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DUAL INVERTER-FED DRIVES ON THE BASE OF THE SYNCHRONISED NEUTRAL-POINT-CLAMPED INVERTERS

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Abstract. *Novel method of synchronous pulsewidth modulation (PWM) is disseminated to cascaded three-level inverters feeding open-end winding induction motor drive with only one dc voltage source. Control algorithms provide in this case full elimination of the common-mode voltages both in each inverter and in the load. Motor phase voltages of the drive system are characterised by quarter-wave symmetry during the whole control range including the zone of overmodulation, and its spectra do not contain even harmonics and sub-harmonics (combined harmonics). Simulations give the behaviour of the proposed methods of synchronous modulation. Continuous, discontinuous and "direct-direct" schemes of synchronous PWM, applied for control of cascaded three-level converters, have been analysed and compared.*

Keywords: *dual three-level inverters, open-end winding induction motor drive, synchronous modulation.*

Introduction

Three-level and multilevel power converters have been exciting an increasing interest during the last years [1]-[3]. In particular, they provide low line voltage *dv/dt* and improved spectral characteristics of the output signals. Three-level neutral-point-clamped voltage source inverters are used widely in adjustable speed ac drive systems, providing less stress on motor winding insulation and bearings.

As the development of the concept of multilevel converters for drive systems, alternate topologies of multilevel converters (cascading inverters) have been recently proposed, which involve series connection of two three-phase inverters through the neutral point of the load [4]-[7]. In particular, these systems can be based on cascading of two-level inverters [4],[5] and multilevel inverters [6],[7].

Control of cascaded converters is based mainly on standard versions of voltage space-vector modulation, which are asynchronous by the nature. The spectra of the output voltage of converters with standard asynchronous PWM include combined harmonics of the fundamental frequency, which are very undesirable for high-power drive systems with low switching frequencies [8].

In order to provide synchronization of the voltage waveforms of inverters, novel method of synchronous pulsewidth modulation has been recently proposed, with application for standard two-level inverters [9], three-level neutral-point-clamped inverters [10], and modular four-level converters based on inverter modules [11]. This paper presents analysis and comparison of some synchronous schemes of modulation, applied for control of cascaded three-level inverters, which provide full common-mode voltage cancellation both in each inverter and in the load.

Dual inverter-fed drive with three-level inverters

Basic topology of the drive system with open-end winding induction motor and two cascaded three-level inverters is presented in Figure 1 [7]. This topology is constructed by connecting two three-level inverters to the corresponding sides of the open-end induction motor windings.

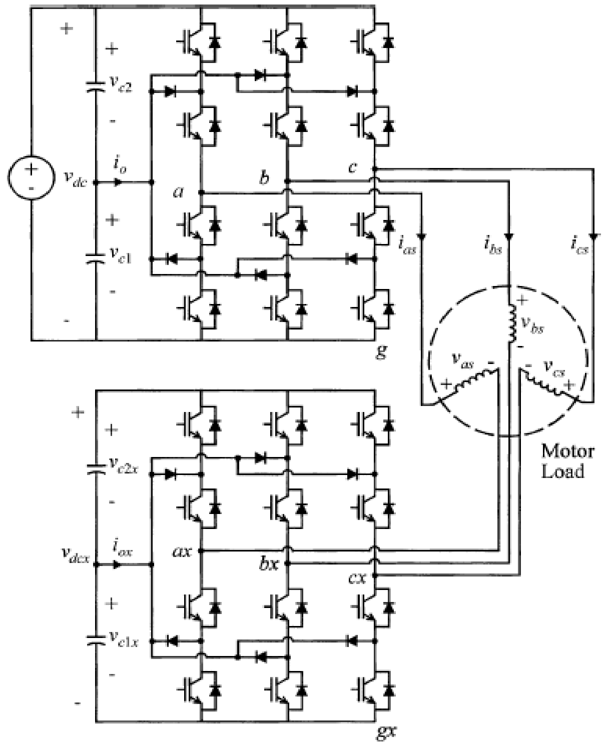


Figure 1. Adjustable speed drive system with two cascaded three-level inverters [7].

