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FLEXIBLE SYNCHRONOUS REGULATION OF POWER ELECTRONIC BLOCKS OF TRANSFORMER-BASED PHOTOVOLTAIC STATIONS

Valentin Oleschuk *, ORCID: 0000-0002-7413-4867

Institute of Power Engineering of Technical University of Moldova, 5 Academy Str., Chisinau, Republic of Moldova
* Corresponding author: Valentin Oleschuk, *oleschukv@hotmail.com*

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Abstract. The paper presents the results of developing a scheme for synchronous pulse-width modulation (PWM) of signals in dual voltage source diode-clamped inverters (VSDCIs) used in grid-tied, transformer-based photovoltaic (PV) stations. This scheme is based on the continuous regulation of the switching frequency of the inverters relative to the magnitude of the DC voltages of the PV strings, ensuring equivalence of switching losses across each inverter. The proposed control and PWM techniques ensure the elimination of even-order harmonics and subharmonics in spectra of voltage at inverter-side windings of power transformer, helping to increase the operating efficiency of inverter-based PV stations. Simulation results showed a behavior of operation of dual-VSDCI-based PV installations with the proposed control strategy.

Keywords: *control and modulation strategy, photovoltaic station, spectral analysis, switching frequency, voltage source diode-clamped inverter, voltage synchronization.*

Abstract. Lucrarea prezintă rezultatele dezvoltării schemei de modulație sincronă a lățimii de impulsuri (PWM) a semnalelor duale invertoarelor de tensiune cu diode clampate (VSDCIs) ale stațiilor fotovoltaice (PV) bazate pe transformator obosit de rețea, bazată pe reglarea continuă a frecvenței de comutare a invertoarelor față de mărimea tensiunilor continue ale șirurilor fotovoltaice în condiția echivalenței pierderilor de comutare în fiecare invertor. Tehnicile de control și PWM propuse asigură eliminarea armonicilor de ordin egal și subarmonicilor în spectrele de tensiune la înfășurările de pe partea invertorului ale transformatorului de putere, ajutând la creșterea eficienței de funcționare a stațiilor fotovoltaice bazate pe invertori. Rezultatele simulării au arătat un comportament de funcționare a instalațiilor fotovoltaice bazate pe VSDCI dual cu strategia de control propusă.

Cuvinte cheie: *strategie de control și modulație, stație fotovoltaică, analiză spectrală, frecvență de comutare, invertor de tensiune cu diodă clampate, sincronizare de tensiune.*

1. Introduction

Photovoltaic stations are very popular installations in the area of renewable electrical energy [1-4], including large grid-tied photovoltaic power plants, integrated into the medium-voltage and high-voltage power supply systems [3].

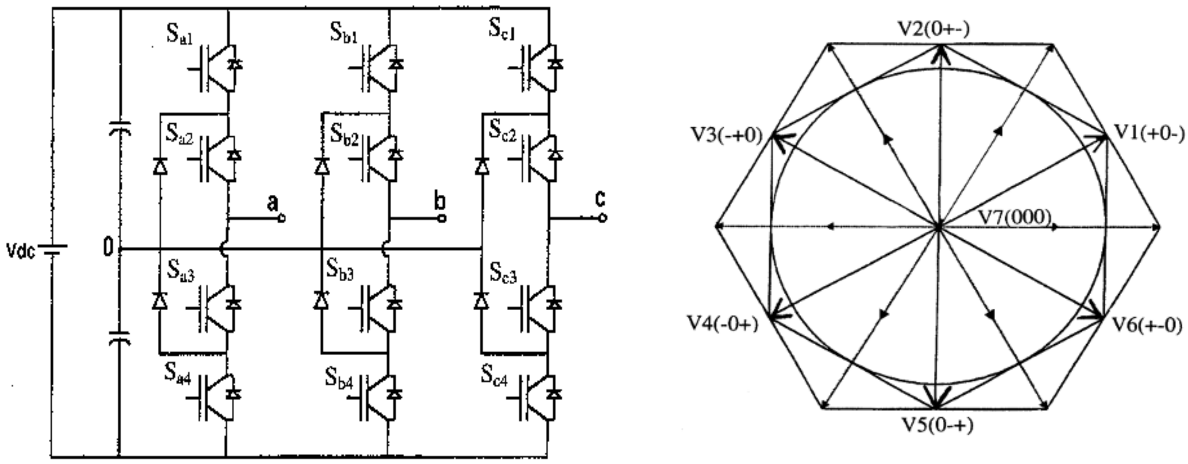
Voltage source inverters of various topologies are the main work-horses of photovoltaic (PV) systems, providing controlled conversion of dc voltage from PV strings into the required ac voltage for electrical energy consumers [5−11], including multilevel inverters [5,9], modular topologies of inverters [6], two-level inverters [7], three-level inverters [8], and multiphase inverters [10,11]. Also, powerful PV systems based on cascaded inverters should be mentioned [12-16], including standard cascaded inverters [12,13], and multilevel cascaded inverters [14−16].

