# DUAL INVERTER-FED DRIVES WITH COMMON-MODE VOLTAGE CANCELLATION BASED ON SYNCHRONOUS PWM

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***Abstract:*** *Novel method of direct synchronized pulsewidth modulation is applied for control of a dual inverter-fed open-end winding induction motor drive with zero common-mode voltages. New strategy and algorithms of synchronized PWM provide symmetry of the phase voltage of the system during the whole control range including the zone of overmodulation. Spectra of the phase voltage do not contain even harmonics and sub-harmonics (combined harmonics), which is especially important for the drive systems with increased power rating. Simulations gave the behaviour of dual inverter-fed system with the proposed synchronized PWM scheme.*

***Key words:*** *voltage source inverters, open-end winding induction motor drive, PWM, common-mode voltages.*

## 1. Introduction

Three-level and multilevel converters are a subject of increasing interest in the last years due to some advantages compared with conventional three-phase inverters. Ones of the interesting and perspective topologies of power converters are now cascaded (dual) two-level converters which utilize two standard three-phase voltage source inverters [1-3]. The structure of adjustable speed drive system based on cascaded converter is constructed by splitting the neutral connection of the induction motor and connecting both ends of each phase coil to a two-level inverter. In this case cascaded converters are capable of producing voltages which are identical to those of three-level and four-level converters [3].

The mentioned above dual two-level inverter-fed open-end winding motor drives have some advantages such as redundancy of the space-vector combinations and the absence of neutral point fluctuations [4]. In particular, in a dual-inverter scheme, a total of 64 space-vector combinations are distributed over 19 space-vector locations compared to 27 space-vector combinations distributed over the same number of locations in typical three-level neutral-point-clamped inverter.

In order to suppress the common-mode voltages (the harmonics of the triplen order), new schemes of pulsewidth modulation have been proposed for control of dual inverter-fed drives [5-6]. In particular, the proposed PWM algorithms were based on the observation that certain voltage space-vector combinations in the dual inverter-fed drive do not contribute to the triplen harmonics, and hence the PWM scheme that exclusively employs these combinations was used to eliminate the triplen harmonic currents.

This paper presents the results of development and dissemination of novel methodology of direct synchronized PWM for a dual inverter-fed open-end winding motor drive with full common-mode voltages and currents cancellation.

## 2. Basic topology of a dual inverter-fed open-end winding motor drive

Fig. 1 presents the basic structure of a dual inverter-fed open-end winding induction motor drive, where INV1 and INV2 are standard three-phase voltage source inverters. The single power supply is used for both inverters in this case, because elimination of the common-mode voltages is provided by the specialized scheme of modulation.

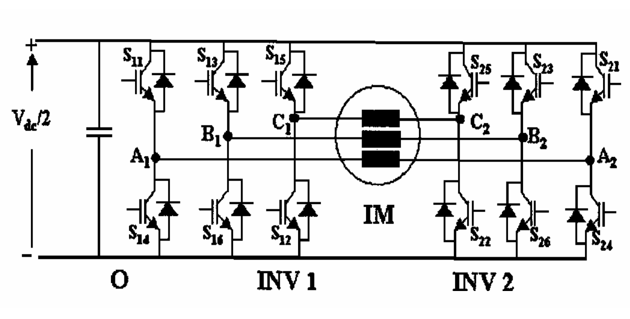



Fig. 1. Topology of dual inverter-fed drive with single dc-link [6].

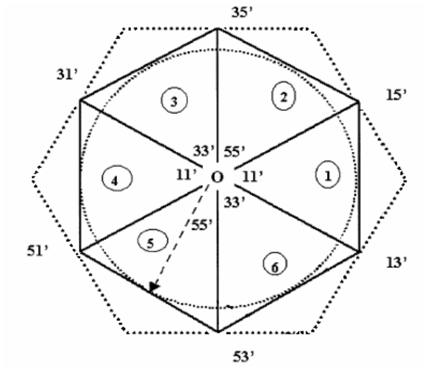



Fig. 2. Basic voltage space-vector combinations [6].

Fig. 2 shows the switching state vectors of two inverters, which provide full cancellation of the common-mode voltages generated by the individual inverters [6]. The conventional definition for the switching state sequences (voltage vectors) for the switches of the phases of ***ABC*** of each individual inverter is used here. In particular, for INV1: **1** – 100; **2** – 110; **3** – 010; **4** –011; **5** – 001; **6** – 101 (1 - switch-on state, 0 – switch-off state); and the same definition are used for INV2: **1'** – 1'0'0'; **2'** – 1'1'0'; **3'** – 0'1'0'; **4'** –0'1'1'; **5'** – 0'0'1'; **6'** – 1'0'1', where 1' - switch-on state of switches of INV2, and 0' – switch-off state in INV2.

In order to eliminate generation of the common-mode voltages by individual inverters, only odd switching sequences (combinations of voltage space-vectors **1**, **3**, **5** and **1'**, **3'**, **5'**, see Fig. 2) are used in this scheme of modulation [6]. So, the possibility of bearing currents and leakage currents are fully avoided by this scheme.

