METHODS AND TECHNIQUES OF SYNCHRONOUS MULTI-ZONE MODULATION FOR THE CONTROL OF POWER ELECTRONIC CONVERTERS FOR ELECTRIC TRANSPORT AND PHOTOVOLTAIC SYSTEMS

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Doctor Habilitat in Engineering **Valentin OLESCHUK**
Laureate of the ASM Prize in the Engineering Science ”Boris Lazarenko”
for the years 2019–2020
E-mail: oleschukv@hotmail.com
ORCID: http://orcid.org/0000-0002-7413-4867
Institute of Power Engineering of Moldova

Summary. This paper presents a short survey of the results of elaboration and investigation of novel methods, schemes, and algorithms of synchronous multi-zone space-vector modulation of signals in power electronic converters of electrical energy parameters, focused on improvement of operation efficiency of converter-based transport-oriented electric drives and of photovoltaic power conversion systems, which were published mainly in the two-year period 2019–2020. These methods and algorithms of synchronous pulse-width modulation (PWM) allow providing continuous synchronization and symmetries of waveforms of the converters output voltage, with minimization of undesirable sub-harmonics in spectra of voltage and current, and also with minimization of undesirable common-mode voltage in electric transport systems and in photovoltaic systems, which leads to corresponding loss reduction and efficiency increasing of these systems.

Keywords: voltage source inverter, algorithms of control and modulation, adjustable speed ac drive, induction motor, transformer-based photovoltaic installation, voltage waveforms, voltage spectra.

METODE ȘI TEHNICI DE MODULARE MULTIZONALĂ SINCRONĂ PENTRU CONTROLUL CONVERTOARELOR ELECTRONICE DE PUTERE DESTINATE TRANSPORTULUI ELECTRIC ȘI SISTEMELOR FOTOVOLTAICE

Rezumat. Această lucrare reprezintă un succint studiu al rezultatelor elaborării și investigării unor noi metode, scheme și algoritmi de modulare multizonală spațial-vectorială sincronă a semnalelor convertoarelor electronice de putere ale parametrilor energiei electrice, axată pe îmbunătățirea eficienței funcționării de acționări electrice orientate spre transport pe bază de convertoare și de sisteme de conversie ale energiei fotovoltaice, care au fost publicate preponderent în perioada 2019–2020. Aceste metode și algoritmii de modulare sincronă a lățimii impulsurilor asigură sincronizarea continuă și simetria formei de undă a tensiunii de ieșire a convertoarelor, cu reducerea la minimum a subarmonicilor nedorite în spectrele de tensiune și curent, de rând cu reducerea la minimum a tensiunii de mod comun, nedorite în sistemele electrice de transport și în sistemele fotovoltaice, ceea ce conduce la reducerea corespunzătoare a pierderilor și la creșterea eficienței acestor sisteme.

Cuvinte-cheie: invertor, algoritmi de control și modulare, acționari electrice reglabile de curent alternativ, motor electric, instalație fotovoltaică bazată pe transformator, forme de undă de tensiune, spectre de tensiune.

INTRODUCTION

Power electronic converters are basic workhorses of numerous systems of conversion of parameters of electrical power (conversion of alternative voltage to direct voltage, conversion of direct voltage to alternative voltage, conversion of alternative voltage of one frequency to alternative voltage of other frequency, etc.), and are widely used in industry, in pump installations, in transport, in renewable energy systems, etc. All topologies of power electronic converters are based on semiconductor switches (power transistors and thyristors), and principle of modulation of pulse signals (pulsewidth modulation (PWM)) is the basic for their control.

During the last three decades, special attention has been given to the development of space-vector-based schemes and algorithms of pulsewidth modulation, which are ones of the most suitable for converters and inverters for adjustable speed electric drives and for some other applications [1; 2].

At the same time, classical space-vector modulation has a set of disadvantages, and one of the most important from them is asynchronous character of processes of modulation in systems with algorithms of standard space-vector PWM. It leads to non-symmetrical waveforms of the output voltage of converters of parameters of electrical energy, spectra of which contain subharmonics (of the fundamental frequency of systems), which are very undesirable in many applications [3].

From the other side, alternative (based on new approach for determination of the pulse patterns of voltage source converters (inverters) and on multi-zone control strategy) methods of synchronous space-vector modulation have been proposed for control of some topologies of electrical power conversion systems, assuring continuous voltage synchronization and its improved harmonic spectra during the whole adjustment diapason [4; 5]. So, this paper presents short overview of recently elaborated and investigated specialized schemes, techniques, and algorithms of synchronous multi-zone modulation, modified and disseminated for control of transport-oriented power converters and electric drives, and for transformer-based photovoltaic systems with modulated voltage source inverters [6-21].

BASIC METHODOLOGY

Novel alternative method of synchronous multi-zone space-vector modulation for power electronic inverters (which provide conversion of direct voltage at its input to alternative voltage with controlled frequency at its output) allows continuous voltage synchronization in power conversion systems during the whole control range. The method is based on direct continuous identification of parameters of the output voltage of inverters as a function of its output frequency and switching frequency during flexible multi-zone process of modulation.

Table I presents basic parameters, indices, and control functions of the alternative methodology of synchronous multi-zone space-vector-oriented modulation for scalar control mode of three-phase, five-phase, and six-phase inverters for drive applications [6]. Figure 1 illustrates included in Table I the main control and PWM characteristics, and shows (inside the 60^0-clock-cycle) diagrams of switching state sequence and the pole and line voltages of two-level three-phase inverter controlled by the scheme of synchronous continuous PWM [6].

So, principle of synchronous multi-zone modulation of voltage source inverters is based on continuous determination of intermediate (boun-

Table 1

Control parameters and functions of drive inverters with synchronous multi-zone modulation

Control function	Three-phase and six-phase inverters	Five-phase inverters
Basic parameters	F – fundamental frequency of system F_m – maximum operating frequency of system τ – sub-switching interval	
Modulation index for scalar control	$m = F / F_m$	
Boundary frequencies transient between PWM sub-zones	$F_i = \frac{1}{6(2i-1)\tau}$ $F_{i-1} = \frac{1}{6(2i-3)\tau}$	$F_i = \frac{1}{10(2i-1)\tau}$ $F_{i-1} = \frac{1}{10(2i-3)\tau}$
Index of synchronization	$K_s = 1 - \frac{F - F_i}{F_{i-1} - F_i}$	
The central switch-on state	$\beta_1 = 1.10m\tau$	$\beta_1 = 1.21m\tau$
Others switch-on states	$\beta_j = \beta_1 \times \cos[(j-1)\tau]$	$\beta_j = \gamma'_j + \gamma''_j + \delta'_j + \delta''_j = 1.618\beta_1 \cos[(j-1)\tau]$
Border's active switching state	$\beta'' = \beta_1 \times \cos[(k-1)\tau]K_s$	$\beta'' = 1.618\beta_1 \times \cos[(k-1)\tau]K_s$
The minor part of switch-on states	$\gamma_k = \beta_{i-k+1}[0.5 - 0.9\tan(i-k)\tau]$	$\delta_k' + \delta_k'' = 0.382\beta_{i-k+1}$
Switch-off (zero) states	$\lambda_j = \tau - (\beta_j + \beta_{j+1})/2$	
Boarder's switch-off state	$\lambda_i = \lambda' = (\tau - \beta'')K_s$	

