SYNCHRONOUS PWM CONTROL OF FOUR INVERTERS FEEDING ASYMMETRICAL SIX-PHASE MOTOR DRIVE

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Novel method of space-vector-based pulsewidth modulation (PWM) has been disseminated for synchronous control of four inverters feeding six-phase drive on the base of asymmetrical induction motor which has two sets of windings spatially shifted by 30 electrical degrees. Basic schemes of synchronized PWM, applied for control of four separate voltage source inverters, allow both continuous phase voltages synchronization in the system and required power sharing between DC-sources. Simulations show a behavior of six-phase system with continuous and discontinuous versions of synchronized PWM. References 19, table 1, figures 7.
Key words: space-vector-based pulsewidth modulation, inverters, asymmetrical induction motor.

Introduction. Multiphase, and, in particular, six-phase induction motor drives are a subject of increasing interest in the last years due to some advantages compared with conventional three-phase drives [1,2,6,7,13]. One of the most perspective applications of six-phase induction motor drives lies in the field of high power/high current systems (ship propulsion, locomotive, electrical vehicles, etc.), which are characterized by low switching frequency of power switches.

Recently, novel four-inverter-based topology of dual three-phase drive system with an increased power rating has been proposed, allowing quadrupling the power capability of a single inverter with given voltage and current rating [3]. Fig. 1 shows this system structure, consisting of two groups of two inverters (INV1+INV2 and INV3+INV4), supplying the open-end windings of asymmetrical dual three-phase motor. The induction machine has in this case two sets of winding spatially shifted by 30 electrical degrees.

For electrical drives with increased power and/or current it is necessary to synchronize the output voltage waveforms of converters for elimination of undesirable subharmonics of voltage and current [4,5,8]. In order to avoid asynchronism of standard versions of space-vector modulation, novel method of synchronized space-vector PWM has been proposed and developed with application to different topologies of power electronic converters, electric drives, and renewable energy systems [9−12,14−17].

So, this paper presents results of application of a novel method of synchronized pulsewidth modulation for control of asymmetrical dual three-phase (six-phase) drive on the basis of four cascaded voltage source inverters, supplied by four isolated DC-sources.
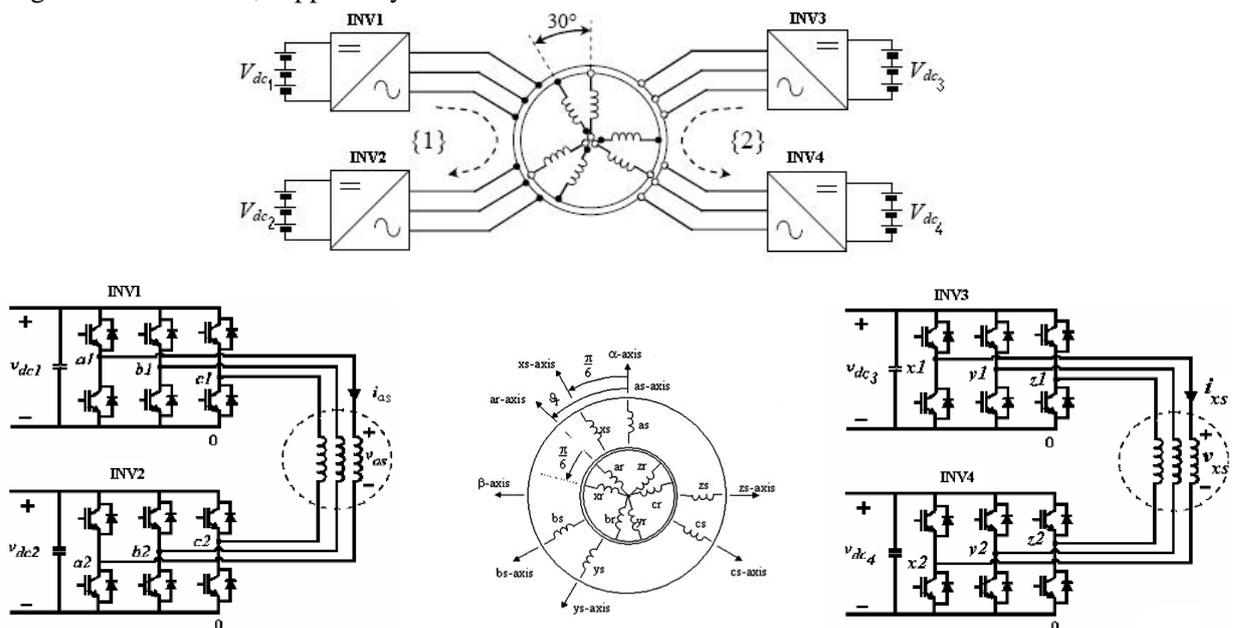