## 3. Synchronised pulsewidth modulation for control of dual inverter-fed drive

Voltage space vector modulation is one of the most suitable modulation methods for the use in adjustable speed ac drive systems fed by voltage source inverters [5-7]. In particular, it is easy to implement and it provides high quality of the output voltage and current in the inverters with high switching frequency. In order to provide synchronous voltage control allowing avoiding of undesirable even harmonics and sub-harmonics of the fundamental frequency in the output voltage of drive systems, a novel method of direct synchronized modulation [7-8] can be used for control of dual inverter-fed open-end winding motor drives.

Fig. 3 presents switching state sequences, the pole voltages of the phase ***A*** $V_{A10}$ and $V_{A20}$ of the inverters INV1 and INV2, and phase voltage of the system $V_{A1A2} = V_{A10} - V_{A20}$. Figs. 4-6 show more in details the corresponding $120^0$-intervals for the proposed scheme of synchronized PWM applied for control of the drive with common-mode voltages elimination (fundamental & switching frequencies are *40* and *650 Hz*).

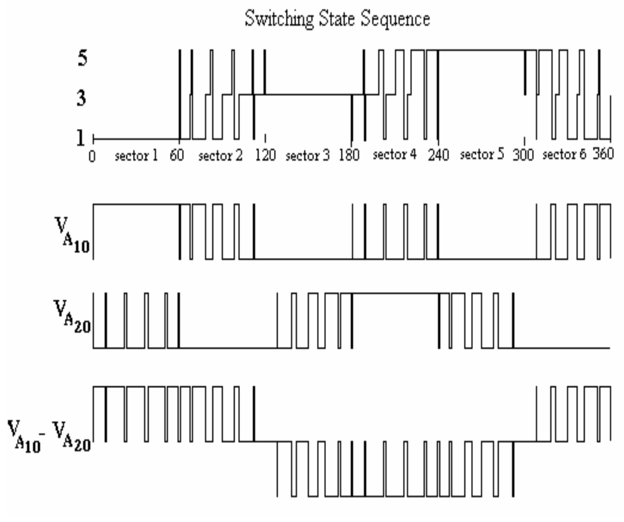



Fig. 3. Control and output signals of the system.

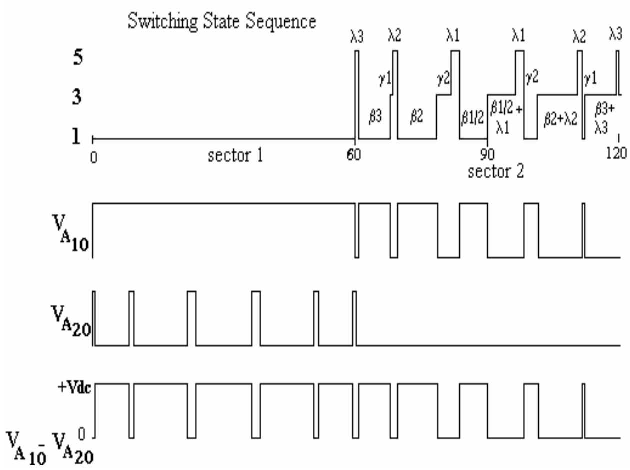



Fig. 4. Control and output signals in sectors 1 and 2.

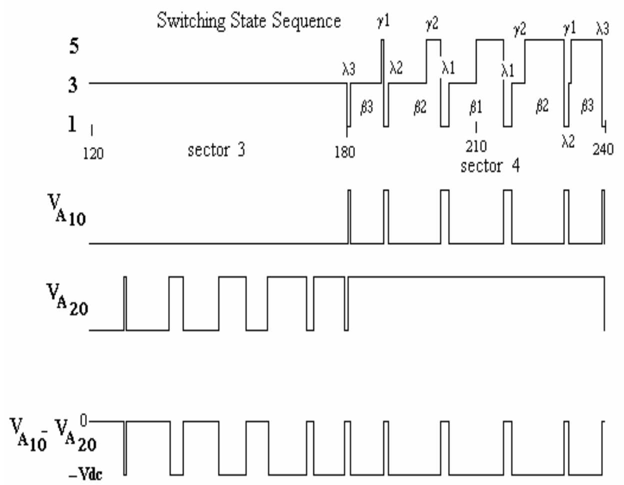



Fig. 5. Control and output signals in sectors 3 and 4.

