# HYBRID SYNCHRONIZED CONTROL OF PWM CONVERTERS OF SIX-PHASE SYSTEM WITH TWO DC SOURCES

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**Abstract –** *Study of dual three-phase (six-phase) drive with open-windings of induction motor, feeding by four inverters with combined PWM control, and supplied by two dc-links, has been executed in the paper. Combined switching strategy and scheme of modulation assures equivalence of the phase fundamental voltages of the system for the case of non-equal voltages of two dc-sources. Symbiosis of combined switching strategy with algorithms of synchronized PWM (applied for separate control of four inverters) insures continuous symmetries of waveforms of the phase voltages, with synchronization of the output voltages of inverters.*
**Keywords –** *induction motor with open-end windings, modulation strategy, PWM voltage control*

# REGLAREA HIBRIDĂ SINCRONIZATĂ A CONVERTIZOARELOR DE TIP MODULAT A SISTEMULUI CU ŞASE FAZE CU DOUĂ SURSE DE CURENT CONTINUU

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**Rezumat –** *S-au studiat procesele în sistemul acţionărilor electrice cu şase faze în baza motorului inductiv cu înfăşurări deschise, alimentată de la patru invertoare de tip modulat şi cu două surse de curent continuu. S-a demonstrat că strategia de control combinat a invertoarelor asigură echivalenţa tensiunilor de fază a sistemului cu şase faze pentru cazul tensiunilor neechilibrate a ambelor surse de curent continuu. Simbioză strategiei de control combinat cu algoritmii modulării sincrone (utilizat la reglarea invertoarelor), asigură simetria şi sincronizarea continuă a formei tensiunilor de fază în sistemul cu şase faze.*
**Cuvinte cheie –** *motor de inducţie cu înfăşurări deschise, strategie de modulare, control sincronizat de tensiune*

# ГИБРИДНОЕ СИНХРОННОЕ РЕГУЛИРОВАНИЕ ШИМ-ПРЕОБРАЗОВАТЕЛЕЙ ШЕСТИФАЗНОЙ СИСТЕМЫ С ДВУМЯ ИСТОЧНИКАМИ ПОСТОЯННОГО ТОКА

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**Реферат –** *Исследованы процессы в сдвоенной трехфазной (шестифазной) системе с двумя источниками постоянного тока на базе асинхронного электродвигателя с разомкнутыми обмотками, питающегося от четырех ШИМ-инверторов. Показано, что использование комбинированной схемы ШИМ-регулирования инверторов позволяет обеспечить равные значения фазных напряжений в шестифазной системе в случае неодинаковых напряжений двух источников постоянного тока. При этом благодаря симбиозу гибридной схемы управления инверторами с алгоритмами синхронной модуляции, на всем диапазоне регулирования обеспечивается симметрия и синхронизация форм фазных выходных напряжений системы шестифазного электропривода.*
**Ключевые слова –** *электродвигатель с разомкнутыми обмотками, стратегия модуляции, регулирование напряжения*

## 1. INTRODUCTION

Nowadays, multiphase converters and drives are powerful alternative of existing three-phase solutions for the medium-power and high-power adjustable speed drive systems [1]-[2].

Topology of six-phase drive systems with asymmetrical induction machine with two sets of winding, spatially shifted by 30 el. degrees, can be based on four inverters, supplying open-end windings of ac motor [3]-[4]. Structure of such system (with two dc-links) based on control with elimination of common-mode voltages is presented in Fig. 1.

In this case increased number of inverters allows using combinations of schemes and techniques of modulation for control of inverters of the system. So, this paper presents results of analysis of operation of six-phase system with hybrid switching strategy of modulated three-phase inverters.

## 2. SWITCHING SCHEMES PROVIDING ELIMINATION OF COMMON MODE VOLTAGES

To insure elimination of undesirable common-mode voltages in drives on the base of cascaded inverters, special PWM techniques can be used [5]-[6]. Fig. 2 illustrates switching scheme (voltage space vectors) perspective for control of cascaded inverters of six-phase system (conventional definition of switching sequences **1, 3,-5** (for the first inverter of each section) and **1', 3', 5'** (for the second inverter of the same section) is used here [6]).

