УДК 621.314.572

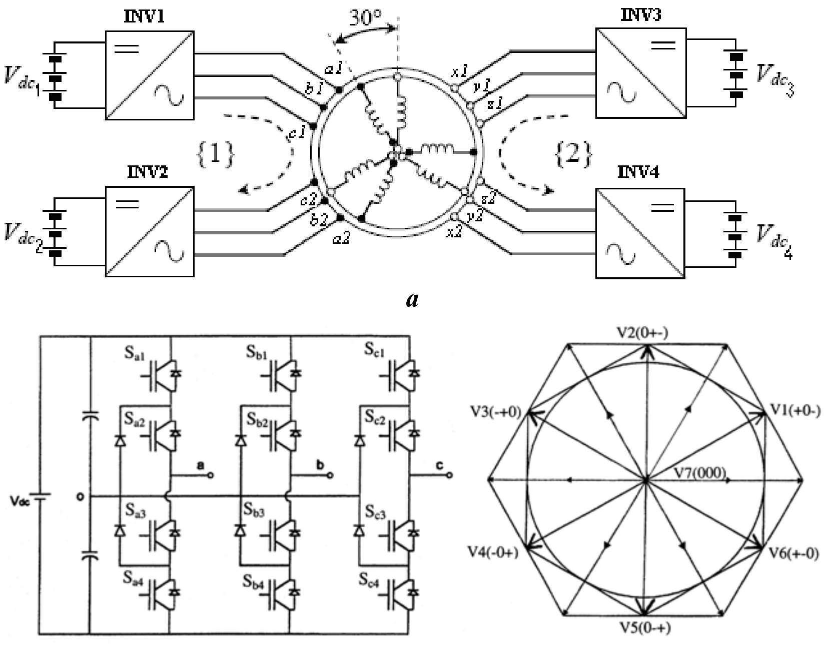
DUAL THREE-PHASE MULTIINVERTER SYSTEM CONTROLLED BY SPECIALIZED ALGORITHMS OF SYNCHRONIZED PWM: MATLAB-BASED STEADY-STATE ANALYSIS

V.Oleschuk, R.Prudeak, A.Sizov
Institute of Power Engineering of the Academy of Sciences of Moldova
Akademicheskaya Str. 5, Kishinev, MD-2028, Moldova
e-mail: oleschukv@hotmail.com

Algorithms of synchronized pulsewidth modulation (PWM), based on special space-vector-based control scheme (with the use of minimal number of voltage space vectors), have been applied for synchronous control of four neutral-point-clamped (NPC) inverters feeding six-phase (dual three-phase) drive on the base of asymmetrical open-end windings induction motor. It allows providing continuous synchronization and symmetry of the phase voltage of system during the whole control range for any ratio of voltage magnitudes of DC-sources, and for any configuration of DC-sources. Therefore, in this case four inverters of the system can be supplied by reduced number of insulated DC-sources (by one, or by two, or by three DC-sources instead of four DC-sources for standard system topology based on four two-level inverters). MATLAB-based simulations show behaviour of the system at steady-state control modes. References 11, table 1, figures 6.
Keywords: neutral-point-clamped inverter, six-phase open-end windings motor drive, modulation strategy, phase voltage synchronization.

Introduction. Six-phase (dual three-phase) induction motor drives can be used successfully in the field of the medium power/high power systems (ship propulsion, more electric aircraft, locomotive, electric vehicles, etc.), which are characterized by low switching frequency of power switches [3], [7].

Recently, a novel four-inverter topology of six-phase system has been proposed (based on four standard three-phase two-level inverters), allowing quadrupling the power capability of a single inverter with given voltage and current rating [2], [8]. Fig. 1, *a* shows generalized structure of this system, consisting of two groups of two inverters, supplying the open-end windings of asymmetrical dual three-phase motor. Induction machine has in this case two sets of winding spatially shifted by 30 el. degrees.



a

b *c*

Fig. 1

It is known, that for drives with increased power and/or current it is necessary to synchronize the output voltage waveforms of converters for elimination of undesirable sub-harmonics of voltage and current [4]. To provide phase voltage synchronization of drive inverters, a novel method of synchronized space-vector PWM has been proposed for standard two-level inverters [1, 6], and for neural-point-clamped inverters [5]. So, this paper presents results of MATLAB-based research of steady-state operation of six-phase system on the base of four neutral-clamped inverters (Fig. 1, *b*) with synchronized PWM with specialized control scheme, based on the use of the minimal number of voltage space vectors, marked by the big arrows in Fig. 1, *c*, which allows elimination of the common-mode voltages in system (Fig. 1, [5]). In this case four NPC inverters can be supplied or by one DC-source, or by 2-4 insulated DC-sources.