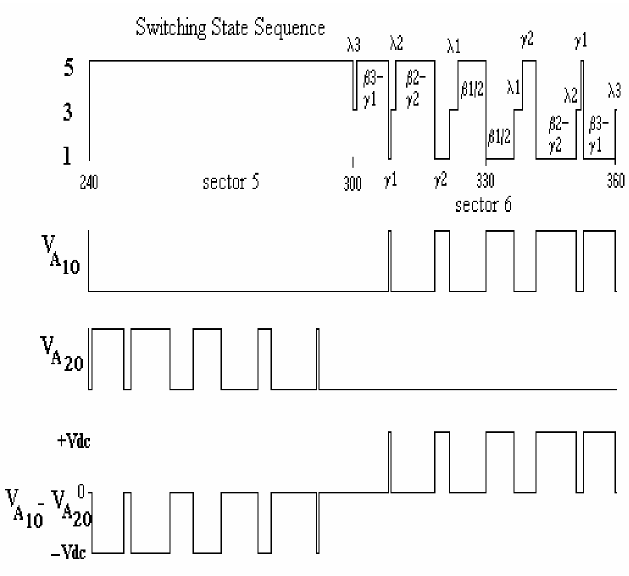



Fig. 6. Control and output signals in sectors 5 and 6.

A novel approach and new algorithm are used in the presented control scheme 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 [7]. In particular, in Figs. 4 - 6 the signals $\beta j$ represent the total active switching state durations during the switching period (sub-cycle) $\tau$ , and the signals $\gamma_k$ are generated on the boundaries of the corresponding $\beta$ . The widths of notches $\lambda_j$ represent zero state sequences.

Special signals $\lambda'$ ($\lambda_3$ in Figs. 4-6), with the neighboring $\beta''$ ($\beta_3$ in Figs. 4-6), are formed in the clock-points ($60^0$,$120^0$..) of the output curve (Fig. 3). 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.

## 4. Basic control correlations

The proposed algorithm of modulation provides a continuous adjustment of the voltage waveform of each inverter, with smooth shock-less pulses-ratio changing until the maximum fundamental frequency $F_m$. Boundary frequencies $F_i$ are calculated in a general form as a function of the width of sub-cycles $\tau$ in accordance with (1), and the neighboring $F_{i-1}$ - 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 the $60^0$-clock-intervals and it is determined from (3), where fraction is rounded off to the nearest higher integer:

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

$$F_{i-1} = \frac{1}{6(2i-3)\tau} \tag{2}$$

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

Relative durations of active switching states and the pulses of the output voltage of the inverter for this symmetrical scheme of PWM can be written in accordance with the principle of voltage space vector modulation [7]:

$$\frac{\beta_j}{\beta_1} = \sin(60^0 - \alpha_j) + \sin(\alpha_j) \tag{4}$$

$$\frac{\gamma_k}{\beta_{i-j+1}} = \frac{\sin(\alpha_k)}{\sin(60^0 - \alpha_k) + \sin(\alpha_k)}, \tag{5}$$

where $\alpha$ - angle position of the centre of the corresponding $\beta$ -signal from the beginning of the $60^0$ -clock-intervals; $\beta_1$ - the signal, which is formed in the centers of the $60^0$-clock-intervals, where $\alpha = 30^0$; $j = 2,...i-1$; $k = i - j + 1$.

Equations (6)-(11) present a trigonometric set of the basic control functions, based on some transformation of (4)-(5), for determination of parameters for control and output signals of three-level inverter in absolute values (seconds) for scalar control mode of the drive system during the whole range including the zone of overmodulation:
for $j=2,...i-1$:

$$\beta_j = \beta_1 \cos[(j-1)\tau K_{ov1}] \tag{6}$$

$$\gamma_j = \beta_{i-j+1} \{0.5 - 0.87 \tan[(i-j)\tau]\} K_{ov2} \tag{7}$$

$$\beta_i = \beta'' = \beta_1 \cos[(i-1)\tau K_{ov1}] K_s \tag{8}$$

$$\gamma_1 = \beta'' \{0.5 - 0.87 \tan[(i-2)\tau + (\beta_{i-1} + \beta_i + \lambda_{i-1})/2]\} K_s K_{ov2} \tag{9}$$

$$\lambda_j = \tau - (\beta_j + \beta_{j+1})/2 \tag{10}$$

$$\lambda_i = \lambda' = (\tau - \beta'') K_{ov1} K_s, \tag{11}$$

where: $\beta_1 = 1.1\tau m$ until $F_{ov1} = 0.907 F_m$, 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 $F_m$.

The basic peculiarities of the modified method (methodology) of direct synchronized modulation, applied to a dual inverter-fed drives with zero common-mode voltages, can be summarized as the following [8]:

