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RAPORT ŞTIINŢIFIC FINAL
privind executarea proiectului de cercetări științifice din cadrul programului
„Inițiative comune de cercetare-dezvoltare STCU, 2018-2019"

Proiectul: "Multifunctional Power Converters with Advanced Methods of Synchronous Space-Vector Modulation"

Cifrul Proiectului: 6328

Direcția Strategică: Efecienta energetica si valorificarea surcelor regenerabile de energie (programa 16.03, 5807)

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CHIȘINĂU 2019

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1. Scopul și obiectivele propuse spre realizare în cadrul proiectului

Multifunctional power electronic converters have increasing utilization in different areas, especially in adjustable speed traction drives with wide power rating, in the field of renewable energy systems, and in the area of high-power electric transmission. In particular, modern topologies of power converters provide less voltage stress on switches and motor windings due to the special converters' configurations, and lower harmonic distortion of output voltage due to more levels of the output waveforms. Improvement of characteristics of these converters and power conversion systems, based on advanced methods and techniques of pulsewidth modulation, is an important practical problem.

Medium-power and high-power converters are characterized by low switching frequency of converters. Problem of synchronization of output voltage waveforms is an important problem for these converters. At the same time almost all versions of standard space vector modulation (the most suitable for adjustable speed electric drives) are based on asynchronous principle.

In order to provide continuous voltage synchronization in power conversion systems (with elimination of subharmonics in voltage spectra of converters) novel alternative method of synchronous space-vector modulation for three-phase voltage source inverters has been proposed and elaborated by Moldovan team-members. This method is based on an original time-domain approach for analysis and synthesis of control signals of converters, it includes new multi-zone scheme of modulation and novel analytical representation of control functions.

So, basic purposes of this project have been focused on further development of novel control and modulation methods and techniques for power electronic converters (mainly for large converters) for electrified transport systems (for green transportation) and for renewable energy systems (photovoltaic systems).

Between the main objectives of the project regarding investigation of modulated converters for electrified transport systems, there are:

a) Modification of basic schemes of synchronous modulation for control of converters of new topology of medium-power open-winding drive system for transport application;

b) Development of algorithms of synchronous space-vector modulation for control of multiphase multi-inverter system for traction drive with increased power rating;

c) Research of new methods and techniques of synchronous multi-zone modulation for control of novel structures of modular converters with multilevel output voltage;

d) Adaptation of schemes and algorithms of synchronous modulation for regulation of transport-oriented combined and cascaded topologies of medium-power and high-power converters.

Between the main objectives of the project regarding research of modulated converters for renewable energy (photovoltaic) systems there are:

a) Development of strategy of synchronous multi-zone modulation for inverters for new structure of multi-panel and multi-string photovoltaic system with four-winding transformer;

b) Study of control and multi-zone modulation schemes and algorithms for novel topology of photovoltaic installation on the base of synchronized neutral-point-clamped converters.

2. Rezultatele științifice obținute în cadrul proiectului

2.1. Multiphase and multi-inverter power conversion systems have some advantages in comparison with standard three-phase systems. One of perspective topologies of multiphase systems is dual three-phase (six-phase) drive with asymmetrical induction machine with two sets of open-end winding, feeding by four inverters supplied by the corresponding insulated dc sources. In some transport-oriented power systems it is necessary to provide wide power balancing capability regarding dc sources. So, this part of report presents results of research of six-phase system with four inverters, controlled by the modified algorithms of continuous and discontinuous pulsewidth modulation (PWM), providing both power balancing operation and improved spectra of the phase and line voltages in power conversion system.

Fig. 1 presents basic structure of dual three-phase (six-phase) drive with asymmetrical induction machine with two sets of open-end winding, feeding by four PWM inverters supplied by the corresponding insulated dc sources. The system includes four inverters: **INV1+INV2**, supplied by the **V_{dc1}** and **V_{dc2}** dc sources, as the first section, and **INV3+INV4**, supplied by the **V_{dc3}** and **V_{dc4}** dc sources, as the second section.

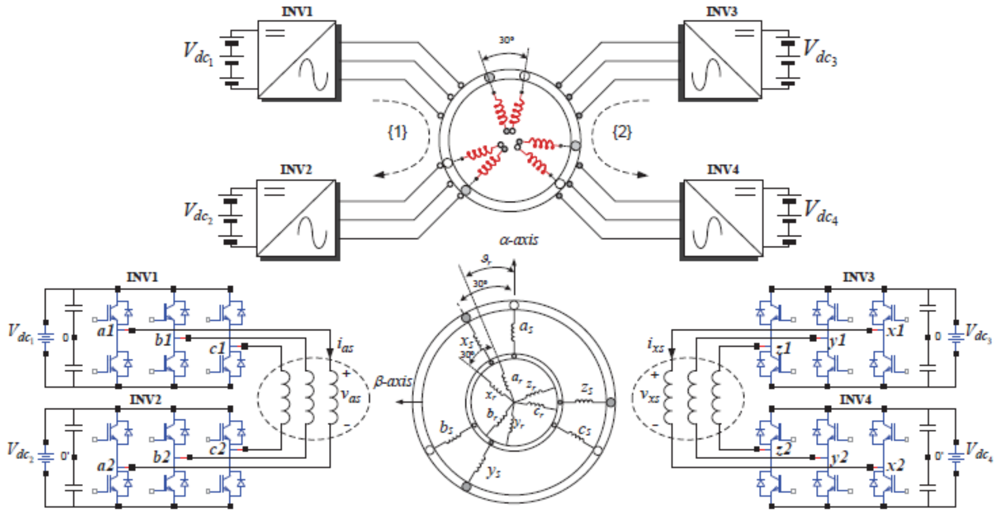

Fig. 1.

In order to provide equivalence of the output fundamental voltages (and also power balancing) of two converters of each converter section during scalar *V/F* control of the system, it is necessary to provide linear dependences between its coefficients of modulation and magnitudes of dc voltages:

$$m_1 V_{dc1} = m_2 V_{dc2}, \qquad m_3 V_{dc3} = m_4 V_{dc4}$$

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:

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

Also, for six-phase drive on the basis of four converters it is important to allow equal power distribution between two groups of converters feeding asymmetrical six-phase machine:

$$\backslash P_1 + P_2 = P_3 + P_4$$

In this case, for balanced operation of six-phase system it is necessary to allow:

$$m_1 V_{dc1} P_2 + m_2 V_{dc2} P_1 = m_3 V_{dc3} P_4 + m_4 V_{dc4} P_3,$$

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

Fig. 2 – Fig. 5 present results of MATLAB-simulation of six-phase system controlled by two versions of modified synchronous PWM (DPWM30 and DPWM60), and operating under required power balancing conditions regarding four dc sources of the system (Figs. 2-3 correspond to the system with algorithms of DPWM30, and Figs. 4-5 correspond to the system controlled by algorithms of DPWM60). In particular, diagrams in Figs. 2-5 show basic voltage waveforms (normalized voltages) of six-phase open-winding drive system, together with spectral composition of the phase (V_{as}) voltages of system.

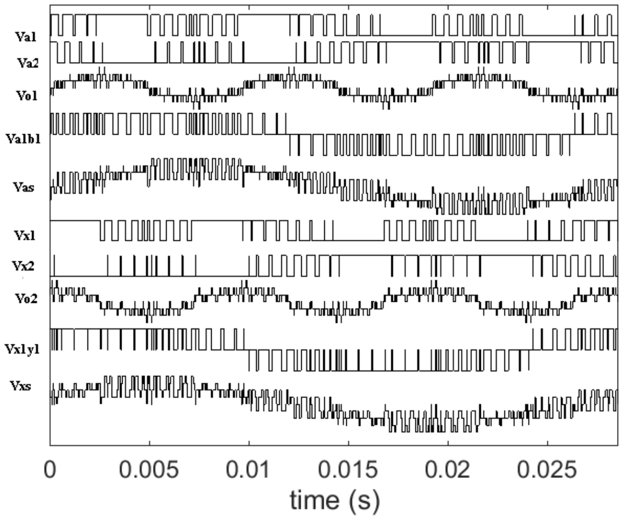

Fig. 2.

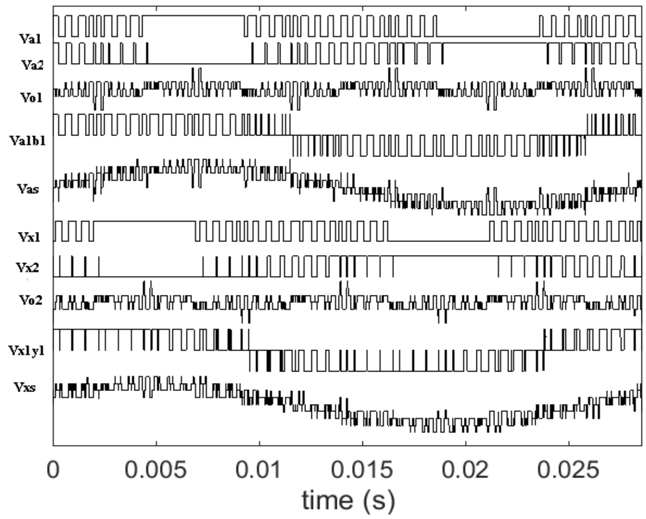

Fig. 4.

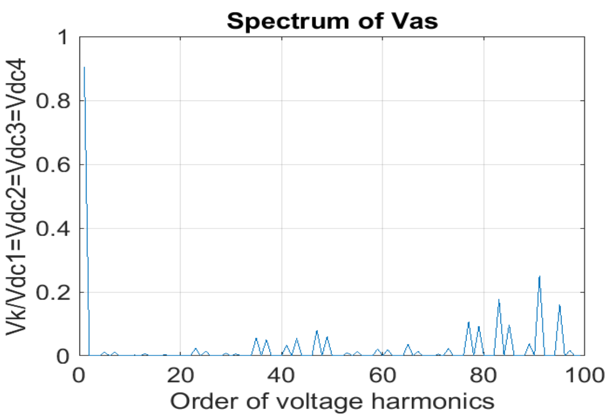

Fig. 3.

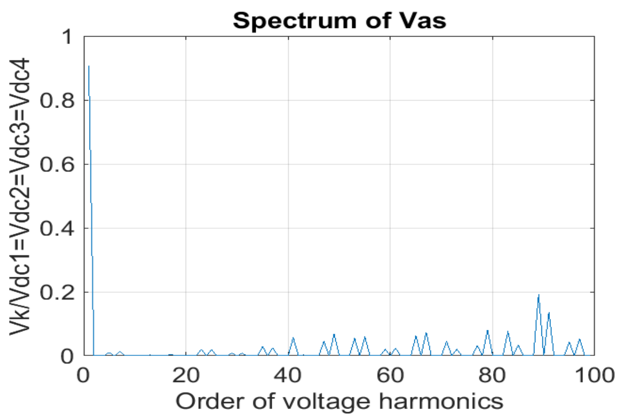

Fig. 5.

Analysis of basic waveforms of the phase and line voltages of the system (and of spectra of voltages), presented in Figs. 2-5, illustrates the fact, that the used algorithms of control and modulation allowing providing quarter-wave and (or) half-wave symmetry of phase and line voltages for any conditions and modes of power balancing between four dc sources of the system. In all these cases spectra of the basic voltages contain only odd (non-triplen) harmonics, and do not contain even harmonics and subharmonics

Fig. 6 presents results of calculation of Weighted Total Harmonic Distortion factor ($WTHD = (1/V_{as_1})(\sum_{k=2}^{1000}(V_{as_k}/k)^2)^{0.5}$) of the phase voltage V_{as} versus modulation index $m_0=F/F_m$ for the cpecial operation mode of the system controlled by modified schemes of discontinuous multi-zone

PWM with the 30^0-non-switching intervals (DPWM30) and 60^0-non-switching intervals (DPWM60). Switching frequency of inverters is equal to *1kHz* in this case.

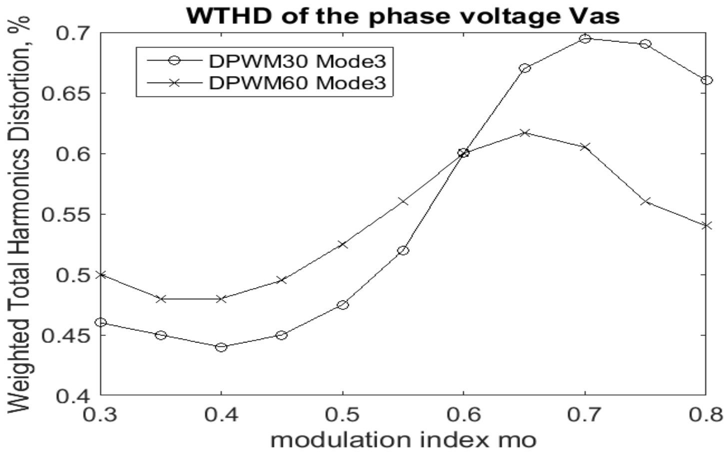

Fig. 6.

Comparative analysis of results of determination of Weighted Total Harmonic Distortion factor, presented in Fig. 6, shows, that, in particular, for the analyzed control modified algorithms of discontinuous PWM with the 30^0-non-switching intervals (DPWM30) assure better integral spectral composition of the phase voltage V_{as} of system in the zone of low and medium coefficients of modulation, in comparison with integral harmonic composition the of phase voltage of system controlled by algorithms of modulation with the 60^0-non-switching intervals (DPWM60).

2.2.Power converters and adjustable speed drives with increased number of phases have some advantages in comparison with standard three-phase systems (losses decrease, motor torque pulsation reduction, reliability increase of system operation, etc.). 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. In order to avoid some disadvantages of classical versions of space-vector modulation, novel methods and techniques of modulation for multiphase systems have been elaborated and investigated, allowing minimization of undesirable subharmonics in voltage spectra of systems. So, this part of report presents results of research of multiphase (five-phase) installation with dual converters, adjusted by the modified scheme of synchronous space-vector modulation, insuring symmetry of phase voltages in multiphase system during the whole control range.