Method of synchronized space-vector PWM. Method of synchronized space-vector PWM [1] (disseminated for neutral-point-clamped inverters in [5]) can be used for control of each inverter of six-phase (dual three-phase) drive system. Table presents generalized properties and basic control correlations for the proposed method of synchronized PWM [1]. In particular, this method is based on two-stage strategy of modulation and includes some additional control parameters providing continuous voltage synchronization during the whole control range including the zone of overmodulation. Its basic properties have been compared in Table with conventional scheme of standard asynchronous space-vector modulation.

Control (modulation) parameter	Conventional scheme of space-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 subcycles	T	τ	
Center of the k-signal	α_k (angles/degr.)	$\tau(k-1)$ (sec)	
Switch-on durations	$T_{ak} = 1.1mT[\sin(60^0 - \alpha_k) + \sin\alpha_k]$ $t_{ak} = 1.1mT\sin\alpha_k$ $t_{bk} = 1.1mT \times \sin(60^0 - \alpha_k)$	**Algebraic PWM** $\beta_k = \beta_1[1 - A \times (k-1)\tau F K_{ov1}]$ $\gamma_k = \beta_{i-k+1}[0.5 - 6(i-k)\tau F]K_{ov2}$ $\beta_k - \gamma_k$	**Trigonometric PWM** $\beta_k = \beta_1 \times \cos[(k-1)\tau K_{ov1}]$ $\gamma_k = \beta_{i-k+1}[0.5 - -0.9tn(i-k)\tau]K_{ov2}$ $\beta_k - \gamma_k$
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		$\beta'' = \beta_1[1 - A \times (k-1)\tau F K_{ov1}]K_s$ $\lambda' = (\tau - \beta'') \times K_{ov1}K_s$	$\beta'' = \beta_1 \times \cos[(k-1)\tau K_{ov1}]K_s$ $\lambda' = (\tau - \beta'') \times K_{ov1}K_s$

Operation of dual three-phase system on the basis of four NPC inverters with synchronized PWM. Four inverters of the basic system topology (Fig. 1, *a*) 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. Control of each inverter of each inverter group by algorithms of synchronized PWM provides synchronous symmetrical regulation of voltage in the corresponding induction machine phase windings. Rational phase shift 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) [9].

Phase voltages V_{as} and V_{xs} of the system on the basis of four NPC inverters (Fig. 1) with specialized control scheme, based on the use of only seven voltage vectors marked by the big arrows in Fig. 1, *c* [5], providing elimination of the common-mode voltages, are calculated in accordance with (1)-(2) [10],[11]. Specifically, it corresponds to a two-level operation of neutral-point-clamped inverters.

$$V_{as} = V_{a1} - V_{a2}, \qquad V_{xs} = V_{x1} - V_{x2}, \qquad (1),(2)$$

where V_{a1}, V_{a2}, and V_{x1}, V_{x2}, are the corresponding pole voltages of the corresponding inverter group of three-phase NPC inverters (Fig. 1, *a*).

Two basic schemes of synchronized space-vector PWM have been elaborated for control of neutral-point-clamped inverters with elimination of zero sequence voltage [5],[9], which can be applied for control of the corresponding asymmetrical four-inverter fed open-end winding motor drive. It is necessary to mention, that for power conversion systems on the base of voltage source inverters, the phase and line-to-line output voltages are the most universal characteristics for estimation of processes of electrical power conversion, because output voltage waveforms are in this case almost independent from load parameters [5]. So, the presented estimation of steady-state control modes of four-inverter-based dual three-phase system is based mainly of analysis and comparison of spectra of output voltage waveforms. Also, for more universality of analysis, magnitudes of voltage waveforms in systems (during MATLAB-simulation) are presented as relative values of basic voltage (usually it is basic DC-voltage, and it is equal to V_{dc1}=1 in our case).

