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MEDIUM-POWER DRIVE INSTALLATIONS BASED ON TRIPLE VOLTAGE SOURCE INVERTERS ADJUSTED BY ALGORITHMS OF SYNCHRONOUS MULTI-ZONE PWM

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This paper presents short overview of the development and dissemination of specialized schemes and algorithms of space-vector-based synchronous multi-zone pulsewidth modulation (MZ PWM) for control of triple inverters of the medium-power variable speed drives characterized by relatively low switching frequency of inverters. It insures providing synchronization and symmetry of the basic voltage waveforms in triple-inverter-based configurations of drive installations on the base of standard voltage source inverters (VSIs). It assures also minimization of magnitudes of even-order harmonics and undesirable subharmonics in spectra of the basic voltages of drive installations, leading to reducing of losses in the corresponding apparatuses and to increasing of its efficiency. Examples of application of the basic techniques of multi-zone PWM for regulation of three typical structures of triple-VSI-based medium-power motor drives are presented. Modeling and simulations give a behavior of drive installations based on triple inverters adjusted by algorithms of synchronous MZ PWM. References 12, figures 11, table 1.

Keywords: AC motor drives, regulated inverters, modulation strategy, voltage synchronization, voltage spectra.

Introduction. Progress in technical development and in expansion of application areas of adjustable speed electric drives is based both on the development of system topologies and on the development of methods and techniques of control and PWM for power electronic converters [1, 2].

Three-phase motor drives based on three VSIs feeding induction machine are ones of perspective structures of the medium-power drive installations, which are characterized by multilevel phase and line voltages in systems [3–7]. Space-vector-based schemes of PWM are ones of the most suitable for adjustment of inverters of drive installations [8, 9]. So, specialized strategies and schemes of synchronous PWM can be applied for regulation of triple VSIs of the mentioned above medium-power drives [9–12], and this paper presents a short survey of application of specific techniques of synchronous multi-zone PWM [9] for adjustment of triple-VSI-based drives, assuring continuous synchronization and symmetry of the basic voltage waveforms in these installations.

Fundamentals of the method of synchronous MZ PWM, and analysis of some aspects of its computational efficiency.

An alternative method of synchronous space-vector-based MZ PWM of control and output signals of VSIs makes it possible to ensure synchronization and symmetry of the output voltage waveforms of inverters over the entire control range. Fig. 1 shows (within a 120-degree clock interval) five basic diagrams of switching state sequences of a three-phase VSI, corresponding to a continuous synchronous MZ PWM (CPWM, Fig. 1, *a*), to a discontinuous MZ PWM of the first type (DPWM1, Fig. 1, *b*), to a discontinuous MZ PWM of the second type (DPWM2, Fig. 1, *c*), to a discontinuous MZ PWM with the 30-degree non-conducting states (DPWM30, Fig. 1, *d*), and to a discontinuous MZ PWM with the 60-degree non-conducting states (DPWM60, Fig. 1, *e*) [9].

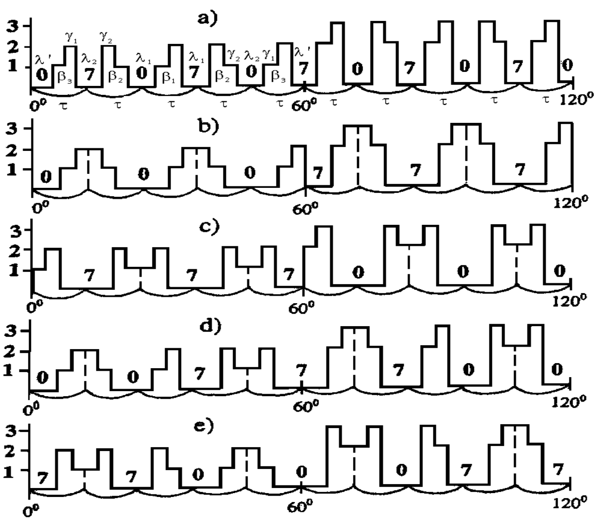

Fig. 1 [9]

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Principle of synchronization of the output voltage wave-form of three-phase VSI is based on continuous synchronization of positions of the central control signals in the centers of the 60^0-clock-intervals, and in symmetrical generation of all other signals around the corresponding central signal [9]. The scheme of synchronous multi-zone PWM includes step-by-step determination of the boundary frequencies F_i and F_{i-1}, transient between control sub-zones, as functions of the width of sub-cycles τ. Fig. 2 presents generalized flow-chart for determination of voltage pulse patterns (with its definitions, presented, in particular, in Fig. 1, *a*) for VSIs regulated by algorithms of synchronous MZ PWM for scalar control modes of drive inverters [9]. In this case, the determination of the parameters of control signals can be carried out both on the basis of trigonometric (providing higher accuracy in determining the signal parameters) functional relationships, and on the basis of simplified algebraic functional dependencies.

