SYNCHRONOUS PWM CONTROL OF SYMMETRICAL DUAL THREE-PHASE DRIVE IN THE OVERMODULATION ZONE

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Abstract. The analysis of operation of symmetrical six-phase (dual three-phase) ac drive system (which is a promising solution for the medium-power and high-power applications) with synchronized pulse-width modulation (PWM) during overmodulation has been performed. The induction machine of this system topology has two sets of windings spatially shifted by 60 electrical degrees with isolated neutral points, which are connected with two standard three-phase inverters. Algorithms of synchronized PWM provide continuous synchronization of the phase voltage of the system in the zone of overmodulation. Simulation results are given for dual three-phase systems with two discontinuous versions of synchronized PWM and with combined synchronized scheme of pulsewidth modulation.

Key words: symmetric six-phase induction motor, converter control, modulation strategy, phase voltage synchronization.

REGLAREA SINCRONĂ A ACŢIONARULII ELECRTIC SIMETRIC DUBLU TRIFAZAT ÎN ZONA DE SUPRAMODULARE

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Rezumat. A fost efectuată analiza funcţionării actionarului elecrtic simetric dublu trifazat (şase faze) în zona de supramodulare (fiind de perspectiva pentru aplicare în sisteme de putere medie şi mare), reglate în baza algoritmilor modulaţiei sincrone prin impulsuri de durată variabilă. Motorul electric asincron al sistemului include în acest caz două grupuri de înfăşurări trifazate cu fir neutru izolat, cu decalaj de 60 grade electrice faţă de celelalt, care sunt conectate prin doua invertoare trifazate standard. Algoritmi modulaţiei sincrone asigură sincronizarea continuă a curbelor tensiunii fazice ale sistemului în zona de supramodulare. Sunt prezentare rezultatele simulării proceselor în sisteme cu două versiuni a modulatiei sincrone discontinue, precum şi într-un sistem cu modulare sincronă combinată.

Cuvinte-cheie: motor electric simetric cu şase faze, controlul convertizoarelor, strategia modulaţiei, sincronizarea curbei tensiunii fazice.

СИНХРОННОЕ РЕГУЛИРОВАНИЕ СИММЕТРИЧНОГО СДВОЕННОГО ТРЕХФАЗНОГО ЭЛЕКТРОПРИВОДА В ЗОНЕ СВЕРХМОДУЛЯЦИИ

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Аннотация. Выполнен анализ функционирования в зоне сверхмодуляции шестифазного (сдвоенного трехфазного) электропривода переменного тока (перспективного для использования в системах средней и большой мощности), регулируемого на базе алгоритмов синхронной широтно-импульсной модуляции (ШИМ). Асинхронный электродвигатель системы включает в этом случае две трехфазные группы обмоток с изолированными нейтралями, пространственно сдвинутых на 60 эл. градусов относительно друг друга, и соединенных с двумя стандартными инверторами напряжения. Алгоритмы синхронной ШИМ обеспечивают при этом непрерывную синхронизацию кривых фазных напряжений в системе в зоне сверхмодуляции. Приведены результаты моделирования процессов в системах с двумя разновидностями прерывистой синхронной ШИМ, а также в системе с комбинированной синхронной модуляцией.

Ключевые слова: симметричный шестифазный электродвигатель, управление преобразователями, стратегия модуляции, синхронизация фазного напряжения.

Introduction

Multiphase converters and adjustable speed drives have an increasing interest in the last years due to some advantages compared with standard three-phase systems. One of the perspective structures of multiphase systems is symmetrical six-phase (dual three-phase) induction motor drive fed by two three-phase voltage source inverters [1]-[4]. The induction machine has in this case two sets of windings spatially shifted by 60 electrical degrees with isolated neutral points (Fig.1).

