Open-End Winding Motor Drive with Synchronous PWM in the Overmodulation Region

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***Abstract*—The paper presents analysis of operation of dual inverter-fed motor drive with synchronized pulsewidth modulation (PWM) in the zone of overmodulation. This drive topology includes two insulated dc sources (with equal or different voltages), feeding two standard three-phase inverters, connected with an open-end winding induction motor. Algorithms of synchronized PWM provide both continuous synchronization of the phase voltage of the induction motor and required sharing of the output power between two dc sources. Simulation results are given for open-end winding drive systems with continuous and discontinuous versions of synchronized PWM.**

***Index Terms*—adjustable speed drive, converter control, inverter, pulsewidth modulation, voltage synchronization**

I. INTRODUCTION

Multilevel converters and drives are a subject of increasing interest in the last years due to some advantages compared with conventional three-phase systems. Some of the 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 the 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. Dual inverter-fed open-end winding motor drives have some ad-vantages such as redundancy of the space-vector combina-tions and the absence of neutral point fluctuations [4]-[7].

Almost all versions of classical space-vector PWM are based on the asynchronous principle, which results in sub-harmonics (of the fundamental frequency) in the spectrum of the output voltage of converters, that are very undesirable in medium/high power applications [8]-[9]. In order to provide voltage synchronization in dual inverter-fed drives, a novel method of synchronized PWM has been applied for control of dual inverter-fed drives with single dc voltage source [10], and for the systems with two dc sources: without power balancing between sources [11], and also with power balancing PWM algorithms in linear control range [12].

High power/high current traction drives (ship propulsion, locomotive, electrical vehicles, etc.) are the perspective area of application of dual inverter-fed drives. Flexible PWM control of dual two-level inverters can provide increased effectiveness of traction systems. So, this paper presents results of investigation of dual inverter-fed drives with synchronized PWM with required power sharing between two dc sources at the highest fundamental frequencies in the zone of overmodulation.

II. BASIC Topology of A Dual inverter-fed OPEN-END winding motor drive with Two DC SOURCES

Fig. 1 presents basic structure of a dual inverter-fed open-end winding induction motor drive with two standard voltage source inverters with pulsewidth modulation, which are supplied by two separate dc-link sources with voltages V_{dc1} and V_{dc2} [3]. Separate dc supply is used for each inverter to block the flow of third harmonic currents.

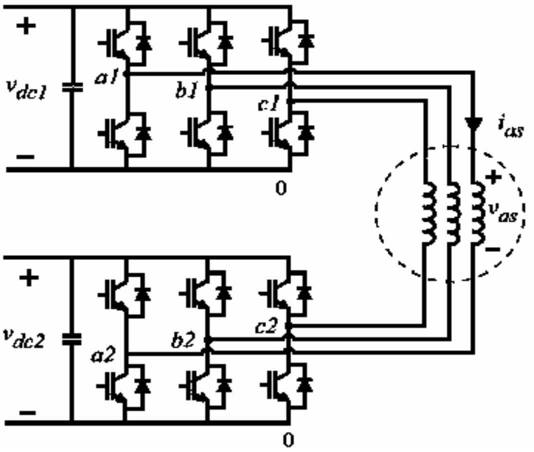

Figure 1. Basic topology of dual inverter-fed open-end winding induction motor drive with two separate dc-link sources [3].

III. FEATURES OF THE SCHEMES OF SYNCHRONIZED PWM

In order to avoid asynchronism of conventional space-vector modulation, a novel method of synchronized PWM [13],[14] can be used for control of each inverter in dual inverter-fed traction drives.

Figs. 2 - 3 present switching state sequences of standard three-phase inverter inside the interval 0^0-90^0. It illustrates schematically basic continuous (CPWM, Fig. 2) and discontinuous (DPWM, Fig. 3) versions of space-vector

PWM, which are used typically in adjustable speed drives.

The upper traces in Figs. 2 – 3 are switching state sequences (in accordance with conventional designation [13]), then – control signals for the cathode switches of the phases ***a1***, ***b1, c1*** (***a2, b2, c2***) of each inverter. The lower traces in Figs. 2 - 3 show the corresponding quarter-wave of the line output voltage of inverters. Signals *bj* represent total switch-on durations during switching sub-intervals t , signals g_k are generated on the borders (Fig. 2) or in the centers (Fig. 3) of the corresponding b . Widths of notches l_k represent the duration of the zero sequences [13].

