DOI: https://doi.org/10.15407/techned2022.05.023

GRID-CONNECTED PV SYSTEM EMPLOYING THREE INVERTERS REGULATED BY SYNCHRONOUS SCHEME OF PWM

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The paper presents comparative analysis of three versions of the modified scheme of space-vector-based synchronous pulsewidth modulation (PWM), applied for control of three two-level inverters of transformer-based photovoltaic (PV) system, and focused on providing of the symmetry of winding voltage of power transformer during the whole adjustment range. Power supply of inverters is providing by the corresponding three solar strings consisting of a set of PV panels, and the outputs of three inverters are connected specifically with inverter-side windings of multi-winding grid-tired transformer. Results of MATLAB-simulation prove the fact of advanced spectral composition of the winding voltage of triple-inverter-based PV installation regulated by algorithms of synchronous space-vector PWM, assuring potential reduction of losses in these systems. References 10, table 1, figures 9.
Keywords: voltage source inverter, photovoltaic installation, control and modulation strategy, voltage spectrum.

Introduction. Photovoltaic apparatuses are popular installations between different kinds of renewable electrical energy systems. There are both transformer-less and transformer-based configurations of photovoltaic systems [1 – 5]. Also, there are multiple configurations and topologies of ac modules of PV systems, based mainly on voltage source inverters (two-level three-phase inverters, neutral-point-clamped inverters, multilevel inverters, cascaded inverters, module inverters, etc.) [1 – 3], [5].

Effectiveness of operation of inverter-based power conversion systems, including PV installations, is in big dependence on control and modulation methods and techniques used for regulation of inverters. Therefore, the development and modification of control and modulation schemes for inverters of variable speed drives [6, 7], and for ac voltage stabilizers and regulators [8] has been executed. Also, modified algorithms of synchronous space-vector-based PWM have been applied for adjustment of two-inverter-based topologies of transformer-based photovoltaic systems [9, 10], assuring continuous synchronization and symmetry of the winding voltage at inverter-side windings of power transformer.

In this regard, the purpose of this work is in dissemination of the phase-shifted control scheme and modified algorithms of synchronous PWM for regulation of triple inverters of new structure of PV system, and also in comparative analysis of effectiveness of application of three basic versions of synchronous PWM for inverters of this system topology.

Topology of three-inverter-

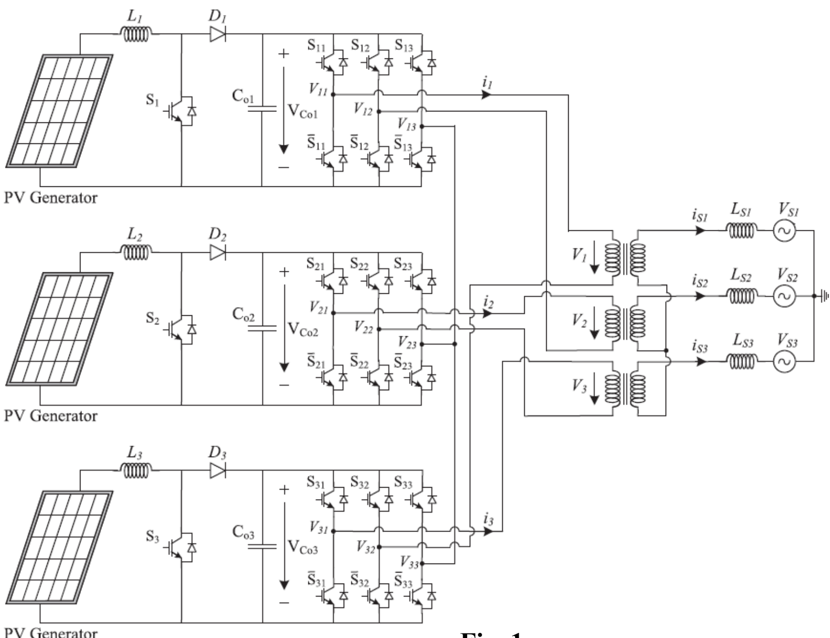

Fig. 1

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based PV system. Recently, three-inverter-based photovoltaic installation with specific interconnection between outputs of modulated inverters and windings of power transformer has been described (Fig. 1 [5]).

Therefore, this topology of PV system assures the increase of the maximum voltage applied to the multi-winding transformer (in comparison with two-inverter-based PV systems), reducing its weight and volume [5].