As an illustration of steady-state operation of dual three-phase system on the base of four NPC inverters with synchronized PWM, supplied by one common DC-source (or by 2, or by 3, or by 4 DC-sources with equal voltages ($V_{dc1}=V_{dc2}=V_{dc3}=V_{dc4}$ in these cases)), Figs. 2 present results of MATLAB-simulation of processes in the system. Therefore, Fig. 2, present basic voltage waveforms (pole voltages V_{a1}, V_{a2}, V_{x1}, V_{x2}, and the phase voltages V_{as} and V_{xs} (with spectra of the V_{as} (V_{xs}) voltages)) of two groups of inverters, controlled by algorithms of synchronized PWM. Figs. 2, *a*, *b* illustrate processes in system with the "direct-direct" scheme of synchronized PWM (DDPWM [9]), and Figs. 2, *c*, *d* illustrate processes in system

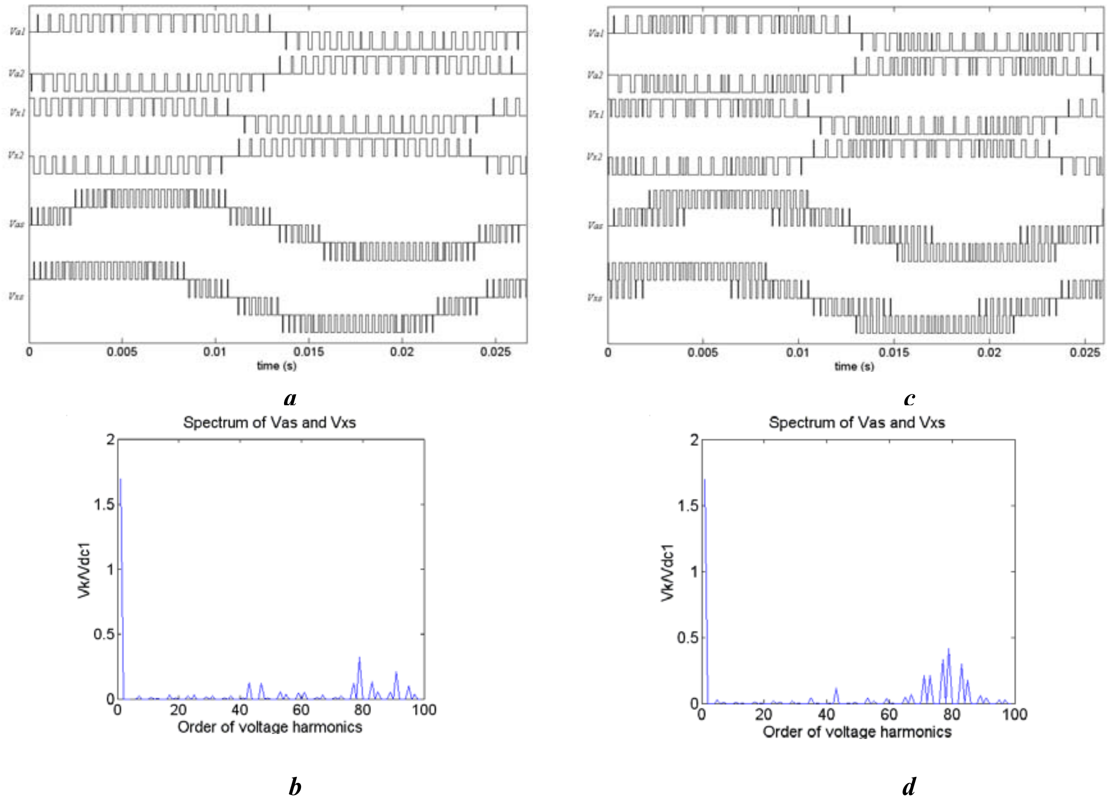

Va1
Va2
Vx1
Vx2
Vas
Vxs
time (s)
a
c
Spectrum of Vas and Vxs
Vk/Vdc1
Order of voltage harmonics
b
d

