Synchronous PWM Control of Triple Transformer-Connected Inverters for Photovoltaic System

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***Abstract*-This paper presents results of research of modulation processes in power conversion system with triple voltage source inverters, supplied by photovoltaic (PV) strings, and connected to a four-winding transformer. The transformer has in this case specific connections between the secondary windings and inverters, allowing providing of multilevel voltages at secondary windings of the transformer. Specialized space-vector-based strategy of pulsewidth modulation (PWM) has been used for control of inverters, insuring quarter-wave symmetry of winding voltages for any modulation indices and switching frequency of inverters. Analysis and comparison of harmonic composition of winding voltages and output voltages of inverters has been done. The validity of the analyzed processes has been verified by simulations: three basic variants of the scheme of modulation have been applied for control of inverters.**

I. INTRODUCTION

Development of photovoltaic-focused power conversion systems is growing rapidly. Novel transformer-less and transformer-based topologies and configurations of solar photovoltaic installations for solar farms and solar factories have been proposed and investigated [1]-[4].

Recently, modified structure of transformer-based system with triple three-phase voltage source inverters has been proposed [5],[6]. Fig. 1 shows topology of this system for the case of delta-connection of secondary windings, supplied by three insulated strings of photovoltaic panels. Fig. 2 presents the corresponding secondary windings for the case of star-connection [6]. It has been shown in [6], that simple modification of connection between outputs of standard two-level inverters and windings of the transformer allow providing multilevel winding voltages for systems with insulated dc-sources. Also, winding voltages can be expressed in this case by the phase voltages of triple inverters.

Operation of inverter-based photovoltaic systems is in dependence of the used methods and techniques of PWM. Space-vector modulation is perspective method for control of inverters, including PV application. During system operation, for some regimes of photovoltaic systems (grid frequency fluctuation, different voltages of strings of PV panels, etc.) it is necessary to ensure voltage synchronization. So, this paper presents results of research of modulation processes in PV system with triple transformer-connected inverters, controlled by specialized schemes and techniques of space-vector PWM, insuring voltage synchronization and voltage symmetries for any operating conditions of the system.

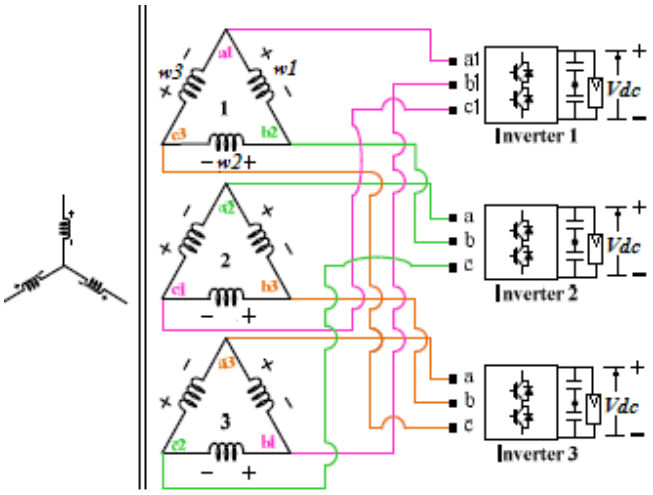

Fig. 1. Topology of transformer-based photovoltaic system with triple inverters specifically connected to secondary windings of the transformer (case of delta-connection of windings).

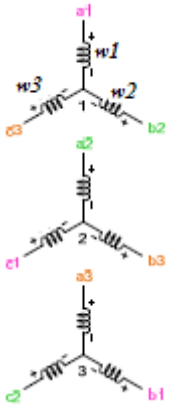

Fig. 2. Secondary windings of transformer of the system for the case of star-connection.

II. TWO-LEVEL INVERTERS WITH SYNCHRONOUS PWM

To assure voltage synchronization and waveform symmetries of inverters, specialized method of space-vector modulation can be used for control of triple inverters of PV system. Table I presents peculiarities and the main control dependences of this method of synchronous modulation, which are compared here with the corresponding parameters of conventional space-vector PWM [7]-[9].