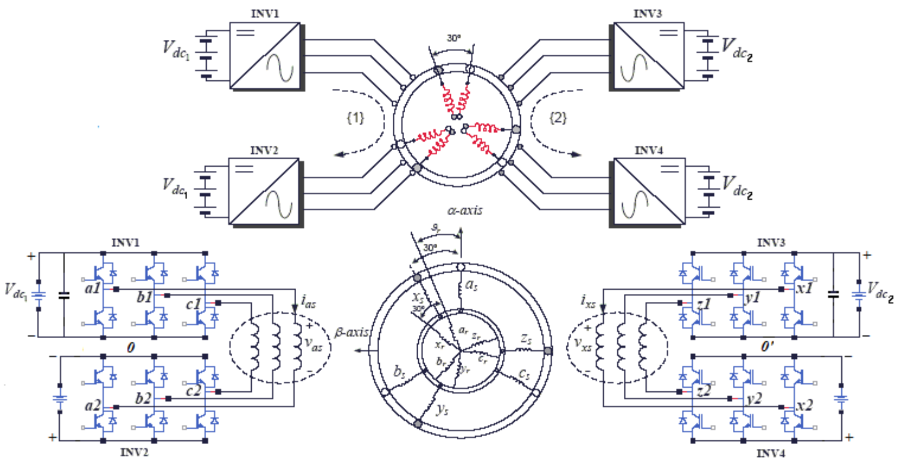



Fig. 1. Six-phase drive on the basis of four inverters (**INV1+INV2**, as the first group, and **INV3+INV4**, as the second group) and with open-end winding asymmetrical six-phase induction motor.

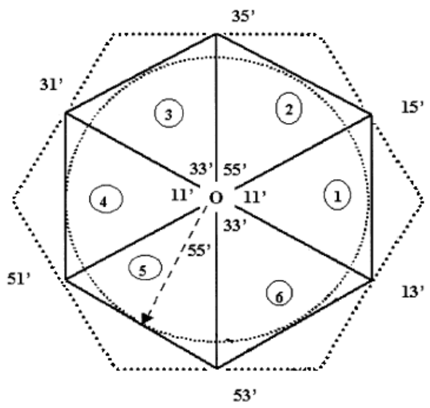



Fig. 2. Sequences of voltage space-vectors of dual inverters assuring cancellation of alternative common-mode voltages in drive system.

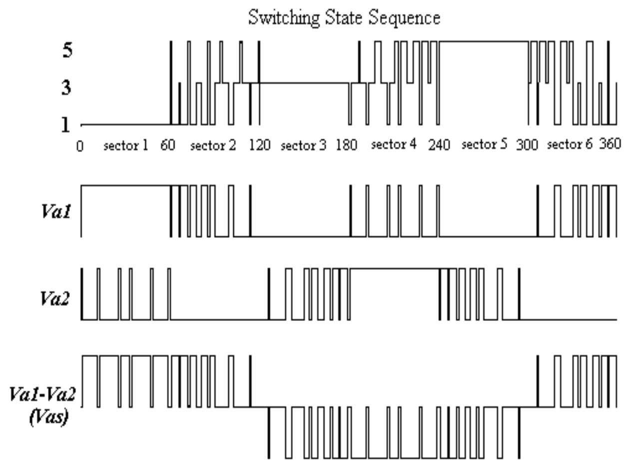



Fig. 3. Control signals and waveforms of the output voltage of the first group of inverters **INV1+INV2** with **NCMPWM1** control algorithm.