1. Only three switching state sequences (voltage space vectors) with odd numbers (**1**, **3**, **5** and **1'**, **3'**, **5'**, see Fig. 2) are used during the whole control range of each inverter.
2. In accordance with the available space vector combinations, presented in Fig. 2, control of the drive system is based on the $180^0$-shift between control and output signals of INV1 and INV2.
3. So, in the first control sector (see Fig. 2), during time-interval $0^0$ – $60^0$, INV1 is in the state **1** without any switch commutations (Fig. 4). In the third control sector, during time-interval $120^0$ – $180^0$, INV1 is in the state **3** without switchings (Fig. 5). And in the fifth sector, during time-interval $240^0$ – $300^0$, INV1 is in the state **5** without commutations (Fig. 6).
4. Correspondingly, in accordance with Fig. 2, for INV1 in the sector 2 the switching state **5** is an equivalent of zero states during conventional operation. In the sector 4 the state **1** is an equivalent of zero states for INV1. And in the sector 6 the state **3** is an equivalent of zero states for INV1.
5. Continuous synchronization of voltage waveforms of each inverter and full symmetry of the phase voltage of drive system is provided by the corresponding synchronous control of pulse patterns around the clock-points ($60^0$ - $90^0$ – $120^0$ in sector 2, $180^0$ - $210^0$ – $240^0$ in sector 4, $300^0$ - $330^0$ - $360^0$ in sector 6, see Figs. 4-6), by the using of the specialized algorithm of synchronized PWM, described above [7].
6. Linear control of the first harmonic of the fundamental phase voltage $V_{A1A2}$ of the drive system is provided by the corresponding modification of the basic PWM algorithm [7] by the use of two special linear coefficients of overmodulation $K_{ov1}$ and $K_{ov2}$ in (6)-(9) and (11). The phase voltage waveforms are characterized by quarter-wave symmetry during the whole control range including the zone of overmodulation.

## 5. Operation of the Drive System with Synchronous PWM

Fig. 7 – Fig. 12 present some results of simulation of a dual inverter-fed open-end winding induction motor drive with elimination of the common-mode voltages on the base of the scheme of synchronized modulation. Operation of the drive system is here under standard scalar *V/F* control. Average switching frequency $F_s$ of each inverter is equal to *1 kHz*. Figs. 7, 9 and 11 present switching state sequences for INV1, pole voltages of two inverters $V_{A10}$ and $V_{A20}$, phase voltages $V_{A1A2}$ and $V_{B1B2}$ and their difference $V_{A1A2}$ - $V_{B1B2}$ (line-to-line voltage). Figs. 8, 10 and 12 show the corresponding spectra of the pole and phase voltages.

In particular, curves in Fig. 7 and Fig. 8 correspond to the zone of low fundamental frequencies (*F=15 Hz*, modulation index *m=0.3*). Spectrum of the pole voltage (Fig. 8,a) includes both odd (not-triplen) harmonics and even harmonics, but no one triplen order harmonic is here. And spectrum of the phase voltage (Fig. 8,b) includes only small odd (non-triplen) harmonics, and all even harmonics are lacking here due to the described algorithm of synchronized pulsewidth modulation.

Figs. 9-10 show the corresponding characteristics of the dual inverter-fed drive system for the zone of middle fundamental frequencies (*F=30Hz*, *m=0.6*), and Figs. 11-12 correspond to the zone of higher frequencies (*F=45Hz*, *m=0.9*).

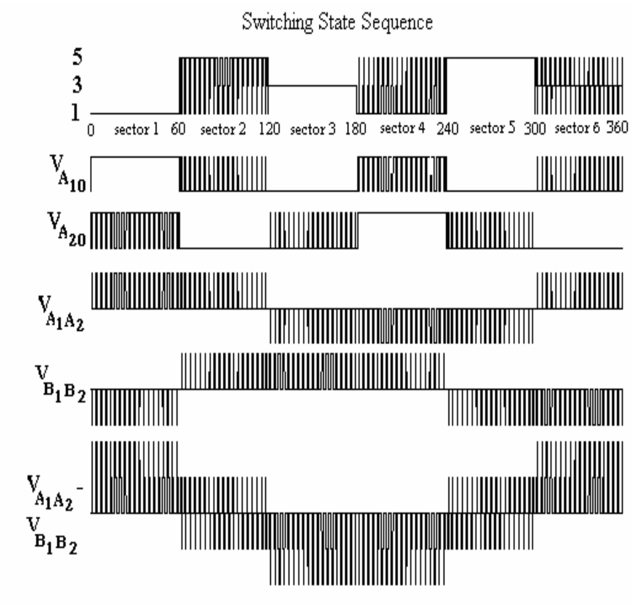
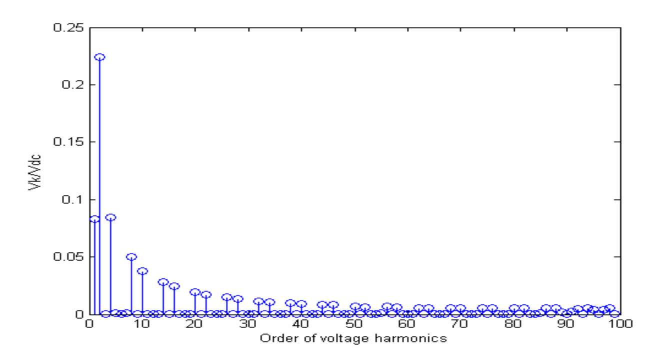
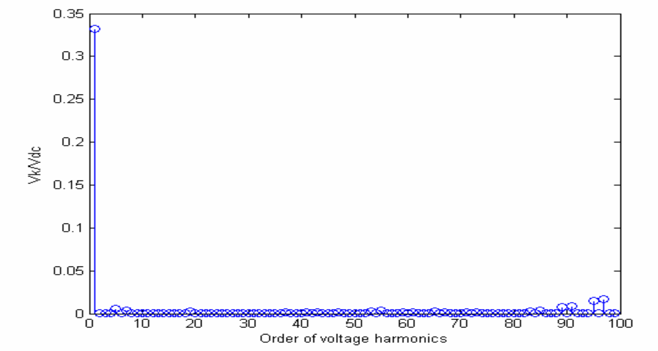