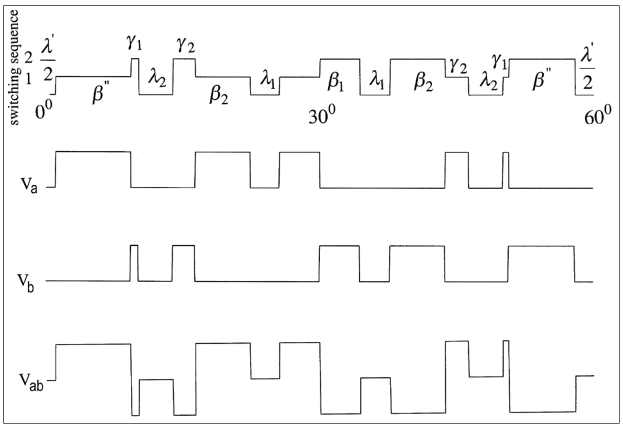


Figure 1. Switching state sequence, phase voltages V_a, V_b, and line voltage V_{ab} of three-phase inverter with synchronous multi-zone modulation for the 60^0-clock-cycle [6].

dary)requencies $F_i = \frac{1}{6(2i-1)\tau}$ and $F_{i-1} = \frac{1}{6(2i-3)\tau}$ (as functions of switching sub-cycle τ) on the axis of the fundamental frequency F of drive system, and in calculation of coefficient of synchronization $K_s = [1-(F-F_i)/(F_{i-1}-F_i)]$, which is component of basic functions (see Table 1) for determination of PWM pulse patterns of the corresponding scheme of synchronous space-vector modulation

The main properties of this new method of synchronous multi-zone PWM can be summarized as: (a) Universality of the methodology which can be applied to systems with any number of phases and switches of converters and drive systems, and is not limited by standard three-phase inverters. Also, this method is applicable for both scalar linear *Volts/Hertz* control and for others non-linear control modes of drive systems; (b) Synchronous character of the process of PWM, providing quarter-wave or half-wave symmetry of the output voltage of inverters (for any (integral or fractional) ratio between the switching frequency of inverters and fundamental frequency of system), spectra of which do not contain even harmonics and subharmonics during the whole control range; and (c) High quality linear control of the fundamental voltage of systems in the zone of the highest fundamental frequencies of systems or of the highest modulation indices of inverters of systems (in the zone of overmodulation).

RESULTS AND DISCUSSIONS

Dual three-phase transport systems with inverters controlled by synchronous multi-zone modulation [6; 12; 16]

Figure 2 presents structure of electrical vehicle drive system on the base of dual three-phase induction motor feeding by two standard three-phase inverters, controlled by algorithms of synchronous multi-zone modulation, and supplied by with two different dc sources (battery and fuel cells) [6]. Figures 3-4 present some basic signals (voltage and current, with its spectra) of the 10 kW six-phase drive with continuous synchronous PWM (CPWM) with two dc sources with unequal voltages, where $V_{dc1}=0.5V_{dc2}$. The switching and fundamental frequencies of each inverter are equal to *1kHz* and *40Hz*. Figures 4-5 present also phase current I_{xs} (and its spectrum) of the drive system with synchronous PWM with the 10 kW dual-three-phase induction machine [6]. The phase voltages have quarter-wave symmetry during the whole control range, and its spectra do not contain even harmonics and subharmonics, which is especially important for drive systems with increased power.

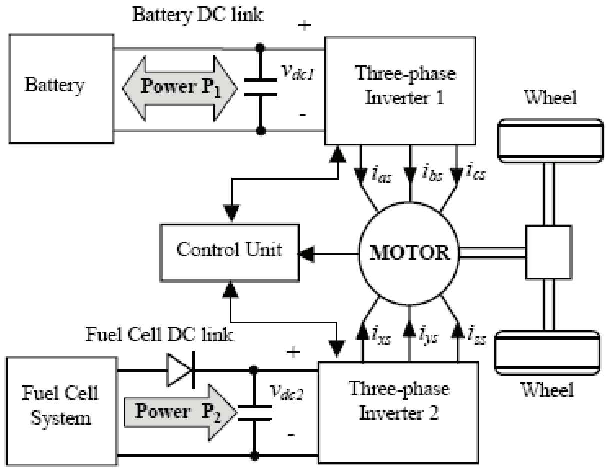


Figure 2. Dual-source fed dual three-phase drive for electrical vehicle [6].

Specific overmodulation control regimes of inverters of dual three-phase drive systems have been described in [16].

Figure 5 presents results of calculation of Total Harmonic Distortion factor (*THD*) for the phase currents I_{as} and I_{xs} of the 10 kW dual three-phase drive with two separate DC voltage sources ($V_{dc1}=0.5V_{dc2}$). The average switching frequency for each inverter is equal to *1kHz* during standard *Volts/Hertz* control mode in the undermodulation zone. Modulation indices for the first and the second inverters have to be in this case in linear dependence $m_2=0.5m_1$. So, the phase current I_{xs} of the second inverter with low modulation index is characterized by much higher level of distortion, than current I_{as} of the first inverter. In this case, if $m_2<0.6m_1$, the scheme of continuous synchronous PWM (CPWM) provide better spectral composition of the phase current I_{xs} of dual three-phase drive system in comparison with the schemes of discontinuous space-vector modulation (DPWM1 and DPWM3 in Figure 5) [12].