Fig. 1

Operation of four-inverter-based dual three-phase system with synchronized PWM. In order to avoid asynchronism of conventional space-vector modulation, novel method of synchronized PWM [9,10] can be used for control of each inverter in the six-phase (dual three-phase) drive system.

Table I presents generalized properties and basic control correlations for the proposed method of synchronized PWM [9]. It is also compared here with conventional asynchronous space-vector modulation.

Control of four three-phase inverters supplying asymmetrical six-phase induction motor has some specific peculiarities. In particular, these inverters are grouped into two groups with two cascaded inverters in each group, and each inverter group is connected with the corresponding open-end windings of dual three-phase induction motor. Synchronous symmetrical control of the output voltage of each inverter of each inverter group in accordance with algorithms of synchronized PWM provides synchronous symmetrical regulation of voltage in the corresponding induction machine phase windings. Rational phase shifting between output voltage waveforms of the two inverters in each inverter group is equal in this case to one half of the switching interval (sub-cycle) τ [19].

In the case, when two DC voltage sources have equal voltages, the resulting voltage space-vectors are equal to the space-vector patterns of conventional three-level inverter [2,3,19]. The phase voltages V_{as} and V_{xs} of the first and the second groups of cascaded inverters with two insulated DC-sources (Fig. 1) are calculated in accordance with (1)−(4) [18]:

$$V_{01}=[3(V_{a1}+V_{b1}+V_{c1}+V_{a2}+V_{b2}+V_{c2})]^{-1}, \qquad V_{as}=V_{a1}+V_{a2}-V_{01}, \qquad (1,2)$$

$$V_{02}=[3(V_{x1}+V_{y1}+V_{z1}+V_{x2}+V_{y2}+V_{z2})]^{-1}, \qquad V_{xs}=V_{x1}+V_{x2}-V_{02}, \qquad (3,4)$$

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 group of three-phase inverters, V_{01} and V_{02} are the corresponding zero sequence (triplen harmonic components) voltages.

At the same time, control of asymmetrical six-phase induction machines is based on the 30^0-phase-shift of control and output signals of the two mentioned above groups of four inverters [1,13]. As an illustration of control of dual three-phase system with synchronized PWM and with equal voltages of the all DC-sources ($V_{dc1}=V_{dc2}=V_{dc3}=V_{dc4}$), Figs. 2,3 present basic voltage waveforms (pole voltages V_{a1}, V_{a2}, V_{x1}, V_{x2}, line-to-line voltages V_{a1b1}, V_{x1y1}, and the phase voltages V_{as} and V_{xs} (with the spectrum of the V_{as} voltage)) of two groups of inverters, controlled by algorithms of continuous (Fig. 2) and discontinuous with the 30^0-non-switching intervals (Fig. 3) synchronized modulation. The fundamental and switching frequencies of each inverter are equal correspondingly to F=35 Hz and F_s=1 kHz, modulation indices of all inverters are equal to $m_1=m_2=m_3=m_4=0.7$ in this case. The phase output voltage of the system has nine levels (like output voltage of three-level neutral-point-clamped converter) in this control mode. In particular, the presented voltage waveforms have symmetry, and its spectra do not contain even harmonics and sub-harmonics.