Fig. 7. Switching state sequence, pole voltages, phase voltages, and their difference for *F =15 Hz* (*m=0.3*).




a)




b)

Fig. 8. Spectrum of the pole (a) and phase (b) voltages ($m=0.3$).

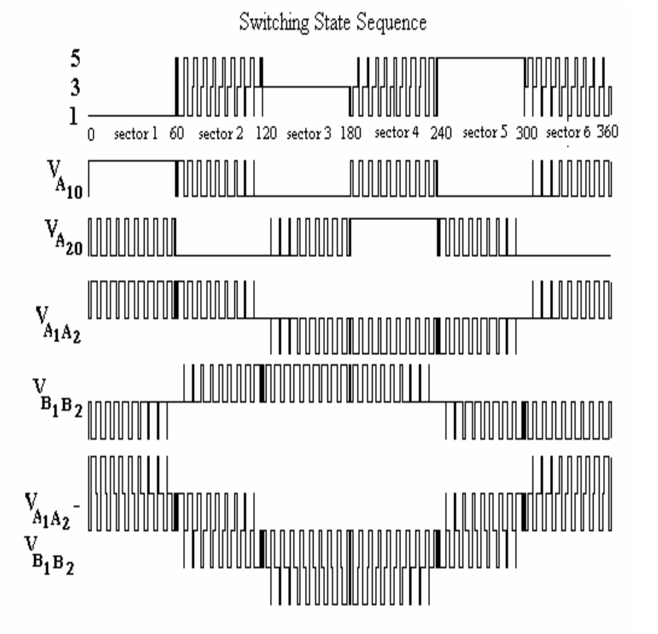
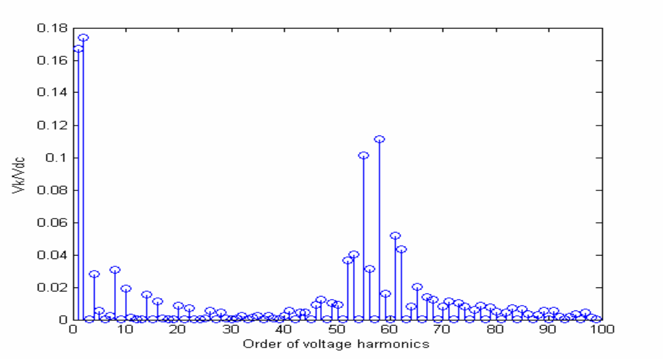
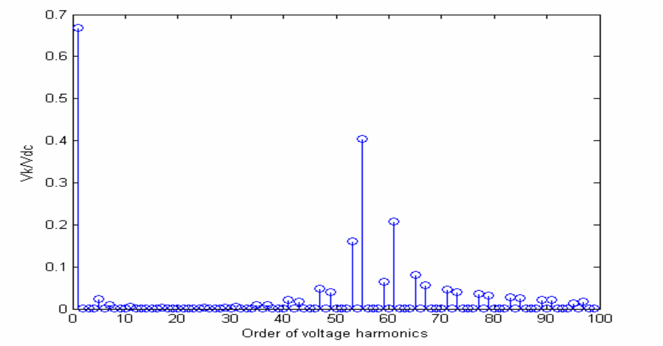



Fig. 9. Switching state sequence, pole voltages, phase voltages, and their difference for $F = 30$ Hz ($m=0.6$).




a)




b)

Fig. 10. Spectrum of the pole (a) and phase (b) voltages ($m=0.6$).