Fig. 3 presents switching states and basic voltages (pole voltages $V_{a1}$ and $V_{a2}$, and the phase voltage of the system $V_{as}$= $V_{a1}$-$V_{a2}$, controlled by one of two basic strategies of pulsewidth modulation of dual inverters with cancellation of common-mode voltage (*No-Common-Mode voltage Pulse Width Modulation 1 (NCMPWM1)*). Figs. 4-7 show the corresponding curves of the second basic version of such PWM strategy for dual inverters *(NCMPWM2).*

In order to provide voltage waveform symmetries of modulated inverters, method of synchronized PWM [7]-[8] can be used. Equations (1)-(6) present set of control dependences for calculation of duration of signals of inverters with synchronous PWM in absolute values (seconds) for scalar *V/F* control regime mode of installation during the whole control diapason [7]-[8]:

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

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

$$\gamma_j = \beta_{i-j+1}\{0.5 - 0.87\tan[(i-j-K_3)\tau]\}K_{ov2} \qquad (2)$$

$$\beta_i = \beta^{"} = \beta_1 \cos[(i-K_3-1)\tau K_{ov1}]K_s \qquad (3)$$

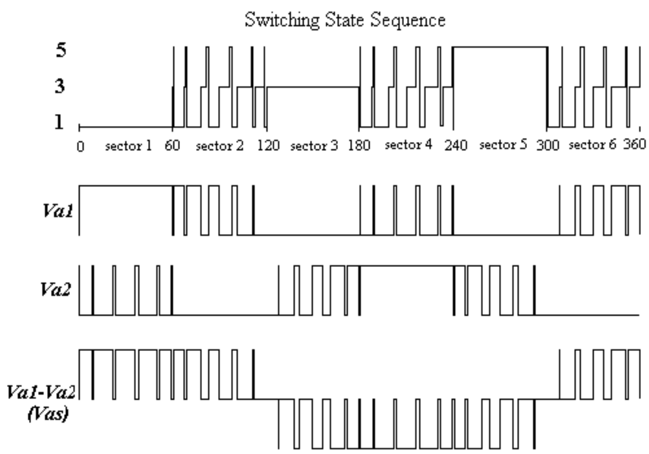



Fig. 4. Control signals and waveforms of the output voltage of the first group of inverters *INV1+INV2* with *NCMPWM2* control algorithm.

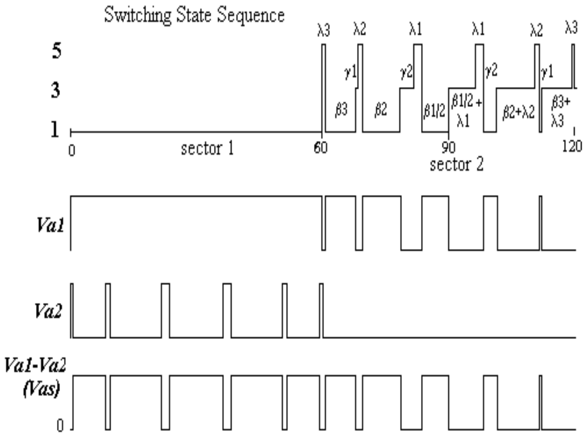



Fig. 5. Control signals and waveforms of the output voltage of the first group of inverters *INV1+INV2* with *NCMPWM2* control algorithm (in sectors 1- 2, in accordance with Fig. 4).

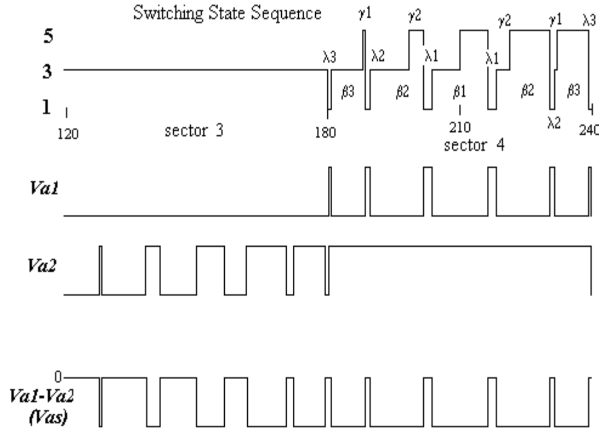



Fig. 6. Control signals and waveforms of the output voltage of the first group of inverters *INV1+INV2* with *NCMPWM2* control algorithm (in sectors 3-4, in accordance with Fig. 4).