Fig. 2

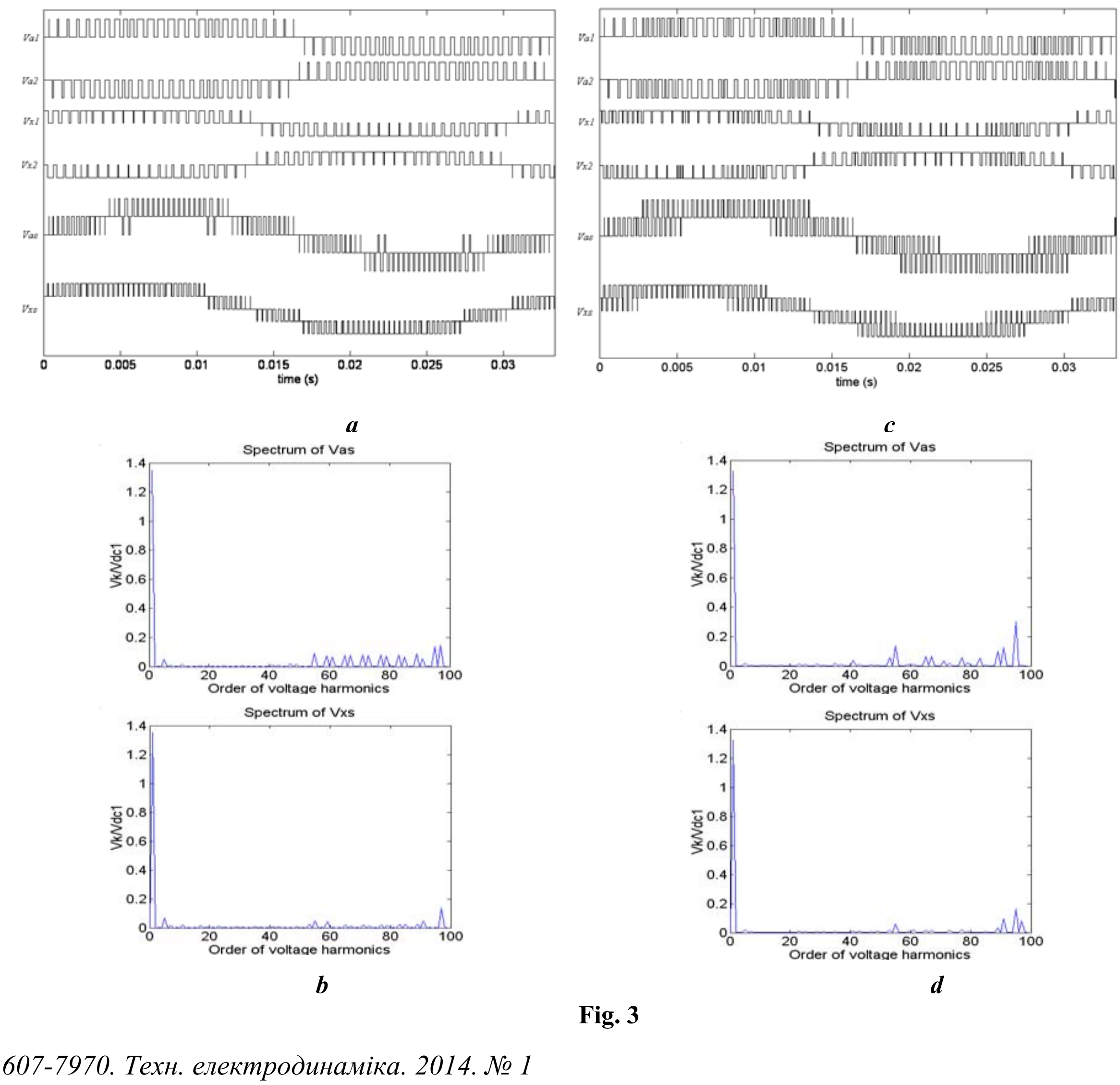

Va1
Va2
Vx1
Vx2
Vas
Vxs
time (s)
a
c
Spectrum of Vas
Spectrum of Vxs
Vk/Vdc1
Order of voltage harmonics
b
d

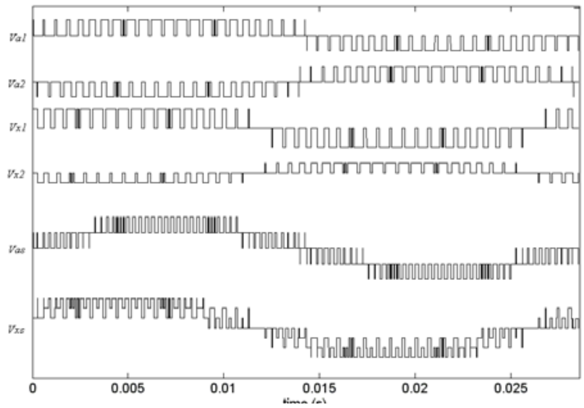
Fig. 3

with discontinuous synchronized PWM (DPWM [9]). The fundamental and switching frequencies of each inverter of the system are equal correspondingly to F = 38 Hz and F_s =1 kHz, modulation indices of all inverters are equal to $m_1=m_2=m_3=m_4$=0.76 in this case. Therefore, the spectra of the presented voltage waveforms do not contain even harmonics and sub-harmonics.