Basic control functions of PV system with three modulated inverters. Based on the developed schemes and techniques of synchronous space-vector PWM [9, 10], and features of the presented in Fig. 1 photovoltaic installation [5], Table presents set of the corresponding control functions for the presented topology of PV system assuring synchronous and symmetrical adjustment of winding voltage of multi-winding power transformer during entire control diapason of PV installation. In this Table F is operation frequency of the electrical grid (usually $F = 50\ Hz$ with some small fluctuations), m is index of modulation of inverters, V_{11}, V_{12}, V_{13}, V_{21}, V_{22}, V_{23}, V_{31}, V_{32}, and V_{33} are the pole voltages of three inverters. Fig. 2 shows (within a 60-degree clock interval) switching state sequence (control pulses) of a three-phase inverter, as well as the curves of the polar (V_a, V_b) and line (V_{ab}) voltages of inverter adjusted by algorithms of continuous synchronous PWM [9].

Switching frequency F_s Switching sub-cycle τ	Parameters of control signals and of the output voltage of inverters (Fig. 2)	Instantaneous values of winding voltages V_1, V_2, and V_3 of system
$F_{s(PWMC)} = F(6n-3)$ $\tau_{PWMC} = 1/2F_s = 1/[6F(2n-1)]$ $F_{s(PWMD)} = F(8n-5)$ $\tau_{PWMD} = 1/[6F(2n-1.5)]$ where $n=2,3,4\ldots$	$\beta_1 = 1.1m\tau$ $\beta_j = \beta_1 \cos[(j-1)\tau]$ $\gamma_j = \beta_{n-j+1}\{0.8 - 0.5\tan[(n-j)\tau]\}$ $\lambda_j = \tau - (\beta_j + \beta_{j+1})/2$	$V_1 = V_{11} - V_{13} - V_{32} + V_{33}$ $V_2 = V_{21} - V_{23} - V_{12} + V_{13}$ $V_3 = V_{31} - V_{33} - V_{22} + V_{23}$

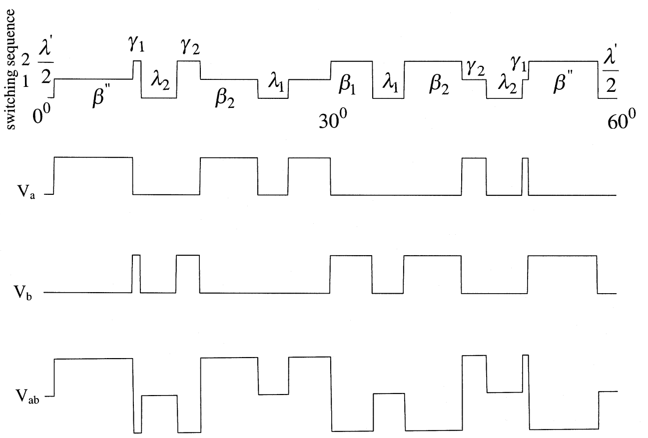


Fig. 2

Operation of PV installation with three voltage source inverters. In accordance with the used control and modulation strategy, control signals of three two-level inverters are shifted by 120^0, and additional mutual phase shift between control pulse signals of three inverters is equal to 1/3 of the width of switching sub-cycle.

Fig. 3 – Fig. 8 present results of MATLAB-simulation of PV installation controlled by algorithms of synchronous space-vector PWM, and show, in the relative scale, pole voltages V_{11}, V_{12} and V_{13} of the first inverter, line voltages of the first and the second inverters ($V_{12} - V_{13}$) and ($V_{21} - V_{23}$), and winding voltage V_2 of multi-winding power transformer. It presents also spectral composition of the line ($V_{21} - V_{23}$) voltage, and of the winding voltage V_2. The fundamental frequency of the output voltage of inverters is equal to $F = 50\ Hz$, and the averaged switching frequency of inverters is equal to $F_s = 1120\ Hz$ in these cases.

Fig. 3 shows basic voltage waveforms and spectra of the line and winding voltages of PV system with inverters controlled by the scheme of continuous synchronous PWM (CPWM), coefficient of modulation of inverters is equal to $m = 0.6$. Fig. 4 presents the corresponding diagrams for PV system with inverters controlled by algorithms of discontinuous modulation with the 30-degrees non-switching intervals (DPWM30). Fig. 5 shows the corresponding diagrams for PV installation with three inverters regulated by techniques of discontinuous PWM with the 60-degrees non-switching intervals (DPWM60).