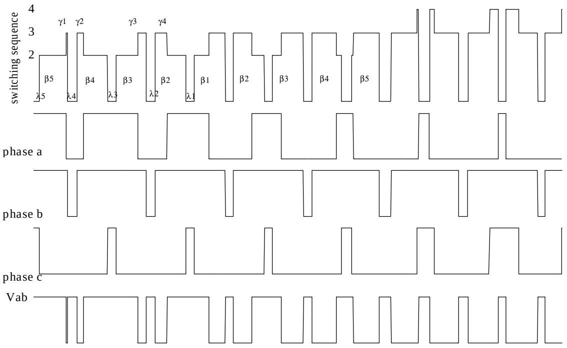

Figure 2. Control and output signals for inverter with continuous PWM.

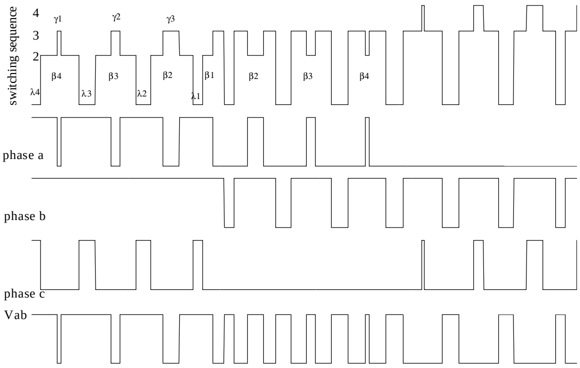

Figure 3. Control and output signals for inverter with discontinuous PWM.

Special signals l' (l_5 in Fig. 2, l_4 in Fig. 3) with the neighbouring b'' signals (b_5 in Fig. 2, b_4 in Fig. 3) are generated in the clock-points (0^0, 60^0, 120^0..) of the output curve of inverters with synchronized PWM. They are reduced simultaneously until close to zero value at the boundary frequencies F_i between control sub-zones. This PWM scheme provides continuous symmetrical voltage control.

Table I presents generalized properties and basic control correlations for the proposed method of synchronized PWM. It is also compared here with conventional asynchronous space-vector modulation. Basic control functions are available for both undermodulation and overmodulation control zones in this case. A more detailed description of laws and algorithms of synchronized PWM based on either algebraic or trigonometric control functions is in [13],[14].

IV. OVERMODULATION CONTROL OF DUAL INVERTER-FED SYSTEM WITH TWO DC SOURCES

Synchronous symmetrical control of the output voltage of each inverter of the dual inverter-fed drive system in accordance with algorithms of synchronized PWM provides synchronous symmetrical regulation of voltage in the induction machine phase windings. Rational phase shifting between output voltage waveforms of the two inverters is equal in this case to one half of the switching interval (sub-cycle) t [1].

In the case, when the two dc-link voltage sources have the same voltage (V_{dc2} = V_{dc1}), the resulting voltage space-vectors are equal to the space-vector patterns of conventional three-level inverter [1],[3],[7]. The phase voltage V_{as} of the dual inverter-fed drive with two insulated dc-link sources (Fig. 1) is calculated in accordance with (1)-(2) [4]:

TABLE I.
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
	$T_{ak}=1.1mT[\sin(60^0-\alpha_k)+\sin\alpha_k]$ $t_{ak}=1.1mT\sin\alpha_k$ $t_{bk}=1.1mT\times\sin(60^0-\alpha_k)$	$\beta_k=\beta_1[1-A\times(k-1)\tau F K_{ov1}]$ $\gamma_k=\beta_{i-k+1}[0.5-6(i-k)\tau F]K_{ov2}$ $\beta_k-\gamma_k$	$\beta_k=\beta_1\times\cos[(k-1)\tau K_{ov1}]$ $\gamma_k=\beta_{i-k+1}[0.5-0.9tn(i-k)\tau]K_{ov2}$ $\beta_k-\gamma_k$
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		$\beta''=\beta_1[1-A\times(k-1)\tau F K_{ov1}]K_s$ $\lambda'=(\tau-\beta'')\times K_{ov1}K_s$	$\beta''=\beta_1\times\cos[(k-1)\tau K_{ov1}]K_s$ $\lambda'=(\tau-\beta'')\times K_{ov1}K_s$

$$V_0 = 1/3(V_{a1} + V_{b1} + V_{c1} + V_{a2} + V_{b2} + V_{c2}) \tag{1}$$

$$V_{as} = V_{a1} + V_{a2} - V_0 \tag{2}$$

where V_{a1}, V_{b1}, V_{c1}, V_{a2}, V_{b2}, V_{c2} are the corresponding pole voltages of each three-phase inverter, V_0 is the zero sequence (triplen harmonic components) voltage.