One dc voltage source is used for both inverters in this case (voltage $V_{dc} = V_{dcx}$ in Figure 1), because full elimination of the common-mode voltages in the system is provided by the specialized scheme of synchronous pulsewidth modulation.

Control of the neutral-point-clamped inverter

Figure 2 presents the basic structure of a three-level neutral-clamped inverter. Each of the three legs of the inverter consists of four power switches, four freewheeling diodes and two clamping diodes. Figure 3 shows the switching state vectors of the inverter. Generally, there are twenty-seven different switching states, which correspond to nineteen vectors shown by the big and small arrows in Figure 3 [1].

Recently, new algorithms of PWM have been proposed for three-level inverters, providing the elimination of undesirable common-mode voltages, which are the main reason for bearing currents and bearing failures in induction motor drives with PWM [12],[13]. It is leading to an increase of the reliability and life span of the drive systems.

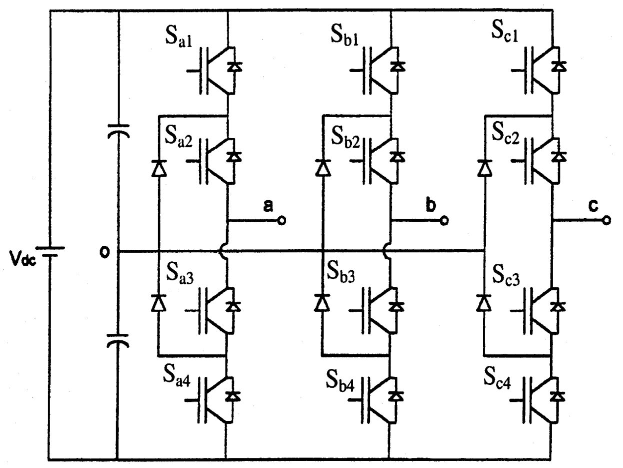


Figure 2. Basic structure of three-level inverter.

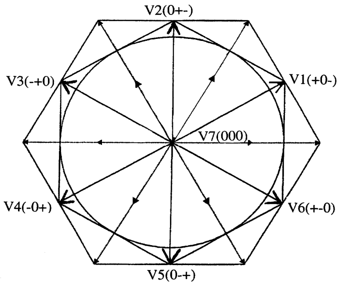


Figure 3. Switching state vectors providing zero common-mode voltage in the load [13].

Twelve (six and six) switching state vectors are located on the periphery of the two presented hexagons, and six small vectors have the position in the middle of the corresponding big vectors. There is also a zero voltage vector. Generally, it can be represented by three different switching states. It is known, that using only seven of the vectors, V_1 - V_7, marked in Figure 3 by the big arrows with the corresponding number of the vector, this can provide elimination of the common-mode voltage in a three-phase load [10],[12]-[13]. A ternary switching variable (+,**0**,-) is defined for the switches of each of the three phase as:

+ *if* S_1, S_2 *are* ***ON*** *and* S_3, S_4 *are* ***OFF***;

0 *if* S_2, S_3 *are* ***ON*** *and* S_1, S_4 *are* ***OFF***;

- *if* S_3, S_4 *are* ***ON*** *and* S_1, S_2 *are* ***OFF***.

The switching state sequences can be written in this case for the corresponding vectors as:

$$V_1(+0-);\ V_2(0+-);\ V_3(-+0);\ V_4(-0+);$$

$$V_5(0-+);\ V_6(+-0);\ V_7(000).$$

Control of the neutral-point-clamped inverter with common-mode voltage cancellation has an important peculiarity. Transition between two neighbouring active switching sequences (or between active switching sequence and zero sequence) is executed here for any scheme of modulation by commutations of the two switches, instead of the single commutation that is typical for a standard three-phase inverter and for three-level inverter with standard control mode. It is necessary to take this into account during synthesis of a rational PWM algorithm.