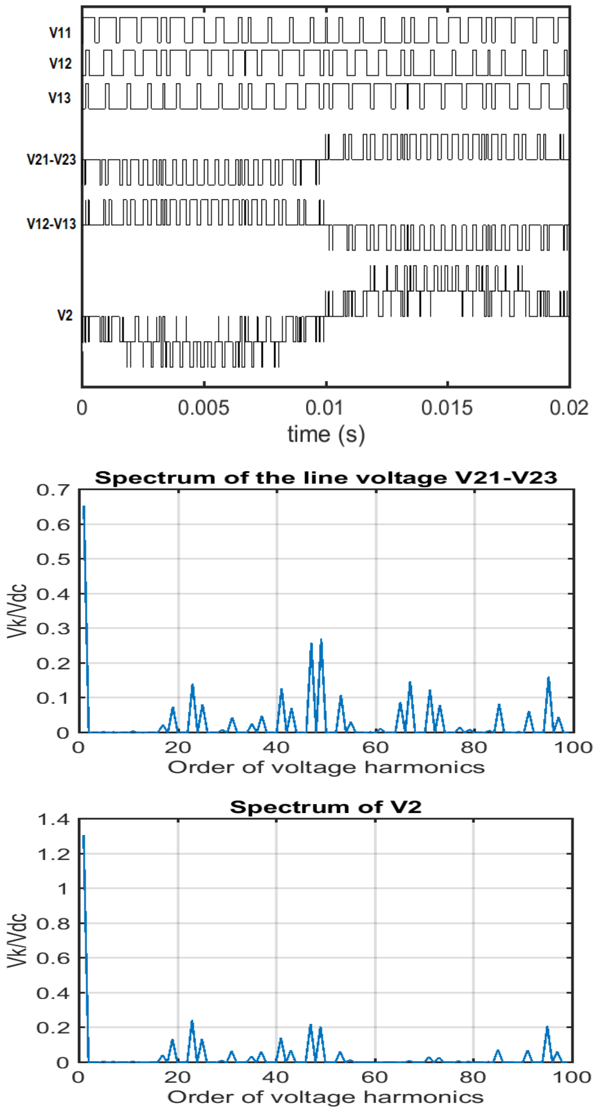


Fig. 3

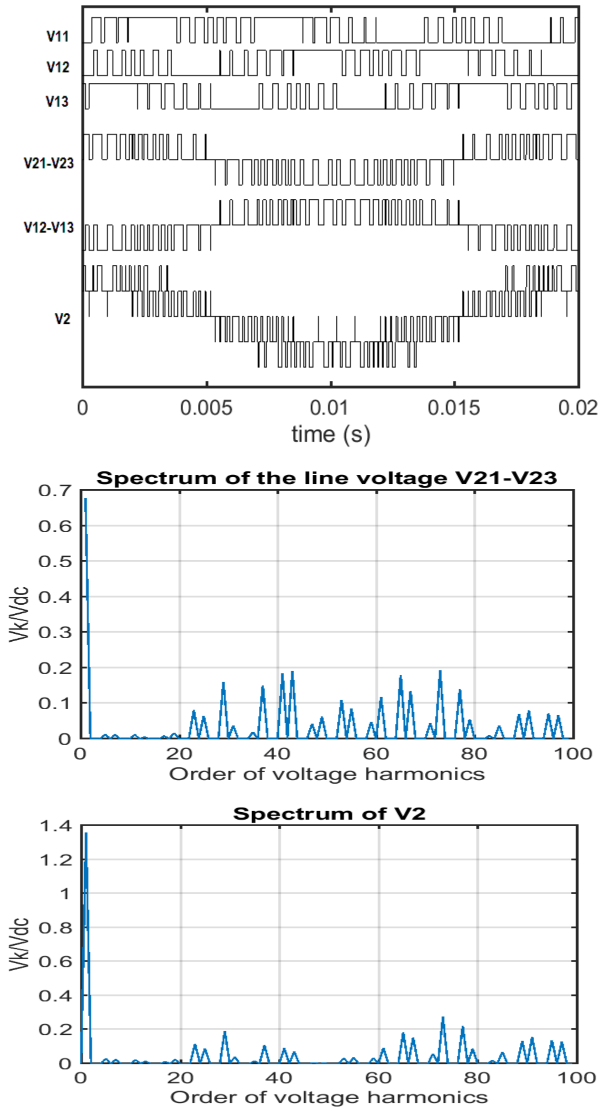


Fig. 4

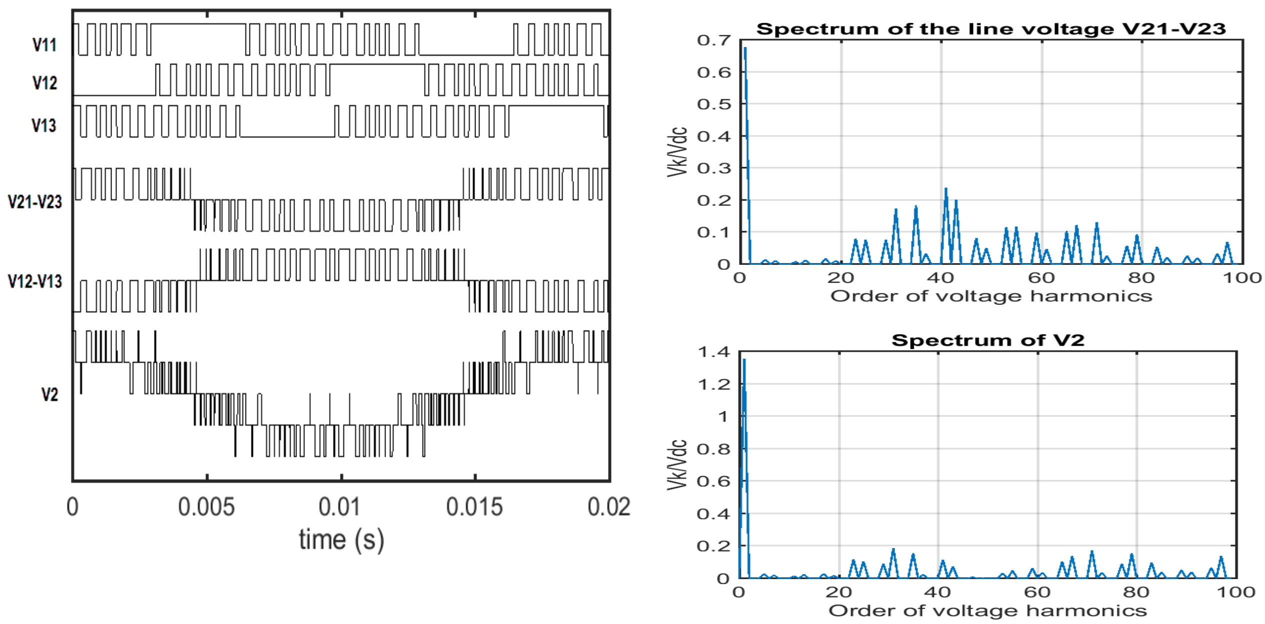


Fig. 5

Fig. 6 – Fig. 8 present the corresponding diagrams for PV system with triple inverters operating in the overmodulation control zone (Fig. 6 – CPWM control of inverters, Fig. 7 – DPWM30 control of inverters, Fig. 8 – DPWM60 control of inverters), index of modulation of inverters is equal to $m=0.95$ in this case.

The presented simulation results show, that basic voltage waveforms of PV system have quarter-wave symmetry and are characterized by the lacking in its spectra of even harmonics and sub-harmonics.