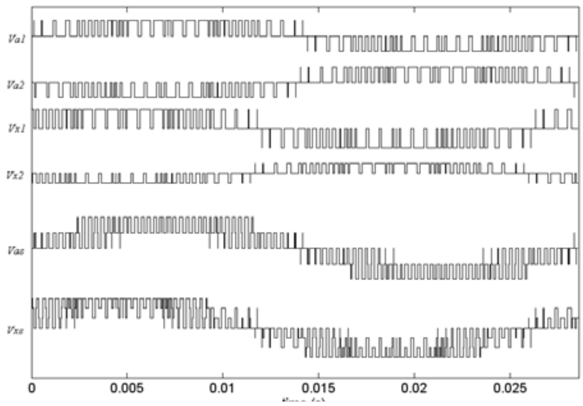
In the case of the topology of four-inverter system with two insulated DC-sources with V_{dc1} and V_{dc3} voltages ($V_{dc1}=V_{dc2}$ and $V_{dc3}=V_{dc4}$ in Fig. 1, *a*), in order to provide equivalence of the output fundamental voltages (and also power balancing) of two groups of NPC inverters during scalar *V/F* control of the system, it is necessary to provide linear correlations between modulation indices of four inverters and magnitudes of DC voltages: $m_1V_{dc1} = m_2V_{dc1} = m_3V_{dc3} = m_4V_{dc3}$ [8]. Fig. 3 illustrate operation of the system with two DC-sources with non-equal DC-voltages, controlled by algorithms of the "direct-direct" scheme of synchronized PWM (Fig. 3, *a, b*), and controlled by algorithms of discontinuous synchronized PWM (Fig. 3, *c, d*). In this case $V_{dc3} = 0.7V_{dc1}$, F = 30 Hz, F_s = 1 kHz, $m_1=m_2$=0.6, $m_3=m_4$=0.86).

In the case of three insulated DC-sources (($V_{dc1} = V_{dc2}$), V_{dc3} and V_{dc4} in Fig. 1, *a*) it is necessary to provide (for scalar *V/F* control mode) the following dependences of modulation indices of four inverters: $m_1V_{dc1} = m_2V_{dc1} = m_3(V_{dc3} + V_{dc4})/2 = m_4(V_{dc3} + V_{dc4})/2$. Fig. 4 illustrate operation of system with synchronized PWM with three DC-sources with non-equal DC-voltages, controlled by algorithms of the "direct-direct" scheme of synchronized PWM (Fig. 4, *a*, *b*), and controlled by algorithms of discontinuous synchronized PWM (Fig. 4, *c, d*). In this case $V_{dc4} = 0.5V_{dc3}$, $V_{dc1} = V_{dc2} = 0.8V_{dc3}$, F = 35 Hz, F_s = 1 kHz, $m_1=m_2$=0.7, $m_3=m_4$=0.74).

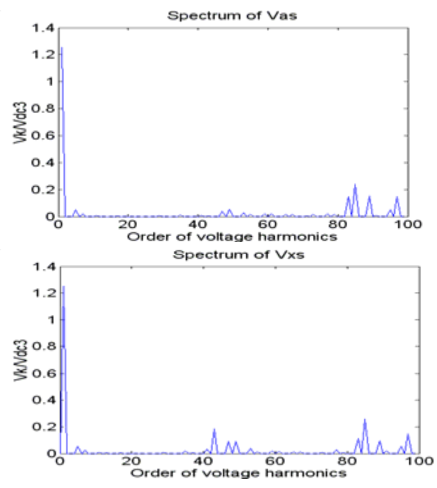
As an illustration of operation of dual three-phase system on the base of four NPC inverters with discontinuous synchronized PWM in the overmodulation zone (PWM algorithms should be modified in this zone [9]), Fig. 5 present basic voltage waveforms with phase voltage spectra correspondingly for the system operated in the first (Fig. 5, *a*, *b* − F=47 Hz, F_s=1 kHz, $m_1=m_2=m_3=m_4$=0.94), and the second (Fig. 5, *c*, *d* − F=49 Hz, F_s=1 kHz, $m_1=m_2=m_3=m_4$=0.98) stages of the zone of overmodulation ($V_{dc1}=V_{dc2}=V_{dc3}=V_{dc4}$ in this case).