In the case of non-equal DC-voltages, if $V_{dc1} \neq V_{dc2}$ and $V_{dc3} \neq V_{dc4}$, but $V_{dc1}=V_{dc3}$ and $V_{dc2}=V_{dc4}$, in order to provide equivalence of the output fundamental voltages (and also power balancing) of two inverters of each inverter group during scalar V/F control of the system, it is necessary to provide linear correlations between its modulation indices and magnitudes of DC-voltages:

TABLE I

BASIC PARAMETERS OF PWM METHODS

Control (modulation) parameter	Conventional schemes of vector PWM	Proposed method of 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)	
		Algebraic PWM	Trigonometric PWM
Switch-on durations	$T_{ak}=1.1mT[\sin(60^0-\alpha_k)+\sin\alpha_k]$ $t_{ak}=1.1mT\sin\alpha_k$ $t_{bk}=1.1mT\times\sin(60^0-\alpha_k)$	$\beta_k=\beta_1[1-A\times(k-1)\tau FK_{ov1}]$ $\gamma_k=\beta_{i-k+1}[0.5-6(i-k)\tau F]K_{ov2}$ $\beta_k-\gamma_k$	$\beta_k=\beta_1\times\cos[(k-1)\tau K_{ov1}]$ $\gamma_k=\beta_{i-k+1}[0.5-0.9m(i-k)\tau]K_{ov2}$ $\beta_k-\gamma_k$
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		$\beta''=\beta_1[1-A\times(k-1)\tau FK_{ov1}]K_s$ $\lambda'=(\tau-\beta'')\times K_{ov1}K_s$	$\beta''=\beta_1\times\cos[(k-1)\tau K_{ov1}]K_s$ $\lambda'=(\tau-\beta'')\times K_{ov1}K_s$

$$m_1 V_{dc1} = m_2 V_{dc2}, \qquad\qquad m_3 V_{dc3} = m_4 V_{dc4}. \qquad\qquad (5,6)$$

Fig. 2

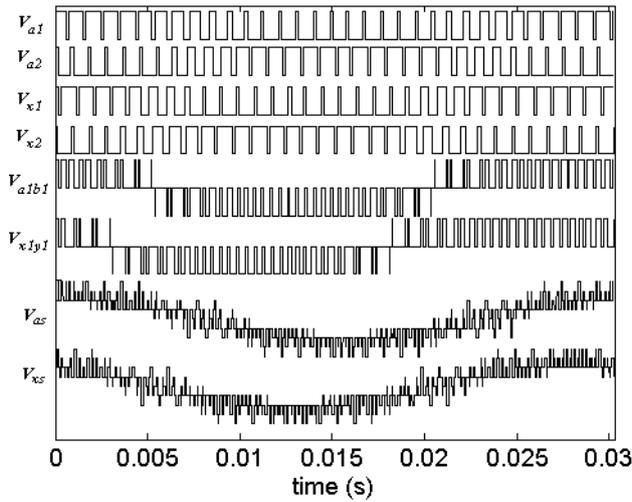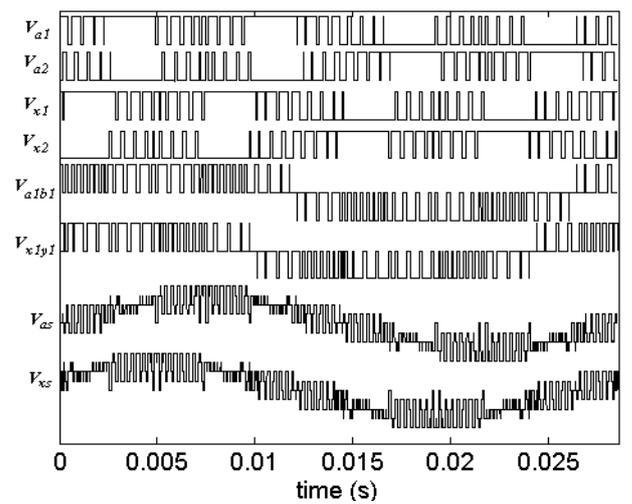**Fig. 3**