Dual-inverter-based traction drives with two stator windings of electrical motor [17-19; 21]

Recently, novel electrical power conversion systems based on double-delta sourced winding, which are perspective for application at high power induction motor drives based on dual-winding induction machine, have been tested at some control modes. Figure 6 presents structure of double-delta-winding drive system [18] with two three-phase (standard) voltage source inverters (VSI1 and VSI2), outputs of which are specifically (see bold lines in Figure 6) connected to the corresponding stator windings of dual-winding induction machine. For the better understanding,

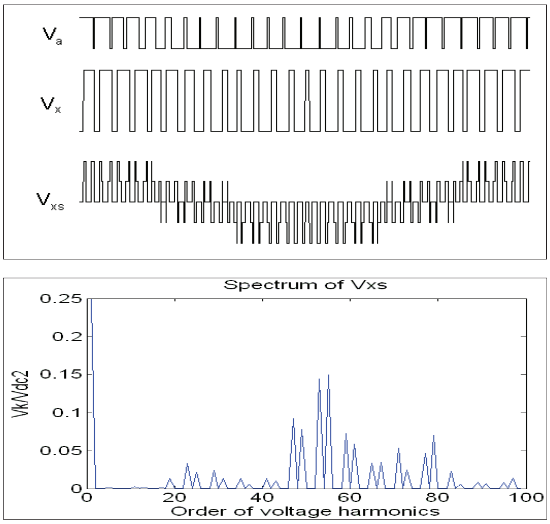


Figure 3. Pole voltages V_a, V_x, phase voltage V_{xs} and its spectrum for system with continuous synchronous PWM ($V_{dc1}=0.5V_{dc2}$) [6].

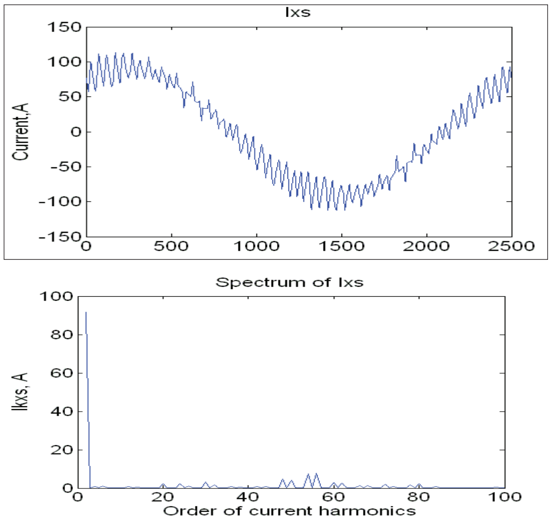


Figure 4. Phase current I_{xs} and its spectrum for system with synchronous PWM ($V_{dc1}=0.5V_{dc2}$) [6].

the magnetic coupling in this installation between the rotor windings and stator windings of dual-winding induction machine is depicted in Figure 6 as specific rotary transformer [18]. Figure 7 shows circuits of stator windings of this double-delta-sourced drive system [18].

At the same time, instantaneous values of winding voltages (stator windings) V_{w11} – V_{w23} (Figure 6) of the system are determined as functions of the corresponding pole voltages of two modulated VSIs as (1)-(6) [18-19]:

$$V_{w11} = (2V_{a1} - V_{b1} - V_{c1})/3 - (V_{a2} - 2V_{b2} + V_{c2})/3 \quad (1)$$

$$V_{w12} = (V_{a1} + V_{b1} - 2V_{c1})/3 - (-V_{a2} + 2V_{b2} - V_{c2})/3 \quad (2)$$

$$V_{w13} = (-V_{a1} - V_{b1} + 2V_{c1})/3 - (-2V_{a2} + V_{b2} + V_{c2})/3 \quad (3)$$

$$V_{w21} = (V_{a1} - 2V_{b1} + V_{c1})/3 - (2V_{a2} - V_{b2} - V_{c2})/3 \quad (4)$$

$$V_{w22} = (-V_{a1} + 2V_{b1} - V_{c1})/3 - (V_{a2} + V_{b2} - 2V_{c2})/3 \quad (5)$$

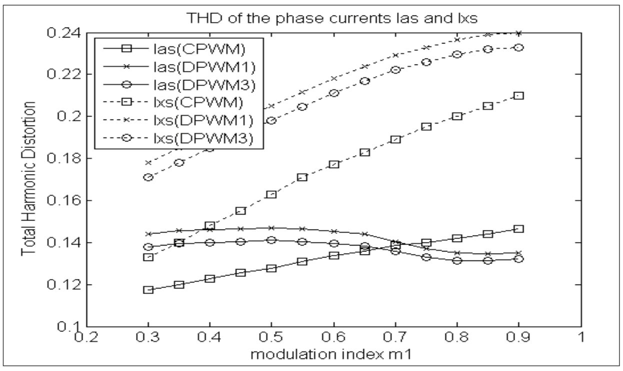


Figure 5. Averaged *THD* of the phase current versus modulation index m_1 [12].

$$V_{w23} = (-2V_{a1} + V_{b1} + V_{c1})/3 - (-V_{a2} - V_{b2} + 2V_{c2})/3 \quad (6)$$

Rational synchronous adjustment of double-delta-winding system with two modulated VSIs is based on the corresponding phase shifts of signals of two inverters, including an additional phase shift between signals of inverters equal to one half of switching sub-cycle [18].

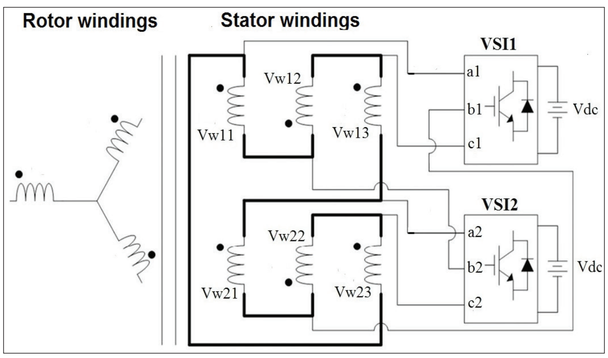


Figure 6. Structure of double-delta winding system with two three-phase VSIs [18].

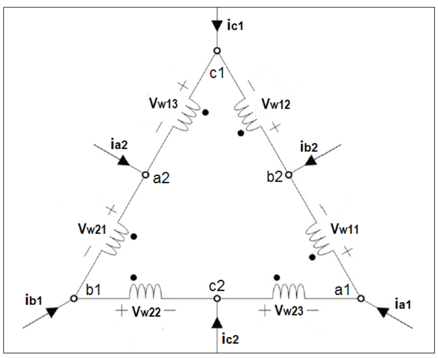


Figure 7. Stator windings of double-delta-sourced winding drive system [18].