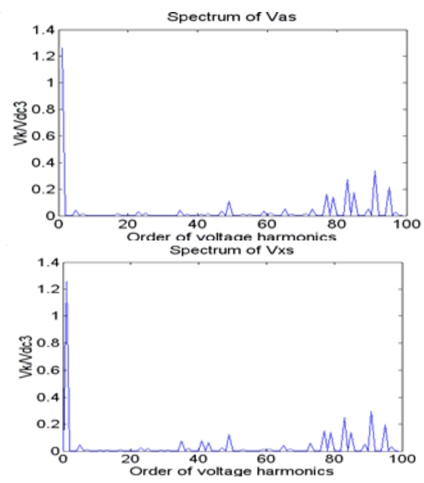
a



c



b



d

Fig. 4

The motor phase voltages V_{as} and V_{xs} of six-phase drives on the basis of four neutral-point-clamped inverters with synchronized PWM have symmetry (quarter-wave symmetry or half-wave symmetry) during the whole control range and for any operating conditions (Figs. 2−5), and its spectra do not contain even harmonics and sub-harmonics, which is especially important for high power/high current applications.

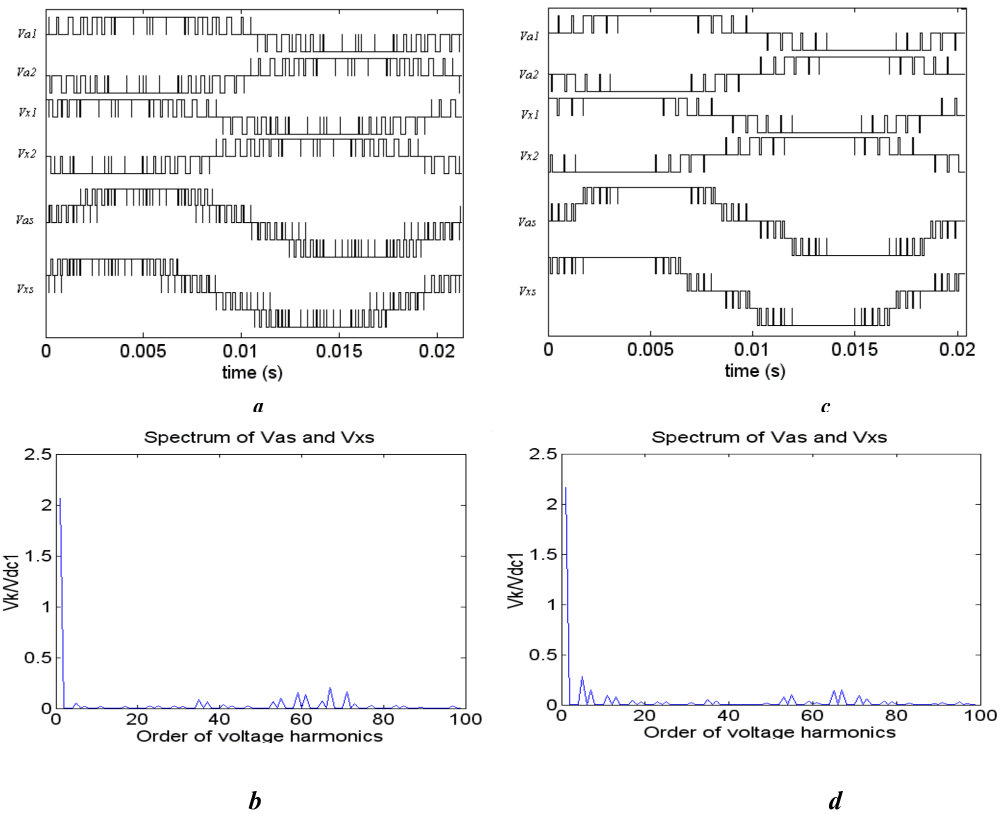


Fig. 5

In order to compare characteristics of asymmetrical dual three-phase (six-phase) systems on the base of two NPC inverters (DPWM-2INV and DDPWM-2INV in Fig. 6), and on the base of four NPC inverters (four-inverter-based topology of six-phase system, analyzed in the paper, DPWM-4INV and DDPWM-4INV in Fig. 6), Fig. 6 presents calculation results of Weighted Total Harmonic Distortion factor (*WTHD*) versus modulation index m for the motor phase voltage V_{as} (averaged values of $WTHD = (1/V_{as_1})(\sum_{k=2}^{1000}(V_{as_k}/k)^2)^{0.5}$) for systems with both discontinuous synchronized modulation (DPWM) and "direct-direct" synchronized PWM (DDPWM). 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 the average switching frequency of each inverter is equal to F_s=1 *kHz*. 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.

Conclusion. Space-vector-based algorithms of synchronized PWM, disseminated for control of four neutral-point-clamped inverters feeding asymmetrical six-phase induction motor with open-end windings, allow continuous synchronization of the phase voltages in the system for any operating conditions. Specialized scheme of control of NPC inverters provides elimination of the common-mode voltages in system, and in this case it is possible to use limited number of insulated DC-sources (one, or two, or three DC-sources instead of four DC-sources of standard topology based on four two-level inverters). Results of MATLAB-based analysis of steady-state control modes of these systems show, that spectra of the phase voltage of dual three-phase drives with algorithms of 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.

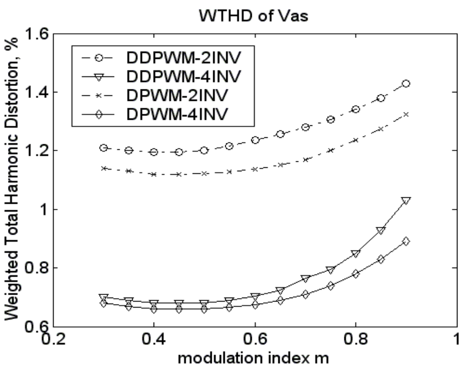


Fig. 6