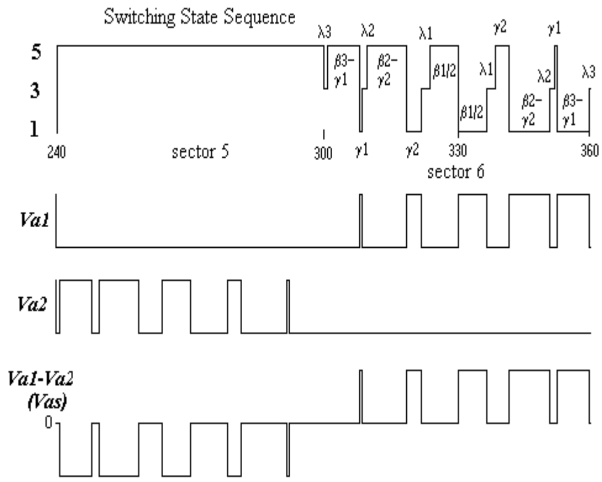



Fig. 7. Control signals and waveforms of the output voltage of the first group of inverters *INV1+INV2* with *NCMPWM2* control algorithm (in sectors 5-6, in accordance with Fig. 4).

$$\gamma_1 = \beta^{''}\{0.5 - 0.87\tan[(i - K_3 - 2)\tau + (\beta_{i-1} + \beta_i + \lambda_{i-1})/2]\}K_s K_{ov2} \quad (4)$$

$$\lambda_j = \tau - (\beta_j + \beta_{j+1})/2 \quad (5)$$

$$\lambda_i = \lambda^{'} = \left(\tau - \beta^{''}\right)K_{ov1}K_s\,, \quad (6)$$

where: $\beta_1 = 1.1\tau m$ until $F_{ov1} = 0.907F_m$ , and $\beta_1 = \tau$ after $F_{ov1}$ ; $K_s = [1-(F-F_i)/(F_{i-1}-F_i)]$ - coefficient of synchronization; coefficient of overmodulation $K_{ov1} = 1$ until $F_{ov1}$, and $K_{ov1} = [1-(F-F_{ov1})/(F_{ov2}-F_{ov1})]$ between $F_{ov1}$ and $F_{ov2} = 0.952F_m$ ; 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 continuous versions of synchronous PWM), and $K_3=0.25$ (for discontinuous version of synchronous pulsewidth modulation).

## 3. MODELING AND SIMULATION OF SIX-PHASE SYSTEM WITH HYBRID CONTROL OF INVERTERS

Figs. 8 – 15 present results of MATLAB simulation (in the general form, with normalized voltages of the system) of six-phase system on the basis of four (two + two) cascaded inverters (Fig. 1). The first inverter group *(INV1+INV2)* is controlled by *NCMPWM1* control scheme, and the second inverter group *(INV3+INV4)* is controlled by *NCMPWM2* control algorithm. Determination of voltage pulse patterns of inverters is based in this case on techniques of synchronous pulsewidth modulation (1)-(5).

Figs. 8 – 9 show output voltages and spectral composition of two phase voltages for the system with equal voltages of dc-links, operating in the zone of low fundamental frequency ($F=20Hz$, coefficients of modulation of four inverters $m_1=m_2=m_3=m_4=0.4$). Switching frequency of inverters is equal to $F_s=1kHz$ for the all presented control modes.

Figs. 10 – 11 present output voltages and harmonic composition of the phase voltages of system with unequal dc-voltages ($V_{dc2}=0.75V_{dc1}$, $m_1=m_2=0.7$, $m_3=m_4=0.933$), operating in the zone of medium fundamental frequency ($F=35Hz$).

Figs. 12 – 13 show output voltages and spectra of the phase voltages for the system with other distribution of unequal dc-sources ($V_{dc1}=0.8V_{dc2}$, $m_1=m_2=0.875$, $m_3=m_4=0.7$, $F=35Hz$).

Figs. 14 - 15 illustrate operation of system with equal voltages of dc-links in the zone of higher fundamental frequency (in the zone of overmodulation, $F=47{,}5Hz$, $m_1=m_2=m_3=m_4=0.95$).