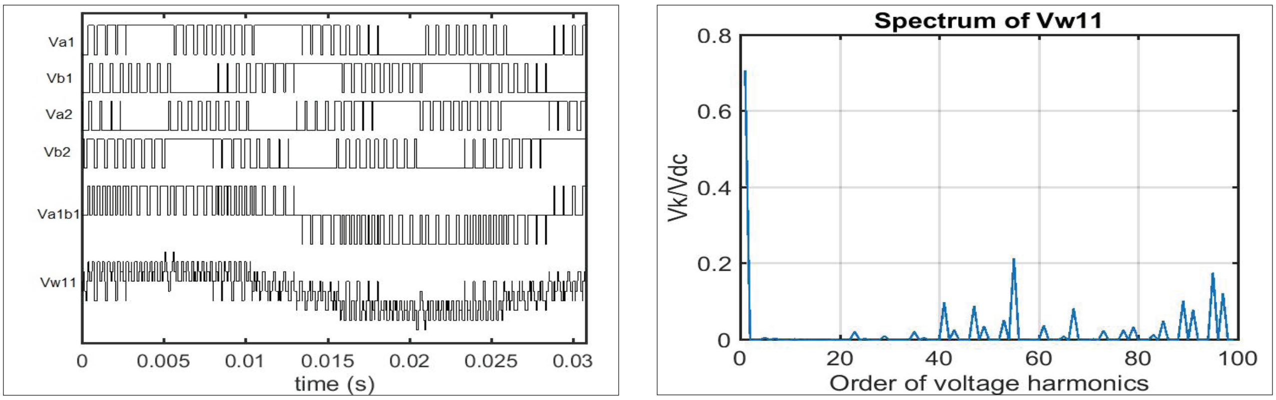


Figure 8. Basic voltages and spectrum of the V_{w11} voltage of double-delta-winding system controlled by PWMD [18].

Results of simulation of processes in the presented drive system with two VSIs control by algorithms of discontinuous synchronous modulation are presented in Figure 8 [18]. It shows basic voltage waveforms of double-delta-winding system (relative values of the pole and line voltages (V_{a1}, V_{b1}, V_{a2}, V_{b2}, and V_{a1b1}), stator winding voltage V_{w11}, and also spectra of the V_{w11} voltage), adjusted by and discontinuous (PWMD) scheme of synchronous modulation. Operating frequency of system is equal to $F=32.5Hz$, modulation index $m=0.65$, and average switching frequency of inverters is equal to $F_s=1.05kHz$.

Analysis of harmonic composition of symmetrical winding voltage of double-delta-winding system shows, that spectra of stator winding voltage of system contain only odd (non-triplen) spectral harmonics, and do not include even harmonics and undesirable (for systems with low switching frequency) subharmonics.

Figure 9 presents averaged results of determination of Weighted Total Harmonic Distortion factor ($WTHD = (1/V_{w11_1})\sqrt{\sum_{i=2}^{1000}(V_{w11i}/i)^2}$) of the V_{a1b1} and V_{w11} voltages of double-delta-winding drive system with VSIs (as function of coefficient of modulation m of two VSIs, under condition of average switching frequency of inverters equal to $1.05kHz$) controlled by the continuous (PWMC) and discontinuous (PWMD) schemes of synchronous modulation during scalar V/F control mode [18]. The presented results show, that at lower modulation indices, when $m<0.55$, algorithms of the PWMC assure better $WTHD$ of stator winding voltage V_{w11}, and at higher modulation indices ($m>0.55$) algorithms of the PWMD insure better integral spectral composition of V_{w11}.

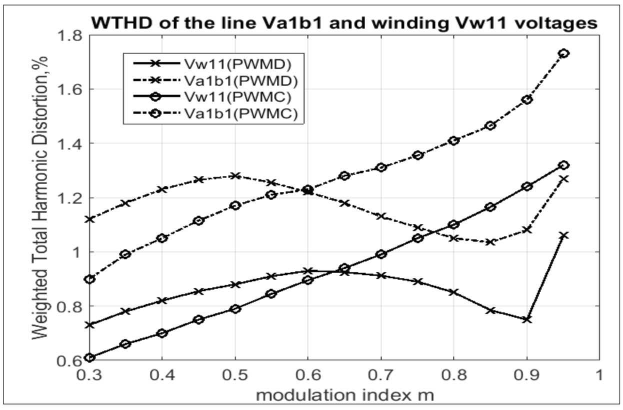


Figure 9. *WTHD* factor of basic voltages versus modulation index *m* [18].

Quad-inverter-based six-phase systems controlled by algorithms of synchronous multi-zone PWM [7; 11-13]

Recently, a four-inverter-based topology of six-phase induction motor drive, perspective for application in transport systems, has been proposed and analyzed, allowing quadrupling the power capability of a single inverter with given voltage and current rating [7; 11-13]. Figure 10 illustrates this system topology, consisting of two sections of two three-phase voltage source inverters, supplying open-end windings of asymmetrical dual three-phase motor. Induction machine has in this case two sets of windings spatially shifted by 30 el. degrees [12-13].

For six-phase drive on the basis of four converters with unequal voltages of dc sources, in order to provide the required power ratio P_1/P_2 and P_3/P_4 between four power sources of two sections of dual converters, it is necessary to provide the corresponding dependences between magnitudes of dc voltages, coefficients of modulation of four converters, and the required power ratio in accordance with (7) [7]:

$$\frac{m_1 V_{dc1}}{m_2 V_{dc2}} = \frac{P_1}{P_2} \qquad \frac{m_3 V_{dc3}}{m_4 V_{dc4}} = \frac{P_3}{P_4} \qquad (7)$$

In this case, in accordance with (7), for balancing operation of six-phase system it is necessary to allow:

$$m_1 V_{dc1} P_2 + m_2 V_{dc2} P_1 = m_3 V_{dc3} P_4 + m_4 V_{dc4} P_3, \qquad (8)$$

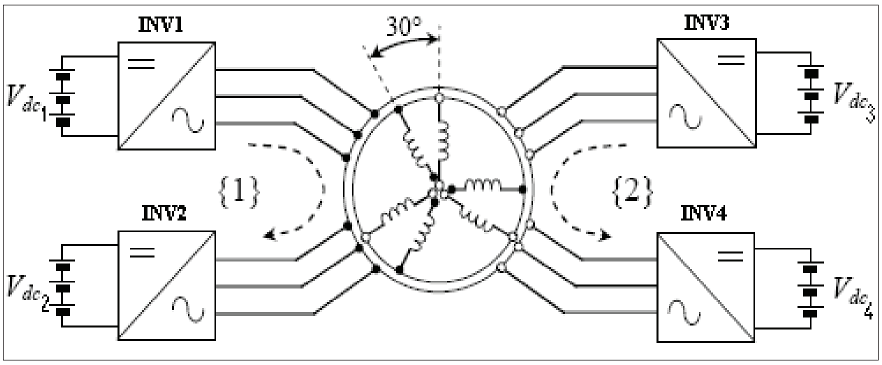


Figure 10. Topology of six-phase system on the base of four inverters (the first inverter group **INV1+INV2**, and the second inverter group **INV3+ INV4**) supplying open-end windings of asymmetrical six-phase induction motor with two sets of winding spatially shifted by 30 el. degrees [12].

where corresponding power of each inverter (and dc source) can be described as relative value of the total power of system.