Synchronous schemes of space-vector PWM

There is a big variety of the methods, schemes and techniques of digital vector pulsewidth modulation for power converters [8],[14]-[16]. Vector approach is the most suitable for synthesis of the PWM pulse patterns for drive converters. It allows easy implementation of the modulator of the control system, and allows to provide high quality of the output voltage and current of the converters with high switching frequency. At the same time it is known [8], that for power systems with low switching frequency the asynchronous principle of standard vector PWM leads to undesirable combined harmonics in the spectrum of theirs output voltages.

Between the most popular schemes of vector PWM for both two-level and three-level voltage source inverters for drive application classical continuous voltage space vector modulation [14], discontinuous vector pulsewidth modulation with the 30^0-non-switching intervals [15], and also an interesting less known PWM scheme of "direct-direct" modulation [16] can be mentioned. These schemes are the subject of further analysis and consideration in this paper.

In order to avoid asynchronism of typical voltage space/vector modulation, a novel method of synchronous digital PWM [10] is used for control of three-level neutral-point-clamped inverters. Figure 4 – Figure 6 present switching state sequences, the potentials V_a and V_b, and the line voltage V_{ab} for basic schemes of synchronous PWM, applied to three-level inverters with common-mode voltage eliminateon. Figure 4 (mode 1) corresponds to the period of the fundamental frequency of the classical scheme of voltage space-vector modulation [14]. Figure 5 (mode 2) corresponds to the scheme of "direct-direct" modulation [16]. Figure 6 (mode 3) corresponds to discontinuous PWM with the 30^0-non-switching intervals [15]. Figure 6 shows more in details the first 60^0 clock-interval for the classical vector PWM (mode 1 [14], Figure 4).

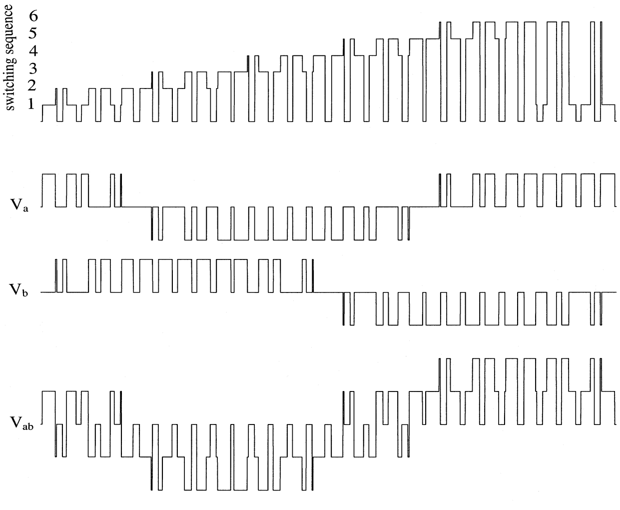


Figure 4. Control and output signals of three-level inverter with continuous PWM (mode 1).

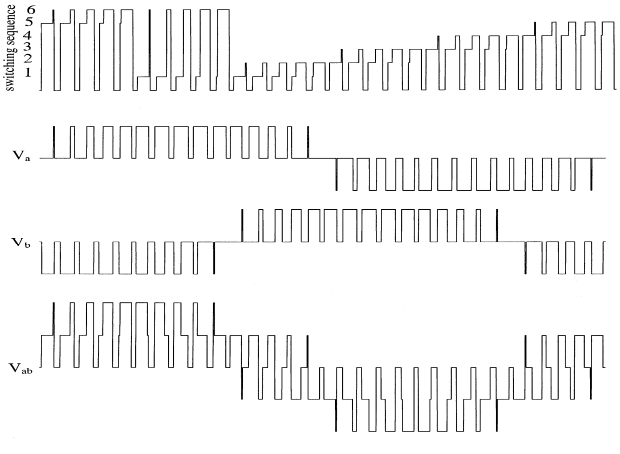


Figure 5. Control and output signals of three-level inverter with the "direct-direct" scheme of PWM (mode 2).