TABLE I. BASIC PARAMETERS OF PWM METHODS

Control (modulation) parameter	**Conventional schemes of space-vector PWM**	**Specialized method of modulation**	
Operating and max parameter	Operating & max voltage V and V_m	Operating & maximum fundamental frequency F and F_m	
Modulation index m	V / V_m	F / F_m	
Duration of sub-cycles	T	τ	
Center of the k-signal	α_k (angles/degr.)	$\tau(k-1)$ (sec)	
Switch-on durations	$T_{ak} = 1.1mT[\sin(60^0 - \alpha_k) + \sin\alpha_k]$ $t_{ak} = 1.1mT\sin\alpha_k$ $t_{bk} = 1.1mT \times \sin(60^0 - \alpha_k)$	Algebraic PWM $\beta_k = \beta_1[1 - A \times (k-1)\tau FK_{ov1}]$ $\gamma_k = \beta_{i-k+1}[0.5 - 6(i-k)\tau F]K_{ov2}$ $\beta_k - \gamma_k$	Trigonometric PWM $\beta_k = \beta_1 \times \cos[(k-1)\tau K_{ov1}]$ $\gamma_k = \beta_{i-k+1}[0.5 - 0.9tn(i-k)\tau]K_{ov2}$ $\beta_k - \gamma_k$
Switch-off states (zero voltage)	$t_{0k} = T - t_{ak} - t_{bk}$	$\lambda_k = \tau - \beta_k$	
Special parameters providing synchronization of the process of PWM		$\beta" = \beta_1[1 - A \times (k-1)\tau FK_{ov1}]K_s$ $\lambda' = (\tau - \beta") \times K_{ov1}K_s$	$\beta" = \beta_1 \times \cos[(k-1)\tau K_{ov1}]K_s$ $\lambda' = (\tau - \beta") \times K_{ov1}K_s$

III. SYNCHRONOUS PWM OF INVERTERS IN TRIPLE-INVERTER-BASED SYSTEM

Phase voltages V_{as1}, V_{bs1} and V_{cs1} of the first standard three-phase inverter (**Inverter 1** in Fig. 1) of the system are calculated in accordance with (1)-(3) [7]:

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

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

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

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

Winding voltages of secondary windings of the system (V_{w1}, V_{w2}, V_{w3} in Fig. 1) can be expressed by the phase voltages of triple inverters in accordance with (4)-(9) [6]. Dependences (4)-(6) correspond to the case of delta-connection of windings, presented in Fig. 1, dependences (7)-(9) correspond to the case of star-connection, presented in Fig. 2.

$$V_{w1} = V_{as3} - V_{bs1} \quad (4)$$

$$V_{w2} = V_{bs1} - V_{cs2} \quad (5)$$

$$V_{w3} = V_{cs2} - V_{as3} \quad (6)$$

$$V_{w1} = 0.667V_{as1} - 0.333V_{bs2} - 0.333V_{cs3} \quad (7)$$

$$V_{w2} = -0.333V_{as1} + 0.667V_{bs2} - 0.333V_{cs3} \quad (8)$$

$$V_{w3} = -0.333V_{as1} - 0.333V_{bs2} + 0.667V_{cs3} \quad (9)$$

Control and output signals of triple inverters of the system are shifted by 120^0 (120^0 interleaving in accordance with some definitions). Also, small additional shift between control signals of three inverters, equal to 1/3 of duration of the switching period (switching sub-cycle) has been provided by the used scheme of control and modulation.

Fig. 3 – Fig. 13 .present results of simulation of processes in the system on the base of triple synchronously modulated inverters, and show basic voltage waveforms (pole voltages V_{a10}, V_{b10}, V_{c10} of the first inverter, phase V_{as1} and line-to-line V_{a1b1} voltages of the first inverter, and also winding voltages $V_{w1phase}$ and V_{w1line}, corresponding to the cases of star-connection and delta-connection of windings). It present also spectra of the phase V_{as1} and line V_{a1b1} voltages of inverters, and also spectra of winding voltages $V_{w1phase}$ and V_{w1line}.

Figs. 3-4 show voltage waveforms and voltage spectra of the system controlled in accordance with scheme of continuous synchronous modulation [7]. The fundamental frequency of the system is equal to $F=50Hz$, and switching frequency is equal to $F_s=1.13kHz$. Modulation index is equal to $m=0.65$ in this case.

Figs. 5-7 present voltage waveforms and the corresponding voltage spectra of system controlled by the scheme of synchronous discontinuous space-vector PWM with the 30^0-non-switching intervals ([7], DPWM30, $F=50Hz$, average $F_s=1.13kHz$, $m=0.75$).