In order to illustrate balanced operation of six-phase system with required power balancing (unequal normalized power distribution) between dc sources with unequal dc voltages, diagrams in Figures 11-12 show basic voltage waveforms (normalized voltages) of six-phase drive (Figure 10), together with spectral composition of the phase V_{as} and V_{xs} voltages (Figure 12) of the system [12].

The presented diagrams show, that motor phase voltages V_{as} and V_{xs} of six-phase drives on the base of four inverters with synchronous PWM have symmetry during the whole control range and for any operating conditions, and its spectra do not contain even harmonics and undesirable subharmonics, which is especially important for high power systems. Also, neutral-point-clamped inverters with specialized schemes of control and synchronous modulation can be used successfully in quad-inverter drive systems [13].

Three-inverter-based modular converters controlled by synchronous multi-zone PWM [8; 10]

One of perspective structures of the medium-voltage converters for power alternative current drive systems is transformer-based installation consisting from triple converters specifically connected with the corresponding windings of 0.33 p.u. output transformer ([8], Figure 13).

Figure 14 presents results of simulation (under condition of the ideal transformer) of modular converter with standard three-phase inverters controlled by algorithms of continuous synchronous PWM (CPWM). It shows line voltages V_{a1b1} and V_{ab} (normalized values), together with harmonic spectra of the V_{ab} voltage (fundamental frequency $F=35Hz$ ($m=0.7$ in the case, if the maximum fundamental frequency $F_m=50Hz$), and average switching frequency of inverters is $F_s=1kHz$).

It is necessary to mention, that voltage quality of different topologies of modular converters is in big dependence from value of the phase shift between signals of separate converters of modular converter. Mainly, it

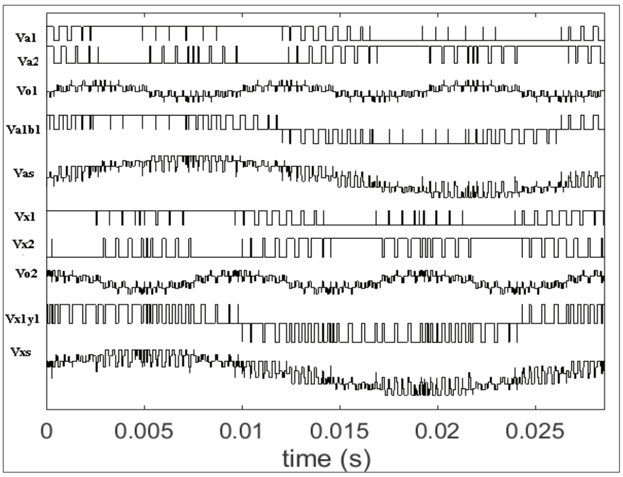


Figure 11. Basic voltage waveforms of six-phase system with synchronous discontinuous PWM ($P_1=0.23, P_2=0.27, P_3=0.24, P_4=0.26, V_{dc1}=0.75V_{dc4}, V_{dc2}=0.9V_{dc4}, V_{dc3}=0.8V_{dc4}, V_{dc4}=1, m_1=0.93, m_2=0.78, m_3=0.87, m_4=0.7$) [12].

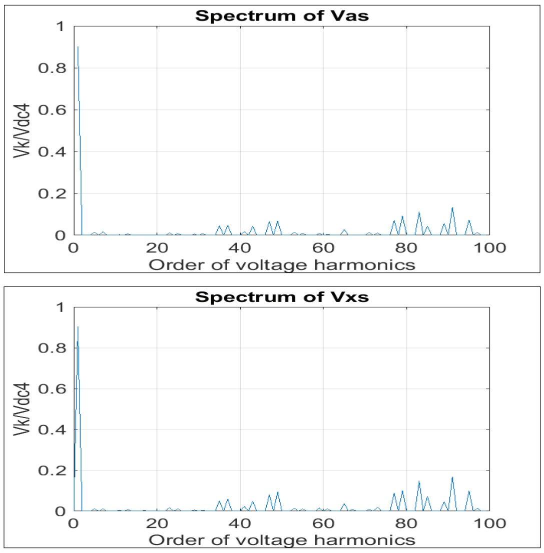


Figure 12. Spectra of the phase voltages of the balanced six-phase system [12].

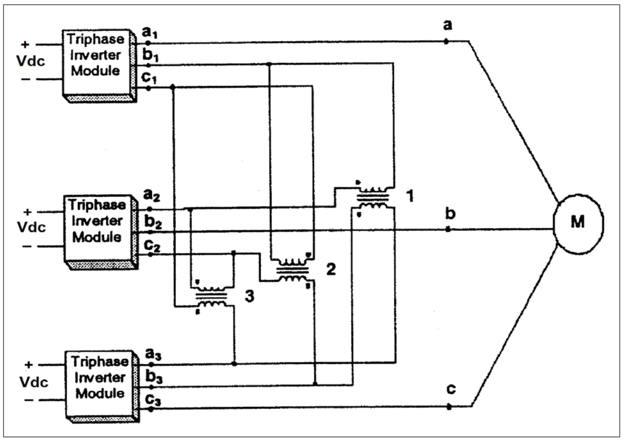


Figure 13. Topology of modular multilevel converter on the base of three inverters feeding induction motor M [8].