Thus, the performance of PV stations depends on the pulsewidth modulation (PWM) strategies used to regulate the inverters. To ensure synchronization and symmetry of voltage waveforms of PV inverters at increased power levels, original schemes of synchronous modulation have been developed for control of inverters of some structures of PV systems [17-23], based on dual diode-clamped inverters [17,19,23], based on two standard three-phase inverters specifically connected to windings of the power transformer [18], and based on triple modulated inverters [20−22].

Accordingly, this paper provides the results of research of topology of PV installation based on two voltage source diode-clamped inverters (VSDCIs) adjusted by the modified control strategy based on flexible regulation of switching frequency (SwF) of VSDCIs in function of value of dc voltage of PV strings.

2. Structure and basic control and modulation schemes of VSDCI

Fig. 1,a shows topology of VSDCI. Fig. 1b presents the base voltage space vectors **V 1 ÷ V 7** (marked by big arrows) of each VSDCI [17,23], and this control scheme assures elimination of common-mode voltage in PV systems on the base of VSDCI [17, 19, 20, 23]. Figs. 2 – 3 present switching state sequence and the base voltages of VSDCI adjusted by continuous (CPWM) and discontinuous (DPWM) synchronous PWM, Figures 2 and 3 [23].



a) b)

Figure 1. Topology of VSDCI (a), and its voltage space vectors (b) [17].

Basic set of control functions for determination of pulse patterns of VSDCIs for PV generation includes four formulas (1) – (4), where *m* is coefficient of PWM of VSDCI, and τ is duration of sub-interval which is in dependence of the SwF of VSDCI [17,23]. Figure 4 demonstrates switching sequence of VSDCI inside the 60° clock interval, and the corresponding pole V_a, V_b, and line V_{ab} voltages of VSDCI controlled by the scheme of CPWM [17].

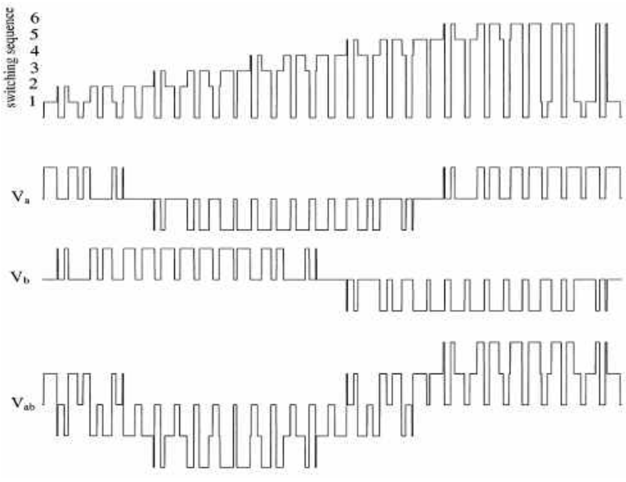


Figure 2. Switching state sequence and the base voltages of VSDCI adjusted by the scheme of synchronous space-vector CPWM [23].