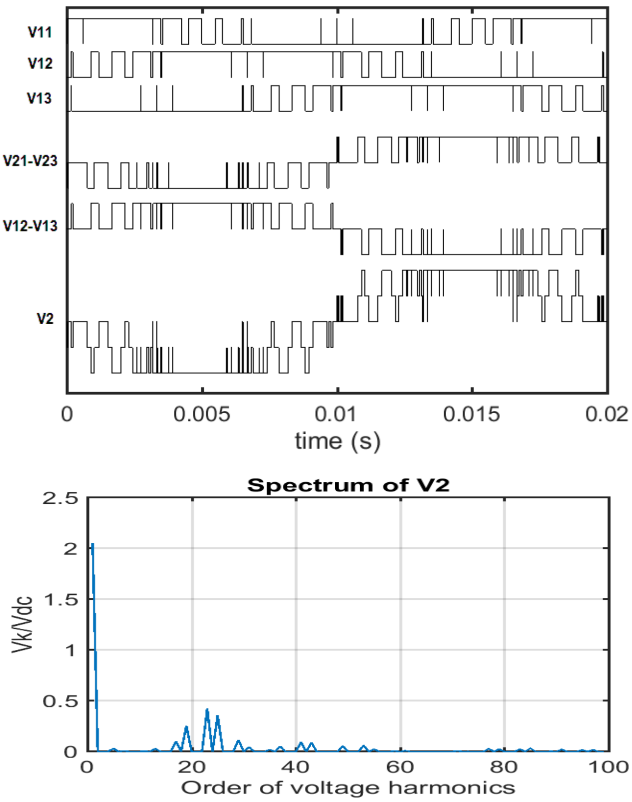


Fig. 6

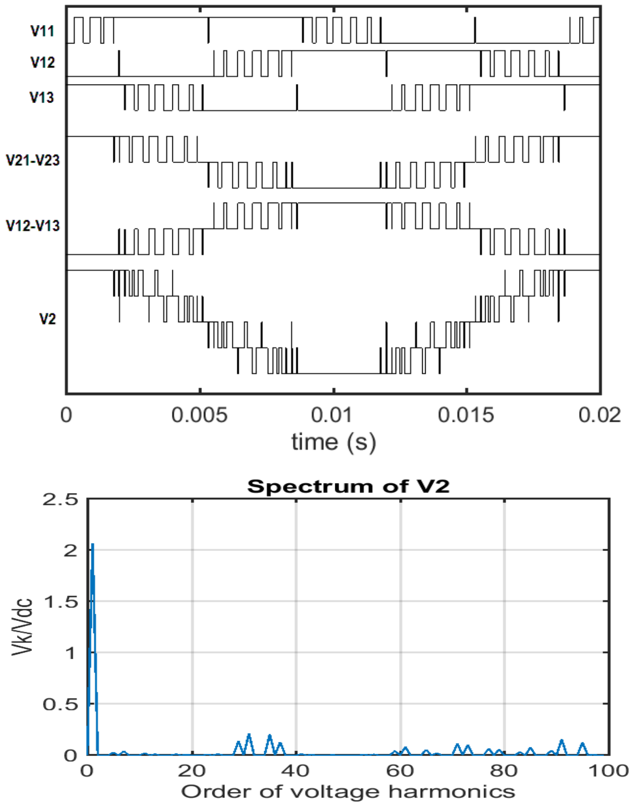


Fig. 7

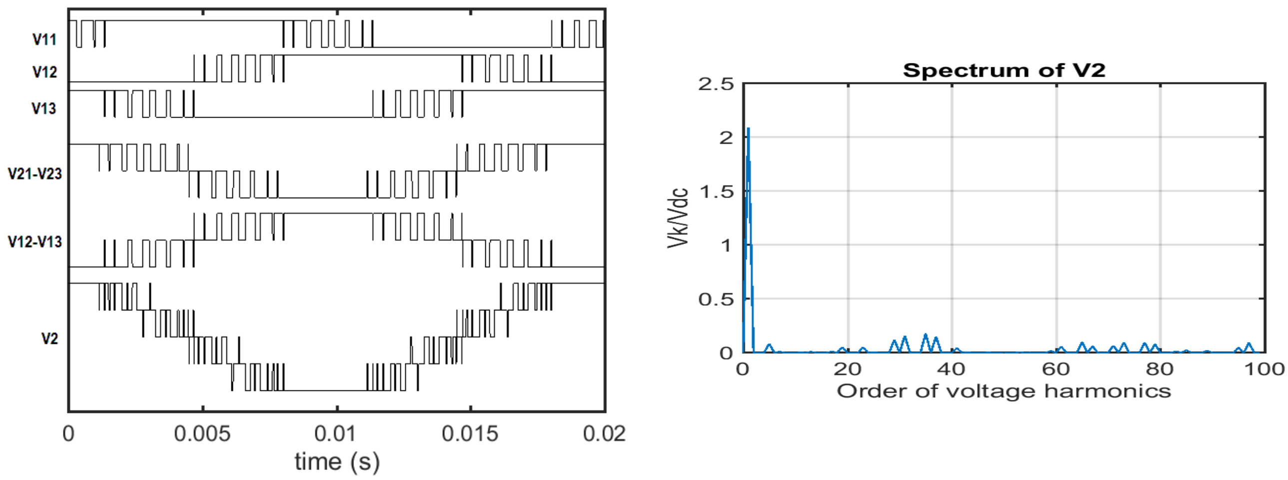
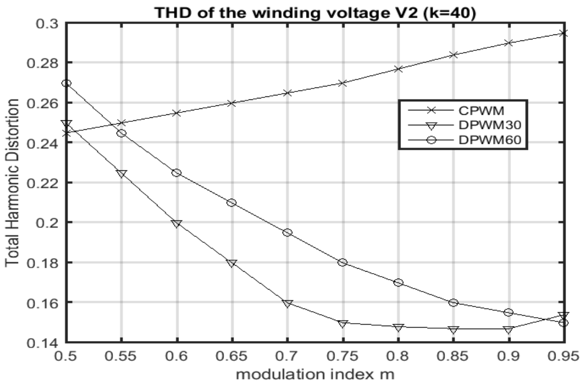


