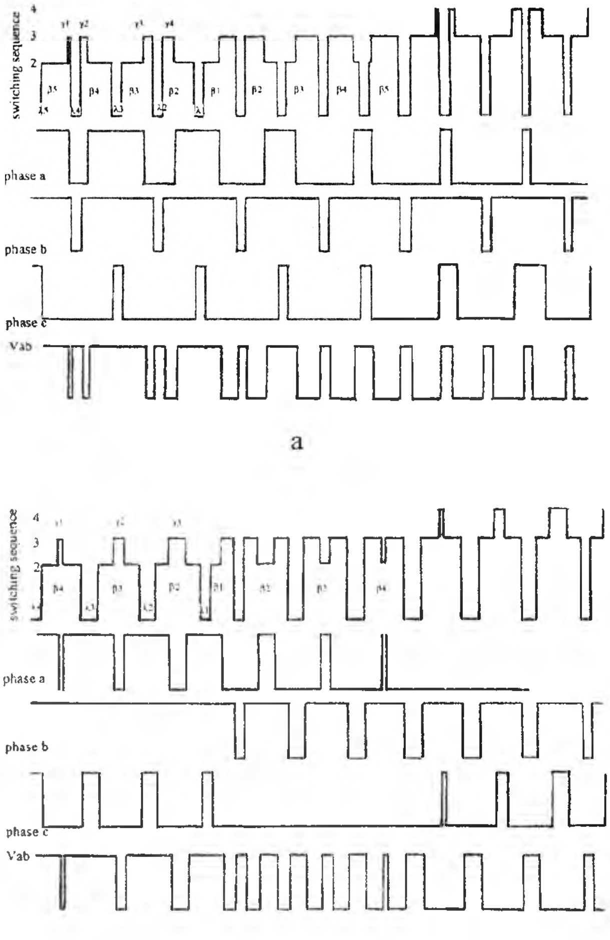


Рис. 1

To provide continuous synchronization of the motor phase voltage, novel method (methodology) of synchronized PWM has been recently proposed for control of standard three-phase inverters [7]. So, this paper presents results of dissemination of this new method of modulation for control of symmetrical split-phase drives, including comparative analysis of operation of the basic schemes of synchronized PWM in symmetrical six-phase systems.

Basic Schemes of Synchronized PWM. In order to avoid asynchronism of conventional versions of voltage space-vector modulation, novel method of synchronized PWM can be used for control of six-phase motor drives [7].

Fig. 2 illustrates basic continuous (CPWM, Fig. 2,*a*) and discontinuous (DPWM, Fig. 2,*b*) schemes of



a

b

Рис. 2

synchronized space-vector-based PWM inside the interval 0^0-90^0. The upper traces in Fig. 2 are switching state sequences (in accordance with conventional designation [7]), then — control signals for the cathode switches of one of the group (***a***, ***b***, ***c***) of the six-phase inverter. The lower traces in Fig. 2 show the corresponding quarter-wave of the line output voltage V_{ab} of six-phase inverter. Signals βj represent total switch-on durations during switching sub-cycle τ, signals γ_k are generated on the borders (Fig. 2,*a*) or in the centers (Fig. 2,*b*) of the corresponding β-signals. Widths of notches λ_k represent duration of zero sequences.

Special signals λ', with the neighboring β'', are formed in the clock-points (0^0,60^0,120^0...) of the output curve. They are reduced simultaneously till close to zero width at the special boundary frequencies, situated on the axis of the fundamental frequency F of the drive system. It provides continuous adjustment of the output voltage waveforms of each inverter with smooth pulses-ratio changing until the maximum fundamental frequency F_m. Modulation index $m=F/F_m$ for standard V/F control.

Equations (1)—(8) present set of control functions for determination of parameters of signals of inverters with synchronized PWM in absolute values (seconds) for scalar control mode of the system during the whole control range including the zone of overmodulation [8]:

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

$$\beta_j=\beta_1\cos\left[\left(j-1-K_3\right)\tau K_{ov1}\right]; \qquad (1)$$

$$\gamma_j=\beta_{i-j+1}\left\{0{,}5-0{,}87\mathrm{tg}\left[\left(i-j-K_3\right)\tau\right]\right\}K_{0v2}, \qquad (2)$$

$$\beta_i=\beta''=\beta_1\cos\left[\left(i-K_3-1\right)\tau K_{0v1}\right]K_s, \qquad (3)$$

$$\gamma_1=\beta''\left\{0{,}5-0{,}87\mathrm{tg}\left[\left(i-K_3-2\right)\tau+\right.\right.$$
$$\left.\left.+\left(\beta_{i-1}+\beta_i+\lambda_{i-1}\right)/2\right]\right\}K_sK_{0v2}, \qquad (4)$$