Fig. 7 shows basic topology of five- phase open-end winding drive system based on dual five-phase converters with two isolated dc links. This topology can be perspective for application in transport drive systems with an increased power rating.

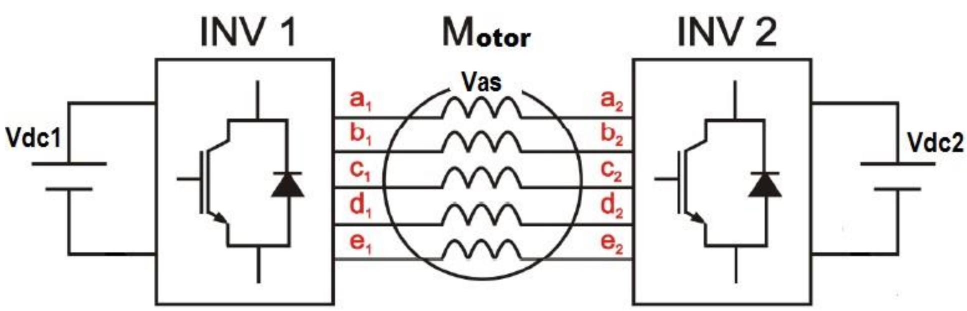

Fig. 7.

For continuous voltage synchronization in five-phase system it is necessary to provide modification of basic control correlations elaborated previously for three-phase converters. So, basic set of the modified control functions for synchronous scalar adjustment of system with dual five-phase inverters includes the following set of control dependences for determination of parameters (duration, and position on period of the fundamental frequency) of pulse control signals (see some of these parameters at time-diagrams in Fig. 8 and Fig. 9):

$$F_i = \frac{1}{10(2i-1)\tau}; \quad F_{i-1} = \frac{1}{10(2i-3)\tau}; \quad i = \frac{1/10F+\tau}{2\tau}; \quad \beta_1 = 1.03m\tau; \quad K_s = 1 - \frac{F-F_i}{F_{i-1}-F_i}$$

$$\beta_i = \beta^{''} = \beta_1 \cos[(i-1)\tau]K_s; \quad \lambda_i = \lambda^{'} = (\tau - \beta^{''})K_s; \quad \gamma_1{}' = 3.1\beta^{''}(\lambda^{'} + \beta^{''})F; \quad V_{an} = (4/5)V_a - (1/5)(V_b+V_c+V_d+V_e)$$

Fig. 8 and Fig. 9 present control and output signals for one five-phase converter of multiphase system controlled by modified algorithm of space-vector modulation. It presents switching state sequence and the pole (V_a - V_e) and phase-to-neutral (V_{an}) voltages of five-phase converter, inside the corresponding intervals 36^0-72^0 (Fig. 8) and 72^0-108^0 (Fig. 9) on the period of fundamental frequency. The presented principle of generation of control signals allows providing symmetry of the phase-to-neutral and line voltage of five-phase installation during the whole control range.

Fig. 10 – Fig. 13 present results of simulation of five-phase installation on the basis of dual converters adjusted by modified scheme of synchronous modulation in linear modulation range. It illustrate basic voltages of five-phase system (pole voltages V_{a10}, V_{a20}, V_{b10}, V_{b20}, common-mode voltage V_0, and phase voltages V_{as}, V_{bs}), and its spectra. Operating frequency of dual-inverter installation is equal to 31Hz, V_{dc2}=V_{dc1} (Figs. 10-11), V_{dc2}=0.5V_{dc1} (Figs. 12-13).

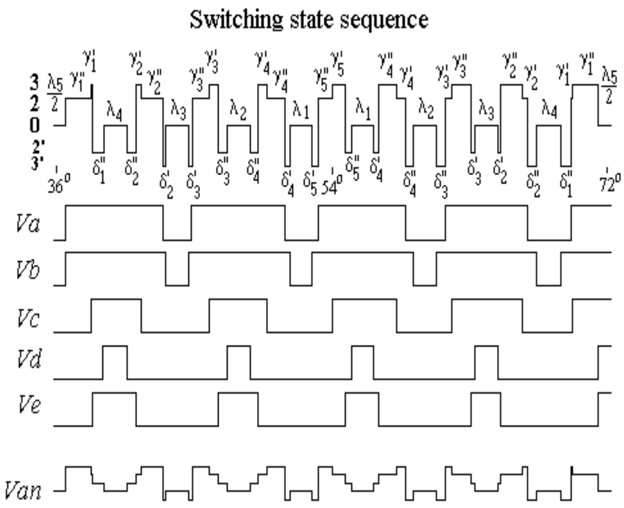

Fig. 8.

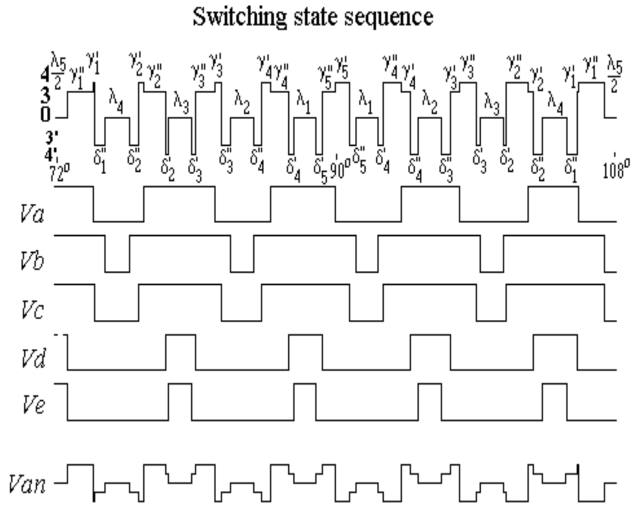

Fig. 9.

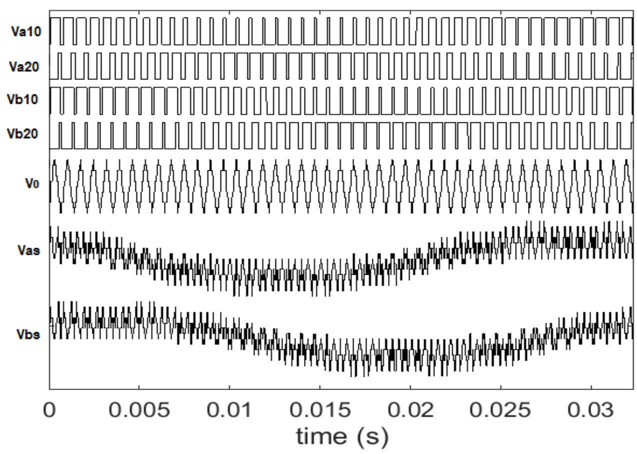

Fig. 10.

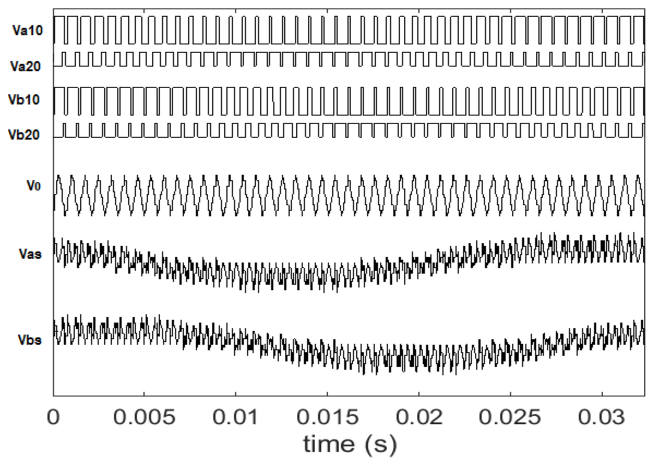

Fig. 11.

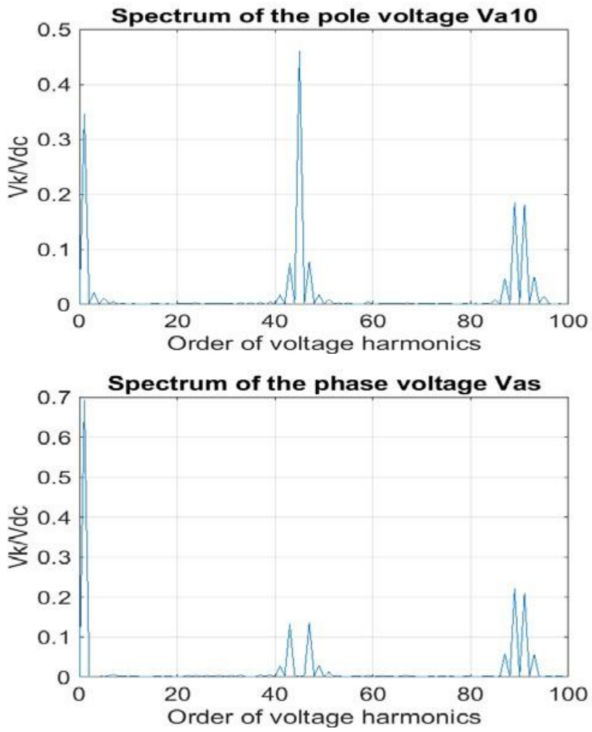

Fig. 12.

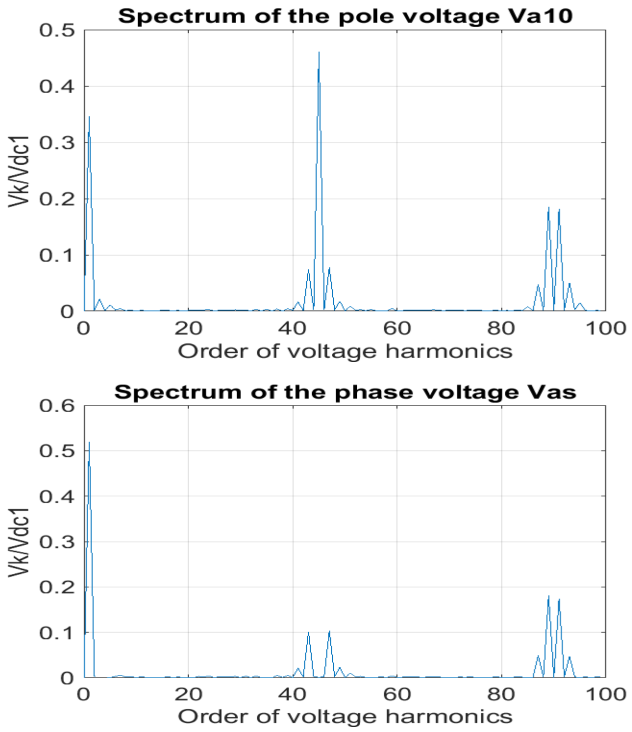

Fig. 13.

Analysis of basic voltage waveforms of the system (and of spectra of basic voltages), presented in Figs. 8-13, illustrates the fact, that the modified algorithms of control and synchronous multi-zone modulation allowing providing quarter-wave and (or) half-wave symmetry of the phase voltage of system for any operating conditions. Spectra of the basic voltages contain only odd harmonics, and do not contain even harmonics and subharmonics, and this positive factor is especially important for medium-power and high power systems which are characterized by low switching frequency.

2.3. Novel structures of power electronic converters with multilevel output voltage, which is characterized by better spectral composition in comparison with standard two-level output voltage of majority of converters, can be attractive for application in different traction systems. Ones of perspective topologies of converters with multilevel output voltage are modular converters consisting from several inverters. In particular, three-phase diode-clamped inverters with space-vector pulsewidth modulation can be used as basic components of modular converters. So, this part of report presents results of investigation of modular converters, based on several diode-clamped inverters, controlled by specific scheme of synchronous multi-zone modulation, insuring voltage synchronization of the phase voltage of modular converters for any operating conditions and any control modes.

Fig. 14 presents structure of power circuits of modular converter for multiphase drive system for transport application, consisting from four diode-clamped inverters. Fig. 15 shows basic topology of autonomous three-phase diode-clamped inverter, which includes twelve power switches and six clamping diodes.

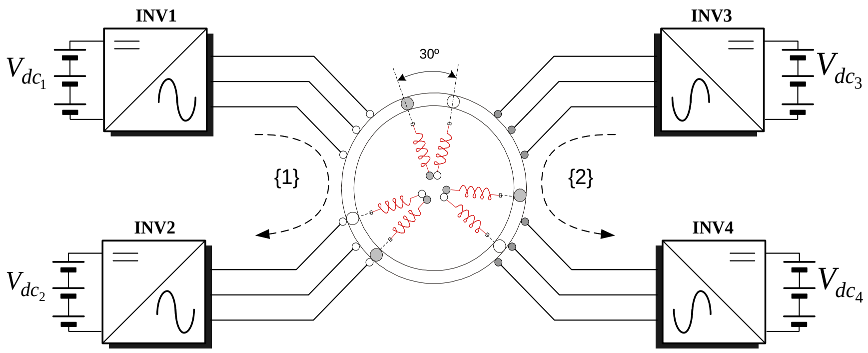

Fig. 14.

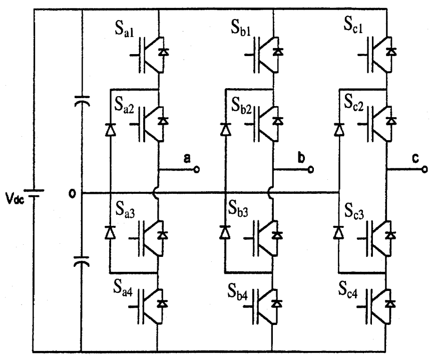

Fig. 15.