Method of synchronized modulation, applied to dual inverter-fed drives, is well suited for synchronous 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} (3) and K_{ov2} (4), providing smooth pulses dropping process in this zone:

$$K_{ov1} = 1- (F - F_{ov1})/(F_{ov2} - F_{ov1}) \tag{3}$$

$$K_{ov2} = 1- (F - F_{ov2})/(F_m - F_{ov2}) \tag{4}$$

Typical control scheme for the inverter with the maximum modulation index for standard V/F control of dual three-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* [8],[13],[15]. 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 the b -parameters until the width of $b_1 = t$ is observed for inverter with the maximum modulation index, with simultaneous smooth reduction of all notches l until zero at the F_{ov2} frequency. The second sub-zone of the drive control during overmodulation, between the second threshold frequency F_{ov2} and the maximum fundamental frequency F_m ($F_m > F > F_{ov2}$), is characterized by a smooth decrease until zero of the widths of all g -parameters of the inverter with higher modulation index.

Overmodulation PWM Control of Dual Inverter-Fed System with Equal Voltages of DC Sources

In order to provide the rated ratio P_1/P_2 between the powers of two dc sources with equal voltages for scalar *V/F* control of dual inverter-fed drives, it is necessary to provide a simple correlation between modulation indices m_1 and m_2 of the two inverters and the rated power ratio in accordance with (5) [12]:

$$\frac{m_1}{m_2} = \frac{P_1}{P_2} \tag{5}$$

As an illustration of the overmodulation control of dual inverter-fed system with equal voltages of dc sources ($V_{dc1}=V_{dc2}$), Fig. 4 and Fig. 5 present its basic voltage waveforms (the pole voltages V_{a1}, V_{a2}, line-to-line voltages V_{a1b1}, V_{a2b2} of the two inverters, and the phase voltage V_{as} (with its spectrum)) for unbalanced power distribution between dc-links ($P_1=0.5P_2$, $m_1=0.5m_2$ in this case), controlled in the first part of the zone of overmodulation ($F < F_{ov2}$: *F=46Hz* (Fig. 4), and *F=47Hz* (Fig. 5)) in accordance with discontinuous synchronized PWM. The average switching frequency of each inverter is *900 Hz*.

Fig. 6 and Fig. 7 present basic voltage waveforms (with spectral characteristics of the phase voltage V_{as}) of unbalanced dual three-phase system with synchronized pulsewidth modulation ($V_{dc1}=V_{dc2}$, $P_1=0.5P_2$, $m_1=0.5m_2$), corresponding to the second control sub-zone at the highest fundamental frequencies (*F=48Hz*, $m_2=0.96$ (Fig. 6), and *F= 49Hz*, $m_2=0.98$ (Fig. 7)). The average switching frequency of inverters is *900 Hz*. And, in particular, Fig. 8 shows the same parameters of the system at the maximum fundamental frequency F_m *=50Hz*. Modulation indices of two inverters in accordance with (5) here are: $m_2=1$, $m_1=0.5$.

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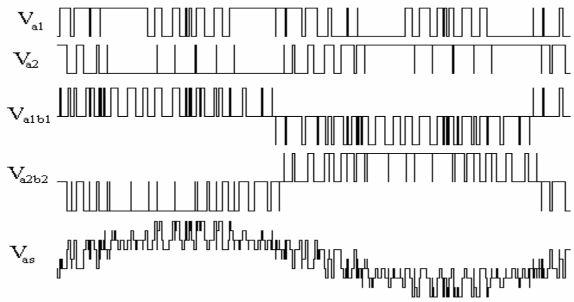