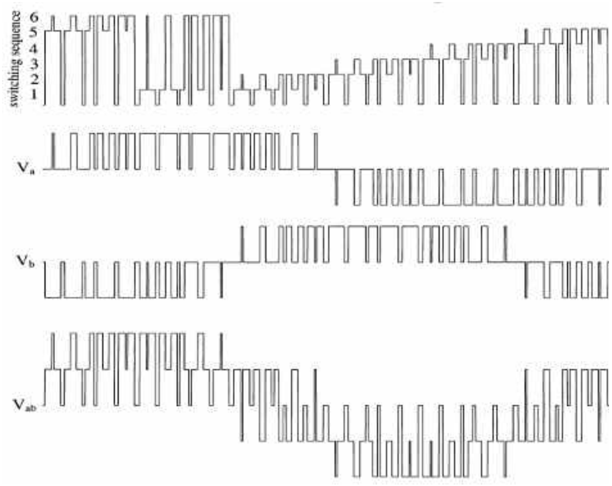


Figure 3. Switching state sequence and the base voltages of VSDCI adjusted by the sche-me of synchronous space-vector DPWM [23].

$$\beta_1 = 1.1m\tau \tag{1}$$

$$\beta_j = \beta_1 \cos[(j-1)\tau] \tag{2}$$

$$\gamma_j = \beta_{n-j+1}\{0.75 - 0.55\tan[(n-j)\tau]\} \tag{3}$$

$$\lambda_j = \tau - (\beta_j + \beta_{j+1})/2 \tag{4}$$

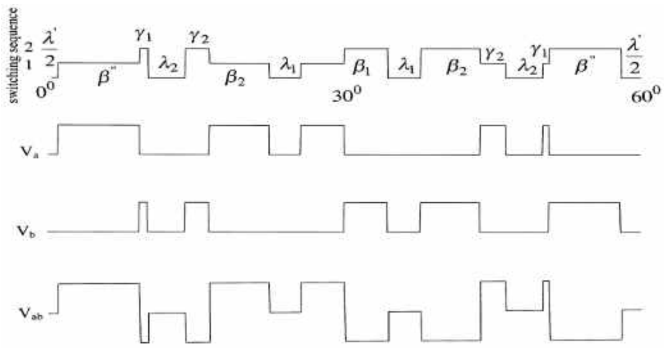


Figure 4. Contol pulses sequence and the base voltages of VSDCI regulated by algorithms of synchronous continuous PWM [17].

3. Grid-tied PV installation with dual VSDCIs

Figure 5 shows the structure of grid-tied PV system with two modulated VSDCIs supplied by dc voltages of two strings of PV panels [23]. The outputs of VSDCIs are tied with the inverter-side windings of the power transformer.

To provide rational operation of inverter-based PV systems, operating modulation index m of two VSDCIs should be controlled in accordance with formula connecting the highest value of dc-voltage $V_{dc\text{-}highest}$, minimum value of modulation index m_{min}, corresponding to this regime, and operating magnitude of dc voltage $V_{dc\text{-}lower}$:

$$m = (m_{min}\ V_{dc\text{-}highest})/V_{dc\text{-}lower} \tag{5}$$

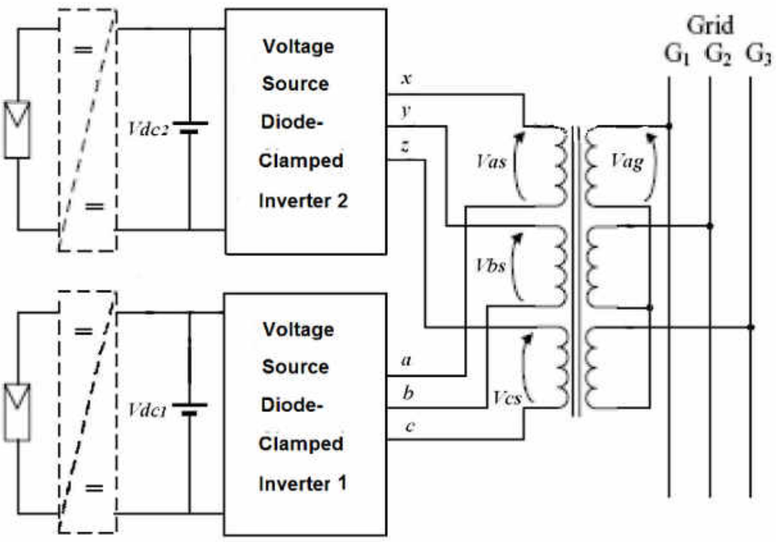
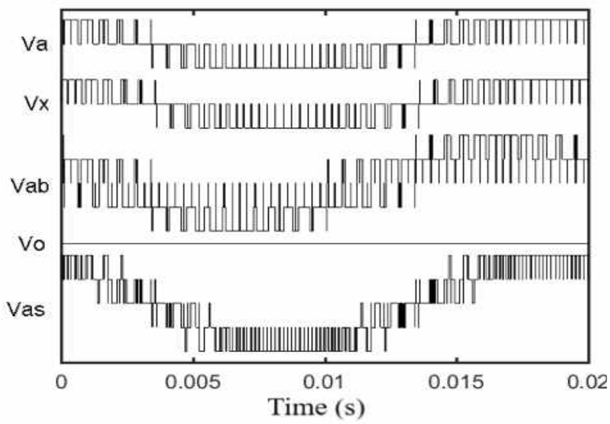