Figs. 8-9 illustrate modulation processes in system controlled by scheme of synchronous discontinuous space-vector PWM with the 60^0-non-switching intervals ([7], DPWM60, $F=50Hz$, average $F_s=1.13kHz$, $m=0.85$).

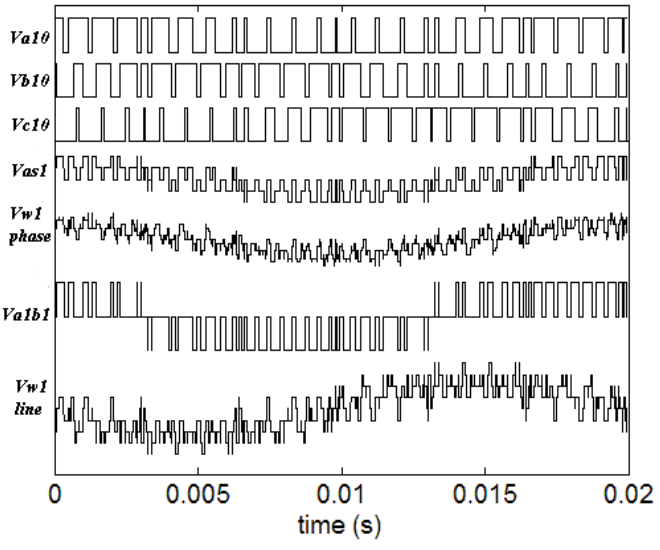

Fig. 3. Pole voltages V_{a10}, V_{b10}, V_{c10}, phase voltage V_{as1}, line voltage V_{a1b1} of the first inverter, and the corresponding winding voltages $V_{w1phase}$ and V_{w1line} of the system with continuous synchronous PWM (CPWM, $F=50Hz$, $F_s=1.13kHz$, $F_s/F=24.6$, $m=0.65$).

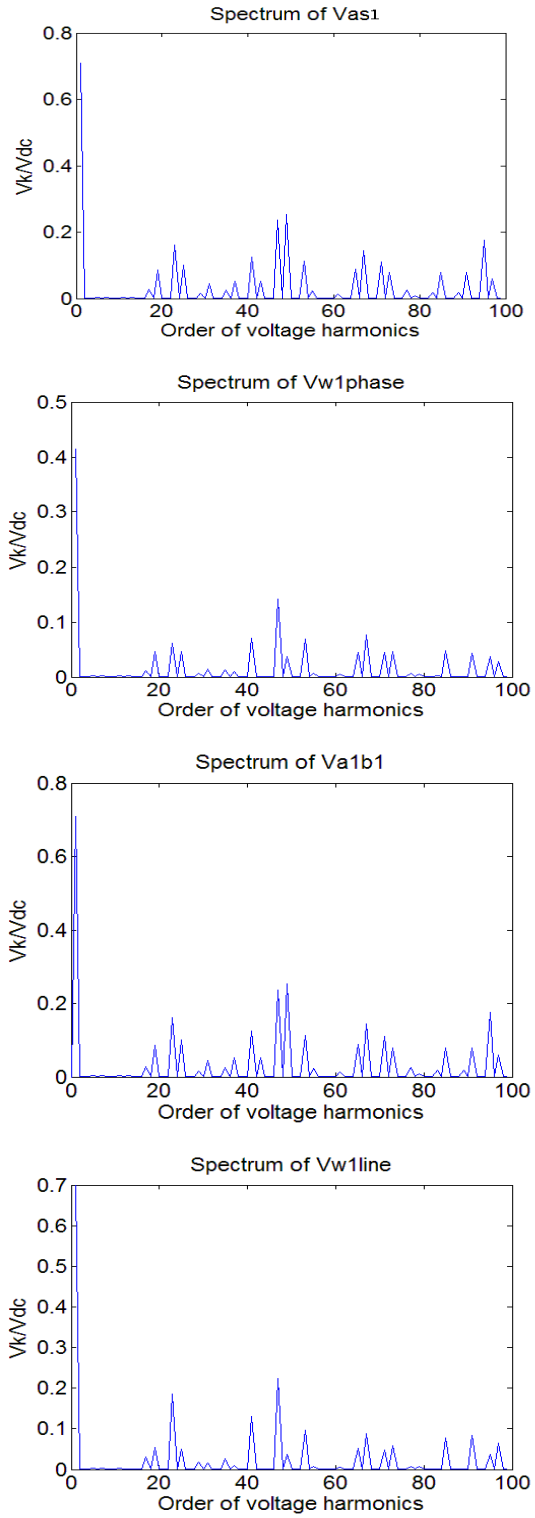

Fig. 4. Spectra of voltage waveforms of the system with continuous synchronous PWM (*F=50Hz*, F_s*=1.13kHz*, *m=0.65*).