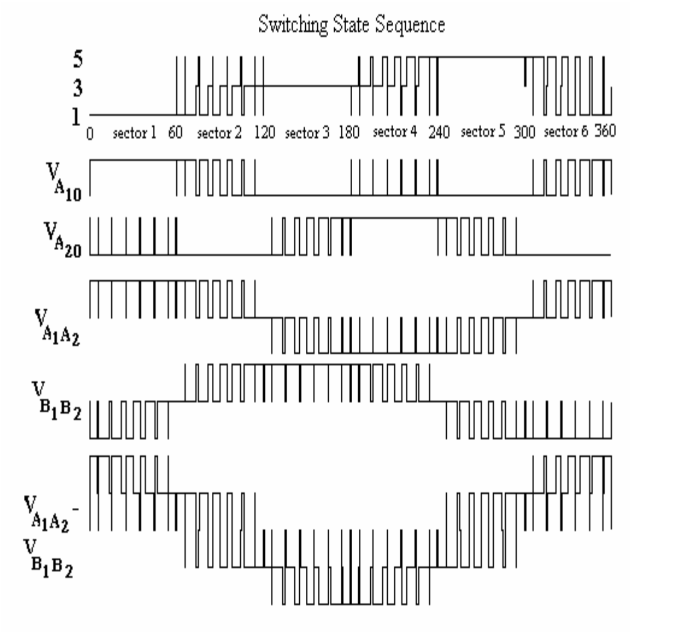
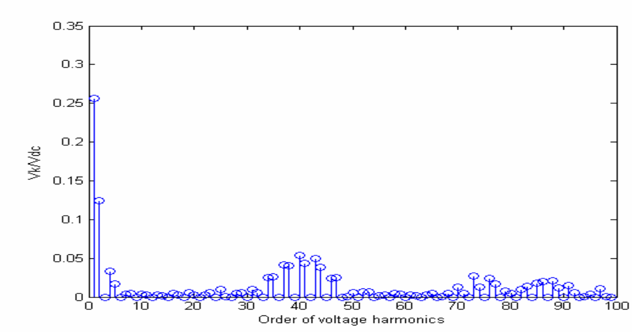
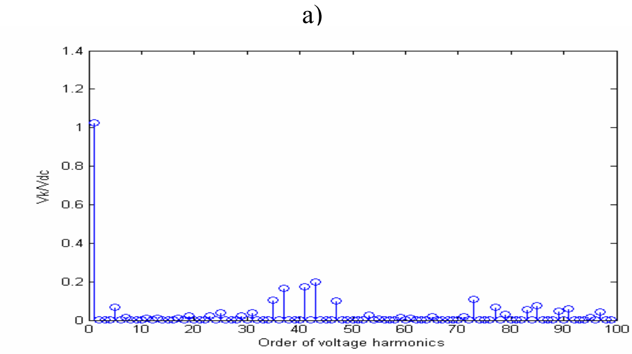



Fig. 11. Switching state sequence, pole voltages, phase voltages, and their difference for $F = 45$ Hz ($m=0.9$).




a)




b)

Fig. 12. Spectrum of the pole (a) and phase (b) voltages (*m=0.9*).

All waveforms of the phase and line-to-line voltages, presented in Figs. 7, 9 and 11, have full quarter-wave symmetry during the whole control range including the zone of overmodulation, and its spectra do not contain even harmonics and combined harmonics (sub-harmonics).

Fig. 13 shows results of calculation of Weighted Total Harmonic Distortion factor (*WTHD*, was calculated as in [7]) for the phase voltage $V_{A1A2}$ of the drive system for different values of averaged switching frequency of each inverter. Tendency of variation of these integral spectral characteristics is close in this case to variation of *WTHD* factor for inverters with discontinuous synchronized PWM, described in [7-8].

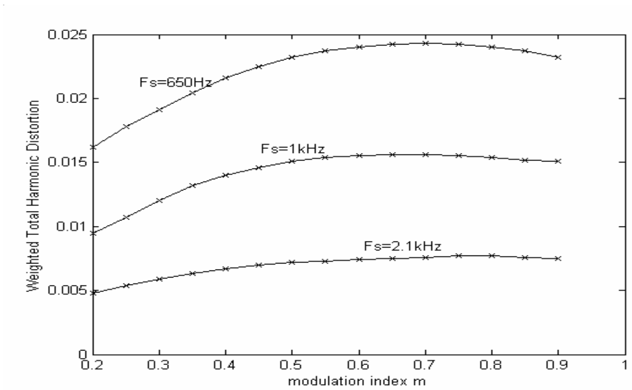



Fig. 13. *WTHD* factor versus modulation index.

## 6. Control of the system in the overmodulation zone

The proposed and described in the previous parts novel method of synchronized modulation is well suited for high quality linear control of both each inverter and dual inverter-fed drive system during the zone of overmodulation. For this purpose basic control correlations of the method of synchronized PWM (6)-(9), (11) include two special coefficients of overmodulation $K_{ov1}$ and $K_{ov2}$ [7]. Control scheme during overmodulation is based in this case on two-stage strategy with two threshold frequencies $F_{ov1}$ and $F_{ov2}$ [7-9].

The detailed description of the control process in accordance with the proposed algorithm of synchronized PWM for standard three-phase inverters in this zone is in [9].

Figs. 14, 16 and 18 present switching state sequences for INV1, pole voltages of two inverters $V_{A10}$ and $V_{A20}$, phase voltages $V_{A1A2}$ and $V_{B1B2}$ and their difference $V_{A1A2}$ - $V_{B1B2}$ (line-to-line voltage) correspondingly for $F = 47.6$ ($m=0.952$), $49$ ($m = 0.98$) and $50$ *Hz* ($m=1$). Figs. 15, 17 and 19 show the corresponding spectra of the phase voltage of the drive system with the described algorithm of synchronized PWM, which provides full elimination of the common-mode voltages during smooth pulse dropping process. The presented voltage waveforms have symmetry in this zone.