Figure 5. Structure of PV station with two modulated VSDCIs.

At the same time, to increase the operating efficiency of photovoltaic stations, it is advisable to smoothly regulate the SwF of each modulated VSDCI depending on the voltage magnitude of dc sources (provided that the switching losses of the two inverters are equal approximately). In particular, if PV station is supplied by the higher (highest) dc voltage $V_{dc\text{-}highest}$, the VSDCIs should be operated at lower SwF (at the rated SwF F_{s0} of VSDCIs), and if VSDCIs are supplied by the lower dc-voltage $V_{dc\text{-}lower}$, theirs SwF F_s can be increased correspondingly.

Figures 6 – 11 present the base voltages (pole voltages V_a, V_x, line voltage V_{ab}, common-mode voltage V_0, and winding voltage V_{as} (with its spectrum) of PV station with two VSDCIs (Figure 5), regulated by algorithms of continuous (CPWM) and discontinuous (DPWM) synch-ronous PWM. The fundamental frequency of grid-tied PV station is $F = 50.0\ Hz$. Diagrams in Figures 6 - 7 correspond to a case of relatively low dc voltage of PV panels, diagrams in Figures 8 – 9 correspond to a case of medium value of dc voltage of PV strings, and diagrams in Figures 10 – 11 correspond to a case of relatively high dc voltage. So, SwF of VSDCIs has been chosen for these cases in accordance with the mentioned above conditions of flexible regulation of system.



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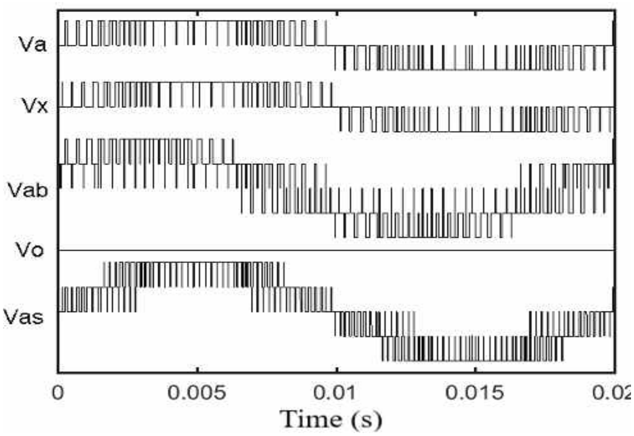

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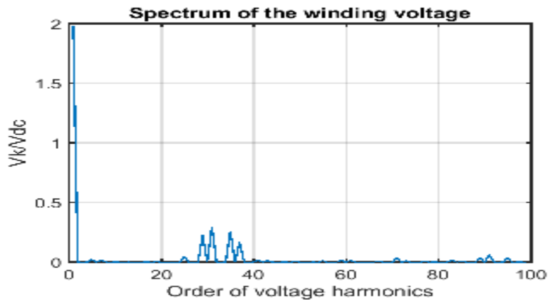
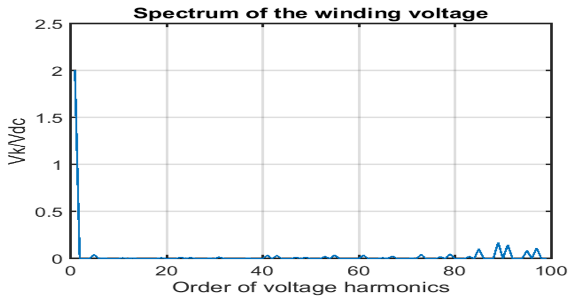