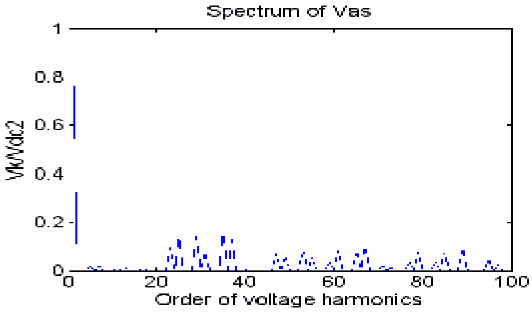
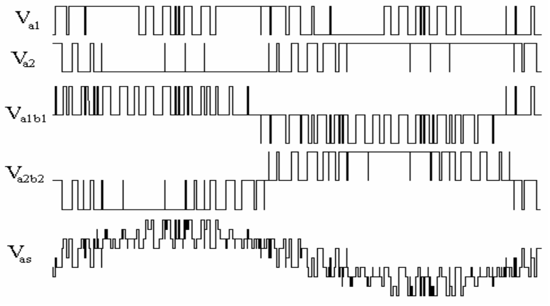


Figure 4. Pole voltages V_{a1} and V_{a2}, line voltages V_{a1b1} and V_{a2b2}, and phase voltage V_{as} (with its spectrum) for the system with discontinuous synchronized PWM ($F=46Hz$, $m_2=0.92$, $V_{dc1}=V_{dc2}$, $P_1=0.5P_2$).



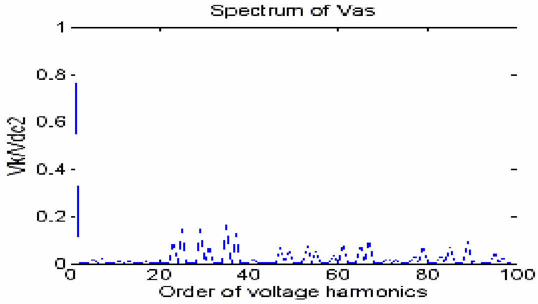
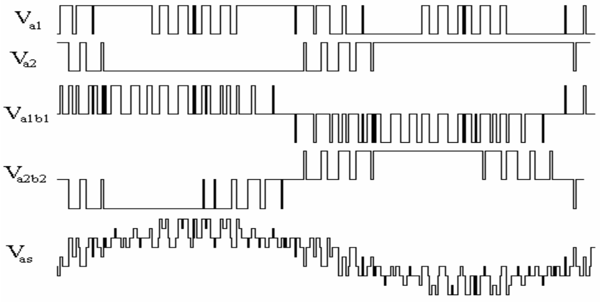


Figure 5. Pole voltages V_{a1} and V_{a2}, line voltages V_{a1b1} and V_{a2b2}, and phase voltage V_{as} (with its spectrum) for system with discontinuous synchronized PWM ($F=47Hz$, $m_2=0.94$, $V_{dc1}=V_{dc2}$, $P_1=0.5P_2$).



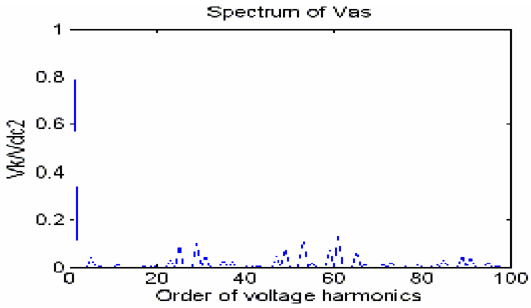


Figure 6. Pole voltages V_{a1} and V_{a2}, line voltages V_{a1b1} and V_{a2b2}, and phase voltage V_{as} (with its spectrum) for the system with discontinuous synchronized PWM ($F=48Hz$, $m_2=0.96$, $m_1=048$, $V_{dc1}=V_{dc2}$, $P_1=0.5P_2$).

overmodulation control zone of dual inverter-fed drives with synchronized PWM the spectra of the phase voltage of the induction motor contain only odd harmonics (without triplen harmonics), for any ratios (integral or fractional) between the switching and fundamental frequencies. These PWM algorithms provide also smooth shock-less pulses-ratio changing during the whole control range.