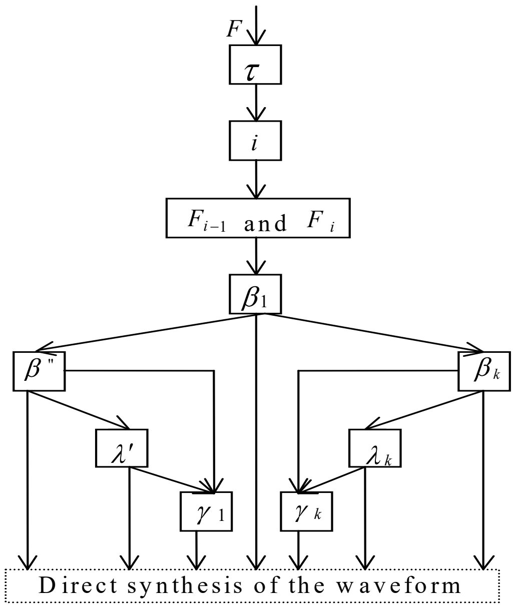


Fig. 2 [9]

The majority of algorithms of conventional space-vector PWM for drive VSIs are based on continuous calculation of trigonometric functions, which are not good for fast real-time computing during process of determination of the pulse patterns of modulated drive inverters. Thus, the problem of computational effectiveness of PWM schemes and techniques is between important problems in the area of control of power electronic converters for drive application. So, some contribution to the solution of this problem can be done by the using of techniques of MZ PWM based on algebraic control functions [9].

Table presents the averaged results of the comparison of normalized computing time between algebraic and trigonometric variants of discontinuous MZ PWM with the 30^0-non-switching states (see Fig. 1, *d*) [9]. The results presented in Table show that computation time for algebraic variants of techniques of MZ PWM is 0.33 compared to the PWM schemes based on trigonometric PWM functions, and it is mainly due to the absence of costly functions such as tangents and cosines in algebraic variants of MZ PWM.

Table [9]

Computing time for the basic functions, %	Trigonometric PWM	Algebraic PWM
tangents	48.3	---
cosines	38.7	---
Total	100	33.4

Drive system with cascade converter based on triple bridge VSIs with synchronous PWM.

Fig. 3 shows a diagram of the main power circuits of ac drive based on a cascade three-level converter, which includes three bridge inverters [5, 10]. Fig. 4 shows the pole V_{a0} and line V_{ab} voltages of a three-level converter regulated by three schemes of synchronous multi-zone PWM with fractional ratio between the switching frequency F_s and fundamental frequency F (F = 35 Hz, F_s/F = 1000/35= 28.6 in this case). Diagrams shown in Fig. 4, *a*, illustrate operation of system controlled by scheme of continuous synchronous PWM (CPWM), diagram in Fig. 4, *b* illustrates operation of system with scheme of discontinuous synchronous PWM with the 30^0-non-switching intervals (DPWM30), and diagram in Fig. 4, *c* illustrate operation of system with scheme of discontinuous PWM with the 60^0-non-switching intervals (DPWM60) [10]. Spectra of the line voltage V_{ab} are also presented in Fig. 4. The average switching frequency of VSIs is F_s = 1.0 kHz.