In particular, for the case when $V_{dc1}=0.7V_{dc2}$, $V_{dc3}=0.7V_{dc4}$ and $m_2=m_4=0.7$, in accordance with (5)−(6) $m_1=m_3=0.93$, and the last value of modulation indices corresponds to overmodulation control mode of the two corresponding inverters. To illustrate the mentioned above process in dual three-phase drive system on the base of four inverters supplied by four isolated DC-sources with non-equal voltages ($V_{dc1}=0.7V_{dc2}$, $V_{dc3}=0.7V_{dc4}$, $V_{dc2}=V_{dc4}$), Figs. 4, 5 present results of simulation of processes in this system. In particular, Fig. 4 shows basic voltage waveforms and spectra of the V_{a1b1}, V_{a2b2} and V_{as} voltages for the system controlled by algorithms of continuous synchronized PWM. Fig. 5 presents basic voltage waveforms during period of the fundamental frequency for the system with discontinuous synchronized modulation with the 30^0-non-switching intervals, and spectra of the line-to-line and phase voltages of the first group of cascaded inverters. The fundamental and switching frequencies of each inverter are equal to F=35 Hz and F_s =1 kHz. It is necessary to mention, that spectra of the corresponding output voltages of inverters of the second inverter group will have the same nature for the presented control mode.

For dual three-phase drive system on the base of four inverters with non-equal voltages of DC-sources, in order to provide the rated power ratio P_1/P_2 and P_3/P_4 between four power sources of two groups of cascaded inverters (for scalar V/F control mode), it is necessary to provide the corresponding correlations between magnitudes of DC-voltages, modulation indices of four inverters and the rated power ratio in accordance with (7),(8) [12]:

$$\frac{m_1 V_{dc1}}{m_2 V_{dc2}} = \frac{P_1}{P_2}, \qquad\qquad \frac{m_3 V_{dc3}}{m_4 V_{dc4}} = \frac{P_3}{P_4}. \qquad\qquad (7,8)$$

For dual three-phase drive system it is practically important to provide equal power distribution between two groups of inverters feeding asymmetrical six-phase induction motor:

$$P_1+P_2=P_3+P_4. \qquad\qquad (9)$$

For this case, in accordance with (7), (8), for balancing operation of dual three-phase system it is necessary to provide