Presented in Figs. 9, 11, 13, 15 spectrograms show, that spectra of the phase voltages of six-phase system with hybrid control and modulation strategy of inverters include only odd (non-triplen) components, without other undesirable spectral components. Comparison of spectrograms, presented in Fig. 11 and Fig. 13, shows, that the proposed hybrid switching techniques of inverters insure, by the corresponding linear variation of coefficients of modulation of inverters, equal value of the fundamental harmonics of the phase voltages for different ratios between magnitudes of dc-voltages of six-phase system.

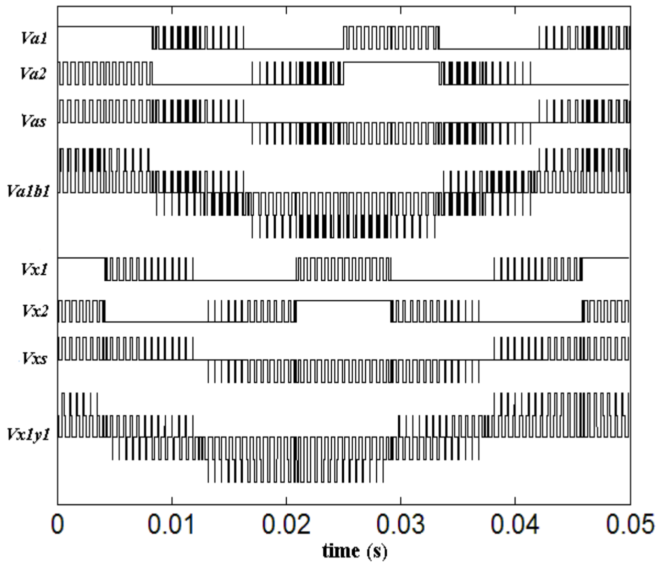



Fig. 8. Basic voltage waveforms of six-phase system with combined control strategy of dual inverters *(NCMPWM1 + NCMPWM2, F=20Hz,* $V_{dc1}=V_{dc2}$*,* $m_1=m_2=m_3=m_4=0.4$*,* $F_s=1kHz$*).*

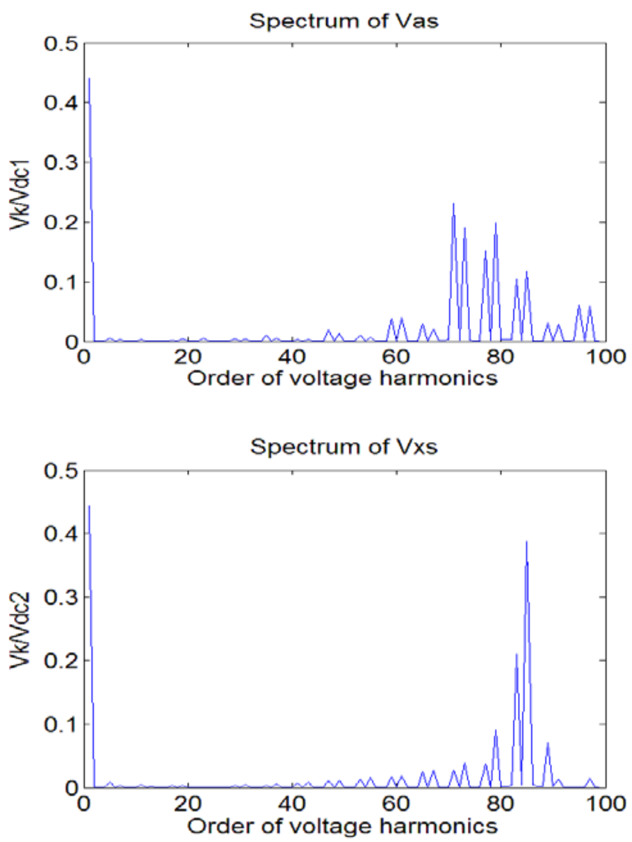



Fig. 9.Spectral composition of the phase voltages $V_{as}$ and $V_{xs}$ of six-phase system with hybrid switching strategy of inverters (*F=20Hz,* $F_s=1kHz$).