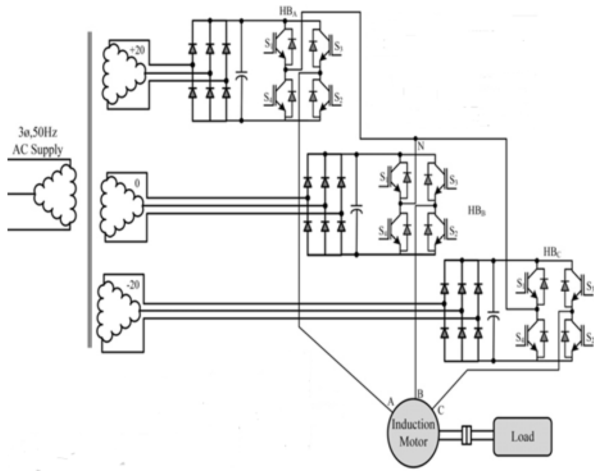
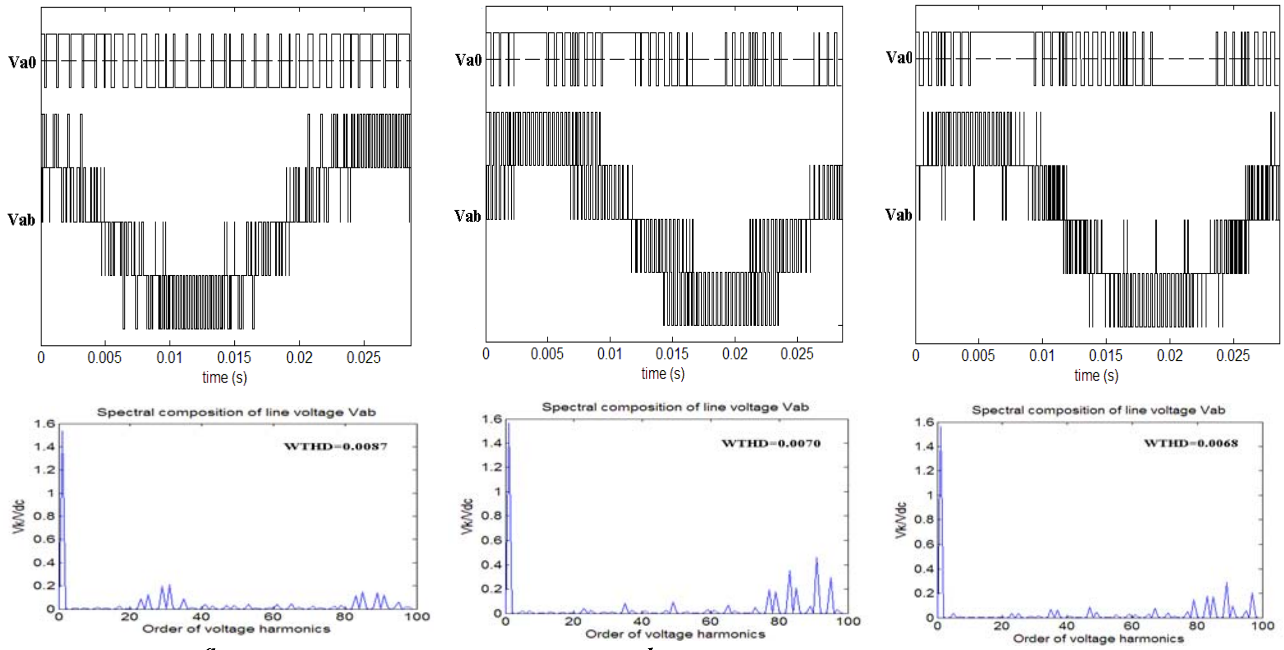


Fig. 3 [5, 10]



a *b* *c*

Fig. 4 [10]

Analysis of the presented in Fig. 4 spectrograms shows that spectra of the output voltage of converters with synchronous PWM contains only odd (not triple-order) harmonics, while subharmonics and even harmonics are completely absent from the spectra.

Fig. 5 presents the average results of the analysis of the integral spectral characteristics of the output voltage of three-level converter with synchronous PWM. In particular, Weighted Total Harmonic Distortion factor of the line voltage V_{ab} was calculated ($WTHD = (1/V_{ab1})\sqrt{\sum_{i=2}^{1000}(V_{abi}/i)^2}$) as a function of the modulation index m of inverters for a system with continuous PWM (CPWM), and with two discontinuous versions of synchronous PWM (DPWM30 and DPWM60) [10]. The average switching frequency of inverters is equal to 1.0 kHz, and control mode corresponds in this case to standard scalar regime with a constant *V/F* ratio.