Figs. 10-13 illustrate regimes of operation of inverters with discontinuous PWM in two parts of the zone of overmodulation (Figs. 10-11: the first part of the zone of modulation – DPWM60, *F=50Hz,* average F_s*=1.13kHz, m=0.95*; Figs. 12-13: the second part of the overmodulation zone – DPWM30, *F=50Hz,* average F_s*=1.13kHz, m=0.975*).

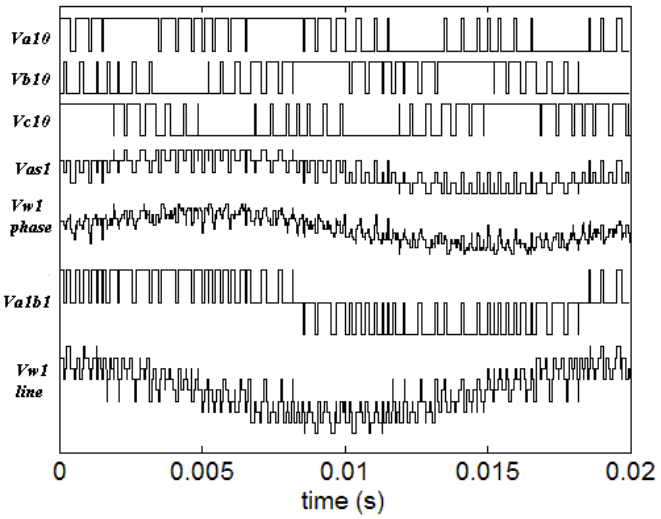

Fig. 5. Pole voltages V_{a10}, V_{b10}, V_{c10}, phase voltage V_{as1}, line voltage V_{a1b1} of the first inverter, and the corresponding winding voltages $V_{w1phase}$ and V_{w1line} of the system with discontinuous synchronous PWM (DPWM30, *F=50Hz*, F_s*=1.13kHz*, F_s*/F=24.6, m=0.75*).

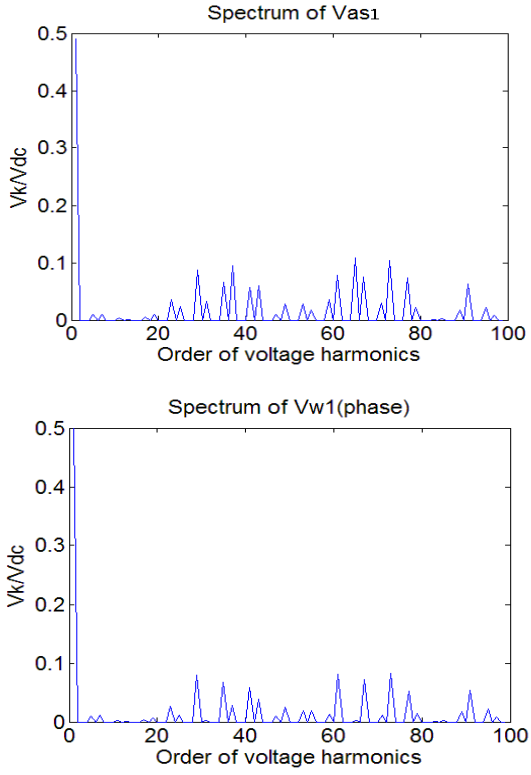

Fig. 6. Spectra of voltage waveforms of the system with discontinuous PWM (DPWM30, *F=50Hz*, F_s*=1.13kHz*, *m=0.75*).

To emphasize properties of the used specialized scheme of PWM, fractional frequency ratio between the switching and fundamental frequencies (equal to *1130Hz/50Hz=22.6*) has been used. Analysis of harmonic composition of symmetrical (with quarter-wave symmetry) voltage waveforms of the system shows (see Figs. 6, 7, 9, 11, 13), that spectra of the all presented waveforms do not include even harmonics and subharmonics for any values of modulation indices of inverters operating at both linear and overmodulation zones.