Control of modular power converter with diode-clamped inverters on the basis of new methodology of synchronous space-vector modulation is characterized by some peculiarities. Fig. 16 presents basic switching state vectors (vectors marked by the big arrows) of diode-clamped inverter, the use of which insures elimination of undesirable zero sequence voltage. Fig. 17 shows switching state sequence, pole voltage V_a and V_b, and line-to-line voltage V_{ab} (with indication of duration of the corresponding pulses (control signals) by the corresponding control parameters marked by Greek letters), on the interval 0^0-60^0 of the period of the fundamental frequency for one of diode-clamped inverters of modular converter for transport application.

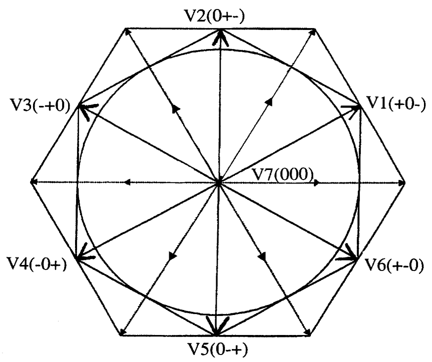

Fig. 16.

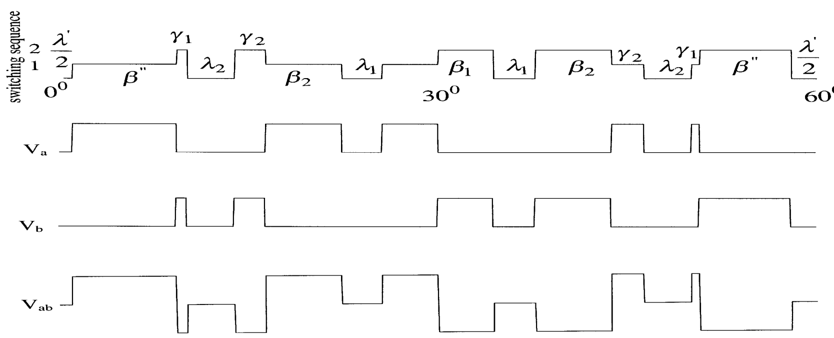

Fig. 17.

Switching states (+,**0**,-) are defined for the switches of diode-clamped inverter of modular converter (Fig. 2) as: **0** if **S_2, S_3** are **ON** and **S_1, S_4** are **OFF**; **+** if **S_1 S_3** are **ON** and **S_2, S_4** are **OFF**; **-** if **S_1, S_2** are **ON** and **S_3, S_4** are **OFF**. Switching sequences can be written in this case as:**V_6 (+0-); V_7 (0+-); V_1 (-+0); V_2 (-0+); V_3 (0-+); V_4 (+-0); V_5 (000)**.

In accordance with the methodology of synchronous space-vector modulation, modified control correlations for determination of current parameters (duration, in absolute values (seconds)) of control pulses (see Fig. 17) for synchronous adjustment of diode-clamped inverters of modular converter, presented in Fig. 1, under scalar control mode, can be presented as:

$$V_{as} = V_{a1} - V_{a2}; \quad V_{xs}=V_{x1} - V_{x2}; \quad \beta_i = \beta'' = \beta_1 \cos[(i - K_3 - 1)\tau K_{ov1}]K_s, \quad \lambda_j = \tau - (\beta_j + \beta_{j+1})/2;$$

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

where $K_s = [1-(F-F_i)/(F_{i-1}-F_i)]$ - coefficient of synchronization (*F*- operating frequency of system).

Fig. 18 – Fig. 21 present results of simulations of transport-oriented drive system on the base of modular converter with several diode-clamped inverters controlled by modified algorithms of space-vector modulation. In particular, diagrams in Figs. 18-19 show the main voltages (normalized values) of modular converter, together with harmonic spectra of the phase (V_{as} and V_{xs}) and line-to-line (V_{a1b1}, V_{a2b2}, V_{x1y1}) voltages of system, controlled by algorithms of discontinuous synchronous pulsewidth modulation (DPWM) under the following control parameters: F=32.5Hz, $V_{dc1}=V_{dc2}=0.75V_{dc4}$, $V_{dc3}=0.9V_{dc4}$, $m_1=m_2=0.87$, $m_3=0.47$, $m_4=0.8$.

Diagrams in Figs. 20-21 present the corresponding voltage waveforms and its spectra for modular converter adjusted by algorithms of "direct-direct" synchronous multi-zone modulation (DDPWM) under the same control parameters. Average switching frequency of all inverters is equal to 1kHz.

Investigation of basic voltage waveforms of modular converter (and of harmonic composition of basic voltages), presented in Figs. 18-21, confirms the fact, that the used algorithms of control and modulation allow providing quarter-wave and (or) half-wave symmetry of phase and line voltages of modular converter for any conditions and modes of operation. In all these cases spectra of the basic voltages contain only odd (non-triplen) harmonics, and do not contain even harmonics and undesirable subharmonics

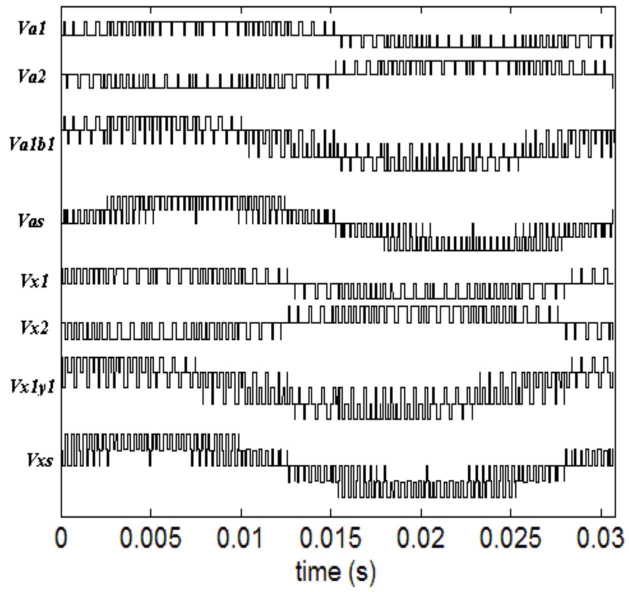

Fig. 18.

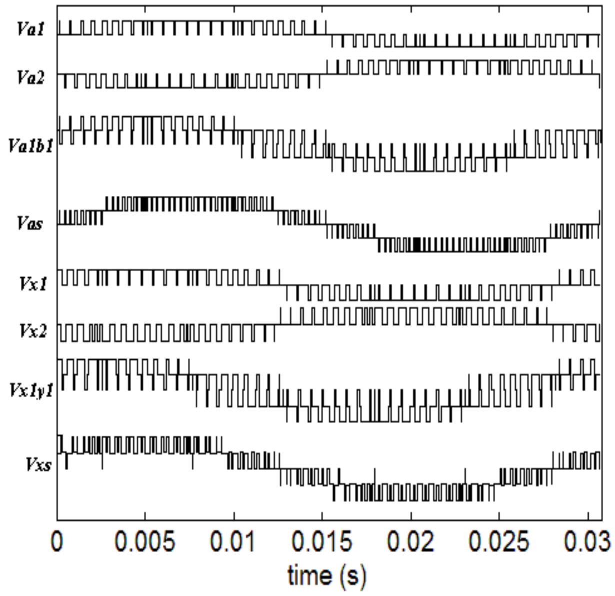

Fig. 20.

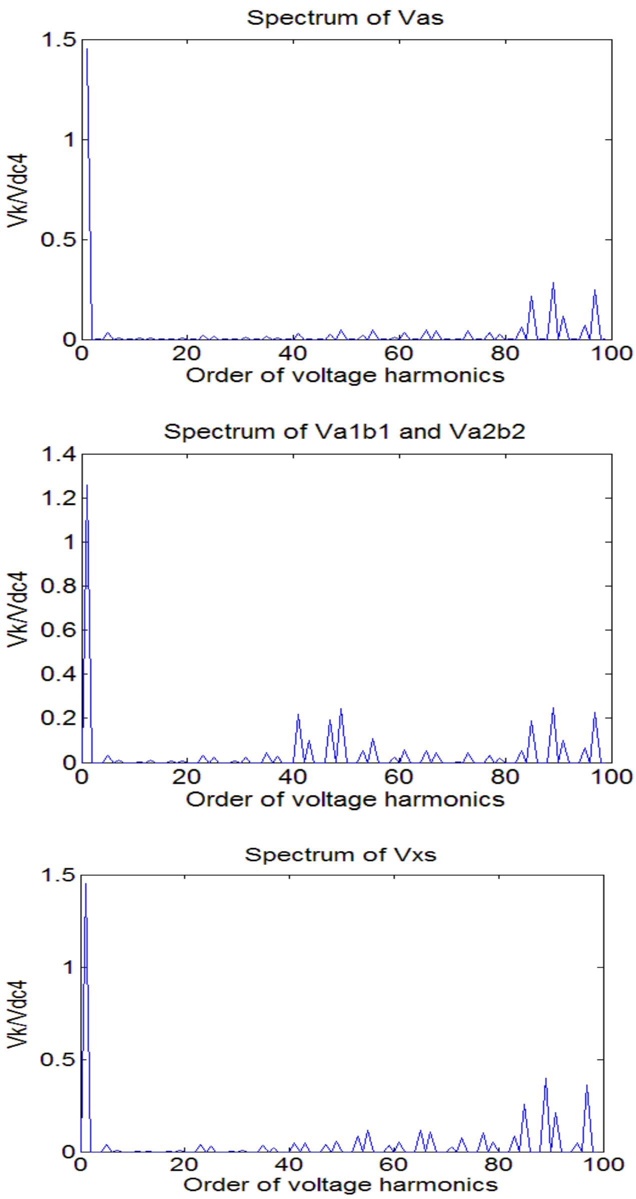

Fig. 19.

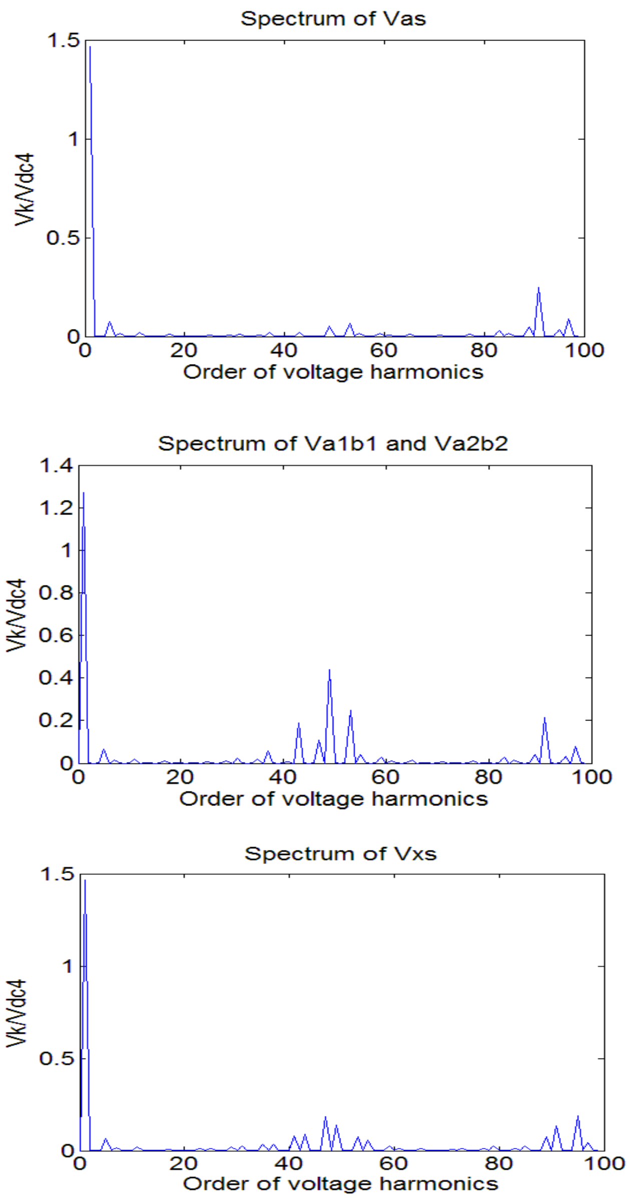

Fig. 21.

2.4. New topologies of power converters with multilevel output voltage, which is characterized by better spectral composition in comparison with standard two-level output voltage of the majority of converters, can be attractive for different transport applications. Ones of perspective structures of converters with multilevel output voltage are transformer-based cascaded converters consisting from triple neutral-point-clamped inverters with space-vector pulsewidth modulation (PWM). It is known, that for the medium-power medium-voltage power conversion system it is necessary to assure voltage synchronization (on period of the fundamental frequency) during the whole control range of converters. So, this part of report presents results of study of cascaded converters on the base of three neutral-point-clamped inverters adjusted by modified scheme of synchronous modulation, assuring synchronization and symmetry of the line-to-line voltage of cascaded system for any operation conditions and for any control and regulation modes.

Fig. 22 presents topology of the basic power circuits of transformer-based three-phase cascaded converter, consisting from multi-winding power transformer and from specifically connected three neutral-point-clamped inverters feeding three-phase induction motor **M.** This system topology is characterized by a three-level and four-level line voltage. Modular character of this cascaded converter provides also easy maintenance of the system in the case of necessity.

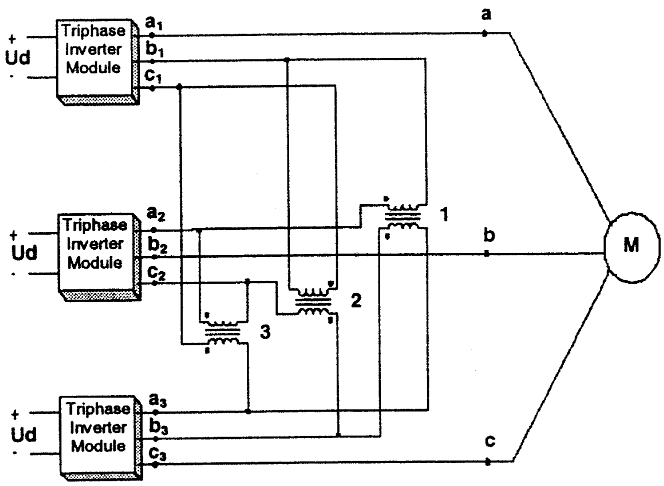

Fig. 22.