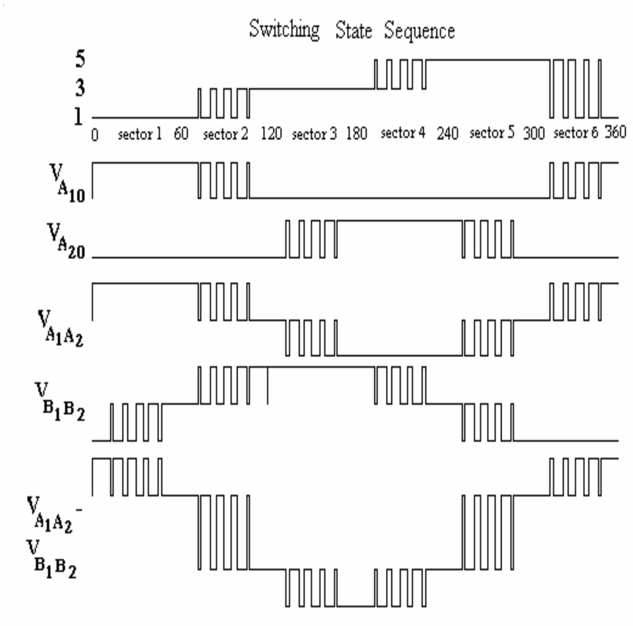



Fig. 14. Switching state sequence, pole voltages, phase voltages, and their difference for *F =47.6 Hz* (*m=0.952*).

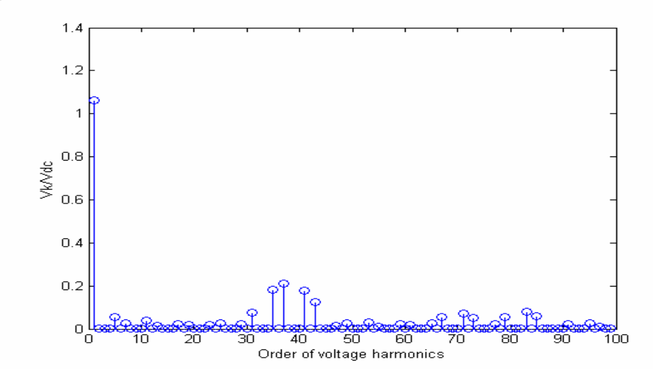



Fig. 15. Spectrum of the phase voltage of the drive system ($m=0.952$).

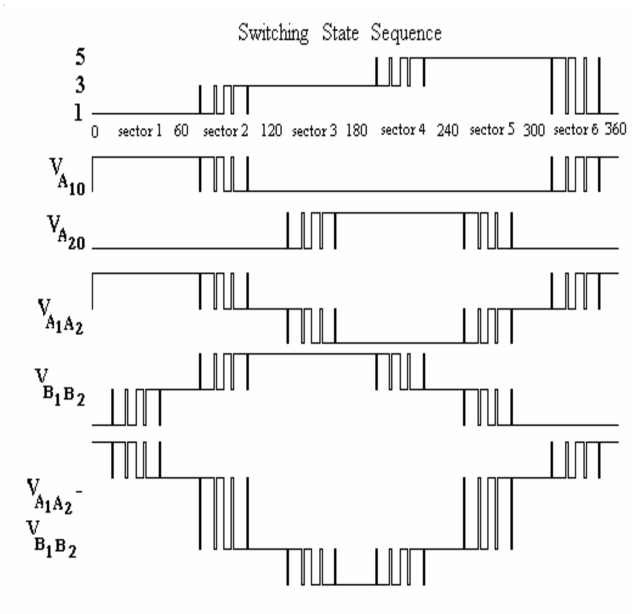



Fig. 16. Switching state sequence, pole voltages, phase voltages, and their difference for $F = 49$ Hz ($m=0.98$).

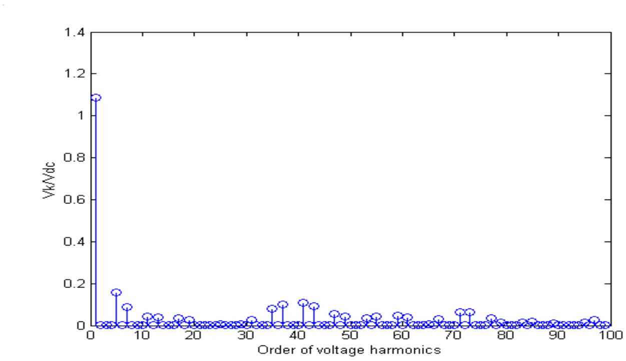



Fig. 17. Spectrum of the phase voltage of the drive system ($m=0.98$).