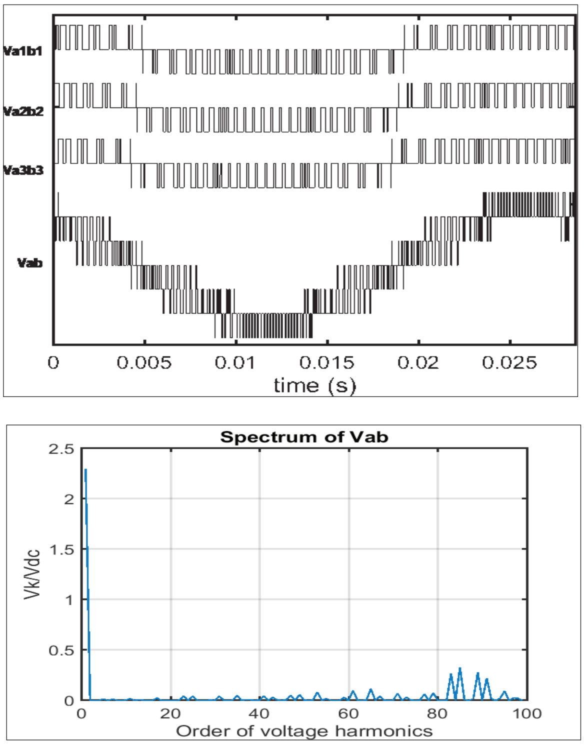


Figure 14. Line voltages, and spectrum of the V_{ab} voltage, of modular converter on the base of standard inverters with continuous synchronous PWM (CPWM, *F=35Hz, m=0.7*) [8].

is known, that optional value of this phase shift should be determined as a part of sub-cycle τ. And in our case (modular converter is based on three voltage source inverters) rational duration of this phase shift should be equal approximately to 1/3 of the width of sub-cycle τ [8].

Figure 15 shows results of determination of Weighted Total Harmonic Distortion factor ($WTHD = (1/V_{ab_1})(\sum_{k=2}^{1000}(V_{ab_k}/k)^2)^{0.5}$) of line voltages V_{a1b1} and V_{ab} versus modulation index $m=F/F_m$ for triple-inverter installation controlled by continuous (CPWM) and discontinuous (DPWM) versions of synchronous multi-zone PWM. Average frequency of switching of three-phase inverters is equal to *1.05kHz*. The presented results show that the using of discontinuous synchronous PWM for control of inverters of modular converters is more preferable in comparison with continuous PWM. Also, diode-clamped inverters with specialized control scheme can be used as basic workhorses in this topology of modular converter [10].

Five-phase drive system with inverters controlled by algorithms of synchronous multi-zone modulation [6; 9; 12; 16]

Five-phase converters and drives are between perspective topologies of multiphase systems, allowing providing an improved effectiveness of operation of adjustable speed drives for many applications [6]. Last years have been marked by intensive investigation of dual-inverter-based five-phase systems with open-end winding of induction motor [9]. Open-end winding topologies of five-phase systems assure providing multilevel voltage waveforms with improved spectral composition, and are perspective for application in such areas, as electrical vehicles/hybrid vehicles, and some other transport applications.

Figure 16 shows basic topology of open-end winding five- phase system based on dual five-phase converters with two insulated dc links, and presents also space vectors of five-phase inverter, which are basic for organization of rational schemes and strategies of adjustment of modulated dual-five-phase inverters [9].

Regarding the analyzed dual-inverter system, synchronous adjustment of voltage of each five-phase converter in accordance with basic PWM scheme insures synchronous symmetrical adjustment of voltage of five-phase motor with open-end winding. Rational phase shift between control and output signals of two

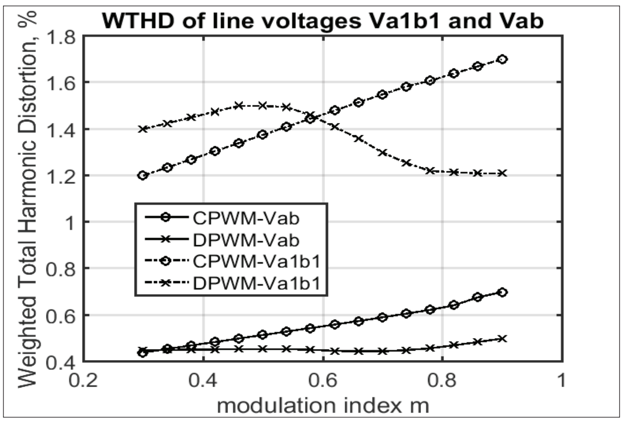


Figure 15. *WTHD* factor of the line voltages of modular converter versus modulation index *m* [8].

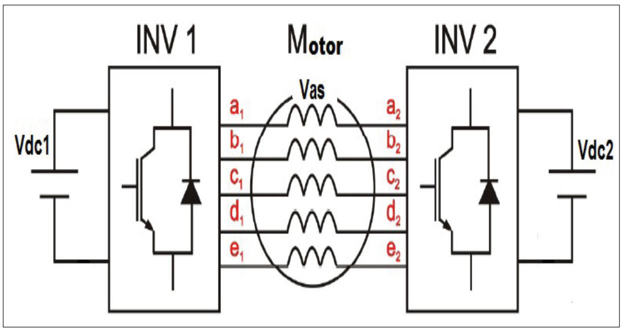


Figure 16. Topology of dual-inverter-based five-phase installation, and its basic voltage vectors [9].

five-phase converters is equal in this case for this system topology to one half of switching sub-cycle τ.

Phase voltages V_{as}, V_{bs}, V_{cs}, V_{ds}, and V_{es} of five-phase dual-inverter installation with isolated dc-links (Figure 16) are determined by (9)-(11) [9]:

$$V_0=1/5(V_{a10}+V_{a20}+V_{b10}+V_{b20}+V_{c10}+V_{c20}+V_{d10}+V_{d20}+V_{e10}+V_{e20}) \quad 9)$$

$$V_{as} = V_{a10} + V_{a20} - V_0 \quad (10)$$

$$V_{bs} = V_{b10} + V_{b20} - V_0, \quad (11)$$

where V_{a10}, V_{a20}, V_{b10}, V_{b20}, V_{c10}, V_{c20}, V_{d10}, V_{d20}, V_{e10}, V_{e20} are pole voltages of dual converters, and V_0 is common-mode voltage of five-phase system.

Figure 17 present results of simulation of five-phase system on the basis of dual inverters adjusted by modified scheme of synchronous modulation in linear modulation range (its boundary frequency is equal to *41.3Hz*, if the maximum fundamental frequency F_m*=50Hz* [9]), with equal voltages of two dc-links. The presented diagrams illustrate basic voltages of five-phase installation (pole voltages V_{a10}, V_{a20}, V_{b10}, V_{b20}, common-mode voltage V_0, and phase voltages V_{as}, V_{bs}), and also present spectrum of the phase voltage of five-phase system. Operating frequency of dual-inverter installation is equal to *31Hz,* and switching frequency of inverters is equal to F_s*=2.3kHz* for this control mode.