1. *Blaabjerg F., Oleschuk V., Lungeanu F.* Synchronization of output voltage waveforms in three-phase inverters for induction motor drives // Proc. of the IEEE Power Conversion Conf. – 2002. – Pp. 528−533.

2. *Grandi G., Tani A., Sanjeevkumar P., Ostojic D.* Multi-phase multi-level AC motor drive based on four three-phase two-level inverters // Proc. of the IEEE Int'l Symp. on Power Electr., Electr. Drives, Automation and Motion. – 2010. – Pp. 1768–1775.
3. *Levi E., Bojoi R., Profumo F., Toliyat H.A., Williamson S.* Multiphase induction motor drives – a technology status review // IET Electr. Power Appl. – 2007. – 1, 4. – Pp. 489–516.
4. *Mohan N., Undeland T.M., Robbins W.P.* Power Electronics, 3rd ed. - John Wiley & Sons, 2003. – 587 p.
5. *Oleschuk V., Blaabjerg F.* Three-level inverters with common-mode voltage cancellation based on synchronous pulsewidth modulation // Proc. of the IEEE Power Electronics Specialists Conf. – 2002. – Pp. 863−868.
6. *Oleschuk V., Blaabjerg F., Bose B.K.* Analysis and comparison of algebraic and trigonometric methods of synchronous PWM for inverter drives // Proc. of the IEEE Power Electronics Specialists Conf. – 2002. – Pp. 1439–1444.
7. *Oleschuk V., Bojoi R., Griva G., Profumo F.* Dual inverter-fed traction drive with DC sources power balancing based on synchronized PWM // Proc. of the IEEE Int'l Electr. Machines and Drives Conf. – 2007. – Pp. 260–265.
8. *Oleschuk V., Grandi G., Sangeevkumar P.* Simulation of processes in dual three-phase system on the base of four inverters with synchronized modulation // Advances in Power Electronics. – 2011. – 9 p.
9. *Oleschuk V., Profumo F., Tenconi A., Bojoi R., Stankovic A.M.* Cascaded three-level inverters with synchronized space-vector modulation // Proc. of the IEEE Ind. Application Society Conf. – 2006. – Pp. 595–602.
10. *Oleschuk V., Sizov A.* Basic schemes of synchronized pulsewidth modulation for cascaded inverters of drive system with two DC-sources // Tekhnichna Elektrodynamika. – 2013. – No. 1. – Pp. 34-39.
11. *Reddy B.V., Somasekhar V.T, Kalyan Y.* Decoupled space-vector PWM strategies for a four-level asymmetrical open-end winding induction motor drive with waveform symmetries // IEEE Trans. on Ind. Electronics. – 2011. – 58, 11. – Pp. 5130-5141.