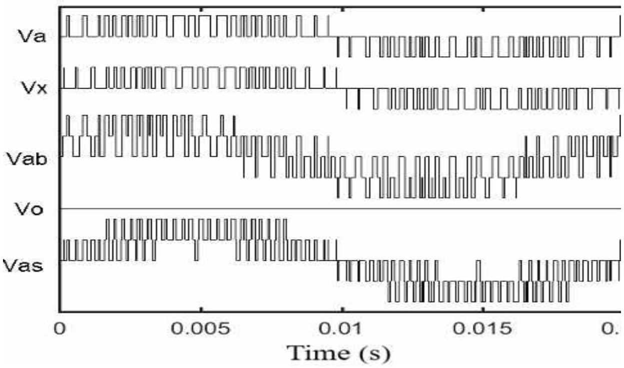
b)

Figure 6. Waveforms of the base voltages (a), and spectrum of the winding voltage (b) in PV system with relatively low dc voltage (CPWM, *m = 0.9*, F_s *= 1.6 kHz*).



b)

Figure 7. Waveforms of the base voltages (a), and spectrum of the winding voltage (b) in PV system with relatively low dc voltage (DPWM, *m = 0.9*, F_s *= 1.6 kHz*).



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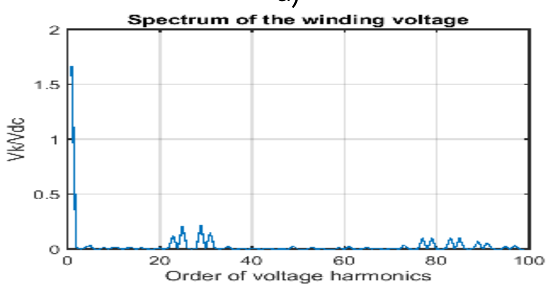
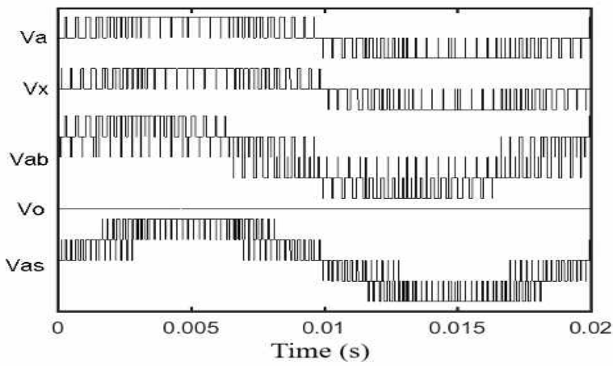


b)

Figure 8. Voltage waveforms (a), and spectrum of the winding voltage (b) in PV installation with medium dc voltage of PV strings (CPWM, *m = 0.75,* F_s *= 1.35 kHz*).



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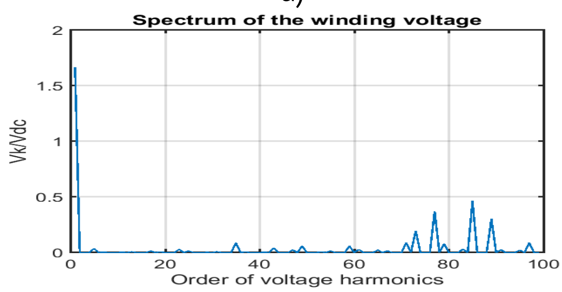
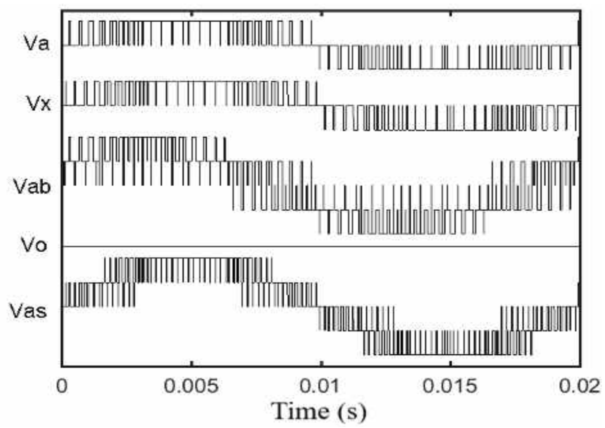


b)