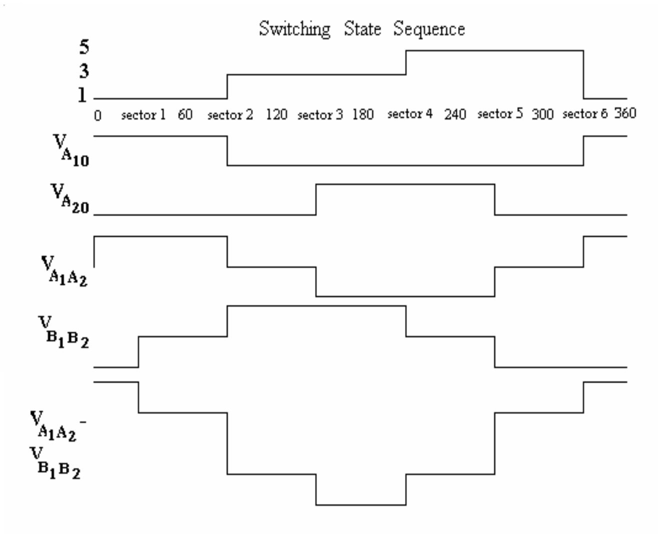



Fig. 18. Switching state sequence, pole voltages, phase voltages, and their difference for $F = 50$ Hz ($m=1$).

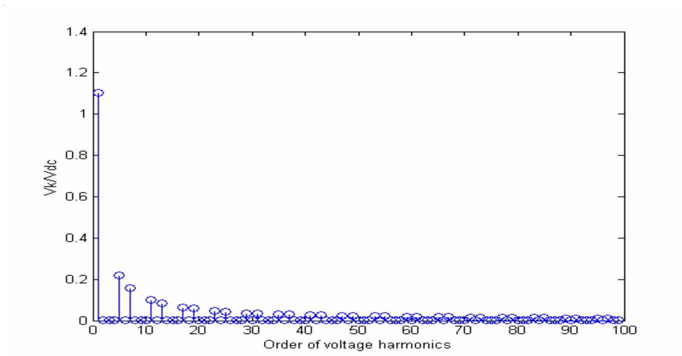



Fig. 19. Spectrum of the phase voltage of the drive system ($m=1$).

## 7. Conclusion

Novel method of direct synchronized pulsewidth modulation is applied for control of a dual inverter-fed open-end winding induction motor drive with zero common-mode voltages. The proposed control algorithms can be useful for the drive systems with increased requirements to the reliability. New strategy and scheme of synchronized PWM provide symmetry of the phase voltage of drive system during the whole control range including the zone of overmodulation. Spectra of the phase voltage do not contain even harmonics and sub-harmonics (combined harmonics), which is especially important for the systems with increased power rating.

## 8. Acknowledgement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**References**

1. Stemmler H., Guggenbach P.: *Configurations of High Power Voltage Source Inverter Drives*. In: Proceedings of the 1993 European Power Electronics Conference EPE'93, pp.7-12.
2. Stemmler H.: *High-power industrial drives*. In: IEEE Proc., Vol.82, no.8, 1994, pp.1266-1286.
3. Corzine K.A., Sudhoff S.D., Whitcomb C.A.: *Performance characteristics of a cascaded two-level converter*. In: IEEE Trans. on Energy Conversion, Vol.14, no.3, 1999, pp.433-439.
4. Somasekhar V.T., Baiju M.R., Gopakumar K.: *Dual two-level inverter scheme for an open-end winding induction motor drive with a single DC power supply and improved DC bus utilisation*. In: IEE Proc. – Electr. Power Appl., Vol.151, no.2, 2004, pp.230-238.
5. Somasekhar V.T., Gopakumar K., Shivakumar E.G., Sinha S.K.: *A space vector modulation scheme for a dual two level inverter fed open-end winding induction motor drive for the elimination of zero sequence currents*. In: EPE Journal, Vol.12, no.2, 2002, pp.12-36.
6. Baiju M.R., Mohapatra K.K., Kanchan R.S., Gopakumar K.: *A dual two-level inverter scheme with common mode voltage elimination for an induction motor drive*. In: IEEE Trans. on Power Electronics, Vol.19, no.3, 2004, pp.794-805.
7. Oleschuk V., Blaabjerg F.: *Direct Synchronized PWM Techniques with Linear Control Functions for Adjustable Speed Drives*. In: Proceedings of the 2002 IEEE Applied Power Electronics Conference APEC'2002, pp.76-82.
8. Oleschuk V., Blaabjerg F., Chen Zhe, Stankovic A.M.: *Synchronized PWM Scheme for Dual Inverter-Fed Drives with Zero Common-Mode Voltages*. In: Proceedings of the 2005 IEEE Industrial Electronics Conf. IECON'2005, pp.1076-1081.
9. Oleschuk V., Ermuratski V., Chekhet E.M.: *Drive Converters with Synchronized Pulsewidth Modulation during Overmodulation*. In: Proceedings of the 2004 IEEE Int'l Symposium on Industrial Electronics ISIE'2004, pp.1339-1344.