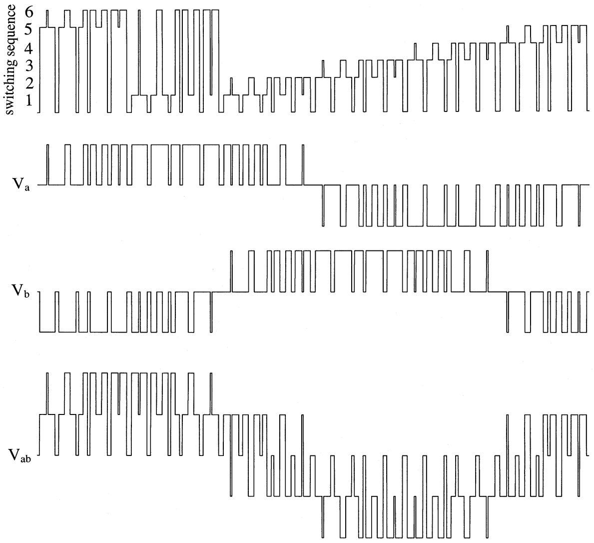


Figure 6. Control and output signals of three-le-vel inverter with discontinuous PWM (mode 3).

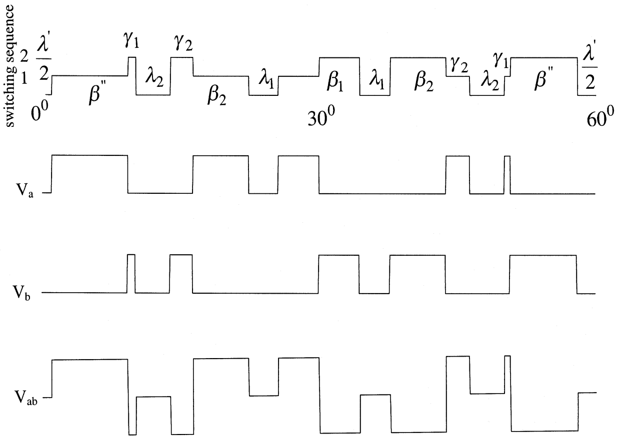


Figure 7. Control and output signals of three-level inverter with common-mode voltage elimi-nation for the first 60^0-clock-interval (mode 1).

A novel approach and new algorithms are used in the presented schemes for synthesis of the PWM waveforms, providing a synchronous character of the process of modulation during the whole control range including the zone of overmodulation [10]. In particular, in Figure 7 the signals βj represent the total active switching state durations during the switching period (sub-cycle) τ, and the signals γ_k are generated on the boundaries (modes 1 and 2) or in the centres (mode 3) of the corresponding β. The widths of notches λ_j represent zero state sequences.

Special signals λ', with the neighbouring β'', are formed in the clock-points (0^0,60^0,120^0..) of the output curve (Figure 7). They are reduced simultaneously till close to zero width at the special boundary frequencies F_i, situated on the axis of the fundamental frequency F of the drive system. It provides a continuous adjustment of the voltage waveform with smooth pulse-ratio changing until the maximum fundamental frequency F_m. F_i is calculated in a general form as a function of the width of sub-cycles τ in accordance with (1), and the neighbouring F_{i-1} - from (2). The modulation index is $m = F / F_m$ in this case. Index i is equal to the numbers of notches inside a half of 60^0 clock-intervals and it is determined from (3), where fraction is rounded off to the nearest higher integer:

$$F_i = \frac{1}{6(2i - K_1)\tau} \tag{1}$$

$$F_{i-1} = \frac{1}{6(2i - K_2)\tau} \tag{2}$$

$$i = \frac{1/6F + \tau K_1}{2\tau}, \tag{3}$$

where $K_1=1$, $K_2=3$ for mode 1 and mode 2, and $K_1=1.5$, $K_2=3.5$ for mode 3.