$$\lambda_j=\tau-\left(\beta_j+\beta_{j+1}\right)/2, \qquad (5)$$

$$\lambda_i=\lambda'=\left(\tau-\beta''\right)K_{0v1}K_s, \qquad (6)$$

$$F_i=\left[6\left(2i-1\right)\tau\right]^{-1}, \qquad (7)$$

$$F_{i-1}=\left[6\left(2i-3\right)\tau\right]^{-1}, \qquad (8)$$

where: β — total switch-on duration inside switching interval; γ — minor parts of the total switch-on durations; λ — duration of notches; τ — switching interval (sub-cycle); F_i and F_{i-1} — boundary frequencies between control subzones (index i is equal to the number of notches inside a half of the 60^0-clock-intervals, including the notch on the border of the clock-intervals); $\beta_1=1{,}1\tau m$ until $F_{ov1}=0{,}907F_m$, and $\beta_1=\tau$ after F_{0v1}; $K_s=[1-(F-F_i)/(F_{i-1}-F_i)]$ — coefficient of synchronization; the first coefficient of overmodulation $K_{0v1}=1$ until F_{0v1}, and $K_{0v1}=[1-(F-F_{ov1})/(F_{ov2}-F_{ov1})]$ between F_{0v1} and $F_{ov2}=0{,}952F_m$; the second coefficient of overmodulation $K_{ov2}=1$ until F_{ov2}, and $K_{ov2}=[1-(F-F_{ov2})/(F_m-F_{ov2})]$ in the zone between F_{ov2} and F_m; $K_3=0$ for CPWM, and $K_3=0{,}25$ for DPWM.

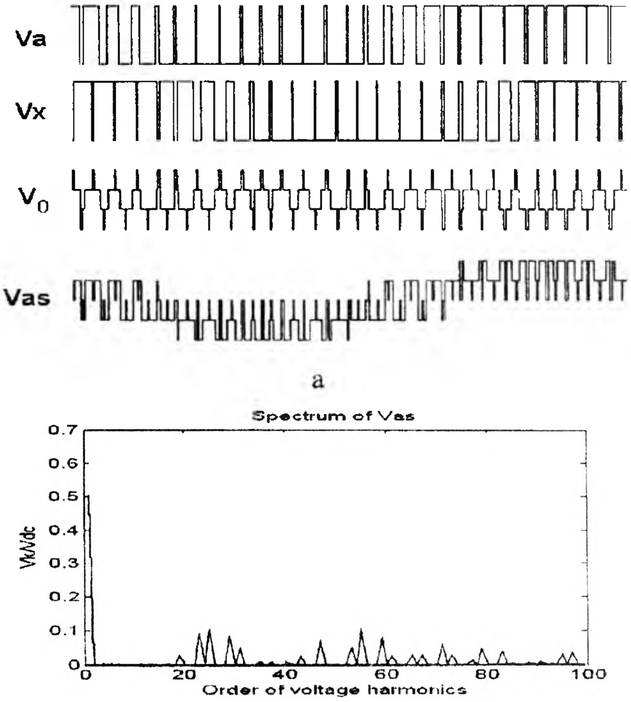
Operation of Symmetrical Split-Phase Drives with Synchronized PWM. In the general case, control of symmetrical six-phase induction machine drive, in both undermodulation and overmodulation regions, is based on the 60^0-phase shifting of control and output signals of two groups (***a***, ***b***, ***c*** and ***x***, ***y***, ***z*** in Fig. 1) of six-phase inverter [1, 2]. In accordance with peculiarities of symmetrical six-phase drives, the zero sequence voltage V_0 in the system is determined in accordance with (9), and the phase voltage V_{as} — in accordance with (10):

$$V_0=\left(1/6\right)\left(V_a+V_b+V_c-V_x-V_y-V_z\right), \qquad (9)$$

$$V_{as}=V_a-V_0, \qquad (10)$$

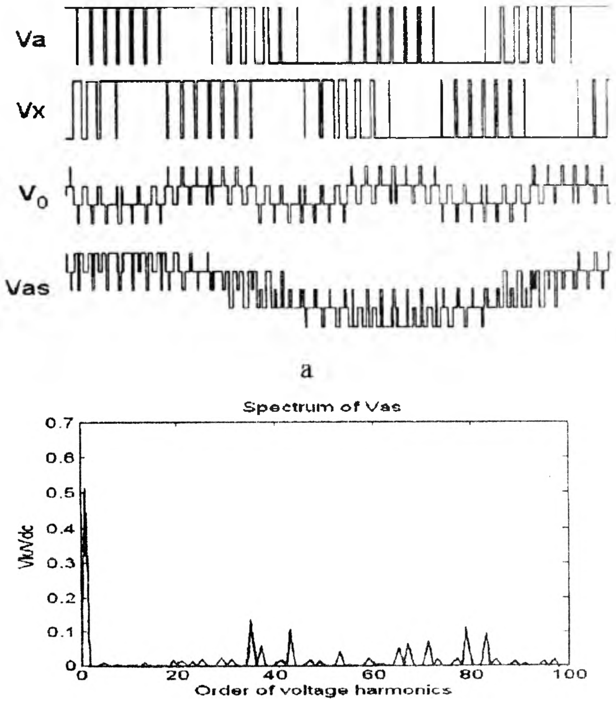
where V_a, V_b, V_c, V_x, V_y, V_z are the corresponding pole voltages of each leg of the six-phase inverter (Fig. 1).