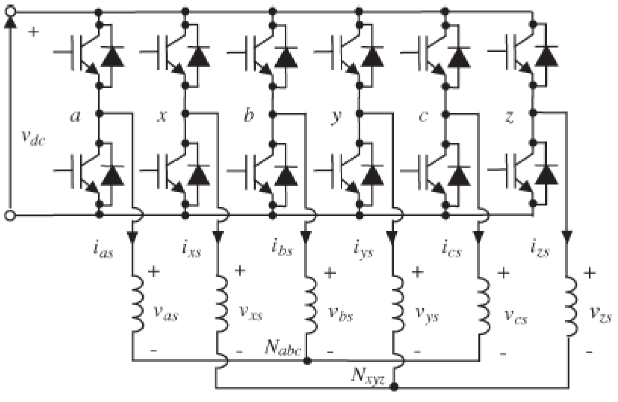


Fig.1. Dual three-phase (six-phase) motor drive with two neutral points

Dual three-phase motor 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 [5].

High power/high current drives (ship propulsion, locomotive, electrical vehicles, etc.) are perspective area of application of six-phase drives. These power systems are characterized by low switching frequency 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 [6]-[7].

To provide continuous synchronization of the motor phase voltage of six-phase drives, novel method (methodology) of synchronized PWM has been disseminated for control of dual three-phase drives in the undermodulation region for both asymmetrical [8] and symmetrical [9] six-phase systems.

At the same time, control and modulation strategies for drive systems have specific peculiarities at the highest fundamental frequencies. So, this paper presents further development of a new method of PWM, applied for synchronous control of symmetrical six-phase converters in the zone of overmodulation.

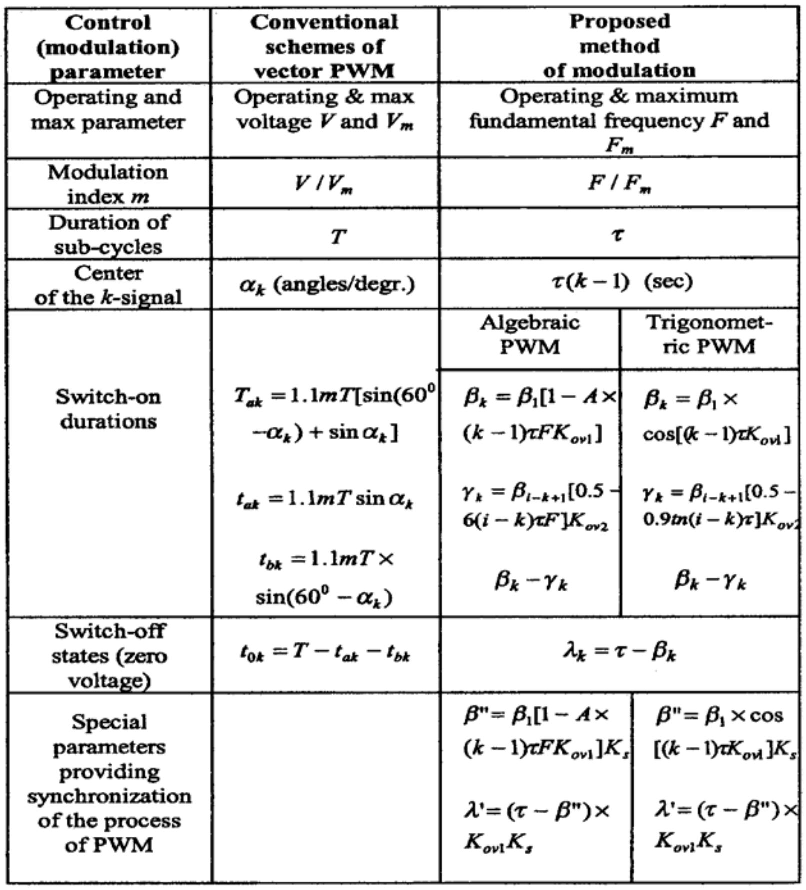
Basic peculiarities of synchronized pulsewidth modulation

In order to avoid asynchronism of conventional versions of voltage space-vector modulation, novel method of synchronized PWM can be used for control of each inverter in a six-phase motor drive system [8]-[10].