Equations (4)-(9) present a set of control functions for determination of parameters of signals of three-level inverters with synchronous PWM in absolute values (seconds) for scalar control mode of the system during the whole range including the zone of overmodulation.

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

$$\beta_j = \beta_1 \cos[(j - 1 - K_3)\tau K_{ov1}] \tag{4}$$

$$\gamma_j = \beta_{i-j+1}\{0.5 - 0.87\tan[(i - j - K_3)\tau]\}K_{ov2} \tag{5}$$

$$\beta_i = \beta'' = \beta_1 \cos[(i - K_3 - 1)\tau K_{ov1}]K_s \tag{6}$$

$$\gamma_1 = \beta''\{0.5 - 0.87\tan[(i - K_3 - 2)\tau + (\beta_{i-1} + \beta_i + \lambda_{i-1})/2]\}K_s K_{ov2} \tag{7}$$

$$\lambda_j = \tau - (\beta_j + \beta_{j+1})/2 \tag{8}$$

$$\lambda_i = \lambda' = \left(\tau - \beta''\right)K_{ov1}K_s\,, \tag{9}$$

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 synchronisation; the first coefficient (function) of overmodulation $K_{ov1} = 1$ until F_{ov1}, and $K_{ov1} = [1-(F-F_{ov1})/(F_{ov2}-F_{ov1})]$ between F_{ov1} and $F_{ov2} = 0.952F_m$; the second coefficient (function) 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 the mode 1 and mode 2, and $K_3=0.25$ for the mode 3.

Operation of the drive system with cascaded neutral-point-clamped inverters

The concept of cascading inverters (ac drives on the base of cascading inverters) involves series connection of two three-phase inverters through the neutral point of the load (Figure 1). Synchronous symmetrical control of the output voltage waveforms of each inverter in accordance with basic PWM algorithm provides synchronous symmetrical regulation of voltage in the induction machine phase windings. Rational phase shifting between output voltage waveforms of the inverters is equal in this case to one half of the switching interval (sub-cycle) τ (is equal to 0.5τ) [6].

Figure 8 presents pole voltages of two inverters V_{ag} and V_{axg}, and motor phase voltage $V_{a\text{-}ax}$. Both three-level inverters are here under control in accordance with the scheme of continuous synchronous pulsewidth modulation (mode 1, see Figs. 4 and 7). Switching frequency F_s of each inverter is equal to *1 kHz*. Curves in Figure 8 correspond to the fundamental frequency F equal to *40 Hz* (modulation index $m=0.8$).

Figure 9 shows spectral composition (relative (V_k/V_{dc}) magnitudes of the k-harmonics) of the voltage presented in Figure 8. Motor phase voltage of the drive with synchronous PWM has quarter-wave symmetry, and its spectrum does not include even harmonics and sub-harmonics.

Figure 10 presents basic voltages waveforms for the drive system with the "direct-direct" scheme of synchronous PWM (mode 2, see Figure 5).