Fig. 23 – Fig. 24 present results of simulation of cascaded converter in the linear modulation range, in the case then modulation indices m of three neutral-point-clamped inverters are 0.907>m>0. Control scheme is based in this case on the using of modified algorithms of discontinuous synchronous modulation, average switching frequency of inverters is equal to 800Hz. Also, special flexible shift between control signals of three inverters has been used, providing improved spectral composition of line voltage of system. All these simulations have been executed for case of ideal transformer.

So, Fig. 23 shows line voltages of three inverters V_{a1b1}, V_{a2b2}, V_{a3b3}, and also resulting line voltage V_{ab}, and spectra of two basic voltages, for cascaded system operated at low fundamental frequency F=15Hz, modulation index of inverters m=0.3. In this case, in the zone of low modulation indices, the resulting line voltage has two-level waveform.

Fig. 24 presents the corresponding voltage waveform and its spectra of basic voltages for the case of the medium fundamental frequency of system and medium modulation indices of inverters (F=25Hz, m=0.5). The resulting line output voltage V_{ab} has three-level waveform in this case.

It is necessary to mention, that due to the modified algorithms of synchronous space-vector modulation, applied for control of three neutral-point-clamped inverters of cascaded converter, and due to special phase shift between signals of three inverters, all presented in Figs. 23-24 voltage waveforms have symmetry during linear control range, and its spectra do not contain even harmonics and subharmonics (of the fundamental frequency), which is especially important for the medium-power medium-voltage drives, perspective for application in power traction systems.

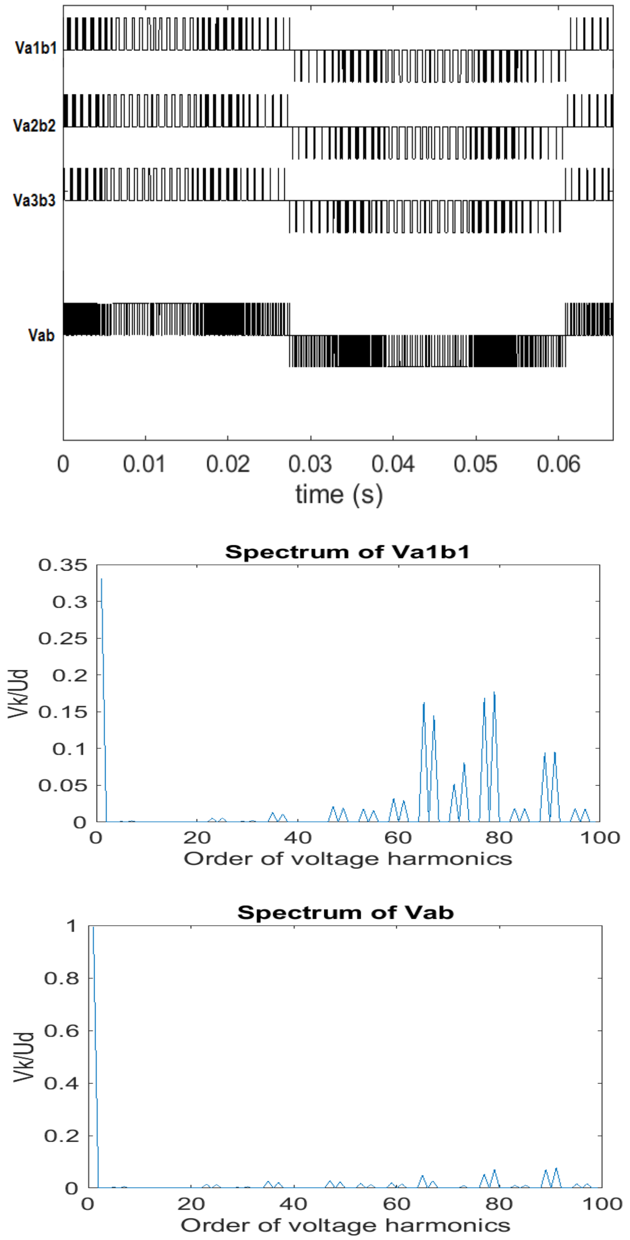

Fig. 23.

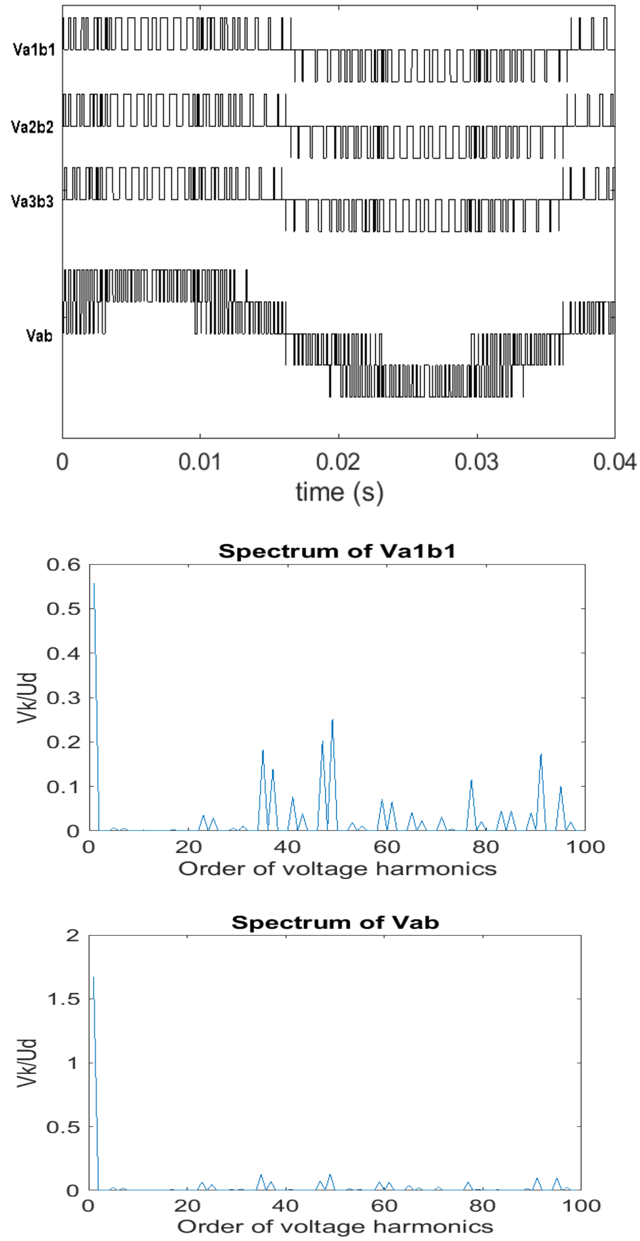

Fig. 24.

Weighted Total Harmonic Distortion (WTHD) factor is an important parameter for evaluation of quality of voltage waveforms of ac drive systems. Fig. 25 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 the line-to-line voltage V_{ab} as function of modulation index $m=F/F_m$ of cascaded converter controlled by algorithms of both continuous (CPWM) and discontinuous (DPWM) synchronous multi-zone modulation in linear modulation range. It has been calculated for two values of the switching frequency of neutral-point-clamped inverters – 800Hz and 1.15kHz.

As it is seen from Fig. 25, WTHD factor has fluctuating character for the analyzed case of operating of cascaded system at relatively low switching frequency. And magnitude of this fluctuation is much bigger for the case of the using of discontinuous synchronous PWM for control of cascaded converter.

Also, increasing of value of switching frequency of inverters (as an example, from 800Hz to 1.15kHz) allows assuring remarkable reduce of value of WTHD factor (for about 1.2 – 1.7 times in average), and this fact should be taken into consideration during practical elaboration of cascaded converters.

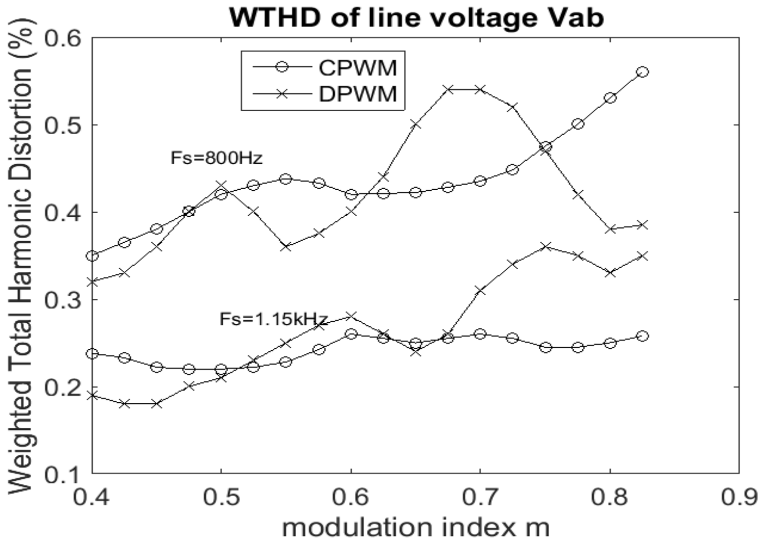

Fig. 25.

2.5. Novel structures of transformer-based photovoltaic systems have been elaborated during the last decade, providing further fast increase of generation of solar-based clean electric power. Ones of perspective topologies of power photovoltaic installations are transformer-based installations with multiple strings of photovoltaic panels, feeding several voltage source converters (inverters) connected with the corresponding windings of power transformer. Operation of these inverter-based photovoltaic installations is in dependence of the used methods and techniques of pulsewidth modulation of converters. In order to provide increased effectiveness of operation of this type of photovoltaic systems it is necessary to assure improved spectral composition of voltages at the windings of power transformer by generation of symmetrical voltage waveforms at outputs of converters of system and at the windings of transformer. So, this part of report presents results of elaboration of control and modulation schemes and algorithms for rational control of converters of new topology of transformer-based (with multi-winding power transformer) photovoltaic installations assuring continuous voltage synchronization and voltage symmetries of both output voltages of converters and winding voltages of the system.

Fig. 26 shows new structure of power circuits of transformer-based photovoltaic system (PV), consisting from several strings of photovoltaic panels, feeding the corresponding voltage source converters. Outputs of these converters are specially connected with the corresponding inverter-side windings of power transformer, and the secondary windings of transformer are connected with power three-phase ac grid.

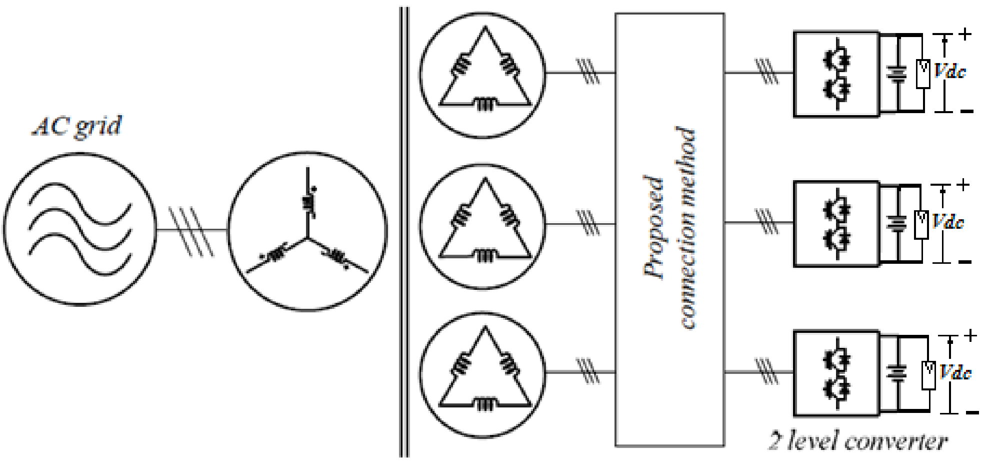

Fig. 26.

Three phase voltages V_{aphase}, V_{bphase} and V_{cphase} of each converter of the presented configuration of photovoltaic system are calculated as functions of the pole voltages V_{apole}, V_{bpole} and V_{cpole} of converter as:

$$V_{aphase} = V_{apole} + (V_{apole} + V_{bpole} + V_{cpole})/3$$

$$V_{bphase} = V_{bpole} + (V_{apole} + V_{bpole} + V_{cpole})/3$$

$$V_{cphase} = V_{cpole} + (V_{apole} + V_{bpole} + V_{cpole})/3$$

Correspondingly, value of voltages $V_{winding1}$, $V_{winding2}$, $V_{winding3}$ of converter-side windings of installation can be determined as function of by the phase voltages of the corresponding converters:

$$V_{winding1} = V_{aphase3} - V_{bphase1}; \quad V_{winding2} = V_{bphase1} - V_{cphase2}; \quad V_{winding3} = V_{cphase2} - V_{aphase3}$$

For the analyzed photovoltaic system with multi-winding transformer and several modulated converters determination of rational value of average frequency F_s of switching of converters and width of sub-cycles τ, insuring continuous symmetry of voltage waveforms of installation during fluctuations of the fundamental frequency F of ac grid, can be based on the correlations presented below, correspondingly for continuous (CPWM) and discontinuous (DPWM) techniques of synchronous multi-zone pulsewidth modulation:

$$F_{s(CPWM)} = F(6n-3)$$

$$\tau_{CPWM} = 1/2F_s = 1/[6F(2n-1)]$$

$$F_{s(DPWM)} = F(8n-5)$$

$$\tau_{DPWM} = 1/[6F(2n-1.5)]$$

In this case, determination of parameters (positions and durations) of pulse control signals for modulated converters of the analyzed photovoltaic installation can be based on the methodology of synchronous space-vector modulation.