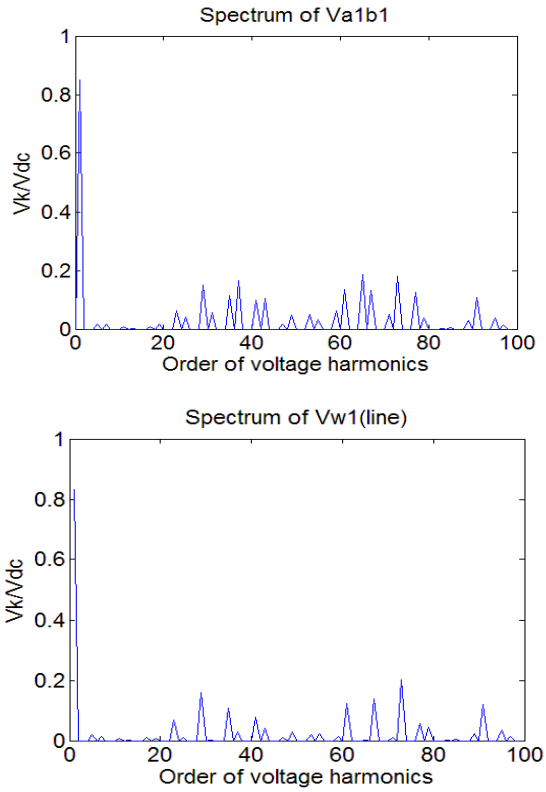

Fig. 7. Spectra of voltage waveforms of the system with discontinuous PWM (DPWM30, $F=50Hz$, $F_s=1.13kHz$, $m=0.75$).

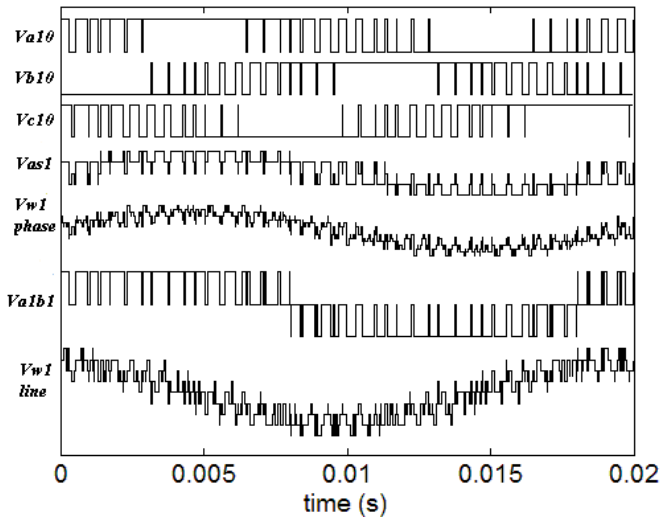

Fig. 8. Pole voltages V_{a10}, V_{b10}, V_{c10}, phase voltage V_{as1}, line voltage V_{a1b1} of the first inverter, and the corresponding winding voltages $V_{w1phase}$ and V_{w1line} of the system with discontinuous synchronous PWM (DPWM60, $F=50Hz$, $F_s=1.13kHz$, $F_s/F=24.6$, $m=0.85$).

Total Harmonic Distortion factor is an important criterion for analysis and comparison of voltage waveforms in photovoltaic systems. In particular, for 50-Hz systems it has been recommended to take into consideration harmonics up to the 40th voltage harmonic for determination of total voltage harmonic distortion factor [10]. Figs. 14-15-present results of calculation of Total Harmonic Distortion factor (*THD*) for basic voltage waveforms of the system as function of