Table I presents generalized properties and basic control correlations for the proposed method of synchronized PWM. Basic control functions are available for both undermodulation and overmodulation control zones in this case. It is also compared here with conventional asynchronous space- vector modulation. A more detailed description of laws and algorithms of synchronized PWM based on either algebraic or trigonometric control functions is in [10].

In the general case, control of symmetrical six-phase induction machine drive, at both undermodulation and overmodulation regions, is based on the 60^0-phase-shift of control and output signals of two inverters [1],[3],[9].

Table 1. 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)	
Switch-on durations		Algebraic PWM	Trigonometric PWM
	$T_{ak}=1.1mT[\sin(60^0-\alpha_k)+\sin\alpha_k]$	$\beta_k=\beta_1[1-A\times(k-1)\tau FK_{ov1}]$	$\beta_k=\beta_1\times\cos[(k-1)\tau K_{ov1}]$
	$t_{ak}=1.1mT\sin\alpha_k$	$\gamma_k=\beta_{i-k+1}[0.5-6(i-k)\tau F]K_{ov2}$	$\gamma_k=\beta_{i-k+1}[0.5-0.9\tau n(i-k)\tau]K_{ov}$
	$t_{bk}=1.1mT\times\sin(60^0-\alpha_k)$	$\beta_k-\gamma_k$	$\beta_k-\gamma_k$
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		$\beta"=\beta_1[1-A\times(k-1)\tau FK_{ov1}]K_s$ $\lambda'=(\tau-\beta")\times K_{ov1}K_s$	$\beta"=\beta_1\times\cos[(k-1)\tau K_{ov1}]K_s$ $\lambda'=(\tau-\beta")\times K_{ov1}K_s$

Synchronous overmodulation control of dual three-phase converters

In accordance with the theory of vector space decomposition, the basic six-dimensional space (*as, bs, cs, xs, ys, zs*) of a dual three-phase induction machine with isolated neutral points can be transformed into two orthogonal two-dimensional subspaces (*sa, sb*) and (*m1, m2*) [1]. Voltage components V_{sa} and V_{m1} in these subspaces, and also the phase voltage $V_{as} = V_{sa} + V_{m1}$, are calculated for symmetrical six-phase drive with two isolated neutrals as [4]:

$$V_{sa}=0.333(V_a-0.5V_b-0.5V_c+0.5V_x-V_y+0.5V_z) \tag{1}$$

$$Vm1 = 0.333(Va - 0.5Vb - 0.5Vc - 0.5Vx + Vy - 0.5Vz) \tag{2}$$

$$Vas = Vsa + Vm1 = Va - 0.333(Va + Vb + Vc) \tag{3}$$

$$Vxs = Vsb + Vm2 = Vx - 0.333(Vx + Vy + Vz), \tag{4}$$

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

In this case, the V_{sa} component, which produces useful rotating MMF k-th order voltage harmonics ($k=12m\pm1$, $m=1,2,3,..$), is the useful component. But the V_{m1} component, which generates loss-producing harmonics ($k=6m\pm1$, $m=1,3,5,..$), is the undesirable voltage component.

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. Basic control correlations of this method (see Table I) include two special linear functions (coefficients) of overmodulation K_{ov1} (5) and K_{ov2} (6), providing smooth pulses dropping process in this zone:

$$Kov1 = 1 - (F - Fov1)/(Fov2 - Fov1) \tag{5}$$

$$Kov2 = 1 - (F - Fov2)/(Fm - Fov2) \tag{6}$$

Typical control scheme for each inverter for standard *V/F* control of six-phase drive system during overmodulation is based on two-stage strategy with two threshold frequencies $F_{ov1} = 45.35$ *Hz* (modulation index $m=0.907$ in this case) and $F_{ov2} = 47.6$ *Hz* ($m=0.952$) for the drive systems with the maximum fundamental frequency equal to *50 Hz* [6],[10]. So, control process consists from two basic parts in the overmodulation zone.