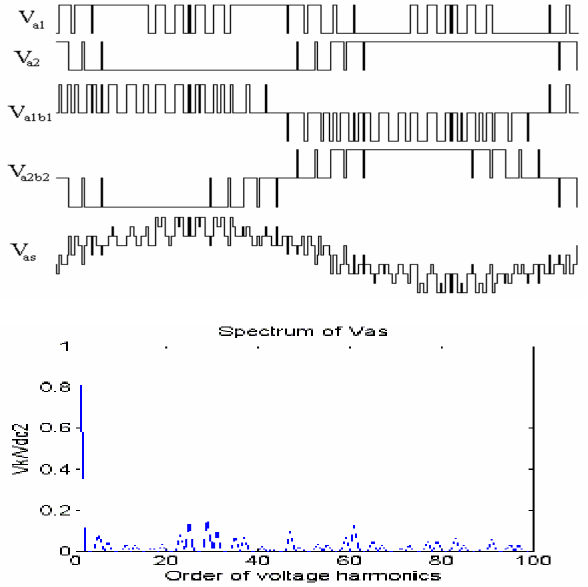


Figure 7. Pole voltages V_{a1} and V_{a2}, line voltages V_{a1b1} and V_{a2b2}, and phase voltage V_{as} (with its spectrum) for the system with discontinuous synchronized PWM ($F=49Hz$, $m_2=0.98$, $m_1=0.49$, $V_{dc1}=V_{dc2}$, $P_1=0.5P_2$).

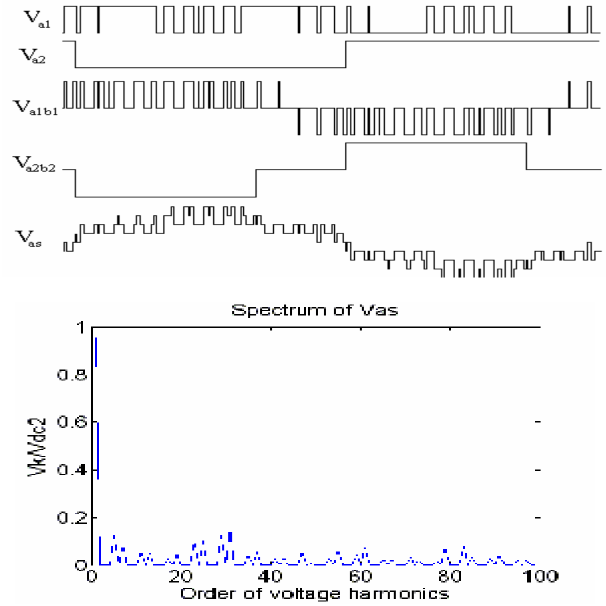


Figure 8. Pole voltages V_{a1} and V_{a2}, line voltages V_{a1b1} and V_{a2b2}, and phase voltage V_{as} (with its spectrum) for the system with discontinuous synchronized PWM ($F=50Hz$, $m_2=1$, $m_1=0.5$, $V_{dc1}=V_{dc2}$, $P_1=0.5P_2$).

A. Overmodulation PWM Control of Dual Inverter-Fed System with Non-Equal Voltages of DC Sources

For the dual inverter-fed drive with different voltages of the dc-links, in order to provide the rated power ratio P1/P2 between two power sources (for scalar V/F control mode), it is necessary to provide the corresponding correlations between magnitudes of dc voltages, modulation indices of the two inverters and the rated power ratio in accordance with (6):

$$\frac{m_1 V_{dc1}}{m_2 V_{dc2}} = \frac{P_1}{P_2} \tag{6}$$

In particular, in the case of equal power distribution between the two dc sources (P1 = P2), it is necessary to provide a simple linear correlation between magnitudes of dc voltages and modulation indices of the two inverters:

$$m_1 V_{dc1} = m_2 V_{dc2} \tag{7}$$

If, as an example, $V_{dc1} = 0.7V_{dc2}$, in this case $m_2 = 0.7m_1$.

For illustration of this control mode in the zone of overmodulation, Fig. 9 - Fig. 13 present the pole voltages V_{a1}, V_{a2}, line-to-line voltages V_{a1b1}, V_{a2b2} of the two inverters, and the phase voltage V_{as} (with its spectrum) of the dual inverter-fed drive with equal power distribution ($P_1 = P_2$) between the two dc sources with different voltages ($V_{dc1} = 0.7V_{dc2}$). Curves in Fig. 9 and Fig. 11 correspond to continuous version of synchronized PWM, and waveforms in Figs. 10, 12 and 13 correspond to discontinuous synchronized PWM. The average switching frequency is *1.05 kHz*, and the fundamental frequency $F = 46$ *Hz* for the control regimes, presented in Figs. 9 and 10, $F = 48$ *Hz* for the control modes, presented in Figs. 11 and 12, and $F = 50$ *Hz* for control regime, presented in Fig. 13.