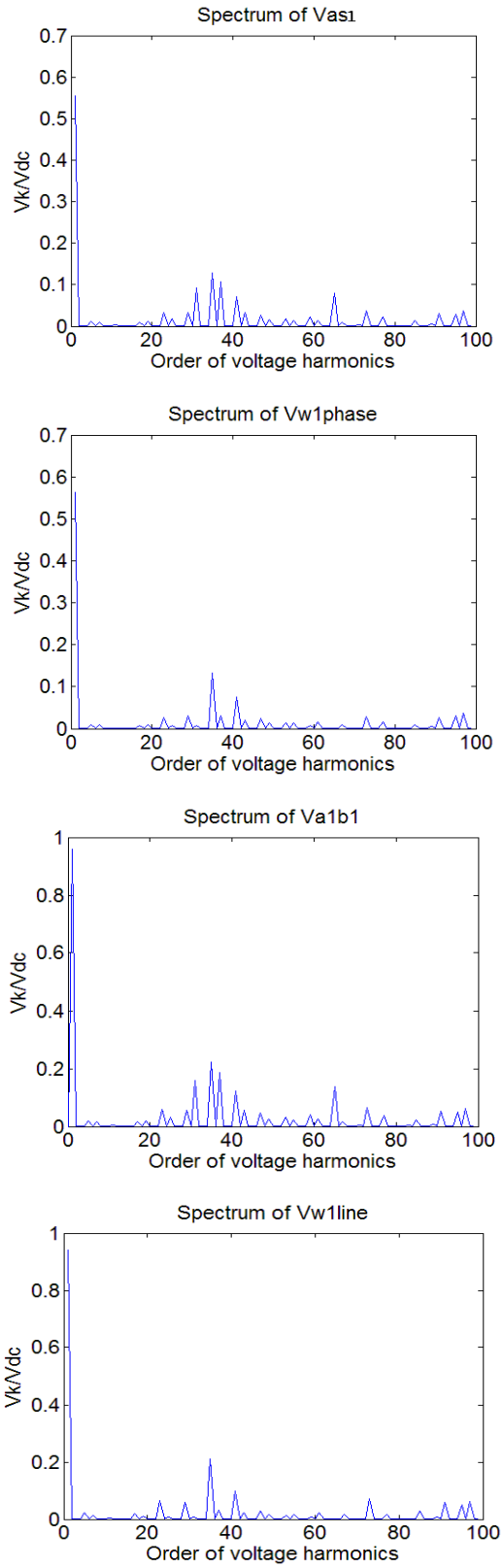

Fig. 9. Spectra of voltage waveforms of the system with discontinuous PWM (DPWM60, $F=50Hz$, $F_s=1.13kHz$, $m=0.85$).

modulation index m of triple inverters, controlled by synchronous techniques of continuous (CPWM) and discontinuous (DPWM30 and DPWM60) pulsewidth modulation.

THD factor has been calculated until the 40-th low-order (*k*-th) voltage harmonic (Fig. 14, $THD = (1/V_{w1_1})\sqrt{\sum_{k=2}^{40} V_{w1_k}^2}$), and also until the 1000-th harmonic (Fig. 15, $THD = (1/V_{w1_1})\sqrt{\sum_{k=2}^{1000} V_{w1_k}^2}$). The fundamental frequency of the system was equal to *50Hz*, and the average switching frequency of triple inverters was equal to *1.4kHz*.

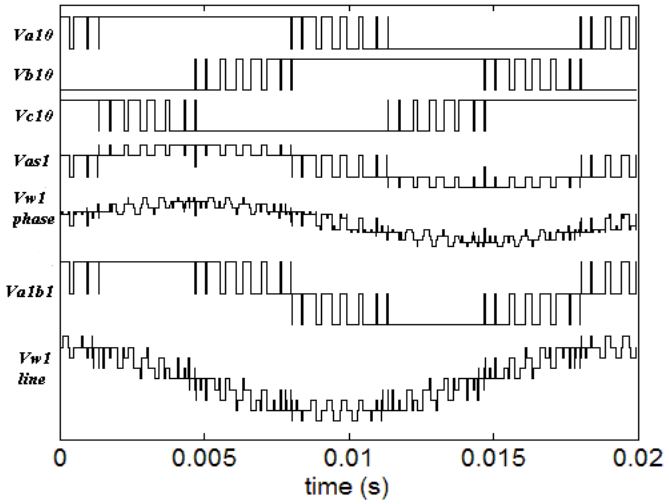

Fig. 10. Pole voltages V_{a10}, V_{b10}, V_{c10}, phase voltage V_{as1}, line voltage V_{a1b1} of the first inverter, and the corresponding winding voltages $V_{w1phase}$ and V_{w1line} of the system with discontinuous synchronous PWM in the overmodulation zone (DPWM60, $F=50Hz$, $F_s=1.13kHz$, $F_s/F=24.6$, $m=0.95$).