During the first control stage of the overmodulation zone, between the fundamental frequencies F_{ov1} and F_{ov2}, a smooth linear increase of total active signals (the β-parameters in Table I) until the width of $\beta_1 = \tau$ (τ - switching cycle) is observed for each inverter, with simultaneous smooth reduction of all notches λ until zero at the F_{ov2} frequency.

It is known, that discontinuous schemes of space-vector PWM are the most preferable for drive control in the overmodulation zone. Fig. 2 – Fig. 3 present basic voltage waveforms (with spectra of the V_{sa} voltage) for period of the fundamental frequency of the symmetrical six-phase converter controlled in the mentioned above first part of the zone of overmodulation ($F < F_{ov2}$: $F=46.5Hz$) in accordance with discontinuous synchronized PWM with the 30^0-non-switching intervals (DPWM30, Fig. 2), and with discontinuous synchronized PWM with the 60^0-non-switching intervals (DPWM60, Fig. 3). Fig. 4 shows basic voltages and spectra of the V_{sa} voltage for symmetrical six-phase converter controlled by the combined scheme of synchronized PWM, where the first three-phase inverter is controlled in accordance with the DPWM30 algorithm, and the second inverter is controlled in accordance with the DPWM60 scheme. The average switching frequency is 900 *Hz*.

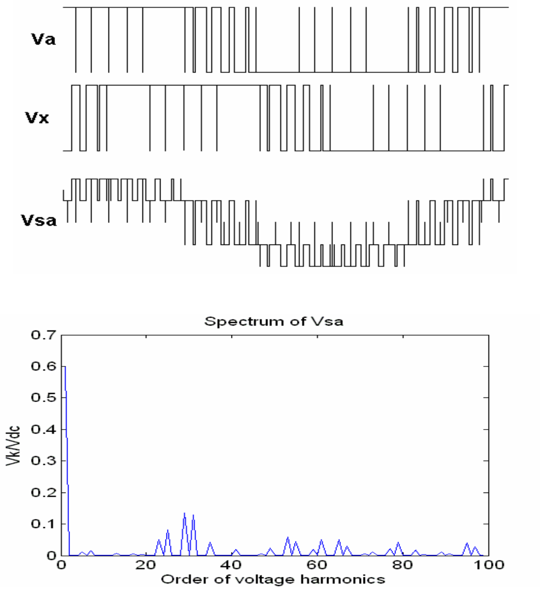


Fig. 2. Pole voltages V_a and V_x, useful V_{sa} component of the phase voltage, and its spectrum, of the system with synchronized DPWM30 ($F=46.5Hz$)

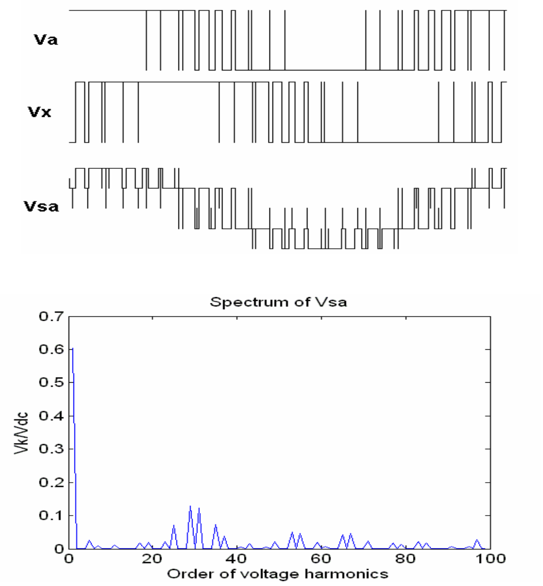


Fig. 3. Pole voltages V_a and V_x, useful V_{sa} component of the phase voltage, and its spectrum, of the system with synchronized DPWM60 ($F=46.5Hz$)