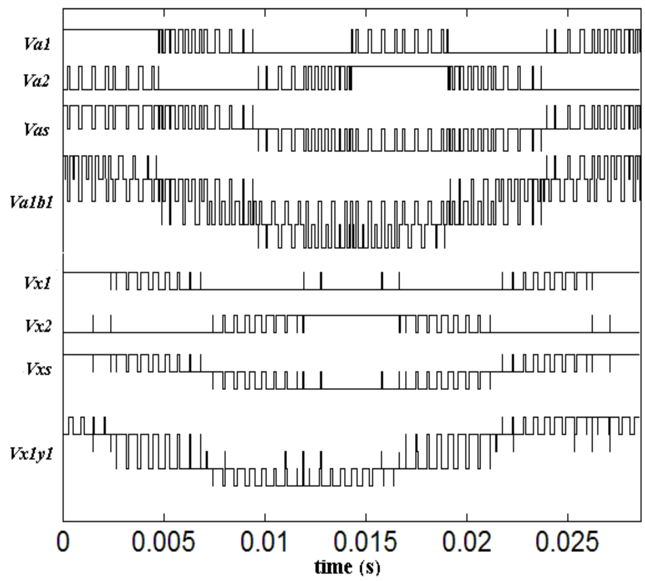



Fig. 10. Basic voltage waveforms of six-phase system with combined control strategy of dual inverters *(NCMPWM1 + NCMPWM2, F=35Hz,* $V_{dc2}=0.75V_{dc1}$*,* $m_1=m_2=0.7$*,* $m_3=m_4=0.933$*,* $F_s=1kHz$*).*

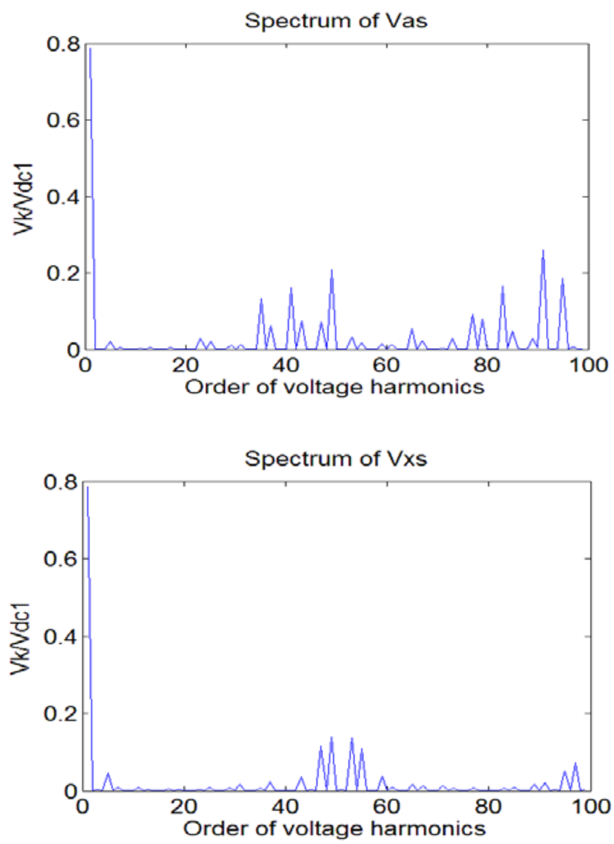
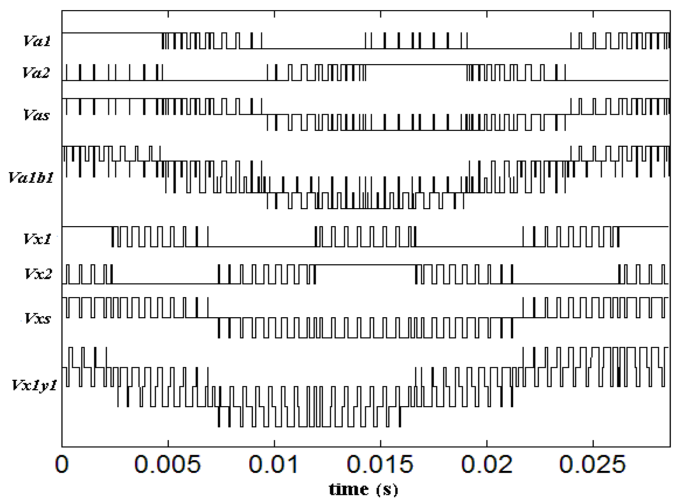