Fig. 8

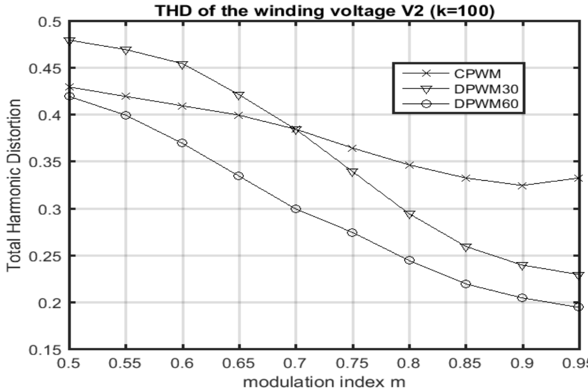
Total Harmonic Distortion factor of the winding voltage of transformer-based PV system. Total Harmonic Distortion (*THD*) factor is an important parameter for analysis and comparison of integral spectral composition of the winding voltage V_2 of the analyzed PV system with average switching frequency of inverters equal to *1120 Hz*, determined (and presented in Fig. 9, *a, b*) in this case for two values of the maximum number of calculated harmonics (*k*-th harmonics) – $k=40$ (Fig. 9, *a*), and $k=100$ (Fig. 9, *b*):

$$THD = (1/V_{2_1})\sqrt{\sum_{k=2}^{40} V_{2_k}^2} \quad \text{(Fig. 9, } a\text{);} \qquad THD = (1/V_{2_1})\sqrt{\sum_{k=2}^{100} V_{2_k}^2} \quad \text{(Fig. 9, } b\text{).}$$

The presented diagrams show a big dependence of the value of the *THD* factor on number of voltage harmonics, taking into account during determining *THD*. But for the both cases of determining of the *THD* factor, presented in Fig. 9,*a* (*k=40*) and in Fig. 9,*b* (*k=100*), better values of *THD* factor can be provided by the using of algorithms of discontinuous PWM (DPWM30 and DPWM60) for control of triple inverters of PV installation. In any case, the use of algorithms of synchronous space-vector PWM insure improved harmonic composition of winding voltage, providing the corresponding reduction of power losses of power transformer of this structure of PV apparatuses.



a



b

Fig. 9

Conclusion. Schemes, techniques, and algorithms of symmetrical space-vector-based PWM can be disseminated successfully for regulation of three two-level inverters of transformer-based grid-tied PV system with specific connection of windings of power transformer with outputs of triple inverters, insuring symmetry of the line-to-line and winding voltages for any control modes of PV installation, including its adjustment during overmodulation control zone.

The presented in Figs. 3 - 8 spectral composition of the line-to-line and winding voltages of PV system with three PWM inverters, adjusted by algorithms of synchronous space-vector-based modulation, underlines the fact of lacking of even-order harmonics and sub-harmonics (of the fundamental frequency) in spectra of the winding voltage of power transformer of PV system.

Improved spectral composition of the winding voltage of the analyzed configuration of PV installation assures to decrease copper losses in the inverter-side windings of multi-winding power transformer.

1. Grandi G., Rossi C., Ostojic D., Casadei D. A new multilevel conversion structure for grid-connected PV applications. *IEEE Trans. Ind. Electron.* 2009. Vol. 56. No 11. Pp. 4416-4426. DOI: https://doi.org/10.1109/TIE.2009.2029587.