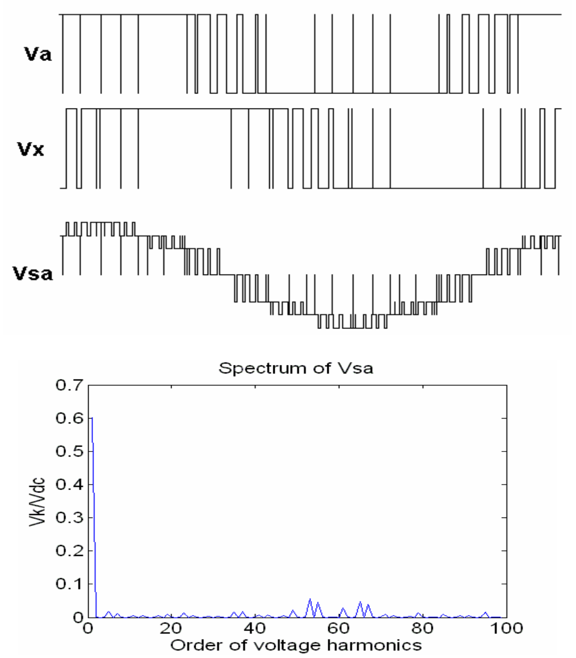


Fig. 4. Pole voltages V_a and V_x, useful V_{sa} component of the phase voltage, and its spectrum, of the system with combined DPWM30+DPWM60 control ($F=46.5Hz$)

Spectra of the useful component of the motor phase voltage (Figs. 2 - 4), and also spectra of the phase voltages of the symmetrical six-phase drives with algorithms of synchronized space-vector modulation include only odd (non-triplen) harmonics, and do not contain even harmonics and sub-harmonics.

In the second sub-zone of the drive control during overmodulation, between the F_{ov2} frequency and the maximum fundamental frequency F_m, there is a smooth decrease until close to zero value of the widths of all minor parts of active signals (of the γ-signals in accordance with definitions of Table I).

Fig. 5 – Fig. 10 present basic voltage waveforms and spectrum of the V_{sa} voltage of symmetrical six-phase system with three basic versions of synchronized PWM at the fundamental frequencies $F=48.5Hz$ (Figs. 5 - 7), and $F=49.5Hz$ (Figs. 8 - 10), which correspond to the control sub-zone of the highest fundamental frequencies, where modulation index $m>0.952$. The average switching frequency is equal to 900 *Hz*.

Fig. 11 presents basic voltage waveforms and spectrum of the V_{sa} voltage of symmetrical six-phase system at the maximum fundamental frequency $F_m = 50\ Hz$.

The motor phase voltage V_{as} (and its useful V_{sa} component) of symmetrical dual three-phase (six-phase) drives have symmetry during overmodulation, and its spectra do not include even harmonics and sub-harmonics, which is especially important for high power/high current drives.

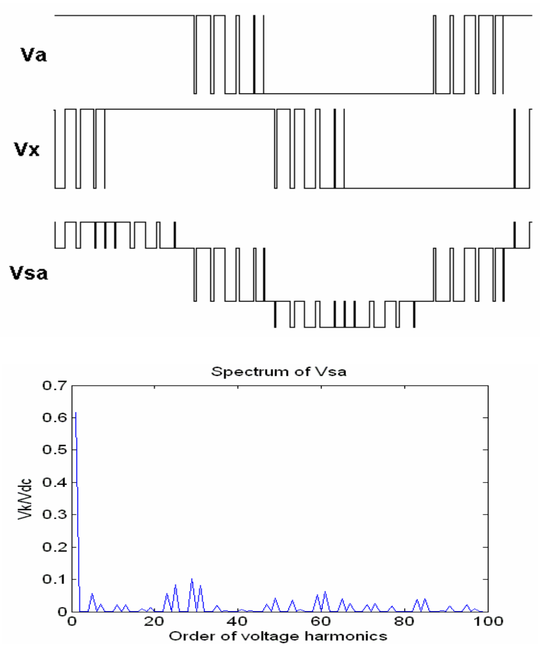


Fig. 5. Pole voltages V_a and V_x, useful V_{sa} component of the phase voltage, and its spectrum, of the system with synchronized DPWM30 (*F=48.5Hz*)