Figure 9. Voltage waveforms (a), and spectrum of the winding voltage (b) in PV installation with medium dc voltage of PV strings (DPWM, *m = 0.75,* F_s *= 1.35 kHz*).



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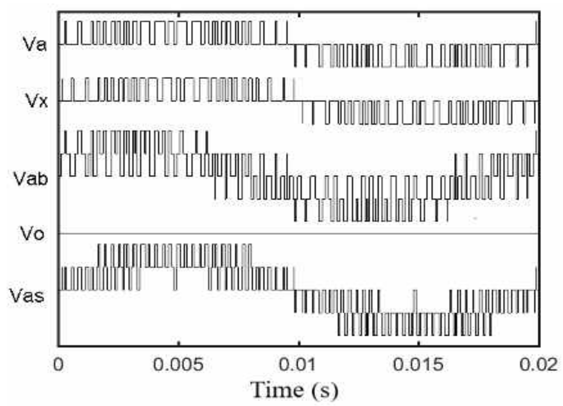

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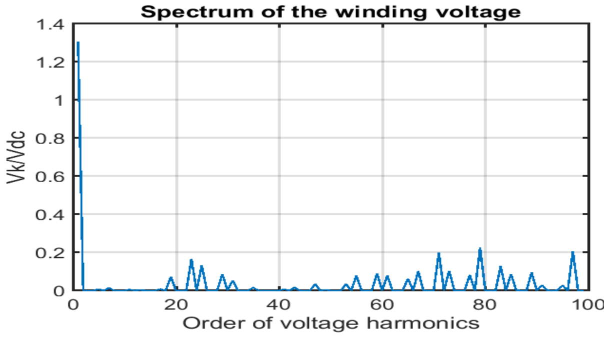
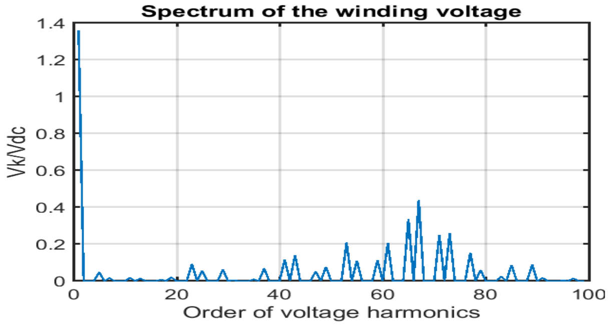


b)

Figure 10. Waveforms of the base voltages (a), and spectrum of the winding voltage (b) in PV installation with relatively high dc voltage of PV strings (CPWM, *m = 0.6,* F_s = *1.1 kHz*).



b)

Figure 11. Waveforms of the base voltages (a), and spectrum of the winding voltage (b) in PV installation with relatively high dc voltage of PV strings (DPWM, *m = 0.6,* F_s = *1.1 kHz*).

The presented in Figures 6 - 11 results of modeling and simulation of system with two VSDCIs show that the winding voltage V_{as} has quarter-wave symmetry, and in its spectrum there are no even harmonics and subharmonics in the analyzed regimes of regulation of grid-tied PV installation.

Also, it is necessary to mention about specific two-stage control mode of operation of modulated VSDCIs in the zone of the highest modulation indices *m* of inverters (in the zone of overmodulation), if *m > 0.907* [19]. Thus, boundary values of two indices of PWM of VSDCIs for standard two-stage regulation of inverters during overmodulation are equal to $m_{ov1} = 0.907$ and $m_{ov2} = 0.952$ ([19], $m_{\max} = 1$ in this case). In particular, basic PWM functions of VSDCIs for determination of duration of pulse control signals (1) – (4) include two special correcting indices of overmodulation $K_{ov1} = [1-(m-m_{ov1})/(m_{ov2}-m_{ov1})]$ and $K_{ov2} = [1-(m-m_{ov2})/(1-m_{ov2})]$ [19].