$$m_1V_{dc1}P_2+m_2V_{dc2}P_1=m_3V_{dc3}P_4+m_4V_{dc4}P_3 \ ,\tag{10}$$

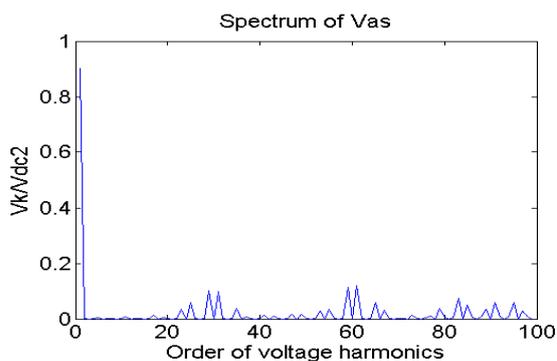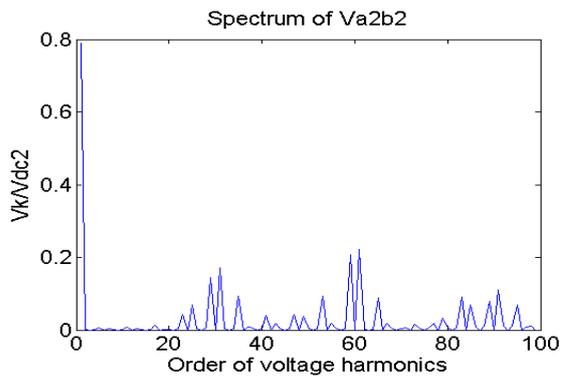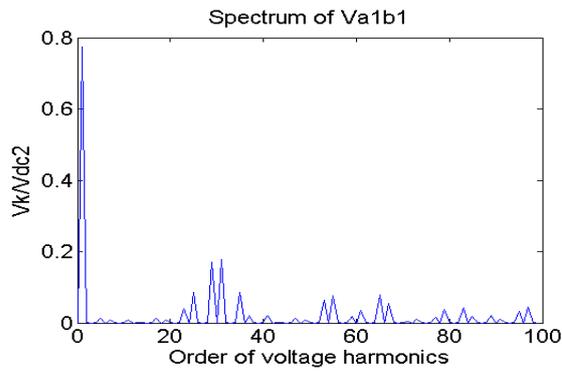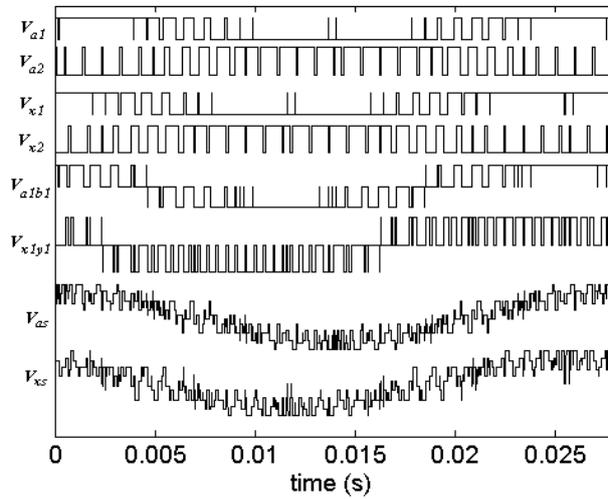where corresponding power of each inverter can be described as relative value of the total power of the system.
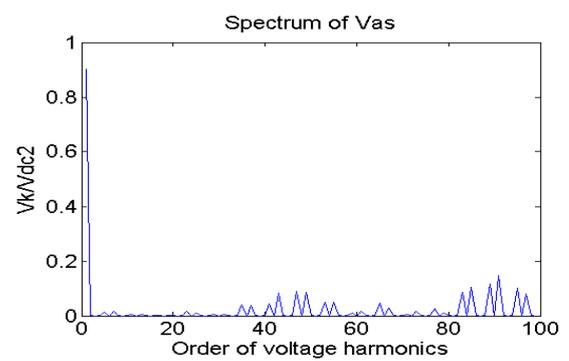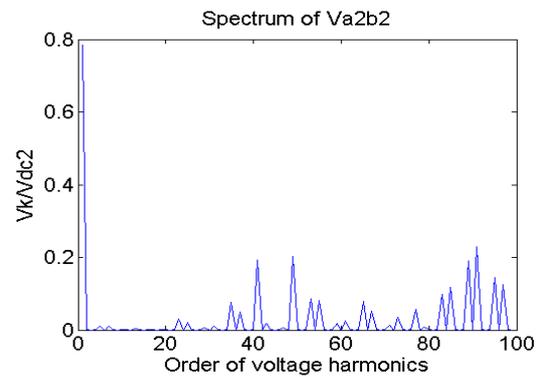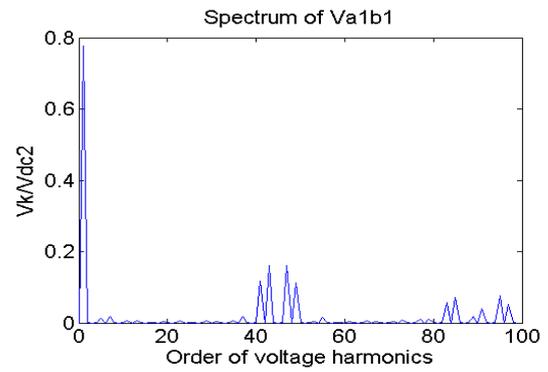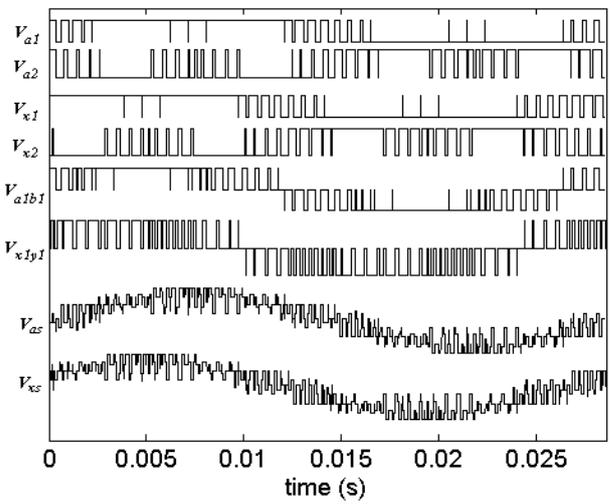