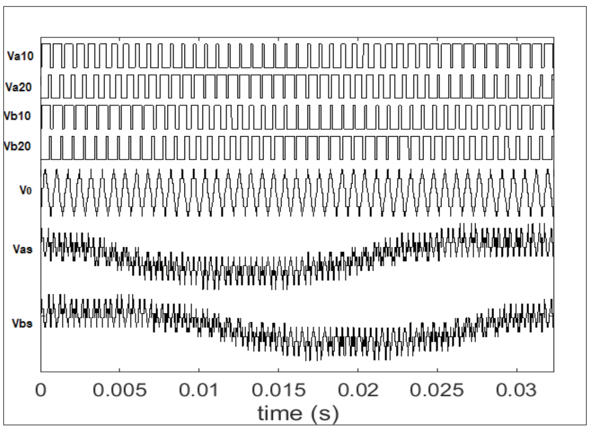
So, modified schemes of synchronous PWM, elaborated for adjustment of five-phase dual-inverter system with open-end winding of induction machine, provide symmetry of the phase voltage during the whole control diapason, including the zone of overmodulation [9; 16]. Spectra of the phase voltage of five-phase systems with schemes of synchronous PWM do not contain even harmonic components and subharmonics, which is especially important for installations with an increased power level.

Transformer-based photovoltaic systems with dual inverters controlled by algorithms of synchronous multi-zone modulation [14-15; 20]

Recently, novel structure of transformer-based grid-connected PV system has been proposed, presented in Figure 18 [14]. The presented topology utilizes two two-level inverters supplied by two strings of photovoltaic panels or directly, or through dc/dc sub-block (dashed lines in Figure 18). Outputs of dual inverters are connected to the open-end windings of three-phase power transformer.

Dissemination of schemes and algorithms of synchronous multi-zone modulation for control of inverters of transformer-based photovoltaic systems assures providing improved spectral composition of voltage on inverter-side windings of power transformer.

As an example of operation of the dual-inverter-based PV system, presented in Figure 18, and based on two inverters controlled by synchronous PWM, Figure 19 presents basic voltage waveforms (period of the pole voltages V_{1H}, V_{1L}, line-to-line voltages V_{1H2H}, V_{1L2L} of the two inverters, and phase voltage V_1 (with its spectrum) for systems controlled by algorithms of synchronous continuous modulation [14]. Fundamental frequency of the system is equal to *F=50Hz*, and average switching frequency of inverters is equal to F_s*= 1.35kHz.*



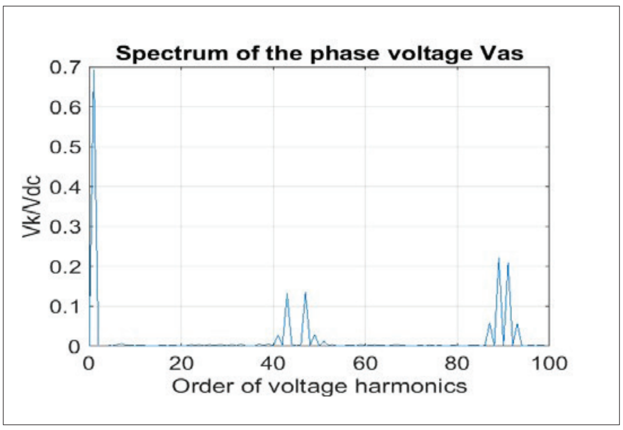


Figure 17. Basic voltage waveforms of five-phase installation, and spectrum of the phase voltage (*F=31Hz*, $V_{dc2}=V_{dc1}$) [9].

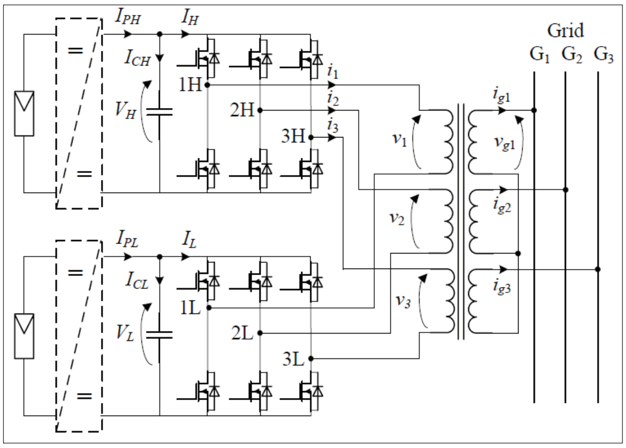


Figure 18. Basic topology of photovoltaic (PV) system with dual two-level inverters [14].

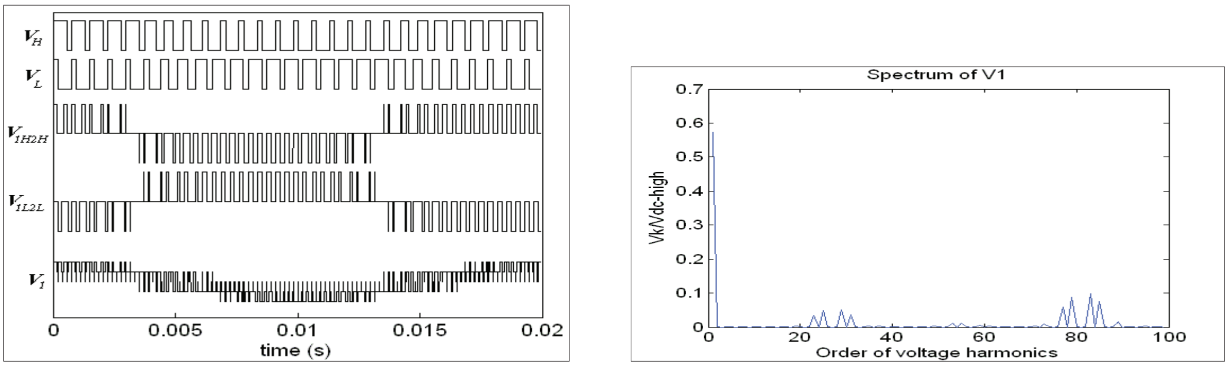


Figure 19. Pole voltages V_{1H} and V_{1L}, line voltages V_{1H2H} and V_{1L2L}, and phase voltage V_1 (with its spectrum) of PV system with continuous synchronous PWM (*F=50Hz, F_s=1.35kHz, V_H=V_L, m_H=m_L=0.45*) [14].