Fig. 27 – Fig. 29 present results of simulation of processes in new topology of transformer-based photovoltaic installation with several voltage source converters controlled by algorithms of synchronous multi-zone modulation. It shows both basic voltage waveforms of the system (pole voltages of converters V_{pole1}, V_{pole2}, line-to-line voltage V_{line}, phase voltage V_{phase}, and voltage $V_{winding}$ of the converter-side windings of transformer) and spectra of the line and winding voltages.

Diagrams in Fig. 27 correspond to system with continuous modulation, curves in Fig. 28 correspond to installation with the first version of discontinuous modulation (DPWM1), diagrams in Fig. 29 correspond to system with the second version of discontinuous modulation (DPWM2). The fundamental frequency of installation is equal to 50Hz, and average switching frequency of inverters is equal to 1.2kHz. Coefficient of modulation of converters is equal to m=0.8.

Mutual comparison of the presented spectra shows, that due to specific structure of the analyzed photovoltaic system spectrum of winding voltages $V_{winding}$ is much better than spectrum of the line-to-line voltages V_{line},. Analysis of the results of simulation proved the fact, that due to the elaborated schemes and algorithms of synchronous control and modulation of converters of photovoltaic system (with both continuous and discontinuous version of modulation), all voltage waveforms have quarter-wave symmetry, and its spectra do not contain even harmonics and subharmonics (of the fundamental frequency), which is especially important for photovoltaic systems with the increased level of generated power.

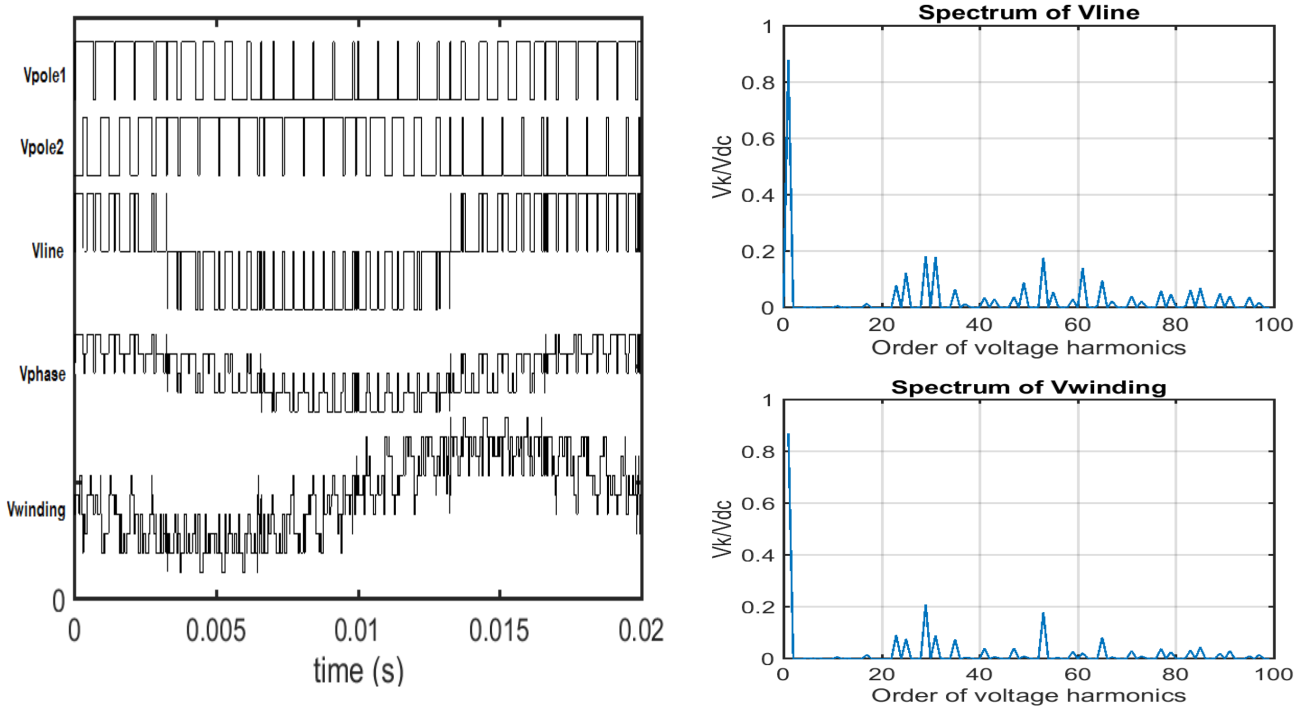

Fig. 27.

3.

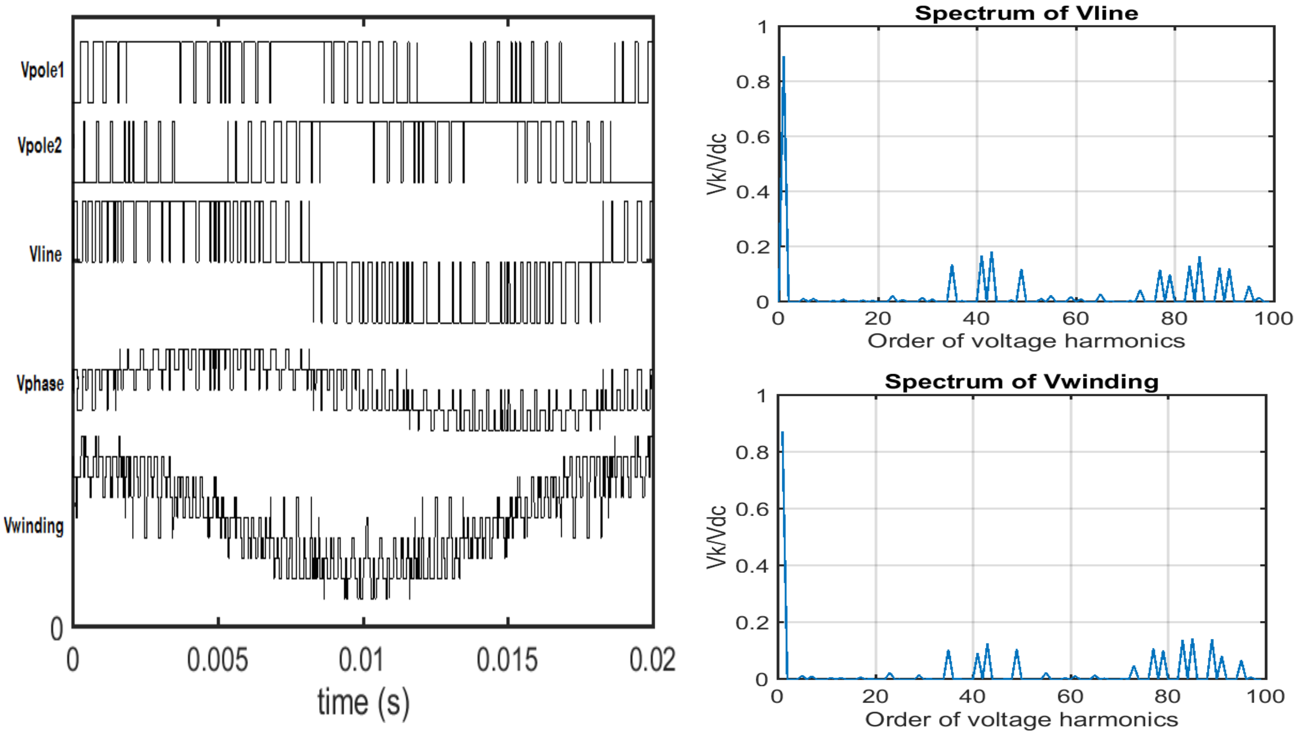

Fig. 28.

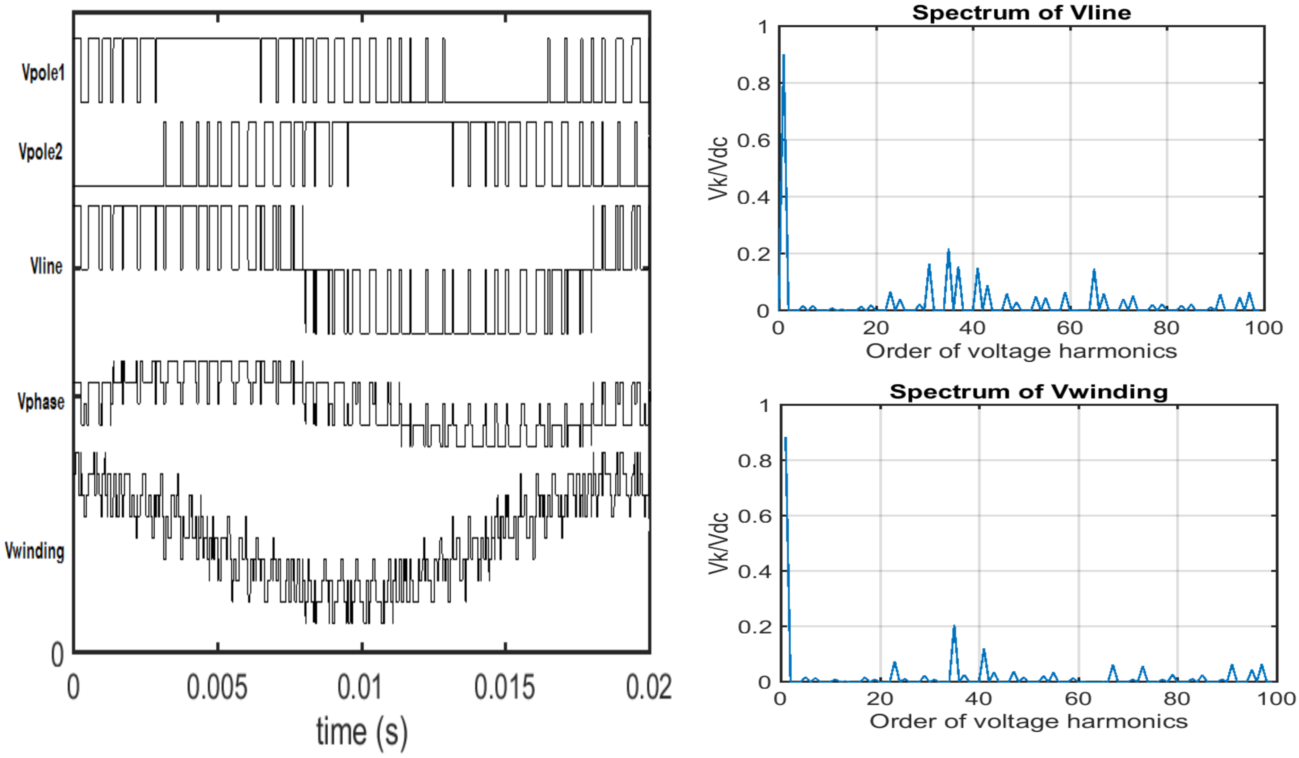

Fig. 29.

Total Harmonic Distortion (THD) factor is the basic parameter for comparison of harmonic quality of voltage waveforms of photovoltaic systems. Fig. 30 presents results of calculation of Total Harmonic Distortion factor ($THD = (1/V_{winding_1})\sqrt{\sum_{k=2}^{40} V^2_{winding_k}}$) of winding voltage V_{wind} and line voltage V_{line} as function of coefficient of modulation of converters of photovoltaic system adjusted by algorithms of both continuous (CPWM) and discontinuous (DPWM1 and DPWM2) synchronous modulation. Value of frequency of switchings of converters is equal to 1.35kHz in this case.

It can be seen from the diagram presented in Fig. 30, that algorithms of the second version of discontinuous synchronous modulation (DPWM2) assure better (smaller) values of THD factor of winding voltages in comparison with two other versions of synchronous pulsewidth modulation. Advanced spectral composition of winding voltages of the analyzed system allows to decrease copper losses in the converter-side windings of transformer. So, this fact should be taken into consideration during practical elaboration of photovoltaic installations on the basis of modulated converters.

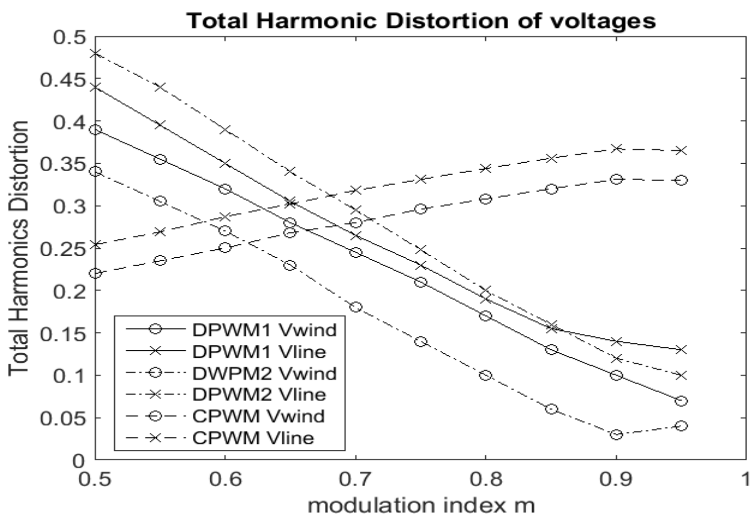

Fig. 30.

2.6. Number of photovoltaic installation is growing rapidly world-wise. New topologies of transformer-less and transformer-based photovoltaic systems have been elaborated and implemented during the last period, assuring further progress in the field of generation of clean solar-energy-based electrical power. Between perspective structures of medium-power photovoltaic systems there are transformer-based systems with multi-winding power transformer, controlled by voltage source inverters supplied by several strings of photovoltaic panels.