Fig. 11. Spectral composition of the phase voltages $V_{as}$ and $V_{xs}$ of six-phase system with hybrid switching strategy of inverters (*F=35Hz,* $F_s=1kHz$*,* $V_{dc2}=0.75V_{dc1}$).



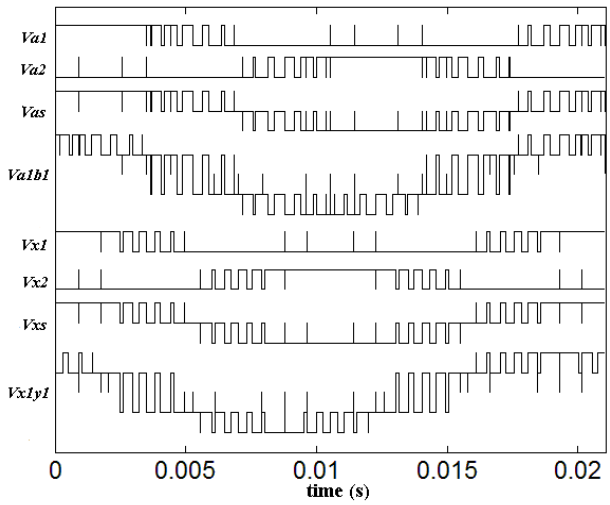




Fig. 12. Basic voltage waveforms of six-phase system with combined control strategy of dual inverters *(NCMPWM1 + NCMPWM2, F=35Hz,* $V_{dc1}=0.8V_{dc2}$*,* $m_1=m_2=0.875$*,* $m_3=m_4=0.7$*,* $F_s=1kHz$*).*

Fig. 14. Basic voltage waveforms of six-phase system with combined control strategy of dual inverters *(NCMPWM1 + NCMPWM2, F=47.5Hz,* $V_{dc1}=V_{dc2}$*,* $m_1=m_2=m_3=m_4=0.95$*,* $F_s=1kHz$*).*

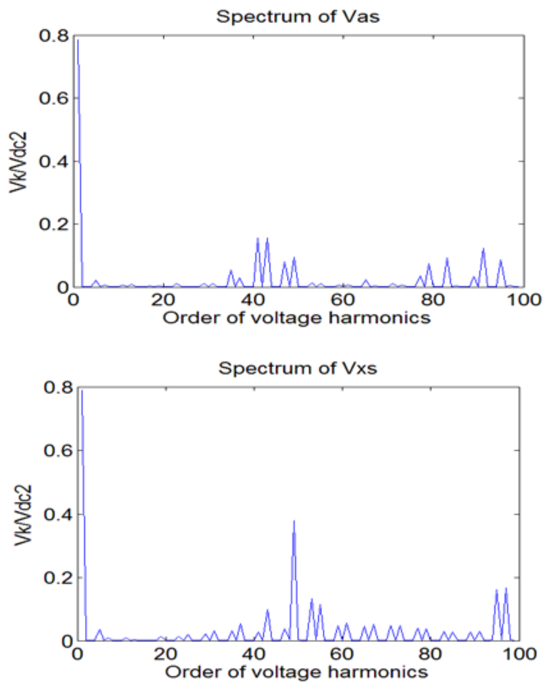



Fig. 13. Spectral composition of the phase voltages $V_{as}$ and $V_{xs}$ of six-phase system with hybrid switching strategy of inverters ($F=35Hz$, $F_s=1kHz$, $V_{dc1}=0.8V_{dc2}$).