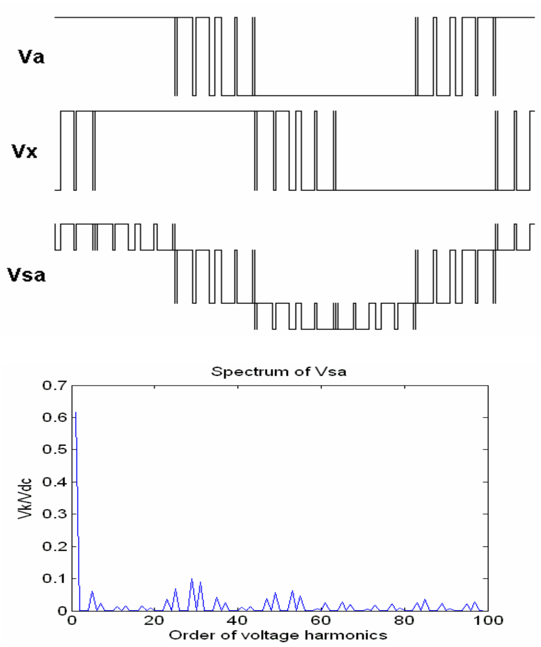


Fig. 6. Pole voltages V_a and V_x, useful V_{sa} component of the phase voltage, and its spectrum, of the system with synchronized DPWM60 (*F=48.5Hz*)

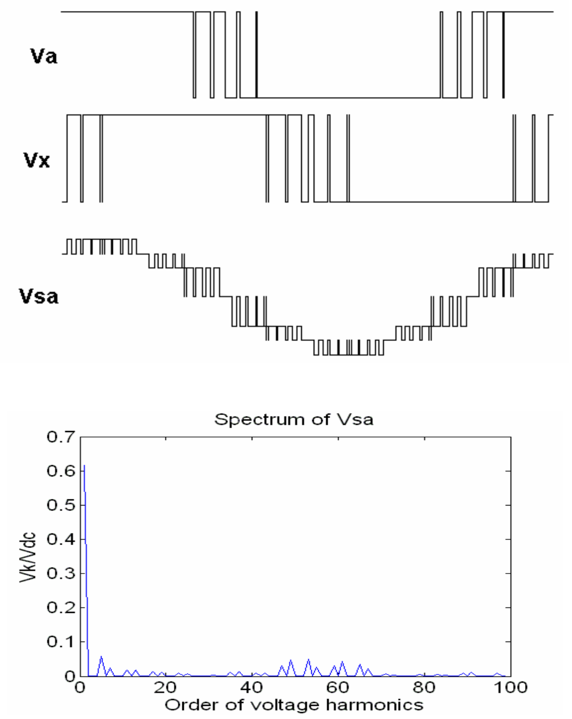


Fig. 7. Pole voltages V_a and V_x, useful V_{sa} component of the phase voltage, and its spectrum, of the system with combined DPWM30+DPWM60 control (*F=48.5Hz*)

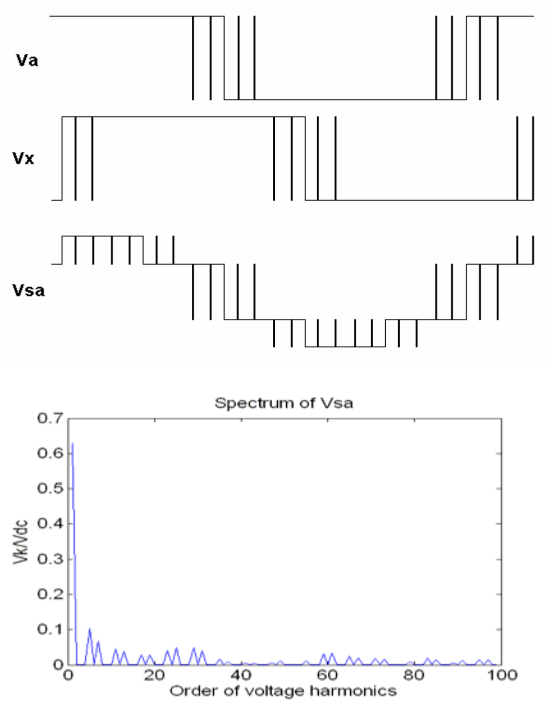


Fig. 8. Pole voltages V_a and V_x, useful V_{sa} component of the phase voltage, and its spectrum, of the system with synchronized DPWM30 (*F=49.5Hz*)