Figure 20 presents the calculation results of Total Harmonic Distortion factor ($THD = (1/V_{1_1})\sqrt{\sum_{i=2}^{k} V_{1_i}^2}$) for the phase voltage V_1 of PV system, presented in Figure 19, in the function of modulation index $m=m_H=m_L$ of the dual-inverter system with standard two-level inverters with equal dc voltages ($V_H=V_L$), controlled by algorithms of continuous (CPWM) and discontinuous (DPWM) synchronous modulation [14]. The fundamental frequency of the system is *F=50Hz*, and the average switching frequency of each modulated inverter is F_s = *1.35kHz*. *THD* factor has been calculated for two numbers of low-order (*i*-th) voltage harmonics (*k=100* and *k=200*).

Analysis of the spectrogram, presented in Figure 19, shows, that spectra of the phase voltage of dual-inverter-based PV systems with synchronous PWM do not contain even harmonics and sub-harmonics. The calculation results of *THD* factor show (Figure 20), that the use of continuous scheme of synchronous PWM allows providing better spectral composition of the phase voltage of dual-inverter PV system in the case of equal voltages of dc-sources (PV panels. Also, diode-clamped inverters can be used in this topology of transformer-based photovoltaic installation [20].

Transformer-based photovoltaic systems with triple inverters controlled by algorithms of synchronous multi-zone modulation [14]

Other perspective structure of grid-connected photovoltaic system can be based on triple-inverter configuration of PV installation with multi-wind-

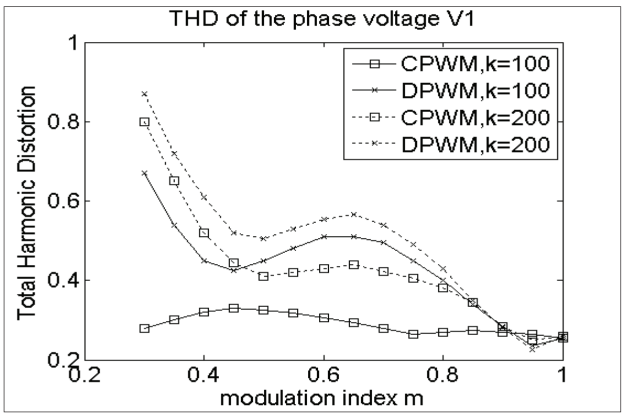


Figure 20. *THD* factor of the phase voltage V_1 versus modulation index m_H=m_L. (*F=50Hz, F_s=1.35kHz, V_H=V_L*) [14].

ing power transformer. So, some results of analysis of operation of PV system based on triple inverters controlled by algorithms of synchronous multi-zone modulation are presented in [14].

CONCLUSIONS

Novel schemes and algorithms of space-vector synchronous multi-zone modulation, developed and disseminated for control of inverters of three-phase, five-phase, and six-phase transport-oriented electrical drives, and of dual and triple inverters of photovoltaic systems, assure continuous voltage synchronization and symmetry of basic voltage waveforms in these systems during the whole control diapason and for any operating conditions. So, spectra of the output voltage of the corresponding inverters, and of the phase and line voltage of the corresponding systems, do not contain sub-harmonics (of the fundamental frequency) and even-order harmonics, which is especially important for the medium-power and high-power power conversion installations, contributing to the corresponding reduces of loses in systems, and leading to increasing the efficiency of these installations. Therefore:

Schemes and techniques of synchronous multi-zone modulation of inverters of transport-oriented ac drives and of transformer-based photovoltaic systems insure symmetry of the basic voltage waveforms for any relationship (fractional or integral) between the switching frequency of inverters and fundamental frequency of systems.

Schemes, techniques, and algorithms of synchronous multi-zone PWM of inverters of elecic drives and of photovoltaic installations assure symmetry of the basic voltage waveforms in the case of different values of voltages of isolated dc-sources in the case of multi-inverter topologies of systems.

The developed schemes and techniques of synchronous multi-zone modulation can be successfully applied for control of both standard two-level three-phase inverters, and of neutral-point-clamped inverters and of five-phase inverters, allow assuring symmetry of the phase voltage of the corresponding electric drives and photovoltaic systems.

Specialized schemes, algorithms, and techniques of synchronous multi-zone PWM applied for adjustment of inverters of electric drives and photovoltaic installations insure also symmetry of the basic voltage waveforms in systems in the case of increased values of modulation indices of inverters operating in the zone of overmodulation.

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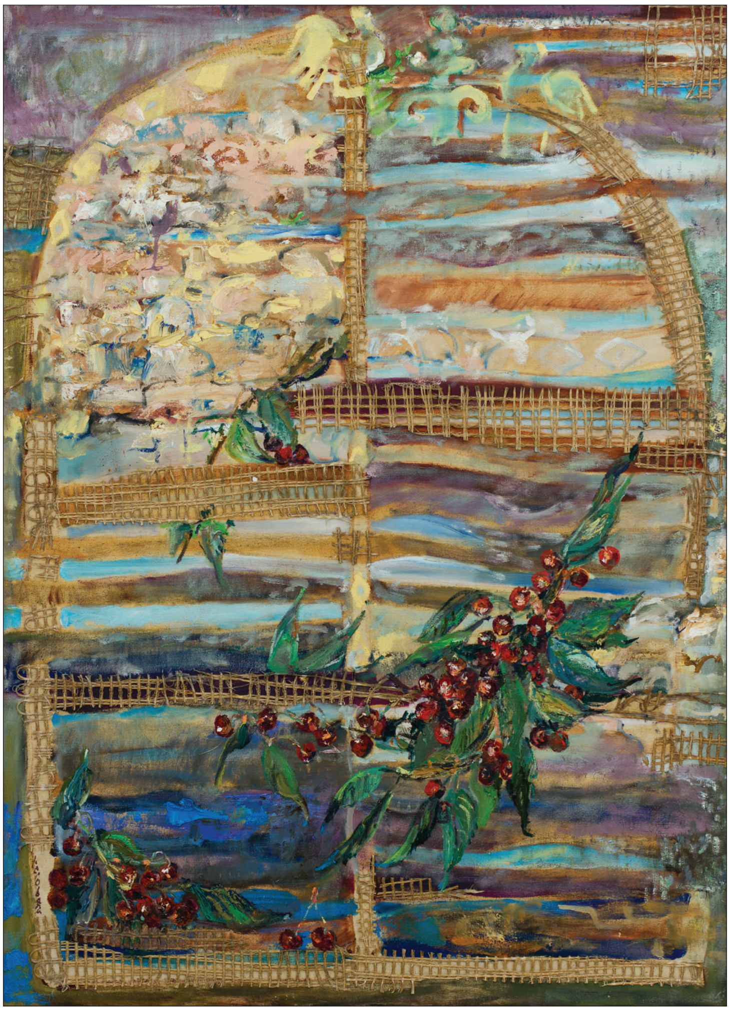

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