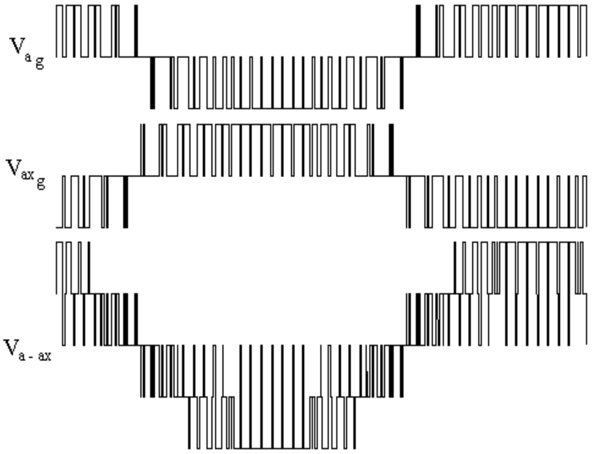
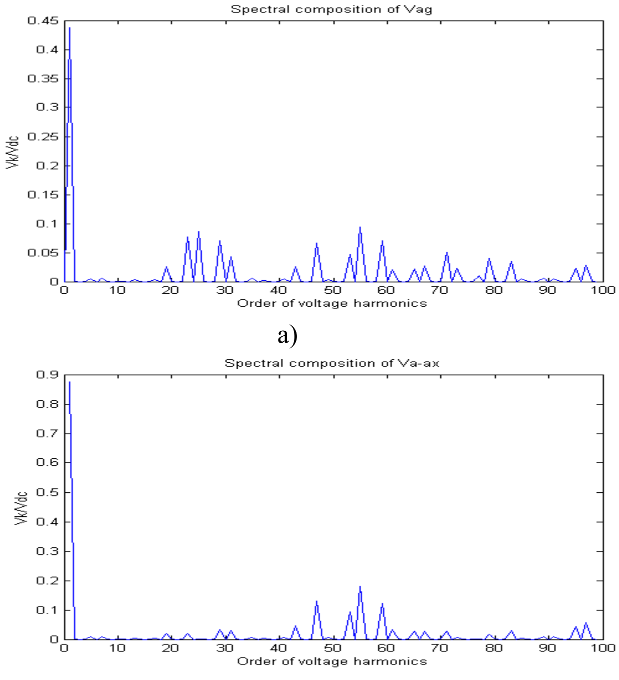


Figure 8. Voltage waveforms of the drive system with continuous synchronous PWM ($F = 40Hz$).



a)

b)

Figure 9. Spectral composition of voltage waveforms for the drive system with continuous synchronous PWM at $F = 40$ Hz: a) V_{ag}; b) $V_{a\text{-}ax}$.

It includes pole voltages of two inverters V_{ag} and V_{axg}, and resulting motor phase voltage $V_{a\text{-}ax}$. The fundamental frequency F is equal to *40 Hz* in this case, and average switching frequency of each inverter is equal to *1 kHz*.

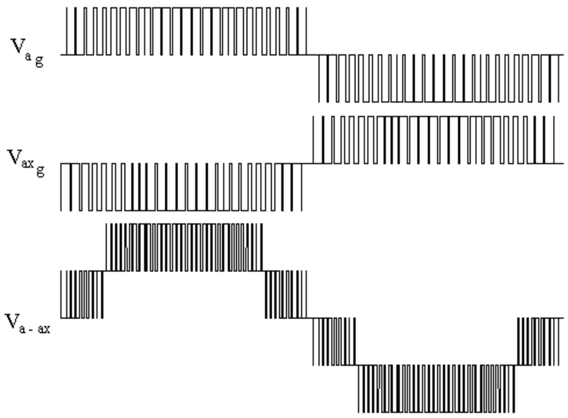
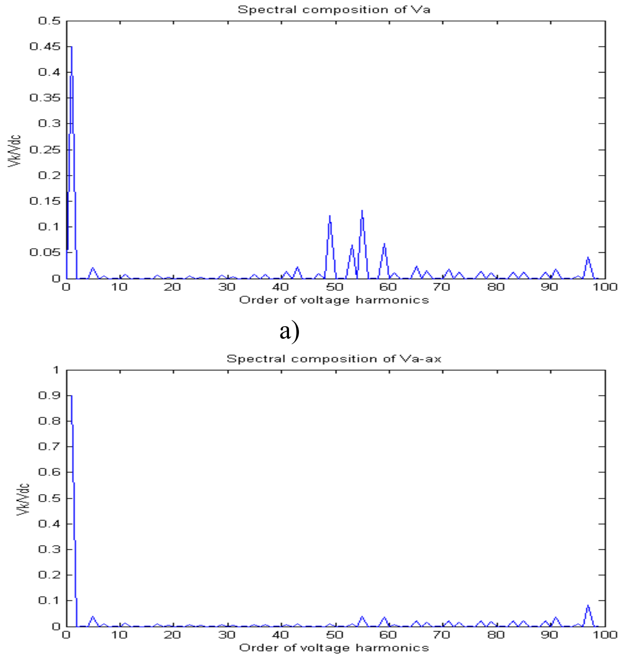


Figure 10. Voltage waveforms of the drive system with the "direct-direct" scheme of synchronous PWM (*F = 40 Hz*).



a)

b)

Figure 11. Spectral composition of voltage wave-forms for the drive system with "direct-direct" synchronous PWM at *F = 40Hz*: a) V_{ag}; b) $V_{a\text{-}ax}$.