Effectiveness of operation of converter-based photovoltaic systems depends on control and modulation strategies applied for adjustment of power converters. So, this part of report presents results of modification and dissemination of control and modulation schemes and techniques for adjustment of neutral-clamped converters of new non-standard structure of transformer-based photovoltaic system with specific double-delta connection of windings of power transformer, insuring continuous voltage waveform symmetry of both output voltages of converters and winding voltages of power transformer of system

Fig. 31 presents one of variants of topology of multi-inverter transformer-based photovoltaic installation with four converters (**con_1 – con_4**), Fig. 32 shows topology of sub-structure of this installation consisting from two inverters feeding by dc voltage of the corresponding photovoltaic strings, which can be used both separately and as part of big multi-module installation. This topology is characterized by specific combined connection (double-delta connection, marked by the bold lines in Fig. 32) between the corresponding six inverter-side windings (W_{11} – W_{23}) of power transformer.

For power conversion systems with increased power rating it is reasonable to use neutral-point-clamped inverters (NPCI, Fig. 15) which are characterized by increased number of power switches and diodes, and assure elimination of undesirable common mode voltage during operation of power conversion systems on the base of NPCI. So, this topology of inverters can be used successfully for control of the presented in Fig. 32 configuration of photovoltaic installation.

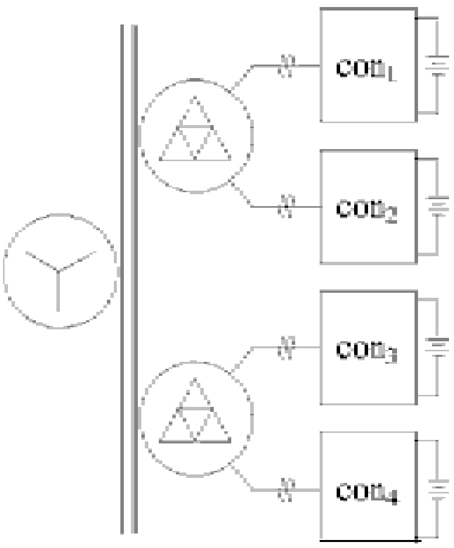

Fig. 31.

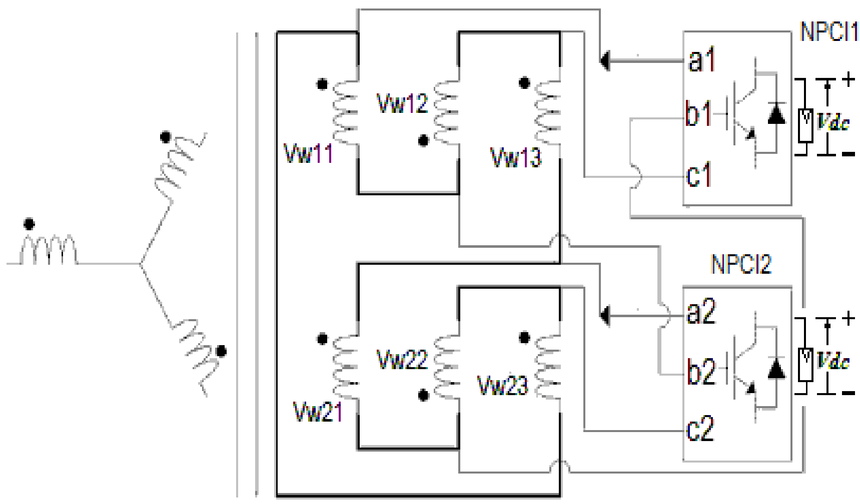

Fig. 32.

On the base of analysis of processes in power circuits of photovoltaic installation (with combined connection of windings of power transformer) presented in Fig. 32, it is possible to elaborate the corresponding correlations for determination of instantaneous values of winding voltages V_{w11} – V_{w23} as functions of the pole voltages V_{a10}, V_{b10}, V_{c10}, V_{a20}, V_{b20}, V_{c20} of the first and the second NPCI:

$$V_{w11} = (2V_{a10} - V_{b10} - V_{c10})/3 - (V_{a20} - 2V_{b20} + V_{c20})/3$$

$$V_{w12} = (V_{a10} + V_{b10} - 2V_{c10})/3 - (-V_{a20} + 2V_{b20} - V_{c20})/3$$

$$V_{w13} = (-V_{a10} - V_{b10} + 2V_{c10})/3 - (-2V_{a20} + V_{b20} + V_{c20})/3$$

$$V_{w21} = (V_{a10} - 2V_{b10} + V_{c10})/3 – (2V_{a20} – V_{b20} - V_{c20})/3$$

$$V_{w22} = (-V_{a10} + 2V_{b10} - V_{c10})/3 – (V_{a20} + V_{b20} - 2V_{c20})/3$$

$$V_{w23} = (-2V_{a10} + V_{b10} + V_{c10})/3 – (- V_{a20} – V_{b20} + 2V_{c20})/3$$

Based on the methodology of synchronous space-vector multi-zone modulation, determination of widths and positions (inside period of the fundamental frequency) of pulse control signals and the corresponding pulses of the pole voltages of each NPCI of the analyzed photovoltaic installation can be based on the corresponding set of specialized dependences presented below (m is coefficient of modulation of inverters, and τ is width of sub-cycles in this case, connected directly with switching frequency of inverters).

$$\beta_1 = 1.1m\tau\ ; \quad \beta_j = \beta_1 \cos[(j-1)\tau]\ ; \quad \gamma_j = \beta_{n-j+1}\{0.75 - 0.55\tan[(n-j)\tau]\}\ ; \quad \lambda_j = \tau - (\beta_j + \beta_{j+1})/2$$

Practical analysis of processes in photovoltaic installation on the base of dual NPCIs controlled by specialized algorithms of synchronous multi-zone modulation has been accomplished based on results of modeling and simulation of systems. Fig. 33 – Fig. 35 show basic voltage waveforms of the system (pole voltages of NPCIs V_{a10}, V_{b10}, V_{a20}, V_{b20}, line voltage V_{a1b1}, and winding voltage V_{iw11}), and also harmonic spectra of voltages V_{a1b1} and V_{iw11} have been presented in these figures. Curves in Fig. 33 correspond to installation with NPCIs controlled by algorithms of continuous synchronous multi-zone modulation (PWMC), diagrams in Fig. 34 correspond to NPCI-based system controlled by the scheme of discontinuous pulsewidth modulation (PWMD), and curves in Fig. 35 correspond to installation with inverters adjusted by algorithms of double-direct multi-zone pulsewidth modulation (PWMDD). Operating frequency of photovoltaic system is equal to 50Hz, and frequency of switching of power switches of NPCIs is equal to 1.1kHz. Modulation index of NPCIs is equal to m=0.75.

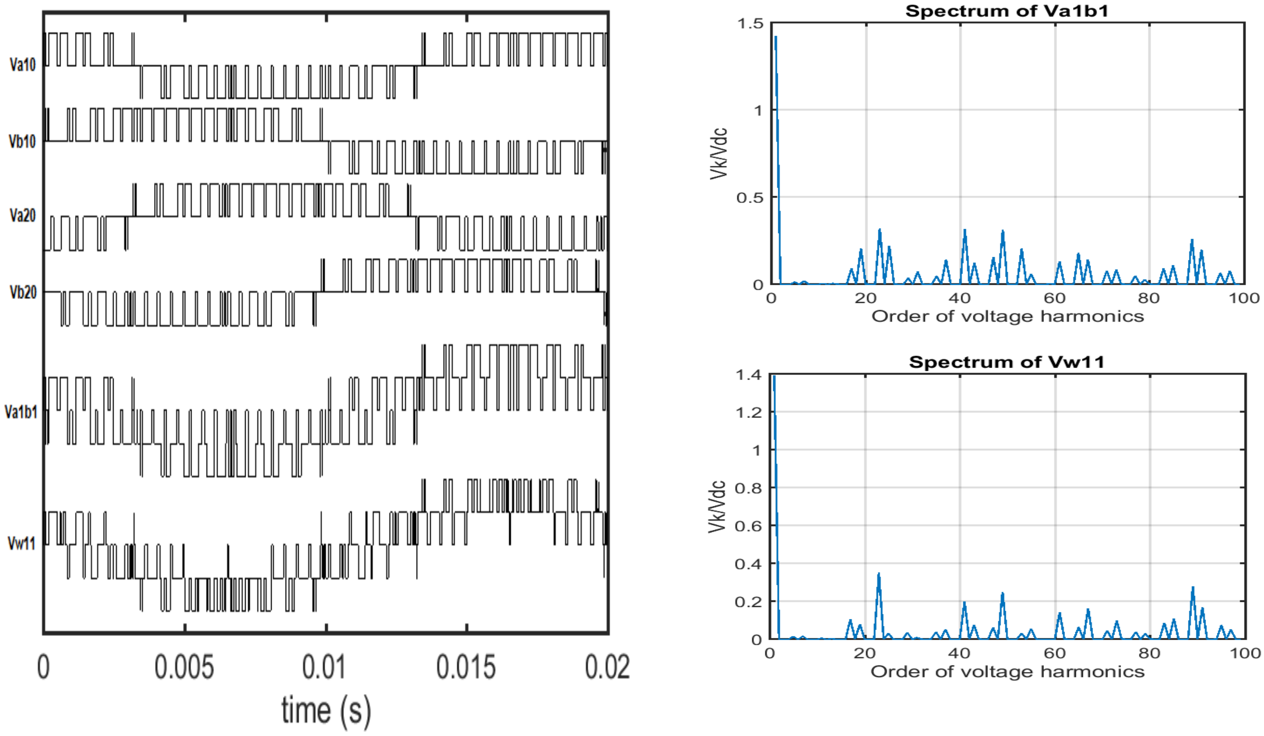

Fig. 33.

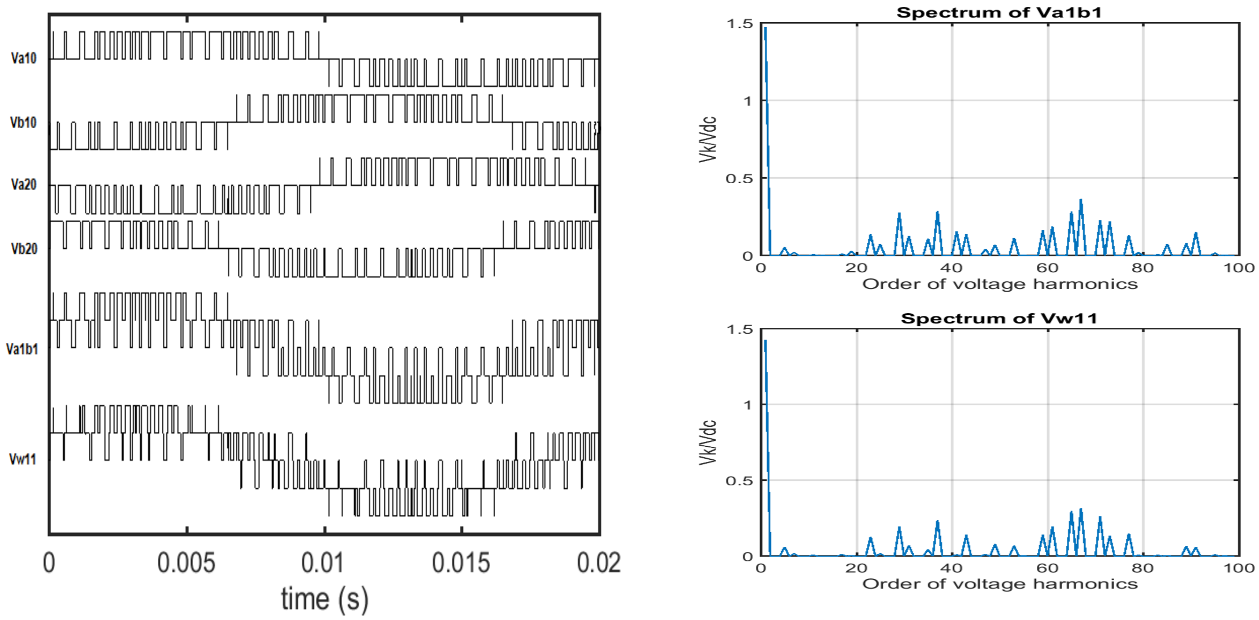

Fig. 34.

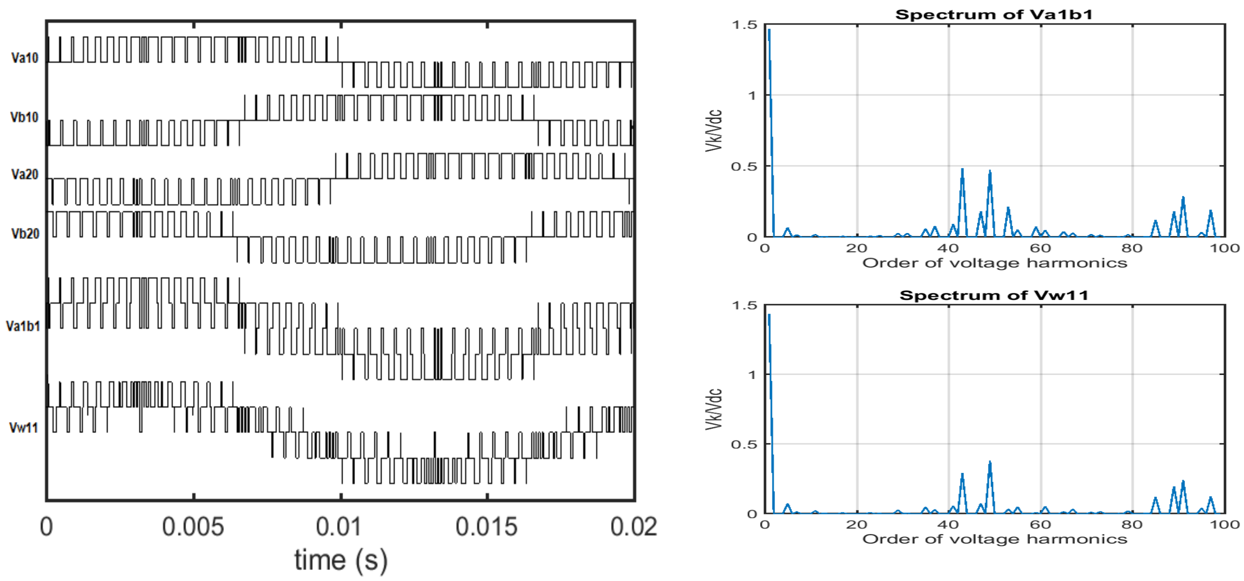

Fig. 35.