Fig. 4

Fig. 5

As an example of balanced operation of the system with four different levels of DC-voltages, Fig. 6 presents basic voltage waveforms and spectra of the V_{a1b1}, V_{a2b2}, V_{as} and V_{xs} voltages for the dual three-phase system with discontinuous synchronized PWM with the 30^0-non-switching intervals. The fundamental and switching frequencies of each inverter are equal to F=35 Hz and F_s =1 kHz. Relative magnitudes of DC-voltages are equal for this case, as parts of the maximum DC-voltage V_{dc4}:

$$V_{dc1}=0.72V_{dc4}; \qquad V_{dc2}=0.9V_{dc4}; \qquad V_{dc3}=0.75V_{dc4}.$$

Modulation index of the fourth inverter, supplied by the maximum DC-voltage V_{dc4}, is equal to m_4=0.7. Taking in consideration equal power distribution between the corresponding sources ($P_1=P_2=P_3=P_4$), in accordance with (10) modulation indices of the corresponding inverters are equal to:

$$m_1=0.97, \qquad m_2=0.777; \qquad m_3=0.933.$$

So, in this case control modes of the two inverters, of the first and the third, correspond to overmodulation control. The proposed algorithm provides equal magnitudes of the phase fundamental voltages V_{as} and V_{xs} of dual three-phase system (Fig. 6), and, correspondingly, equal power distribution between two sets of three-phase windings of six-phase machine.

The motor phase voltages V_{as} and V_{xs} of six-phase drives on the base of four inverters with both continuous and discontinuous synchronized PWM have symmetry during the whole control range and for any operating conditions (see Figs. 2−6), and its spectra do not contain even harmonics and sub-harmonics,
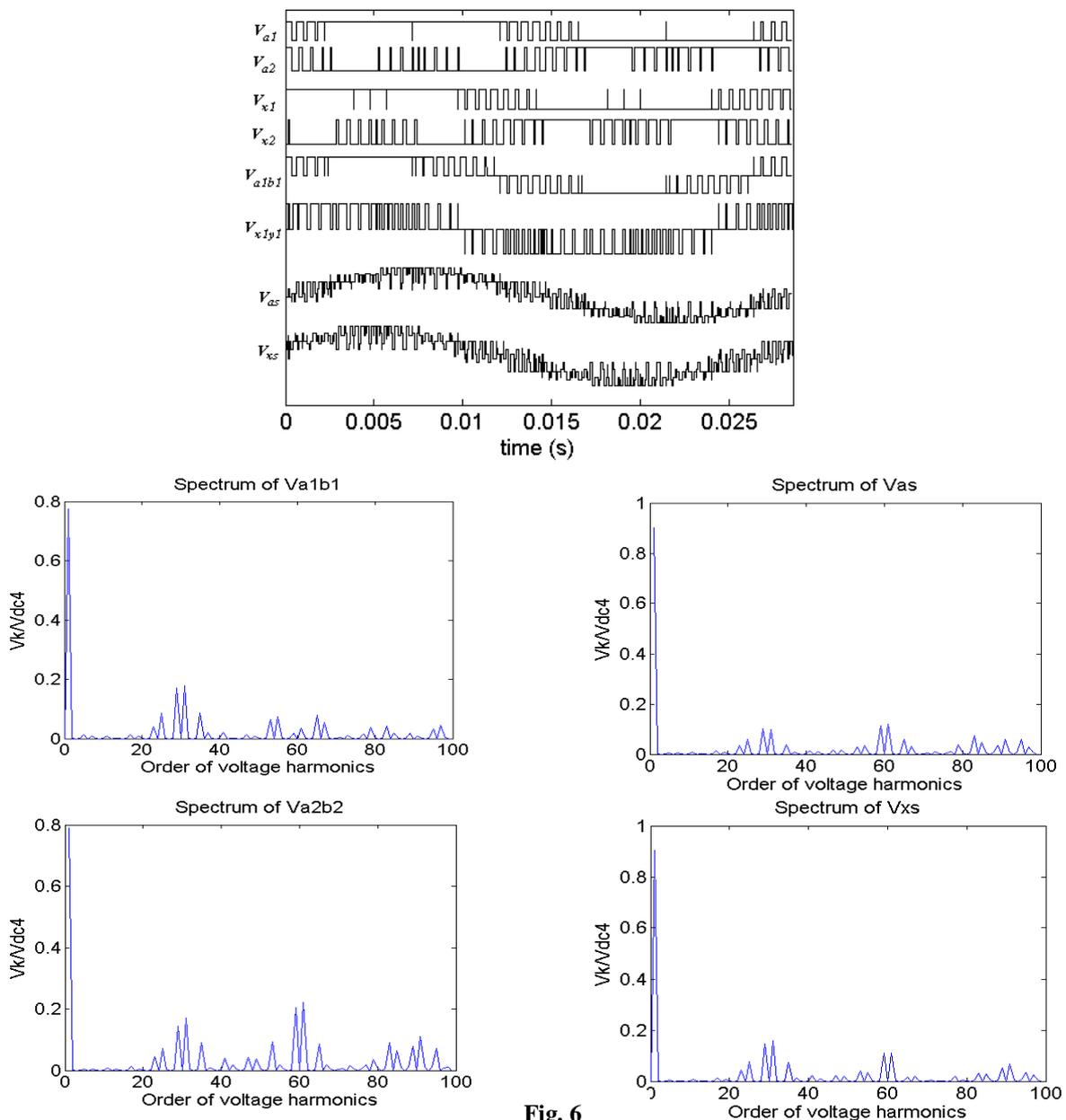