Fig. 14 presents the calculation results of Weighted Total Harmonic Distortion factor (*WTHD*) for the phase voltage V_{as} (averaged values of $WTHD = (1/V_{as_1})\sqrt{\sum_{i=2}^{1000}(V_{as_k}/k)^2}$) in dual inverter-fed drive with continuous (CPWM) and discontinuous (DPWM) schemes of synchronized pulsewidth modulation for the system with equal (P1 = P2) power distribution between the two dc sources with different magnitudes of dc voltages (Vdc1 = 0.7Vdc2). The average switching frequency for each modulated inverter is 1.05 kHz; the control mode corresponds in this case to standard scalar *V/F* control.

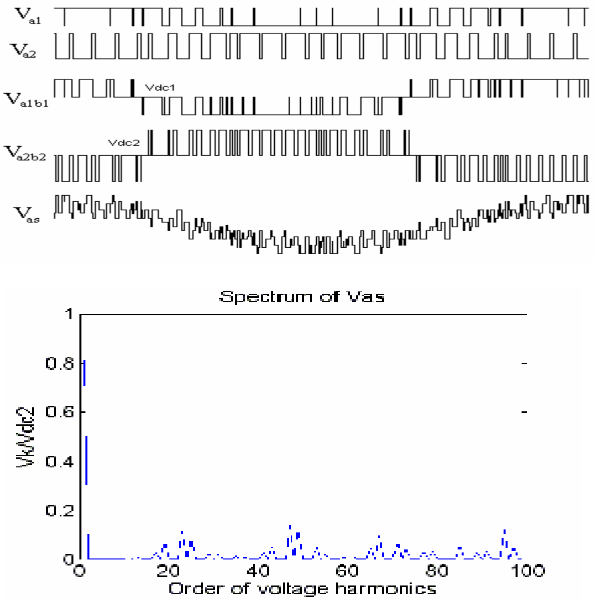


Figure 9. Pole voltages Va1 and Va2, line voltages Va1b1 and Va2b2, and phase voltage Vas (with its spectrum) for the system with continuous synchronized PWM (F=46Hz, Vdc1=0.7Vdc2, P1=P2, m1=0.92, m2=0.64).

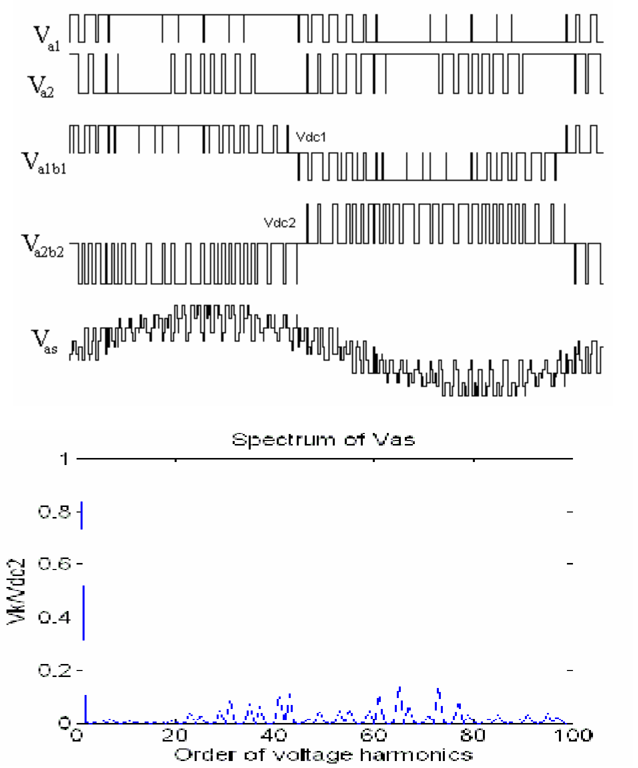


Figure 10. Pole voltages V_{a1} and V_{a2}, line voltages V_{a1b1} and V_{a2b2}, and phase voltage V_{as} (with its spectrum) for the system with discontinuous synchronized PWM ($F=46Hz$, $V_{dc1}=0.7V_{dc2}$, $P_1=P_2$, $m_1=0.92$, $m_2=0.64$).