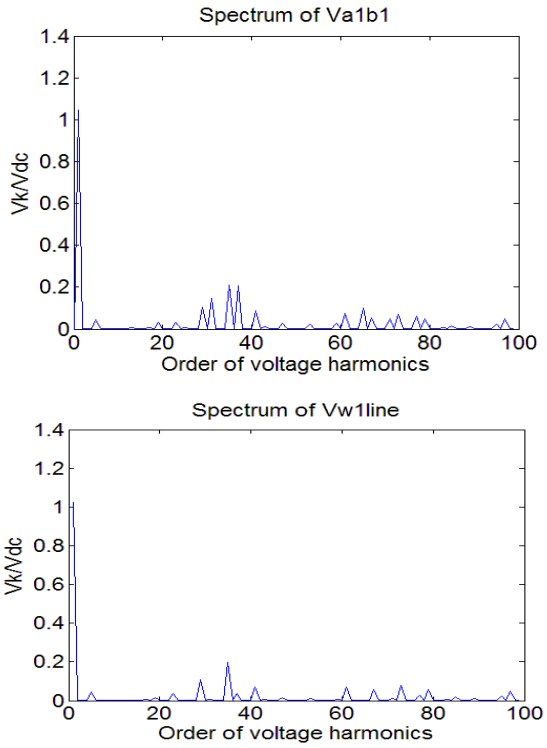

Fig. 11. Spectra of voltage waveforms of the system with discontinuous PWM (DPWM30, $F=50Hz$, $F_s=1.13kHz$, $m=0.95$).

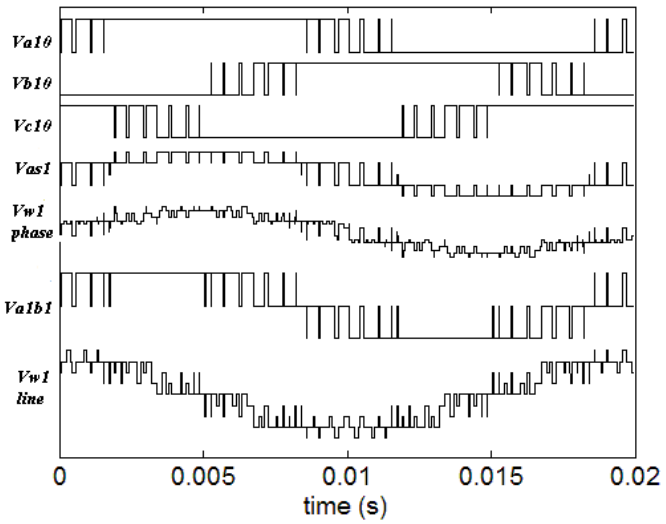

Fig. 12. Pole voltages V_{a10}, V_{b10}, V_{c10}, phase voltage V_{as1}, line voltage V_{a1b1} of the first inverter, and the corresponding winding voltages $V_{w1phase}$ and V_{w1line} of the system with discontinuous synchronous PWM in the overmodulation zone (DPWM30, $F=50Hz$, $F_s=1.13kHz$, $F_s/F=24.6$, $m=0.975$).

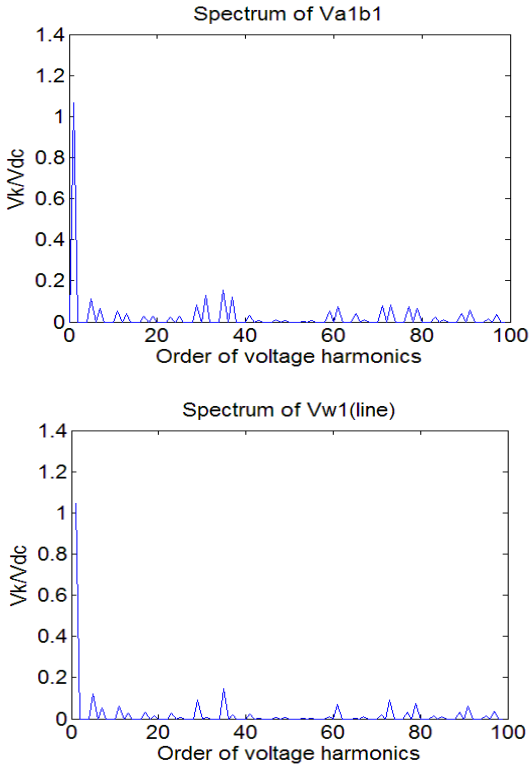

Fig. 13. Spectra of voltage waveforms of the system with discontinuous synchronous PWM (DPWM30, $F=50Hz$, $F_s=1.13kHz$, $m=0.975$).