Therefore, regimes of overmodulation of VSDCIs during flexible regulation of PV system correspond, in accordance with (5), to the case of relatively low dc voltage of PV panels of VSDCI-based photovoltaic station. As an example of operation of VSDCIs in the zone of overmodulation, Figures 12 – 13 show pole voltages V_a, V_x, line voltage V_{ab}, common-mode voltage V_0, and winding voltage V_{as} (with its spectrum) of PV station with dual VSDCIs (Figure 5), regulated by algorithms of continuous (CPWM, Figure 12) and discontinuous (DPWM, Figure 13) synchronous PWM. Modulation index of VSDCIs is equal to *m = 0.945*, SwF of inverters is equal to *1.7 kHz*, and it corresponds to operation of inverters in the first part of the overmodulation zone. The fundamental frequency of grid-tied PV system is *F = 50 Hz*. The presented in Figures 12 – 13 diagrams prove the fact of quarter-wave symmetry of the base voltages in this control zone.

Figure 14 shows the results of calculating the Total Harmonic Distortion factor of the winding voltage V_{as} ($THD = (1/V_{as_1})(\sum_{k=2}^{100}(V_{as_k}/k)^2)^{0.5}$) as a function of modulation index *m* of dual VSDCIs, calculated for three values of SwF of VSDCIs chosen in accordance with the mentioned above strategy of flexible control of the SwF of VSDCIs.

The data presented in Figure 14 show that for the presented topology of PV station regulation of dual VSDCIs by flexible algorithms of discontinuous synchronous PWM (DPWM) assure providing better value of THD factor at medium and higher coefficients of modulation of two VSDCIs. In particular, for the analyzed cases, THD factor is better by the using of DPWM for control of VSDCIs, if $m > 0.45$ (case of relatively low dc voltage and relatively high SwF), if $m > 0.5$ (case of the medium magnitudes of dc voltage and medium SwF of VSDCIs), and if $m > 0.55$ (case of relatively high dc voltage and relatively low SwF).

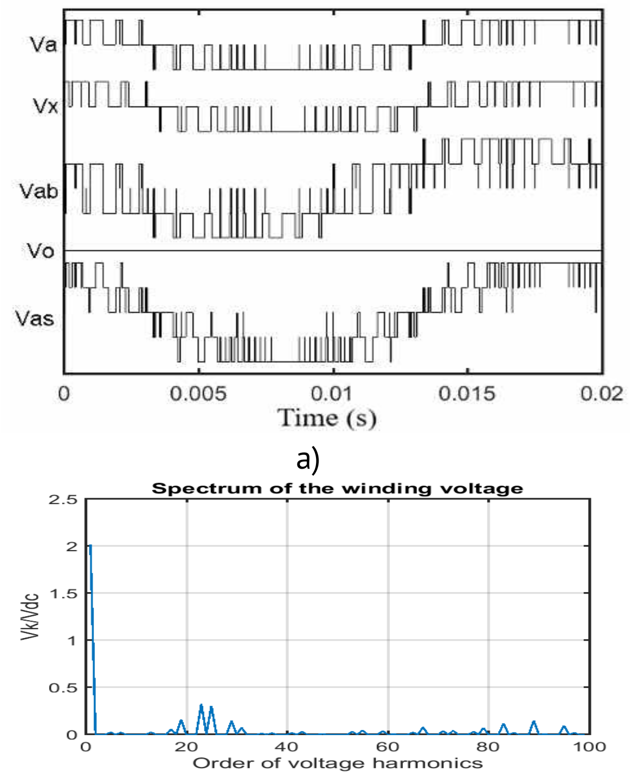


Figure 12. Waveforms of the base voltages (a), and spectrum of the winding voltage (b) in PV system with relatively low dc voltage and overmodulation control zone of VSDCIs (CPWM, $m = 0.945$, $F_s = 1.7\ kHz$).