Figure 11 shows spectral composition of the voltage waveforms presented in Figure 10. It is necessary to mention, that described strategy of modulation provides full common-mode voltage cancellation both in each inverter and in the load of the drive system with synchronous PWM. So, it can lead to an increase of the reliability and the life span of the drive system.

Figure 12 presents pole voltages of two inverters V_{ag} and V_{axg}, and motor phase voltage $V_{a\text{-}ax}$ of the drive system, controlled in accordance with algorithm of discontinuous synchronous PWM (mode 3, Figure 6). Switching frequency F_s of

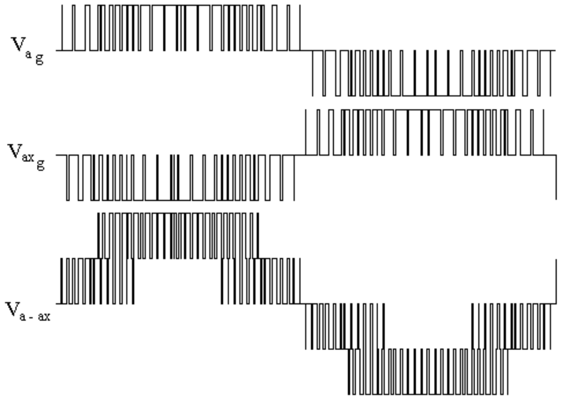
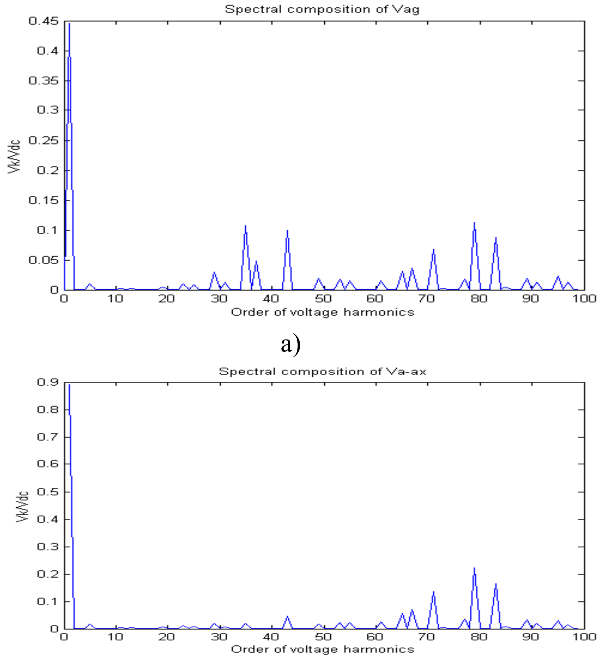


Figure 12. Voltage waveforms of the drive system with discontinuous synchronous PWM (*F = 40 Hz*).



a)

b)

Figure 13. Spectral composition of voltage wave-forms for the drive system with disconti-nuous PWM at *F = 40 Hz*: a) V_{ag}; b) $V_{a\text{-}ax}$.

each inverter is equal to *1 kHz*, the fundamental frequency *F* is equal to *40 Hz* (modulation index *m=0.8*). Figure 13 shows spectral composition (relative (V_k/V_{dc}) magnitudes of the *k*-harmonics) of the voltage waveforms presented in Figure 12. Like for others schemes of synchronous PWM, the motor phase voltage of the drive system has quarter-wave symmetry in this case too, and its spectrum does not include even harmonics and combined harmonics (sub-harmonics).