Results of simulation of system, presented in Figs. 33 – 35, show, that for the all analyzed control modes both line voltages and winding voltages have quarter-wave symmetry which is characterized by the lacking in voltage spectra of even harmonics and sub-harmonics. It is shown also by the presented results, that spectra of winding voltages is much better in comparison with spectra of the corresponding line-to-line voltages of NPCIs.

Total Harmonic Distortion (THD) factor is an important parameter for comparison of integral harmonic composition of basic voltage waveforms of photovoltaic systems. Fig. 36 –Fig. 37 show results of determination of Total Harmonic Distortion factor of line voltages and winding voltages of the analyzed photovoltaic installation with two values of maximum numbers of calculated harmonics (k-th harmonics) - k=40 and k=100:

$$THD = (1/V_{w11_1})\sqrt{\sum_{k=2}^{40} V_{w11_k}^2} \text{ (Fig. 36)}; \qquad THD = (1/V_{w11_1})\sqrt{\sum_{k=2}^{100} V_{w11_k}^2} \text{ (Fig. 37)}.$$

Corresponding determination of value of THD factor of the V_{a1b1} and V_{w11} voltages of photovoltaic installation on the base of NPCIs has been executed for systems controlled by continuous (PWMC), discontinuous (PWMD), and double-direct (PWMDD) versions of synchronous multi-zone pulsewidth modulation. Average frequency of switchings of power switches of NPCIs was equal to 1.1kHz for these calculations. Results of determination of THD factor show some advantage of PWMDD algorithms in comparison with algorithms of PWMD and PWMC.

The presented diagrams show also big dependence of value of THD from number of voltage harmonics taking into consideration during calculation of THD. And this factor should be taken into consideration during comparative analysis of performance of PV systems with power converters controlled by different versions and variants of synchronous multi-zone modulation.

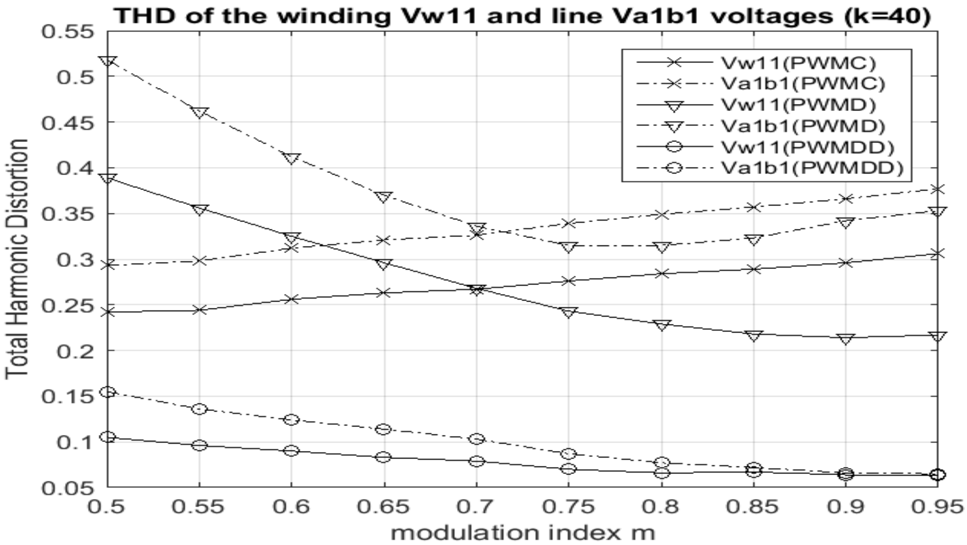

Fig. 36

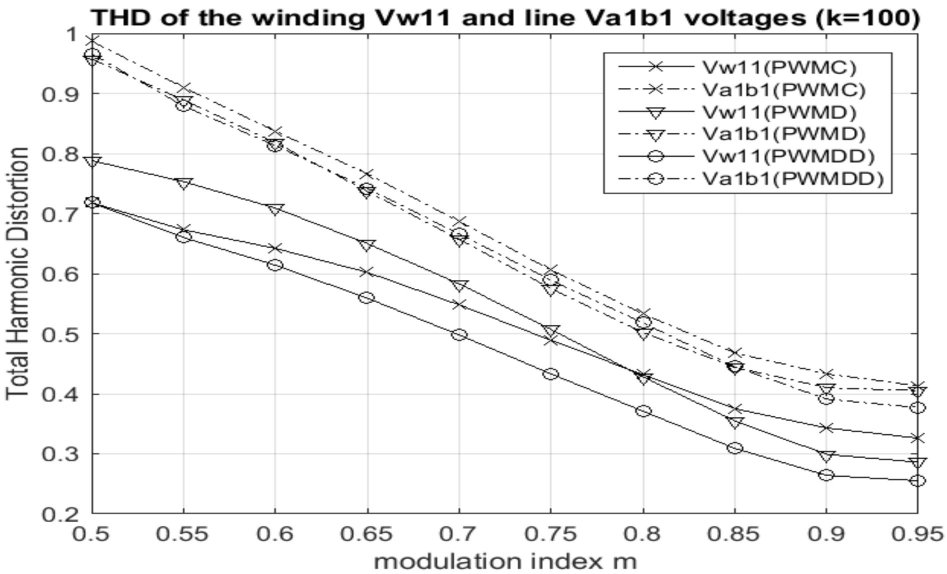

Fig. 37.

3. Cele mai relevante realizări obținute în cadrul proiectului

Novel schemes, techniques, and algorithms of synchronous multi-zone space-vector modulation, elaborated, investigated, and disseminated for control of new perspective topologies of power converters and electric drives, assure (for any control modes of converters) minimization of undesirable sub-harmonics in spectra of the output voltage and current of power converters for electric transport and for photovoltaic systems, thereby providing improvement of efficiency of operation and prolongation of the life-span of power conversion systems with modulated converters, and contributing to the development of energy saving technologies and renewable energy technologies, which are very important fields at both national and international dimensions.

4. Participarea în programe și proiecte internaționale (ORIZONT 2020, COST…)

It is necessary to mention, that Project Manager, d.h.s.t. V. Olesciuk, as Official Representative of the Republic of Moldova in Program Committee of HORIZON'2020 (Transport configuration), participated during 2018-2019 in three meetings of the Program Committee in Brussels (Belgium). Fruitful bilateral contacts and links have been established during these meetings with delegates from other European countries (Member States and Associated Countries).

In particular, useful contacts have been established with Mrs. J. Sarkijarvi from Finland, who informed all delegates regarding 2020 Transport Research Area (TRA'2020) Conference, which will be at April 2020 in Helsinki (Finland). TRA Conferences are the biggest and the most prestigious European conferences in the field of research and innovation of transport systems and transport problems, with participation of more than 1000 representatives. So, in accordance with recommendation of Finnish colleagues we prepared and submitted at TRA'2020 generalized (based on our recent research) paper by V. Oleschuk, V. Ermuratskii, and M. Tirsu "Synchronous Multi-Zone Space-Vector Modulation for Control of Drive Converters of Transport Systems: A Survey", which has been accepted for including in Program of TRA'2020.

5. Colaborări științifice internaționale/naționale

During project duration, strong scientific collaboration has been established with colleagues from our basic collaborative (partner) university - University of Seville (Spain). In particular, with the purpose of joint practical research on the topic of the project, d.h.s.t. V Olesciuk visited twice Department of Electronics of University of Seville (27 October – 5 December 2018, 22 October – 27 November 2019), and results of this joint research has been generalized in joint papers with Professor F. Barrero, head of ACETI research group of University of Seville:

V. Oleschuk, V. Ermuratskii, and F. Barrero, "Synchronous Balanced Control of Dual Split-Phase Drive Topology with PWM Diode-Clamped Inverters," Proc. of IEEE Ukrainian Conf. on Electrical and Computing Engineering (UKRCON'2019), pp. 375-381, 2019.

V. Oleschuk, V. Ermuratskii, and F. Barrero, "Multilevel Installation Based on Diode-Clamped Inverters Controlled by Synchronous Multi-Zone PWM," Proc. of IEEE SIELMEN'2019 Conf., pp. 158-165, 2019.

V. Oleschuk, V. Ermuratskii, and F. Barrero, "Synchronous PWM Control of Dual Neutral-Clamped Converters of PV System with Combined Interconnection of Windings of Power Transformer," prepared for IEEE Development and Application Systems (DAS'2020) Conf.

Also, scientific collaboration with Dr. M. Pastor from Department of Electrical Engineering of University of Kosice (Slovakia) has been established, and results of this collaboration have been published in two joint papers:

V. Oleschuk, V. Ermuratskii, and M. Pastor, "Alternative Methods of Synchronous Space-Vector PWM for Transport-Oriented Converters and Drives," Proc. of IEEE Int'l Conf on Electrical Drives and Power Electronics (EDPE'2019), pp. 327-334, 2019.

V. Oleschuk, V. Ermuratskii, and M. Pastor, "Synchronous Adjustment of Modular Converter Based on Diode-Clamped Inverters with Multi-Zone PWM," Proc. of IEEE Int'l Conf on Electrical Drives and Power Electronics (EDPE'2019), pp. 379-384, 2019.

10. Rezumatul raportului cu evidențierea rezultatului, impactului, implementărilor, recomandărilor (En)

On the basis of the original method (methodology) of synchronous space-vector modulation, elaborated in the Institute of Power Engineering of Moldova, which allows providing improvement of spectral composition of voltage and current in power conversion systems, further development, dissemination and adaptation of basic schemes, techniques and algorithms of synchronous multi-zone modulation have been accomplished for control of new perspective topologies of power electronic converters and electric drives for electric transport and for renewable energy (photovoltaic) systems.

In particular, schemes and algorithms of synchronous space-vector modulation have been modified in order to control synchronously six-phase converter of open-end winding automotive motor drive. Required power balance between four dc sources can be provided in this case due to special control correlations, connecting modulation indices of inverters and magnitudes of voltages of dc sources. It has been shown, that the analyzed schemes of modified modulation insure symmetries of the phase and line voltages of six-phase system with power balancing capability for any ratio (integral or fractional) between the switching frequency and fundamental frequency of each inverter of the system, supplied by both equal dc-voltage and unequal dc-voltages.

Also, basic techniques of synchronous multi-zone modulation have been developed for effective adjustment of five-phase power conversion system for transport application. Control and modulation strategy is based in this case on new concept for determination of the pulse patterns, and includes novel control correlations. Its application provides continuous synchronization and symmetry of voltage waveforms in five-phase systems with dual inverters, allowing minimization of undesirable subharmonics (of the fundamental frequency) in spectra of phase voltages of system.

Algorithms of synchronous space-vector modulation have been specifically modified for control of two topologies of modular converters (transformer-less four-inverter-based topology and transformer-based triple-inverter-based topology), mainly for transport application, consisting from several diode-clamped inverters. Control scheme is based in this case on the using of minimum number of voltage space vectors of diode-clamped inverters, insuring minimization of undesirable common-mode voltages in systems. Multilevel output voltage of modular converters adjusted by the basic versions of modified synchronous modulation, is characterized by lacking in its spectra of even harmonics and subharmonics (of the fundamental frequency).

Elaboration of the developed schemes and algorithms of synchronous space-vector modulation has been executed for synchronous control of two new topologies of transformer-based multi-string photovoltaic installations with several voltage source converters. Special modulation schemes with specific control dependences insures in these cases quarter-wave symmetry of both line voltages of separate converters and of winding voltages at the converter-side windings of power transformer. Spectra of the winding voltages of the analyzed photovoltaic system do not contain even harmonics and undesirable subharmonics (of the fundamental frequency) during the whole control range, which is especially important for photovoltaic installations with increased power rating.

The obtained theoretical results have been verified by modeling and simulation of power conversion systems with new control and modulation schemes and algorithms by the means of the developed special-oriented software-programs. Comparative analysis of behavior of transport-oriented systems and photovoltaic systems on the base of power converters with advanced schemes and techniques of synchronous multi-zone modulation has been done. On the basis of results of investigations, practical recommendations have been elaborated regarding rational choice of schemes and algorithms of synchronous multi-zone modulation for the corresponding installations and their control modes.

Results of research have been generalized in 16 papers, including 10 papers published in Scopus-related journals and proceedings.

10a. Rezumatul raportului cu evidențierea rezultatului, impactului, implementărilor, recomandărilor (Ro)

Pe baza metodei (metodologiei) originale de modulare sincronă-vectorială, elaborată la Institutul de Energetica din Moldova (care permite îmbunătățirea compoziției spectrale a tensiunii și a curentului în sistemele de conversie a energiei electrice), a fost realizată dezvoltarea, diseminarea și adaptarea ulterioară a schemelor și algoritmilor de bază de modulare sincronă multi-zonală pentru controlul topologiilor noi de perspectivă a convertoarelor electronice de energie electrică și a acționărilor electrice pentru transport electric și pentru sisteme de energie regenerabilă (fotovoltaice).

În special, schemele și algoritmii de modulare sincronă-vectorială au fost modificate pentru a controla în mod sincron convertizorul cu șase faze de acționare electrică reglabilă cu înfășurare deschisă pentru transport electric. Echilibrul necesar de energie electrică între patru surse de curent continuu poate fi asigurat în acest caz datorită corelațiilor speciale de control, conectarea indicilor de modulare a invertoarelor și a tensiunilor surselor de curent continuu. S-a demonstrat că schemele analizate ale modulației modificate asigură simetriile tensiunilor de fază și linie ale sistemului cu șase faze (și îmbunătățirea compoziției spectrale a tensiunii) cu capacitate de echilibrare a puterii pentru orice raport (integral sau fracțional) între frecvența de comutație și frecvența fundamentală a fiecărui invertor al sistemului, furnizată atât de tensiune egală de sursă de curent continuu, cât și de tensiune inegală de sursă de curent.