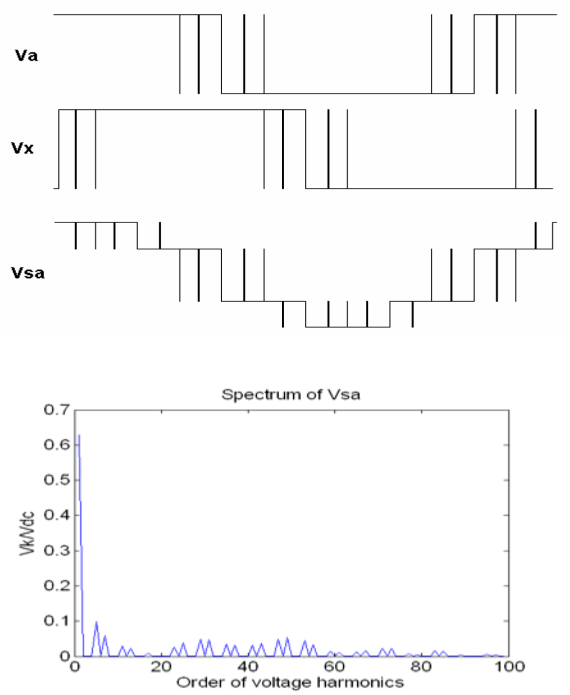


Fig. 9. Pole voltages V_a and V_x, useful V_{sa} component of the phase voltage, and its spectrum, of the system with synchronized DPWM60 (*F=49.5Hz*)

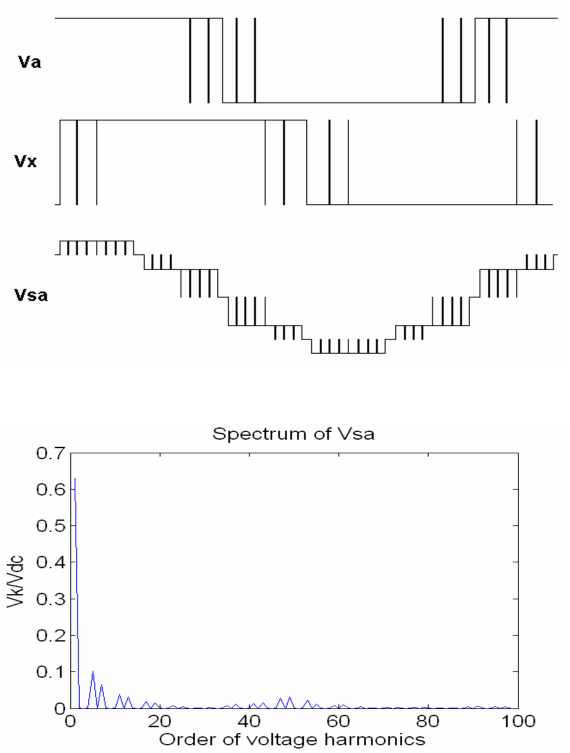


Fig. 10. Pole voltages V_a and V_x, useful V_{sa} component of the phase voltage, and its spectrum, of the system with combined DPWM30+DPWM60 control (*F=49.5Hz*)