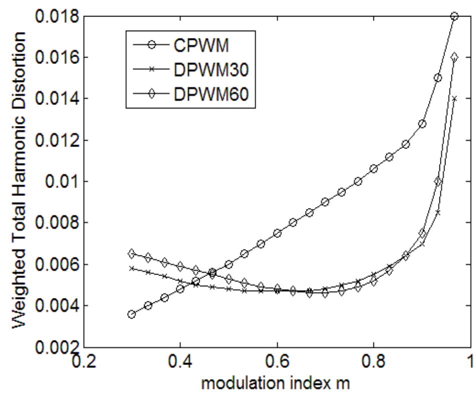


Fig. 5 [10]

Triple-inverters-based drive system with double-delta configuration of power transformer.

Fig. 6 presents the basic power circuits of power conversion system with three VSIs specifically connected with three inverter-side windings of power transformer, which insures decreasing of harmonic distortion of winding voltage and current [6, 11]. So, this system configuration can be perspective for the use in the medium-power ship propulsion drives, which have many phase windings [6].

The values of the phase voltages V_{as1}, V_{bs1} and V_{cs1} of the first VSI of this installation (**Inverter 1,** Fig. 6) are determined by (1)–(3) [11]:

$$V_{as1} = V_{a10} + (V_{a10} + V_{b10} + V_{c10})/3 \qquad (1)$$

$$V_{bs1} = V_{b10} + (V_{a10} + V_{b10} + V_{c10})/3 \qquad (2)$$

$$V_{cs1} = V_{c10} + (V_{a10} + V_{b10} + V_{c10})/3, \qquad (3)$$

where V_{a10}, V_{b10} and V_{c10} are the pole voltages of this inverter.

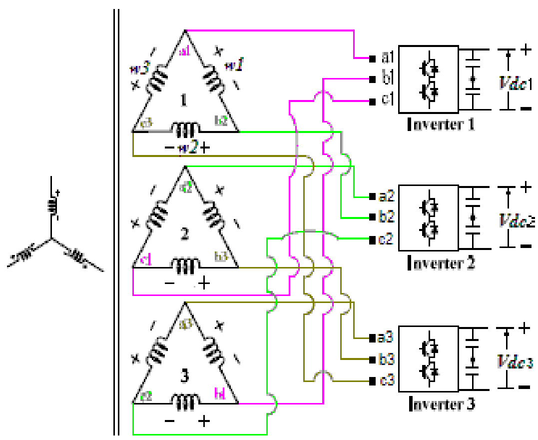


Fig. 6 [6, 11]

The winding voltages (V_{w1}, V_{w2}, V_{w3} in Fig. 4) can be determined in terms of phase voltage of each PWM inverter by (4) [11]:

$$V_{w1} = V_{as3} - V_{bs1} \qquad V_{w2} = V_{bs1} - V_{cs2} \qquad V_{w3} = V_{cs2} - V_{as3}. \qquad (4)$$

Figs. 7, *a* – 7, *b* present simulation results of drive system (Fig. 6) with triple inverters, adjusted by al-gorithms synchronous multi-zone PWM [11]. The presented diagrams show basic voltages in this insta-llation (pole voltages V_{a10}, V_{a20}, V_{a30} of triple VSIs, phase V_{as1} and line V_{a1b1} voltages of **Inverter I** in Fig. 6, and voltages V_{w1star} and $V_{w1delta}$, for versions of star-connection and delta-connection of inverter-side windings of power transformer. Figs. 7, *a* – 7, *b* include also the corresponding spectra of the winding voltage V_{w1}.

Diagrams in Fig. 7, *a* illustrate processes in drive installation with triple VSIs regulated by algorithms of continuous synchronous multi-zone modulation (CPWM), diagrams in Fig. 7, *b* illustrate processes in drive installation with triple VSIs regulated by algorithms of discontinuous synchronous PWM with the 30^0-non-switching intervals (DPWM30) [11]. The operating frequency of drive system F = 35Hz, and switching frequency of VSIs F_s = 1.0 kHz. Coefficient of modulation of VSIs m = 0.70 for this control mode.