De asemenea, au fost dezvoltate tehnici de bază de modulare sincronă multi-zonală pentru ajustarea eficientă a sistemului de conversie a energiei electrice în cinci faze pentru aplicarea în transport electric. Strategia de control și modulare se bazează în acest caz pe un concept nou pentru determinarea parametrilor semnalelor de control ale convertoarelor și include corelații noi de control. Aplicația sa asigură sincronizarea continuă și simetria formelor de undă de tensiune în sistemele cu cinci faze cu invertoare duale, permițând minimizarea subarmonicii nedorite (a frecvenței fundamentale) în spectrele tensiunilor de fază ale sistemului.

Algoritmii de modulare sincronă-vectorială au fost modificate special pentru controlul a două topologii ale convertoarelor modulare (topologie cu patru invertoare fără transformator și topologie pe bază de trei-invertori cu transformator), în special pentru aplicarea transportului electric, constând din mai multe invertoare cu trei niveluri. Schema de control se bazează în acest caz pe utilizarea unui număr minim de vectori spațiali de tensiune a invertoarelor, asigurând minimizarea tensiunilor nedorite de mod-comun în sistem. Tensiunea de ieșire cu mai multe niveluri a convertoarelor modulare ajustate pe bază versiunilor modulației sincrone modificate, se caracterizează prin lipsa in spectrelor tensiunii de armonici pare și subarmonici (a frecvenței fundamentale).

Elaborarea schemelor și algoritmilor de modulare sincronă-vectorială dezvoltată a fost executată pentru controlul sincron a două noi topologii de instalații fotovoltaice cu mai multe secții fotovoltaice și cu transformator, bazate pe mai multe convertoare. Schemele speciale de modulare cu dependențe de control specifice asigură în aceste cazuri simetria de undă sfertă atât a tensiunilor de linie ale convertoarelor separate, cât și a tensiunilor de înfășurare ale transformatorului. Spectrele tensiunilor de înfășurare ale sistemului fotovoltaic analizat nu conține chiar armonice pare și subarmonice nedorite (ale frecvenței fundamentale) pe întregul interval de control, ceea ce este deosebit de important pentru instalațiile fotovoltaice cu putere crescută.

Rezultatele teoretice obținute au fost verificate prin modelarea și simularea sistemelor de conversie a energiei electrice cu scheme și algoritmi noi de control și modulare cu ajutorul programelor (software) dezvoltate specializate. S-a făcut o analiză comparativă a comportamentului sistemelor orientate spre transport electric și a sistemelor fotovoltaice pe baza convertoarelor de energie electrică cu scheme avansate de modulare sincronă multi-zonală. Pe baza rezultatelor investigațiilor, au fost elaborate recomandări practice privind alegerea rațională a schemelor și algoritmilor de modulare sincronă-vectorială pentru instalațiile corespunzătoare și regimurilor lor de control.

Rezultatele cercetărilor au fost generalizate în 16 lucrări, inclusiv 10 lucrări publicate în reviste și culegeri înregistrate în Scopus.

11. Concluzii

Moldovan research team has long-term priority in elaboration of alternative methods and techniques of synchronous space-vector pulsewidth modulation for rational control of power electronic converters for different applications, including general purpose adjustable speed drives, traction drives for electric transport, and converters for renewable energy systems including photovoltaic systems.

Novel schemes, techniques, and algorithms of synchronous multi-zone space-vector modulation, elaborated, investigated, and disseminated (in the range of the reported project) for control of new perspective topologies of power converters and electric drives, assure minimization of undesirable sub-harmonics in spectra of the output voltage and current of power converters for electric transport and for photovoltaic systems, thereby providing improvement of efficiency of operation and prolongation of the life-span of power conversion systems with modulated converters.

Results of the executed research can be used practically during elaboration of modern power conversion systems (on the base of modulated converters) by the corresponding national and (or) international enterprises specializing in the field of production of energy-saving electrical and electronic equipment

So, results of the executed investigation make a certain contribution to:

- further development and deepening of knowledge in theory and practice of pulse modulation as an important part of science, engineering, and technology;

- novel solutions in the field of control technologies for power converters and drives for modern renewable energy systems and for electric transport, providing improvement of effectiveness of operation of these systems;

- prerequisites for successful participation in new “Calls for Proposal” of the recognized international competitions, including Horizon’2020 and Horizon Europe (2021-2027) Programs of the European Commission in the “Energy” and “Transport” fields.

Anexa nr. 1

Volumul total al finanțării *(mii lei)* (pe ani)

Anul	Planificat	Executat	Cofinanțare
2018	100 mii lei	100 mii lei	
2019	150 mii lei	150 mii lei	

Lista executorilor *(funcția în cadrul proiectului, titlul științific, semnătura)*

Nr d/o	Numele/Prenumele	Anul nașterii	Titlul științific	Funcția în cadrul proiectului	Semnătura
1	Olesciuk Valentin	1947	d.h.s.t.	Manager, cercetator	
2	Ermuratschi Vladimir	1938	d.h.s.t.	Cercetator	
	Uzun Galina	1982	cerc.st. stagiar	Cercetator	

Lista tinerilor cercetători

Nr d/o	Numele/Prenumele	Anul nașterii	Titlul științific	Funcția în cadrul proiectului
	Uzun Galina	1982	cerc.st. stagiar	Cercetator

Lista doctoranzilor

Nr d/o	Numele/Prenumele	Anul nașterii	Titlul științific	Funcția în cadrul proiectului

Conducătorul proiectului V. Olesciuk, d.h.s.t., cerc.conf. ____________________

(nume, prenume, grad, titlu științific) (semnătura)

Anexa nr. 2

LISTA

lucrărilor publicate

Capitole în monografii internaţionale:

1. KOHLI, S, MAHAJAN, S.B., SANJEEVIKUMAR, P., FEDAK, V., OLESCHUK, V., "Impact of DC Bias on the Magnetic Loading of Three Phase Three Limb Transformer Based on Finite Element Method," Chapter of the book "*Advances in Power Systems and Energy Management*", Springer Nature Singapore Pte Ltd., 2018, pp. 97-106.

Articole din reviste internaţionale cu impact factor:

2. OLESCHUK, V., ERMURATSKII, V. Synchronous Balanced Regulation of Multiphase System on the Base of Modulated Diode-Clamped Inverters. *Technical Electrodynamics,* ISSN 1607-7970, no. 5, 2019, pp. 27-35 (IF=0.19).

Articole din reviste internaţionale:

3. OLESCHUK, V. Modified Algorithms of Space-Vector Modulation for Synchronous Control of Power Conversion System with Three Converters. *Electrotechnic and Computer Systems*, ISSN 2221-3937, no. 28 (104), 2018, pp.71-78.

Articole din culegeri internaţionale:

4. OLESCHUK, V., ERMURATSKII, V., BARRERO, F. Synchronous Balanced Control of Dual Split-Phase Drive Topology with PWM Diode-Clamped Inverters. In: *IEEE Proceedings: Ukrainian Conf. on Electrical and Computing Engineering (UKRCON'2019),* ISBN 978-1-7281-3882-4, 2019, pp. 375-381 (Scopus-related publication).

5. OLESCHUK, V., ERMURATSKII, V. Open-End Winding Multiphase Installation Regulated by Modified Techniques of Space-Vector PWM. In: *IEEE Proceedings: Ukrainian Conf. on Electrical and Computing Engineering (UKRCON'2019)*, ISBN 978-1-7281-3882-4, 2019, pp. 299-304 (Scopus-related publication).

6. OLESCHUK, V.; ERMURATSKII, V., PASTOR, M. Alternative Methods of Synchronous Space-Vector PWM for Transport-Oriented Converters and Drives. In: *IEEE Proceedings*: *Int'l Conf on Electrical Drives and Power Electronics (EDPE'2019)*, ISBN 978-1-7281-0388-4, 2019, pp. 327-334 ((Scopus-related publication). .

7. OLESCHUK, V.; ERMURATSKII, V., PASTOR, M. Synchronous Adjustment of Modular Converter Based on Diode-Clamped Inverters with Multi-Zone PWM. In: *IEEE Proceedings*: *Int'l Conf on Electrical Drives and Power Electronics (EDPE'2019)*, ISBN 978-1-7281-0388-4, 2019, pp. 379-384 (Scopus-related publication).

8. OLESCHUK, V., ERMURATSKII, V. Novel Methods, Schemes and Techniques of Synchronous Modulation for Control of Power Conversion Systems for Transport: An Overview. In: *IEEE Proceedings: Electrical Vehicle Conf. (EV'2019)*, ISBN 978-1-7281-0791-2, 2019, 6 p. (Scopus-related publication).

9.OLESCHUK, V., ERMURATSKII, V., BARRERO, F. Multilevel Installation Based on Diode-Clamped Inverters Controlled by Synchronous Multi-Zone PWM. In: *IEEE Proceedings: SIELMEN'2019,* ISBN 978-1-7281-4011-7, 2019, pp. 158-165 (Scopus-related publication).

10.OLESCHUK, V.; ERMURATSKII, V. Review of Methods and Techniques of Space-Vector PWM for Dual and Triple Inverters of PV Systems. In: *IEEE Proceedings: SIELMEN'2019,* ISBN 978-1-7281-4011-7, 2019, pp. 205-212 (Scopus-related publication).

11.OLESCHUK, V., ERMURATSKII, V. Six-Phase Multi-Inverter System with Power Balancing and Voltage Waveform Symmetries. In: *IEEE Proceedings: Int'l Conf. on Intelligent Energy and Power Systems (IEPS'2018)*, ISBN 978-1-5386-9545-6, 2018, pp. 259-264 (Scopus-related publication).

Articole din reviste naţionale (categoria A)

12. OLESCHUK, V., ERMURATSKII, V. Balanced Control of Quad-Inverter Installation with Modified Discontinuous PWM. *Problemele Energeticii Regionale*, ISSN 1857-0070, №1-3, 2019, pp. 35-42.

Rapoarte publicate la congrese, conferinţe, simpozioane internaţionale:

13. OLESCHUK, V., ERMURATSKII, V. Five-Phase Open-End Winding System Adjusted by Specialized Scheme of Space-Vector Modulation. *Proc. of Int'l Workshop on Electric Drives: Improvement in Efficiency of Electric Drives (IWED'2019)*, Moscow, Russian Federation, 2019, 6 p.

14. OLESCHUK, V., ERMURATSKII, V. Power Balancing Control of Six-Phase System Based on Diode-Clamped Inverters with Synchronous PWM. *Proc. of Int'l Workshop on Electric Drives: Improvement in Efficiency of Electric Drives (IWED'2019)*, Moscow, Russian Federation, 2019, 6 p.

15. ОЛЕЩУК, В. Электропривод переменного тока на базе трех трехфазных инверторов с синхронной векторной модуляцией. *Труды международной конференции ««Прикладные научно-технические исследования»*, Киев, Украина, 2019, стр. 74.

Rapoarte publicate la congrese, conferinţe, simpozioane naţionale:

16. ОЛЕЩУК, В. Силовые преобразователи с новыми алгоритмами управления и модуляции для систем регулируемого электропривода. *Conferinta Nationala cu Participare Internationala „Ştiinţa în Nordul Republicii Moldova: Realizări, Probleme, Perspective*", Balti, 2019, pp. 347-352.

Conducătorul proiectului Olesciuk Valentin, d.h.s.t., cerc.conf. ____________________
(nume, prenume, grad, titlu științific) (semnătura)

14. Participări la manifestări științifice naționale/internaționale

D.h.s.t. Valentin Olesciuk, Manager and Principal Investigator of the Project, during 2018-2019 participated in several international conferences with presentation of the corresponding raports:

1. IEEE Int'l Conf. on Intelligent Energy and Power Systems (IEPS'2018), September 11-14, 2018, Kharkiv, Ukraine. Title of report:"Six-Phase Multi-Inverter System with Power Balancing and Voltage Waveform Symmetries".
2. IEEE Int'l Ukrainian Conf. on Electrical and Computer Engineering (UKRCON'2019), July 2-6, 2019, Lviv, Ukraine. Titles of two reports:
   a) "Open-End Winding Multiphase Installation Regulated by Modified Techniques of Space-Vector PWM";
   b) "Synchronous Balanced Control of Dual Split-Phase Drive Topology with PWM Diode-Clamped Inverters".
3. IEEE Int'l Conf on Electrical Drives and Power Electronics (EDPE'2019), September 23-26, 2019, High Tatras, Slovakia. Titles of two reports:
   a) "Alternative Methods of Synchronous Space-Vector PWM for Transport-Oriented Converters and Drives";
   b) "Synchronous Adjustment of Modular Converter Based on Diode-Clamped Inverters with Multi-Zone PWM".
4. IEEE Int'l Electrical Vehicles Conf. (EV'2019), October 3-4, 2019, Bucharest, Romania. Title of report: „Novel Methods, Schemes and Techniques of Synchronous Modulation for Control of Power Conversion Systems for Transport: An Overview".
5. IEEE Int'l Conf. on Electromechanical and Energy Systems (SIELMEN'2019), October 11-12, 2019, Chisinau, Moldova. Titles of two reports:
   a) "Multilevel Installation Based on Diode-Clamped Inverters Controlled by Synchronous Multi-Zone PWM";
   b) "Review of Methods and Techniques of Space-Vector PWM for Dual and Triple Inverters of PV Systems".

Conducătorul proiectului:	Olesciuk Valentin, d.h.s.t., cerc.conf. (nume, prenume, grad, titlu științific)	________________ (semnătura)