Fig. 6

which is especially important for high power/high current systems.

In order to compare characteristics of asymmetrical dual three-phase (six-phase) systems on the base of two inverters ([1], standard topology of the system), and on the base of four inverters (novel topology of six-phase system [3], analyzed in the paper), Fig. 7, *a* presents calculation results of Weighted Total Harmonic Distortion factor (*WTHD*) versus modulation index m for the motor phase voltage V_{as} (averaged values of

$$WTHD = (V_{as_1})^{-1}[\sum_{k=2}^{1000}(V_{as_k}/k)^2]^{0,5})$$ for the six-phase drive with continuous (CPWM) and discontinuous (DPWM)

schemes of synchronized modulation. In particular, DC-voltage magnitudes are equal in this case for all DC-sources, so, modulation indices of all inverters are equal too. Control mode of the drive system corresponds here to standard scalar *V/F* control, and average switching frequency of each inverter is equal to F_s=1 kHz.
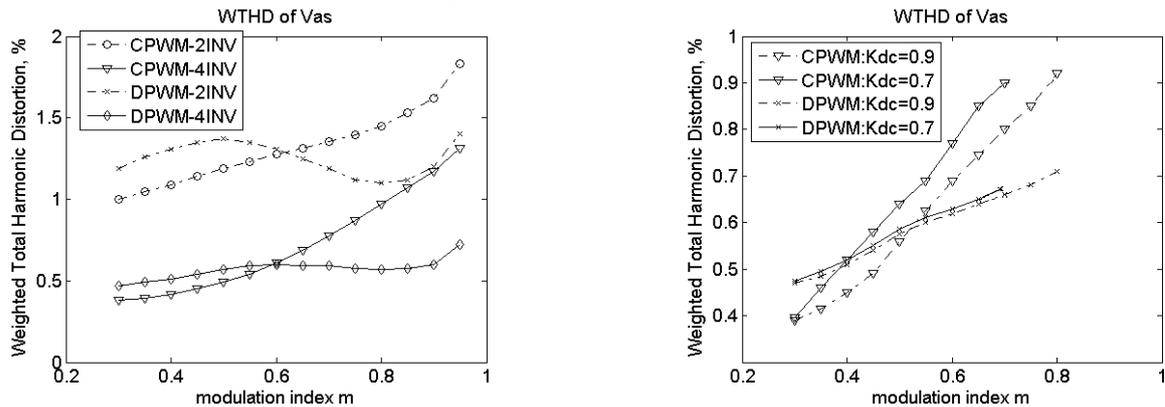

Fig. 7, *a,b*

The presented results show, that integral spectral characteristics of the phase voltage of six-phase system on the base of four inverters are much better, than of the system on the base of two inverters.