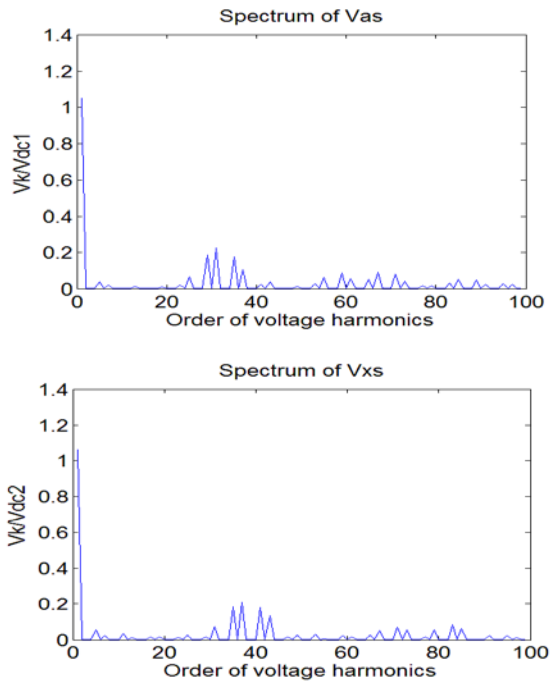



Fig. 15. Spectral composition of the phase voltages $V_{as}$ and $V_{xs}$ of six-phase system with hybrid switching strategy of inverters ($F=47.5Hz$, $F_s=1kHz$).

For comparison of integral harmonic characteristics of phase voltages of asymmetrical dual three-phase (six-phase) system with hybrid switching strategy of modulated inverters, Fig. 16 presents calculation results of averaged Weighted Total Harmonic Distortion factor (*WTHD*) versus coefficient of modulation *m* ($m_1$) 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 the two mentioned above control schemes (*NCMPWM1 and NCMPWM2*), for conventional *V/Hz* adjustment mode of the system ($F_s=1kHz$). Three control modes have been analyzed:

a) $V_{dc1}=V_{dc2}$ (solid curves in Fig. 16);
b) $V_{dc2}=0.85V_{dc1}$ (dash-dot lines in Fig. 16);
c) $V_{dc2}=0.7V_{dc1}$ (dotted lines in Fig. 16).

The presented results of determination of integral spectral characteristics of the phase voltage of six-phase system show big dependences of quality of the phase voltage from relationship of dc voltages of two dc-links of the system.

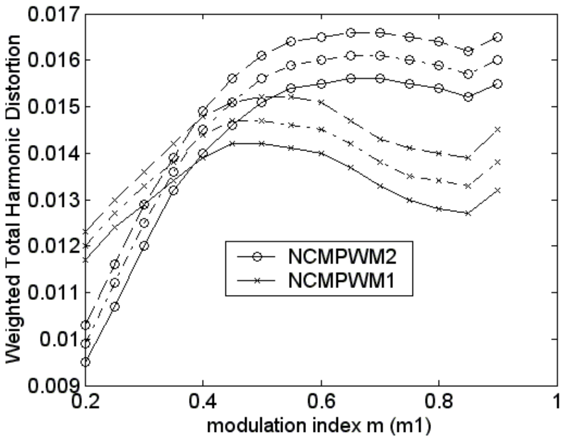



Fig. 16. Averaged *WTHD* factor of the phase voltage $V_{as}$ versus coefficient of modulation $m\ (m_1)$ for six-phase system with hybrid switching strategy of modulated inverters.

## 4. CONCLUSION

It has been shown possibility of hybridization of switching strategies for modulated inverters of six-phase multi-inverter drive. Hybrid switching techniques can be used successfully for control of power system (with low switching frequency of inverters) with non-equal voltages of dc-links. In this case the proposed combined switching techniques of inverters insure, by the corresponding linear variation of coefficients of modulation of inverters, equal magnitude of the fundamental harmonics of the phase voltages for different ratios between dc-voltages of six-phase system. Combination of hybrid switching schemes with algorithms of synchronous PWM for control of inverters assures waveform symmetries of the phase voltages of the system. Voltage spectrograms do not contain in this case undesirable sub-harmonics.

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