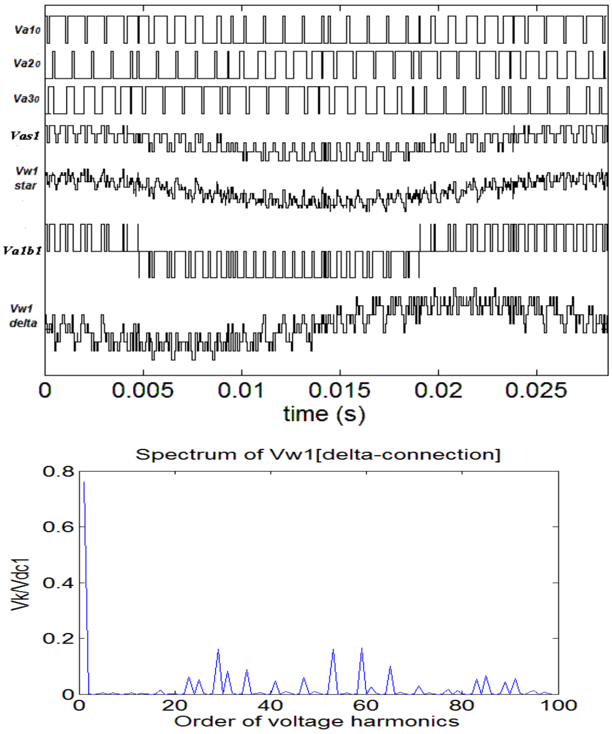


Fig. 7, *a* [11]

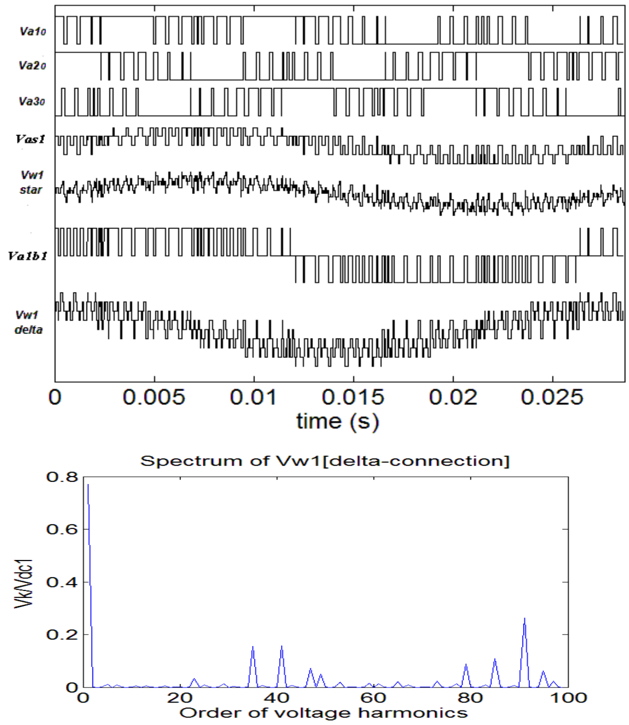


Fig. 7, *b* [11]

Analysis of spectra of the winding voltages in Fig. 5 illustrates the fact that its include only odd (non-triplen) harmonics, and does not include undesirable subharmonics and even harmonics.

Fig. 8 presents diagram of the calculated *WTHD* factor for the winding voltage V_{w1} ($WTHD=(1/V_{w1_1})(\sum_{k=2}^{1000}(V_{w1_k}/k)^2)^{0.5}$) for systems controlled by three basic versions of PWM (CPWM, DPWM30, DPWM60 [11]), and data of this diagram underline the fact, that at the second part of control diapason, if modulation index of VSIs m > 0.60, discontinuous versions of synchronous PWM assure better spectral composition of the winding voltage.

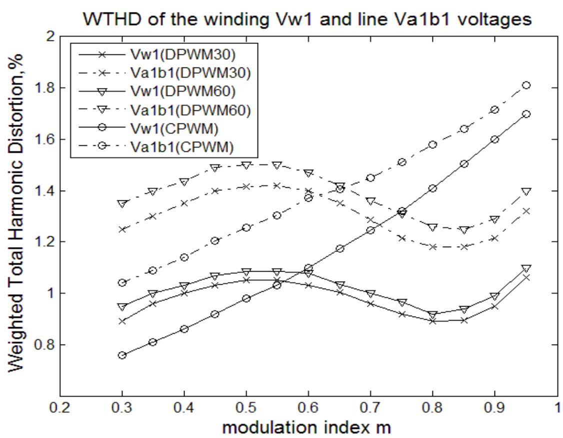


Fig. 8 [11]

Triple-inverter-based modular converter with intermediate transformer. One of perspective topologies of the medium-power converters for powerful drive installations is triple-inverter-based system with an intermediate 0.33 p.u. output transformer (Fig. 9, [3, 12]).