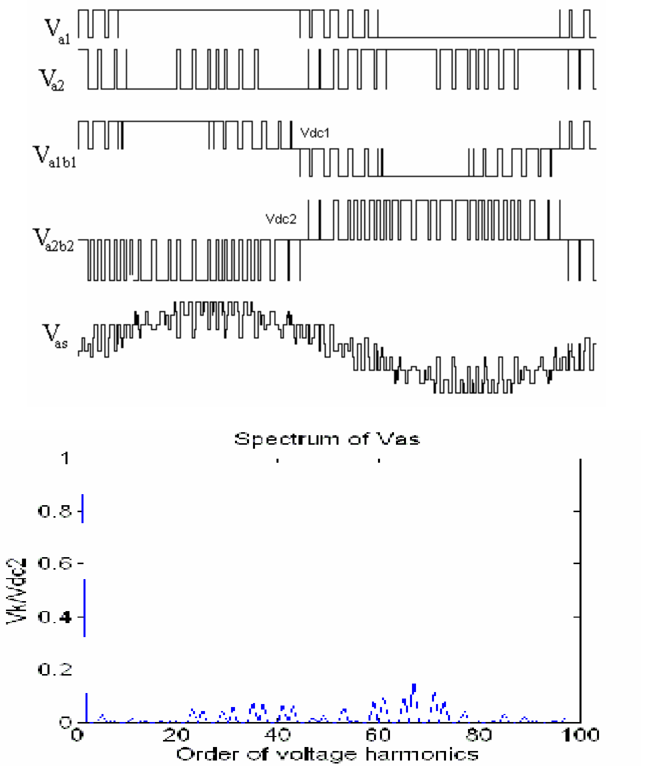


Figure 12. Pole voltages V_{a1} and V_{a2}, line voltages V_{a1b1} and V_{a2b2}, and phase voltage V_{as} (with its spectrum) for the system with discontinuous synchronized PWM ($F=48Hz$, $V_{dc1}=0.7V_{dc2}$, $P_1=P_2$, $m_1=0.96$, $m_2=0.67$).

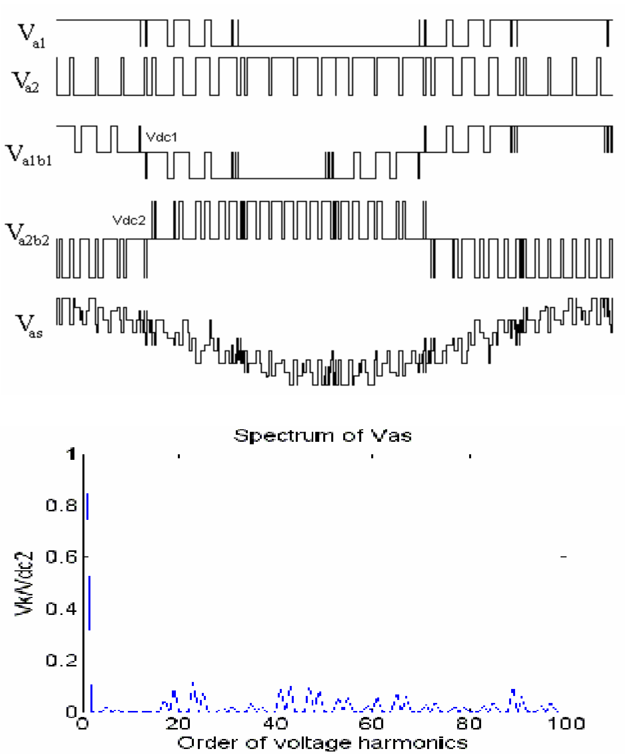


Figure 11. Pole voltages V_{a1} and V_{a2}, line voltages V_{a1b1} and V_{a2b2}, and phase voltage V_{as} (with its spectrum) for the system with continuous synchronized PWM ($F=48Hz$, $V_{dc1}=0.7V_{dc2}$, $P_1=P_2$, $m_1=0.96$, $m_2=0.67$).