УДК 621.314.572

СДВОЕННАЯ ТРЕХФАЗНАЯ МНОГОИНВЕРТОРНАЯ СИСТЕМА, РЕГУЛИРУЕМАЯ НА БАЗЕ СПЕЦИАЛИЗИРОВАННЫХ АЛГОРИТМОВ СИНХРОННОЙ ШИМ, БАЗИРУЮЩИХСЯ НА MATLAB АНАЛИЗЕ СТАЦИОНАРНЫХ ПРОЦЕССОВ

Олещук В., докт.техн.наук, **Прудяк Р., Сизов А.**
Институт энергетики Академии наук Молдовы,
Кишинев, Молдова **e-mail**: oleschukv@hotmail.com

Выполнено исследование системы шестифазного электропривода с асимметричным электродвигателем с разомкнутыми обмотками, питающимся от четырех инверторов со средней точкой в цепи источника питания, регулируемых на базе специализированных алгоритмов синхронной векторной широтно-импульсной модуляции (ШИМ). Указанные алгоритмы ШИМ, базирующиеся на использовании в схеме управления минимального числа векторов напряжения, позволяют обеспечить непрерывную синхронизацию и симметрию фазных напряжений в системе на всем диапазоне регулирования при любых напряжениях источников постоянного тока и для любых конфигураций цепи источников питания. В частности, в данной топологии системы возможно использование уменьшенного количества отдельных источников электропитания (возможно использовать от одного до трех источников, вместо четырех источников, используемых в преобразовательных системах на базе четырех стандартных двухуровневых инверторов). Приведены результаты математического моделирования (на базе MATLAB) стационарных процессов в системе при различных алгоритмах синхронной ШИМ. Библ. 11, табл. 1, рис. 6.

Ключевые слова: инвертор со средней точкой в цепи источника питания, шестифазный электропривод на базе электродвигателя с разомкнутыми обмотками, стратегия ШИМ, синхронизация фазного напряжения.

ПОДВІЙНА ТРИФАЗНА БАГАТОІНВЕРТОРНА СИСТЕМА, ЩО РЕГУЛЮЄТЬСЯ НА БАЗІ СПЕЦІАЛІЗОВАНИХ АЛГОРИТМІВ СИНХРОННОЇ ШІМ ЗА ДОПОМОГОЮ MATLAB АНАЛІЗУ СТАЦІОНАРНИХ ПРОЦЕСІВ

Олещук В., докт.техн.наук, **Прудяк Р., Сізов А.**
Інститут енергетики Академії наук Молдови, Кишинев, Молдова. **e-mail**: oleschukv@hotmail.com

Виконано дослідження системи шестифазного електропривода з асиметричним електродвигуном з розімкненими обмотками, який живиться від чотирьох інверторів з середньою точкою у колі джерела живлення, що регулюються на базі спеціалізованих алгоритмів синхронної векторної широтно-імпульсної модуляції (ШІМ). Зазначені алгоритми ШІМ, що базуються на використанні в схемі керування мінімальної кількості векторів напруги, можуть забезпечити безперервну синхронізацію та симетрію фазних напруг у системі в усьому діапазоні регулювання при будь-яких напругах джерел постійного струму і для будь-яких конфігурацій кіл джерел живлення. Зокрема, в даній топології системи можливе використання зменшеної кількості окремих джерел електроживлення (1-3 замість чотирьох, які використовуються у перетворювальних системах на базі 4-х стандартних дворівневих інверторів). Представлено результати математичного моделювання (на базі MATLAB) стаціонарних процесів у системі при різних алгоритмах синхронної ШІМ. Бібл. 11, табл. 1, рис. 6.

Ключові слова: інвертор із середньою точкою у колі джерела живлення, шестифазний електропривод на базі електродвигуна з розімкненими обмотками, стратегія ШІМ, синхронізація фазної напруги.

Надійшла 27.03.2013
Остаточний варіант 14.06.2013