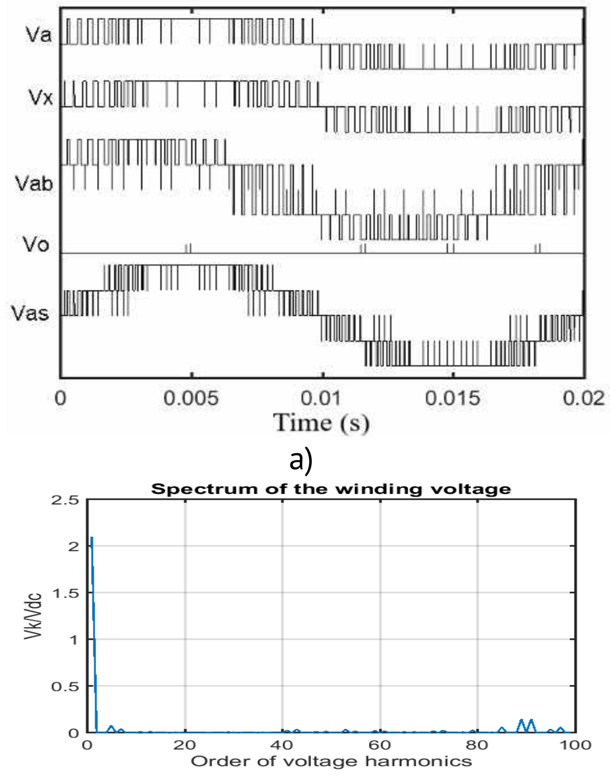


Figure 13. Waveforms of the base voltages (a), and spectrum of the winding voltage (b) in PV system with relatively low dc voltage and overmodulation control zone of VSDCIs (DPWM, $m = 0.945$, $F_s = 1.7\ kHz$).

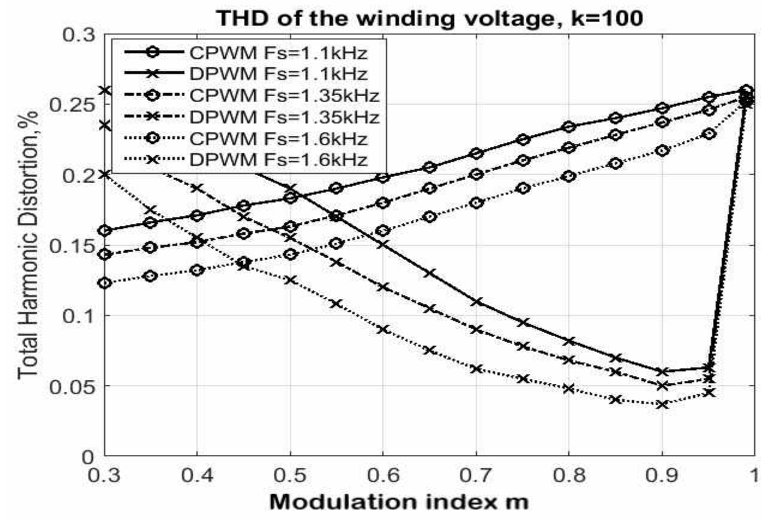


Figure 14. *THD* factor of the winding voltage of power transformer of grid-tied PV station as function of coefficient (index) of modulation *m* of dual VSDCIs for different values of its SwF.

4. Conclusion

The developed strategy of control and synchronous PWM of two VSDCIs of grid-tied PV stations, based on continuous regulation of SwF of VSDCIs in function of current magnitude of dc voltage of PV strings under condition of equivalence of switching losses in each inverter, assures providing an improvement of harmonic composition of the winding voltage of the multi-winding power transformer, thereby helping to reduce losses and to increase the efficiency of operation of PV stations. Simulation results show, that discontinuous scheme of synchronous PWM, applied for regulation of dual VSDCIs, insures a better spectral composition of the winding voltage compared to the using of continuous scheme of synchronous pulsewidth modulation, if modulation index of VSDCIs for the corresponding control regimes has medium and upper medium values.

Conflicts of Interest: The authors declare no conflict of interest.

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Submission of manuscripts: jes@meridian.utm.md