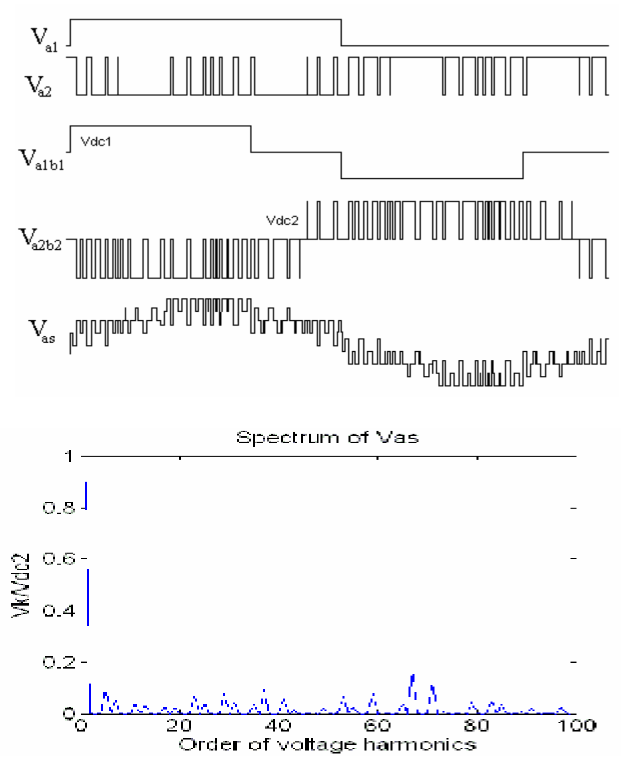


Figure 13. Pole voltages V_{a1} and V_{a2}, line voltages V_{a1b1} and V_{a2b2}, and phase voltage V_{as} (with its spectrum) for the system with discontinuous synchronized PWM ($F=50Hz$, $V_{dc1}=0.7V_{dc2}$, $P_1=P_2$, $m_1=1.0$, $m_2=0,7$).

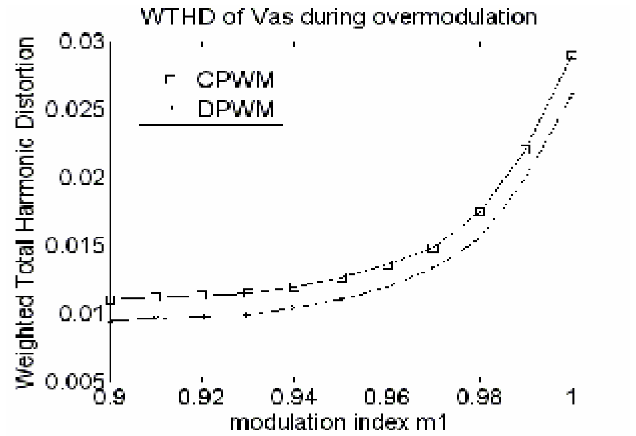


Figure 14. Averaged WTHD factor of the phase voltage Vas versus modulation index m1.

The calculation results presented in Fig. 14 show that for the analyzed control mode the discontinuous scheme of synchronised PWM provides better spectral composition of the phase voltage of dual inverter-fed drives in the zone of overmodulation in comparison with continuous synchronized PWM.

Analysis of spectral characteristics of the phase voltage of the dual inverter-fed system operating in the zone of overmodulation shows, that due to the algorithms of synchronized PWM the spectra of the phase voltage do not contain even harmonics and sub-harmonics for any control regime of the drives, with both equal and different voltages of two dc sources, and for any power ratio between the power sources.

The presented PWM algorithms provide also smooth shock-less pulses ratio changing of converter in the zone of overmodulation. Voltage synchronization in the system is provided continuously for any ratio between the switching and fundamental frequencies. In particular, almost all presented in Figs. 4 – 13 voltage spectral characteristics correspond to control modes with fractional ratios of these frequencies (*900Hz/46Hz=19.6* (Fig. 4), *900Hz/47Hz=19.1* (Fig. 5), *900Hz/48Hz=18.7* (Fig. 6), *900Hz/49Hz=18.4* (Fig.7), *900Hz/50Hz=18* (Fig. 8), *1050Hz/46Hz=22.8* (Figs. 9 and 10), *1050Hz/48Hz=21.9* (Figs. 11 and 12), *1050Hz/50Hz=21* (Fig. 13)).

V. CONCLUSION

Novel method of synchronized space-vector modulation, applied for overmodulation control of dual inverter-fed open-end winding motor drives with two insulated dc-links, allows both continuous phase voltage synchronization and required sharing of the power between two dc sources in the zone of overmodulation.

Control process is characterized in this case by smooth shock-less pulses ratio changing. The spectra of the motor phase voltages do not contain even harmonics and sub-harmonics for any ratio between the switching and fundamental frequencies, which is especially important for the medium power/high power systems.

The described method of synchronous pulsewidth modulation can also be disseminated for control of other structures and topologies of multilevel converters and drives both in the linear modulation range and in the zone of overmodulation.

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