Fig. 7, *b* presents results of analysis of spectral composition of the phase voltage V_{as} of dual three-phase system on the base of four inverters with both continuous (CPWM) and discontinuous (DPWM) versions of synchronized PWM for the case of non-equal magnitudes of DC-voltages. In particular, for this case $V_{dc1} \neq V_{dc2}$ and $V_{dc3} \neq V_{dc4}$, but $V_{dc1}=V_{dc3}$ and $V_{dc2}=V_{dc4}$. Two basic control modes have been analyzed: 1) $V_{dc1}=0.9V_{dc2}$, $V_{dc3}=0.9V_{dc4}$, $K_{dc}=0.9$ for this case;
2) $V_{dc1}=0.7V_{dc2}$, $V_{dc3}=0.7V_{dc4}$, $K_{dc}=0.7$ for this case.

The presented results show, that a value of the *WTHD* factor of the phase voltage of six-phase system on the base of four inverters controlled by algorithms of discontinuous synchronized PWM is not strongly sensitive to relative magnitudes of DC-voltages.

Conclusion. Space-vector-based algorithms of synchronized PWM, applied for control of four voltage source inverters feeding asymmetrical dual-three phase (six-phase) induction motor with open-end windings, allow continuous synchronization of the phase voltages in the system for any operating conditions. In particular, it provides voltage synchronization for any ratios (integral or fractional) between the switching and fundamental frequencies, and for any ratios of voltage magnitudes of four DC-sources.

The phase voltages of six-phase drives on the basis of four inverters with synchronized PWM have symmetry during the whole control range, including the zone of overmodulation, and its spectra do not contain even harmonics and sub-harmonics, which is especially important for high power/high current applications.

Simple linear correlations between modulation indices of four three-phase inverters, magnitudes of DC voltages, and required power sharing between inverters provide requiring power balancing between DC sources and equivalence of the phase fundamental voltages of two groups of inverters.

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ул. Академическая, 5, Кишинев, MD-2028, Молдова.
Метод синхронной широтно-импульсной модуляции применительно к управлению четырьмя инверторами напряжения, питающими асимметричный шестифазный асинхронный электродвигатель.
Выполнена диссеминация нового метода синхронной векторной широтно-импульсной модуляции (ШИМ) применительно к управлению четырьмя инверторами напряжения, питающими асимметричный шестифазный асинхронный электродвигатель с разомкнутыми обмотками. Базовые схемы синхронной ШИМ обеспечивают в этом случае как непрерывную синхронизацию фазных напряжений в системе, так и требуемое распределение мощностей между источниками постоянного тока. Результаты моделирования иллюстрируют характер процессов в шестифазной преобразовательной системе с алгоритмами непрерывной и прерывистой синхронной ШИМ. Библ. 19, табл. 1, рис. 7.
Ключевые слова: широтно-импульсная модуляция, инверторы напряжения, асимметричный асинхронный электродвигатель.

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Метод синхронної широтно-імпульсної модуляції щодо керування чотирма інверторами напруги, що живлять асиметричний шестифазний асинхронний електродвигун.
Виконано дисемінацію нового методу синхронної векторної широтно-імпульсної модуляції (ШІМ) щодо керування чотирма інверторами напруги, що живлять асиметричний шестифазний асинхронний електродвигун з розімкненими обмотками. Базові схеми синхронної ШІМ забезпечують у цьому випадку як безперервну синхронізацію фазних напруг у системі, так і необхідний розподіл потужностей між джерелами постійного струму. Результати моделювання ілюструють характер процесів у шестифазній перетворювальній системі з алгоритмами безперервної і переривчастої синхронної ШІМ. Бібл. 19, табл. 1, рис. 7.
Ключові слова: широтно-імпульсна модуляція, інвертори напруги, асиметричний асинхронний электродвигун.