Analysis of the presented in Fig. 14 and Fig. 15 results of calculation of *THD* factor shows, that due to the proposed in [6] connection between triple inverters and the secondary windings of the transformer, there is appreciable improvement of integral spectral characteristics of winding voltages. As an example, in accordance with diagram of Fig. 14 (for the case, if $m=0.7$), *THD* factor for winding voltages is reduced by 14% (for system with algorithm of CPWM), by 8% (for system controlled by algorithm of DPWM30), and

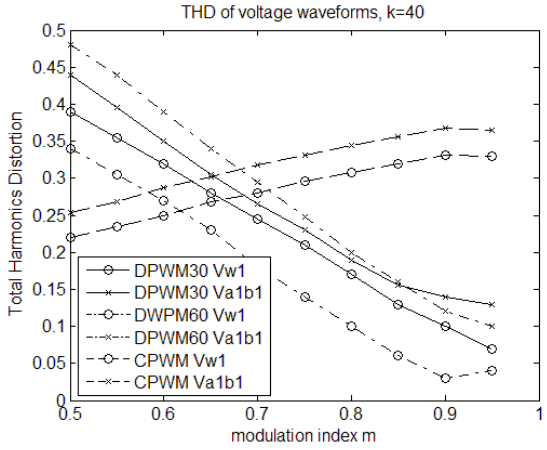

Fig. 14. *THD* factor of voltages of the system versus modulation index *m* (*k=40*).

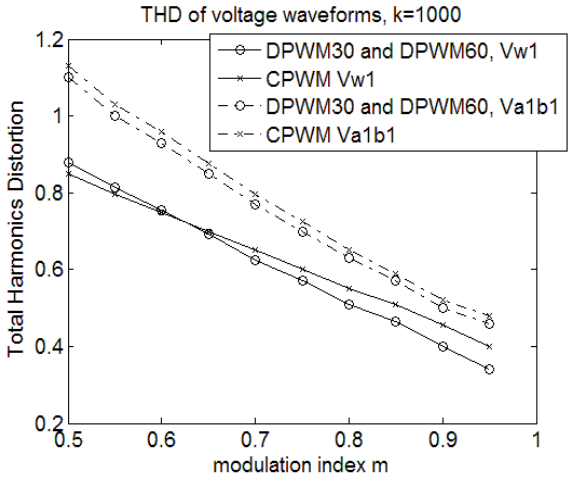

Fig. 15. *THD* factor of voltages of the system versus modulation index *m* (*k=1000*).

by 63% for system with DPWM60, in comparison with the corresponding line voltages. Accordingly, data of the diagram, presented in Fig. 15, show (as an example, for the case, if *m=0.7*), that *THD* factor for winding voltages of system with new connection between inverters and transformer is decreased by 23% (for system with DPWM30 or DPWM60), and by 22% (for system controlled by algorithm of CPWM), in comparison with the corresponding line voltages (case of conventional connection between inverters and transformer).

So, improved spectral composition of winding voltages of transformer-based system assures to reduce copper loss in windings of the transformer, and also to decrease switching and conduction losses at triple inverters.

IV. CONCLUSION

Specialized schemes and techniques of feedforward space-vector modulation, insuring voltage synchronization and voltage symmetries of inverters, can be used effectively in transformer-based photovoltaic systems on the base of triple inverters with novel connection between inverters and windings of the transformer.

The presented voltage spectrograms illustrate qualitatively and quantitatively attenuation of the corresponding harmonics of winding voltages due to new connections inside the system.

To emphasize properties of the used specialized scheme of PWM, fractional frequency ratio between the switching frequency and fundamental frequency (equal to *1130Hz/50Hz=22.6*) has been chosen for analysis of modulation processes in system. Research of harmonic composition of symmetrical (with quarter-wave symmetry) voltage waveforms of the system shows (see Figs. 6, 7, 9, 11, 13), that spectra of the all presented waveforms do not include even harmonics and subharmonics for any values of modulation indices of inverters operating at both linear control zone and zone of overmodulation..

It has been shown, that in general case *THD* factor for winding voltages of secondary windings of the system with new connection between inverters and transformer is decreased (in average) by about 20% for systems with both continuous and discontinuous synchronous PWM, in comparison with the case of conventional connection between inverters and transformer.

ACKNOWLEDGMENT

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