Fig. 10, *a* – Fig. 10, *b* show results of simulation of processes in modular converter with three standard VSIs (Fig. 9) regulated by the schemes of continuous multi-zone PWM (CPWM, Fig. 10, *a*), and by discontinuous synchronous PWM with the 30^0-non-switching states (DPWM, Fig. 10, *b*) [12]. It presents normalized value of the line-to-line voltage V_{ab}, together with spectral composition of this voltage (fundamental frequency of system F = 35 Hz modulation index of VSIs m = 0.70, and switching frequency of three VSIs is F_s = 1.0 kHz).

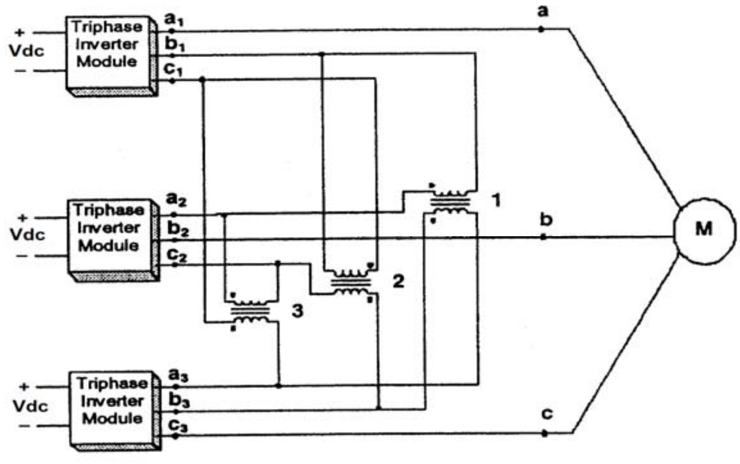
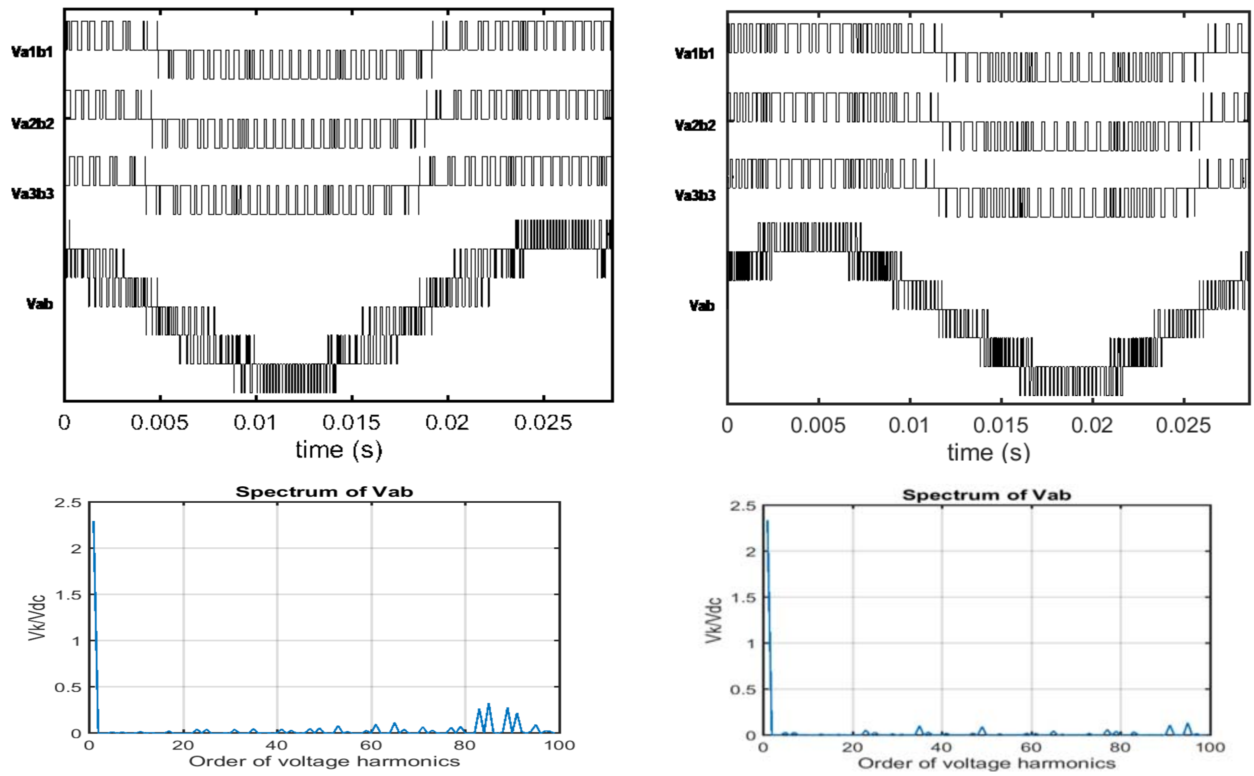