As an example of operation of symmetrical six-



b

Рис. 3



b

Рис. 4

phase system with synchronized PWM, Fig. 3 and Fig. 4 present the pole voltages V_a and V_x, zero sequence voltage V_0 and phase voltage V_{as} for the split-phase drive with continuous synchronized PWM (Fig. 3, *a*), and with discontinuous pulsewidth modulation with the 30^0-non-switching intervals (Fig. 4, *a*). The pole voltages V_a and V_x have phase shift equal to 60 electrical degrees for the symmetrical six-phase drive system. The fundamental frequency is 40 Hz (modulation index $m = 0{,}8$ for scalar V/F control mode of the system with the maximum fundamental frequency equal to 50 Hz), and the average switching frequency of the inverter switches is 1 kHz.

Fig. 3,*b* and Fig. 4,*b* show the spectra of the phase voltage V_{as} for the continuous (Fig. 3,*b*) and discontinuous (Fig. 4,*b*) schemes of synchronized PWM. These spectra include only odd (non-triplen order) harmonics, and do not include even harmonics and subharmonics, due to the continuous quarter-wave symmetry of the phase voltage V_{as}, which is provided for any modulation indices and any ratios between the switching frequency and fundamental frequency. This property of the systems with synchronized PWM is especially important for the high power/high current drives.

In order to compare the presented modulation schemes, a comparative analysis of the phase voltages spectra has been performed on the basis of computer simulation. The Weighted Total Harmonic Distortion factor *WTHD* (11) has been used for determination of its quality:

$$WTHD = V_1^{-1}\left[\sum_{i=2}^{n}\left(V_i/i\right)^2\right]^{0.5}. \qquad (11)$$

Fig. 5 presents averaged calculation results of the *WTHD* factor versus modulation index for the phase voltage V_{as} of the drive system with continuous (CPWM) and discontinuous (DPWM) schemes of synchronized modulation with scalar V/F control in linear modulation range (modulation index $m = 0{,}3$—$0{,}9$). The average switching frequency of the six-phase inverter is 1 kHz for the presented versions of PWM. The results of the spectral analysis of the phase voltage, presented in Fig. 5, show that at low and medium modulation indices the *WTHD* factor is better for the drive system with the continuous scheme of synchronized PWM, and at high modulation indices the discontinuous scheme of synchronized PWM provides better spectral composition of the phase voltage.

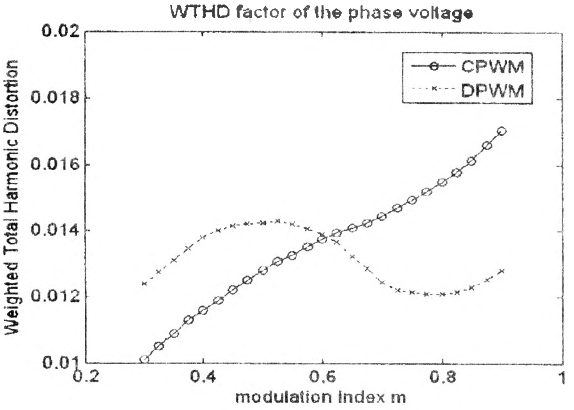


Рис. 5

Method of synchronized modulation, applied for control of symmetrical six-phase drives, is well suited for high quality linear control of the motor phase voltage of the drive system in the zone of overmodulation [9]. Basic control correlations of this method (1)—(4) and (6) include two special linear coefficients of overmodulation K_{ov1} and K_{ov2}, providing smooth pulses dropping process in this zone.

Conclusion. Method of synchronized space-vector modulation has been applied for control of symmetrical split-phase (six-phase) drive, allows synchronization of the motor phase voltage in both undermodulation and overmodulation control zones. Space-vector-based algorithms of synchronized PWM provide also minimum number of switchings and the minimum switching losses during the whole control range.

Continuous scheme of synchronized PWM provides better spectral composition of the phase voltage at low modulation indices. And in the zone of higher fundamental frequencies discontinuous versions of synchronized PWM provide lower weighted total harmonics distortion factor for the phase voltage. During the whole control range the spectra of the motor phase voltage of six-phase drives do not contain even harmonics and sub-harmonics, which is especially important for the high power/current systems.

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Исследовано влияние частоты и фазы импульсов управления в трехфазном ИРМ на основе последовательного RLC-контура и вентильного коммутатора, циклически переключающего индуктивность этого контура на опережающую фазу питающей сети, на величину основной гармоники и несинусоидальность сетевого тока (при работе в индуктивном и емкостном режимах).

Досліджено вплив частоти і фази імпульсів керування в трифазному ДРП на основі послідовного RLC-контуру і вентильного комутатора, що циклічно перемикає індуктивність цього контуру на випереджаючу фазу мережі живлення, на величину основної гармоніки струму та несинусоїдальність струму мережі (при роботі в індуктивному та ємнісному режимах).

В работе [1] были проанализированы регулировочные характеристики и качество кривой сетевого тока (для заданного диапазона регулирования) трехфазного вентильно-реакторного ИРМ при циклическом переключении индуктивностей, входящих в силовую схему ИРМ [2], на отстающую