2. Shavelkin A., Shvedchykova I. Multifunctional converter for single-phase combined power supply systems for local objects with a photovoltaic solar battery. *Tekhnichna Electrodynamika*. 2018. No 5. Pp. 92-95. DOI: https://doi.org/10.15407/techned2018.05.092.

3. Kolantla D., Mikkili S., Pendem S.R., Desai A.A. Critical review on various inverter topologies for PV system architectures. *IET Renewable Power Generation*. 2020. Vol. 14. Issue 17. Pp. 3418-3438. DOI: https://doi.org/10.1049/iet-rpg.2020.0317.

4. Shavelkin A.A. Improvement of the structure for the current control loop with the use of PWM for the grid inverter of the combined power supply system. *Tekhnichna Electrodynamika*. 2019. No 3. Pp. 37-45. DOI: https://doi.org/10.15407/techned2019.03.037. (Ukr)

5. Pires V.F., Cordeiro A., Foito D., Silva J.F. Three-phase multilevel inverter for grid-connected distributed photovoltaic systems based in three three-phase two-level inverters. *Solar Energy*. 2018. Vol. 174. Pp. 1026-1034. DOI: https://doi.org/10.1016/j.solener.2018.09.083.

6. Oleschuk V., Blaabjerg F. Synchronized scheme of continuous space-vector PWM with the real-time control algorithms. *IEEE Int'l Power Electronics Specialists* Conference (PESC'2004). Aachen, Germany, June 20-25, 2004. Pp. 1207-1213. DOI: https://doi.org/10.1109/PESC.2004.1355594.

7. Mikhalsky V.M., Sobolev V.M., Chopyk V.V., Shapoval I.A. Definition of harmonic content and quality factors of voltage-source inverter output voltage with application of discontinuous modulation functions for the PWM. *Tekhnichna Electrodynamika*. 2010. No 2. Pp. 41-51. (Ukr)

8. Lypkivsky K.O., Khalikov V.A., Mozharovsky A.H. Analysis of AC voltage parameters conversion in electrotechnical and electrotechnological systems. *Tekhnichna Electrodynamika*. 2010. No 1. Pp. 30-41. (Ukr)

9. Oleschuk V., Ermuratskii V. Dual inverters with synchronized modulation for transformer-based photovoltaic installations. Chapter of the book *Renewable Energy. Selected Issues*. Vol. 2. Cambridge Scholar Publishing, 2016. Pp. 192-205.

10. Oleschuk V., Ermuratskii V. Two-inverter-based photovoltaic system adjusted by the modified scheme of space-vector modulation. *Tekhnichna Elektrodynamika*. 2020. No 5. Pp. 26-30. DOI: https://doi.org/10.15407/techned2020.05.026.

УДК 621.314.572

ПОВ'ЯЗАНА З МЕРЕЖЕЮ ФОТОПЕРЕТВОРЮВАЛЬНА СИСТЕМА З ТРЬОМА ІНВЕРТОРАМИ, ЩО РЕГУЛЮЮТЬСЯ НА БАЗІ СХЕМИ СИНХРОННОЇ ШИМ

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Представлено порівняльний аналіз трьох варіантів модифікованої схеми просторово векторної синхронної широтно-імпульсної модуляції (ШІМ), що застосовується задля керування трьома дворівневими інверторами трансформаторної фотоелектричної (ФЕ) системи та орієнтованій на забезпечення симетричності напруги обмотки силового трансформатора в усьому діапазоні регулювання. Живлення інверторів забезпечується відповідними трьома сонячними ланцюгами, що складаються з комплекту фотоелектричних панелей, а виходи інверторів з'єднані спеціально з обмотками з боку інвертора багатообмоткового мережевого трансформатора. Результати MATLAB-моделювання доводять факт розширеного спектрального складу напруги обмотки триінверторної фотоелектричної установки, що регулюється алгоритмами синхронного просторово-векторного ШІМ, що забезпечує потенційне зниження втрат у цих системах. Бібл. 10, рис. 9, табл. 1.
Ключові слова: інвертор джерела напруги, фотоелектрична установка, стратегія управління та модуляції, спектр напруги.

Надійшла 01.06.2022
Остаточний варіант 22.06.22