Motor phase voltage quality

In order to compare the analyzed modulation schemes applied for control of dual inverter-fed drive systems, a comparative analysis of the spectra of the motor phase voltage has been executed based on computer simulation. Weighted Total Harmonic Distortion factor (*WTHD*) (10), reflecting the actual level of a harmonic distortion for a first order ac filter, is well suited for using in adjustable speed drive and is used for determination of its quality [2],[10]:

$$WTHD = (1/V_1)\sqrt{\sum_{i=2}^{n}(V_i/i)^2} \qquad (10)$$

Figure 14 presents averaged results of calculation of *WTHD* factor versus modulation index for motor phase voltage $V_{a\text{-}ax}$ of the drive system for the analyzed continuous (mode 1), "direct-direct" (mode 2) and discontinuous (mode 3) schemes of synchronous modulation during standard scalar *V/F* control until the zone of overmodulation (modulation index *m = 0.3–0.9*). Average switching frequency F_s of each inverter is equal to *1000 Hz* for all versions of PWM. Dotted lines in Figure 14 show results of calculation of *WTHD* factor for the phase output voltage of each inverter (V_{ag} = V_{axg}) for all analyzed schemes of synchronous PWM.

Presented in Figure 14 results of analysis of spectral composition of motor phase voltage show that at low values of modulation index *m* Weighted Total Harmonic Distortion factor is better for the system with the "direct-direct" scheme of synchronous PWM, and when *m>0.7*, discontinuous and continuous versions of synchronous PWM provide better *WTHD* factor.

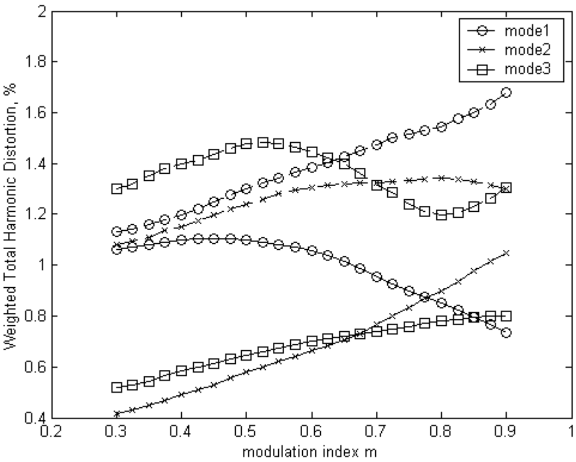


Figure 14. Averaged *WTHD* of the motor phase voltage (––), and of the phase voltage of each inverter (- - -).

Synchronous control in the zone of overmodulation

Synchronous control of cascaded neutral-point-clamped inverters during overmodulation is based on the same basic control functions (4)-(9), by the use of special coefficients (functions) K_{ov1} and K_{ov2} in the overmodulation region. In this zone a two-stage control scheme is used, characterised by two threshold frequencies $F_{ov1} = 0.907F_m$ and $F_{ov2} = 0.952F_m$, which are the basics during control in the zone of overmodulation [9]. Detailed description of the process of synchronous PWM for three-level inverters during overmodulation is in [17].

Conclusion

This paper presents some results of dissemination of the methodology of synchronous pulsewidth modulation to cascaded three-level inverters for drive systems with open-end winding induction motors. Specialized control algorithms provide in this case full elimination of the common-mode voltages both in each inverter and in the load.

The proposed schemes of synchronous PWM allows also to provide quarter-wave symmetry of motor phase voltage during the whole control range including the zone of overmodulation. The spectra of motor phase voltage do not include even harmonics and combined harmonics, which is especially important for the systems with low switching frequencies and increased power rate. At lower modulation indices the "direct-direct" scheme of synchronous PWM provides better spectral composition of the motor phase voltage of drive system, and when m>0.7, discontinuous and continuous versions of synchronous PWM provide better spectrum of motor phase voltage.

Acknowledgment

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