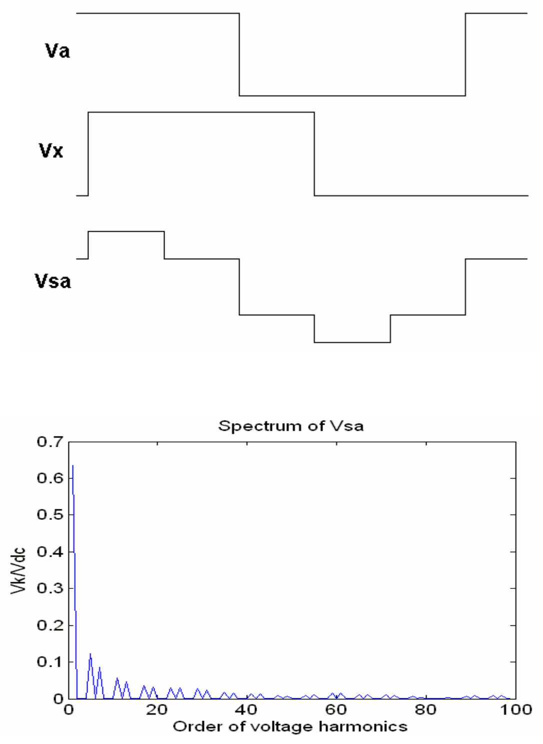


Fig. 11. Pole voltages V_a and V_x, useful V_{sa} component of the phase voltage, and its spectrum, of the system at the maximum fundamental frequency *F=50Hz*

Fig. 12 presents calculation results of Weighted Total Harmonic Distortion factor (*WTHD*) of the useful component of the phase voltage (of the V_{sa} voltage: averaged values of $WTHD = (1/V_{sa_k})\sqrt{\sum_{k=2}^{1000}(V_{sa_k}/k)^2}$) of symmetrical dual three-phase system with both identical and combined schemes of synchronized PWM in the overmodulation zone. The average switching frequency of each three-phase inverter is equal to *900 Hz* during standard *V/F* control. The spectral characteristics, shown in Fig. 12, recommend combined DPWM30+DPWM60 scheme of synchronized PWM as the best choice to get reduced distortion of the useful component of the phase voltage of symmetrical six-phase system in the first half of the overmodulation zone.

Both in the first and the second parts of the overmodulation control zone of symmetrical dual three-phase system with synchronized PWM the spectra of the phase voltage of the induction motor contain only odd harmonics (without triplen harmonics), for any ratios between the switching and fundamental frequencies. These algorithms provide also smooth shock-less pulses-ratio changing during the whole control range.

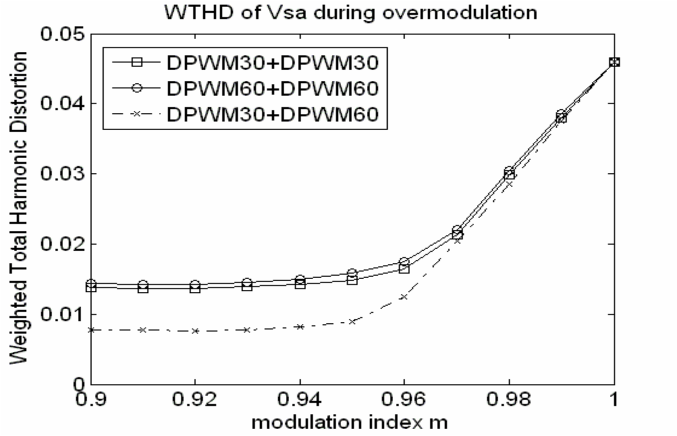


Fig. 12. Averaged *WTHD* factor of the V_{sa} voltage versus modulation index

Conclusion

1. It has been shown, that combined scheme of synchronized PWM provides better spectral composition of the useful component of the phase voltage of dual three-phase drive in the first half of the overmodulation zone, in comparison with two identical schemes of modulation, used for control of the two inverters of six-phase system.
2. Both identical and combined schemes of synchronized space-vector-based PWM, applied for control of six-phase converters and drives, provide minimum number of switchings and minimal switching losses in power conversion systems.
3. Both identical and combined schemes of synchronized PWM allow continuous synchronization of the motor phase voltage during the whole overmodulation zone. The spectra of the phase voltage of symmetrical six-phase drives do not include even harmonics and sub-harmonics, which is especially important for high power/high current applications.

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