Fig. 9 [3, 12]



a ***b***

Fig. 10 [12]

Fig. 11 presents results of calculation 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 voltages V_{a1b1} and V_{ab} versus index of modulation of VSIs m for triple-VSI system adjusted by two variants of synchronous PWM (CPWM and DPWM) [12]. Switching frequency of VSIs is equal to 1.05 kHz. Results on the presented diagram show that the use of discontinuous multi-zone PWM (DPWM) for regulation of triple VSIs of mo-dular converter is more preferable in comparison with the using of scheme of continuous PWM.

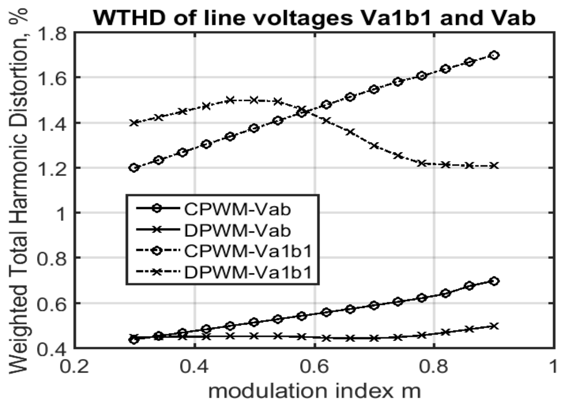


Fig. 11 [12]

Conclusion. Alternative methods, schemes, and techniques of synchronous multi-zone PWM, disseminated for synchronous regulation of three VSIs (with the corresponding phase shift of the output voltages of inverters) of triple-VSI-based drive installations, assure symmetry and improved spectral composition of the resulting multilevel voltage of systems for any operation conditions, including control modes with any frequency ratios (integral of fractional) between the switching frequency of VSIs and fundamental frequency of drive installations.

The presented in Figs. 4, 7, and 10 harmonic compositions of basic voltage waveforms of triple-VSI-based ac drives, regulated by schemes and algorithms of synchronous multi-zone PWM, underline the fact of elimination of even harmonics and subharmonics in voltage spectra during the whole control range of the analyzed motor drive systems. And this factor is especially important for the medium-power and high-power installations which are characterized by low switching frequency of VSIs.

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УДК 621.3

ПРИВОДНІ УСТАНОВКИ СЕРЕДНЬОЇ ПОТУЖНОСТІ НА ОСНОВІ ІНВЕРТОРІВ ПОТРІЙНИХ ДЖЕРЕЛ НАПРУГИ З НАЛАШТУВАННЯМ АЛГОРИТМІВ СИНХРОННОЇ БАГАТОЗОННОЇ ШІМ

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Наведено короткий огляд розробки та розповсюдження спеціалізованих схем і алгоритмів просторово-векторної синхронної багатозонної широтно-імпульсної модуляції (ШІМ) для керування потрійними інверторами частотно-регульованих приводів середньої потужності, що характеризуються відносно низькою частотою комутації. Він забезпечує синхронізацію та симетрію основних форм напруги в триінверторних конфігураціях приводних установок на основі стандартних інверторів напруги (ІН). Це також забезпечує мінімізацію величин парних гармонік і небажаних субгармонік в спектрах основних напруг приводних установок, що призводить до зменшення втрат у відповідних апаратах і підвищення їхньої ефективності. Наведено приклади застосування основних прийомів багатозонної ШІМ для регулювання трьох типових структур електроприводів середньої потужності на базі трьох ІН. Моделювання дає поведінку приводних установок на базі потрійних інверторів, налаштованих алгоритмами синхронної ШІМ. Бібл. 12, рис. 11, табл. 1.

***Ключові слова*:** електроприводи змінного струму, регульовані інвертори, стратегія модуляції, синхронізація напруги, спектри напруги.

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