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DUAL INVERTERS WITH SYNCHRONIZED PWM FOR PHOTOVOLTAIC GENERATION

Analysis of operation of photovoltaic system on the base of dual inverters with synchronized pulsewidth modulation (PWM), supplied by two strings of photovoltaic panels and connected to a grid by a three-phase transformer with the open winding configuration on primary side, has been performed. Algorithms of synchronized PWM are based in this case on continuous control of the switching frequencies of two inverters as function of magnitude of the DC-links voltage, providing both continuous voltage synchronization in each inverter and in the load, and also an improvement of operation of photovoltaic systems during solar irradiance fluctuation.

Выполнен анализ работы фотоэлектрической преобразовательной системы на базе сдвоенных инверторов напряжения с синхронной широтно-импульсной модуляцией (ШИМ), питающихся соответственно от двух фотоэлектрических панелей и связанных с сетью через трехфазный трансформатор с разомкнутыми обмотками на первичной стороне. Алгоритмы синхронной ШИМ базируются на регулировании частоты коммутации двух инверторов в функции амплитуды питающего напряжения, обеспечивая при этом как непрерывную синхронизацию фазных напряжений инверторов и нагрузки, так и повышение эффективности функционирования фотопреобразовательной системы при флюктуациях солнечного излучения.

Introduction. Cascaded (dual) two-level converters which utilize two standard three-phase voltage source inverters are now between perspective topologies of power converters [3, 15, 16]. In particular, dual inverter-fed open-end winding motor drives have some advantages such as redundancy of the space-vector combinations and the absence of neutral point fluctuations [2, 5, 13, 14]. These new drive topologies provide also one of the best possible use of semiconductor switches.

Almost all versions of classical space-vector PWM are based on the asynchronous principle, which results in sub-harmonics (of the fundamental frequency) in the spectrum of the output voltage of converters, which are very undesirable in medium/high power applications [6,7]. In order to provide voltage synchronization in dual inverter-fed drives, a novel method of synchronized PWM has been applied for control of these

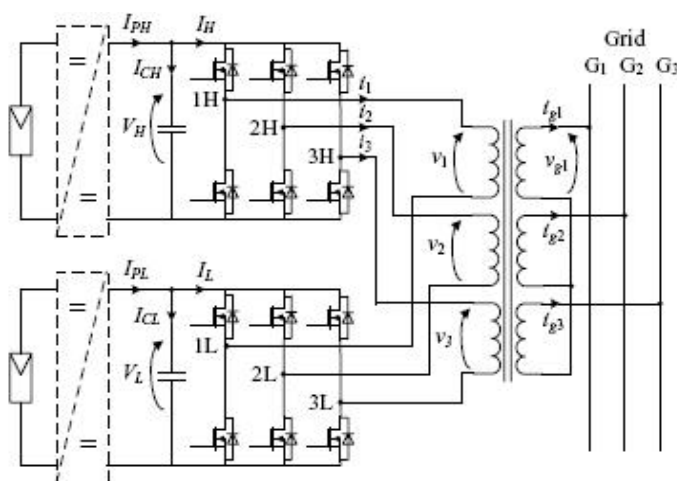


Fig. 1

systems with single DC voltage source [10], and for the systems with two DC sources: without power balancing between sources [11], and also with power balancing PWM algorithms in a linear control range [9].

Besides adjustable speed AC drives, photovoltaic systems are between perspective areas of application of the dual-inverter topology [4],[12]. In particular, Fig. 1 presents dual inverter system supplied by two insulated strings of photovoltaic panels with the resulting DC voltages V_L and V_H [4]. Direct connection of photovoltaic modules to inverters, or their connection through DC/DC link (dashed lines in Fig. 1) is available in this case. Dual inverters are connected to a grid by a three-phase low-frequency transformer with the open winding configuration on primary side, and this configuration is one of

the most suitable for photovoltaic systems with a higher power range, allowing also galvanic isolation between low-voltage photovoltaic panels and the power grid.

Dissemination of a novel method of synchronized space-vector PWM for control of power conversion system on the base of cascaded inverters for photovoltaic application has been done in [12]. So, this paper presents further development of modulation strategy for flexible PWM control of dual inverters, which is based on continuous variation of switching frequencies of the two inverters as function of magnitudes of the DC-links voltages (strings of photovoltaic panels).

Photovoltaic System with Controlled Switching Frequency of Dual Inverters. It is known, that rational phase shift between output voltage waveforms of the two cascaded inverters (with equal switching frequencies) is equal to one half of the switching interval (sub-cycle) [15]. In the case, when the two DC-link voltage sources have equal voltages ($V_L = V_H$), the resulting voltage space-vectors of dual-inverter system are equal to the space-vector patterns of conventional three-level inverter [3, 5, 15]

The phase voltages V_1, V_2, V_3 of the system with two insulated DC-link sources (Fig. 1) are calculated in accordance with (1)–(4) [13]:

$$V_0 = 1/3(V_{1L} + V_{2L} + V_{3L} + V_{1H} + V_{2H} + V_{3H}), \quad (1)$$

$$V_1 = V_{1L} + V_{1H} - V_0, \quad (2)$$

$$V_2 = V_{2L} + V_{2H} - V_0, \quad (3)$$

$$V_3 = V_{3L} + V_{3H} - V_0, \quad (4)$$

where $V_{1L}, V_{2L}, V_{3L}, V_{1H}, V_{2H}, V_{3H}$ – are the corresponding pole voltages of each three-phase inverter (Fig. 1), V_0 – is the zero sequence (tripled harmonic components) voltage.

Control of photovoltaic power conversion systems on the base of dual inverters has some peculiarities. In the case of direct connection between the two photovoltaic strings and the two inverters, in order to provide maximum power point tracking of photovoltaic panels, control of the system should be based on the corresponding specific regulation of modulation indices of dual inverters [4]. And this control is somewhat similar to power sharing process between two dual inverters for traction systems, analyzed in [5, 9].

Also, the fundamental frequency of the phase voltages of dual inverters should be equal to the fundamental frequency of the grid. In the case of fluctuation of the grid frequency the inverters' fundamental frequency should be correlated correspondingly. And control of each inverter in dual-inverter system can be often based on both under-modulation and over-modulation PWM algorithms.

In order to provide maximum power point tracking of photovoltaic panels and stabilization of the magnitude of the fundamental harmonic of the phase voltage of a dual-inverter system for photovoltaic application, the corresponding control system has been proposed, described and verified [4]. In particular, in the case of low DC-links voltages (it corresponds to low solar irradiance) modulation indices m_H and m_L of the two inverters should be high, and the phase voltage has three-level waveform.

In the case of higher DC-link voltages (this control mode corresponds to higher level of solar irradiance), modulation indices of the two modulated inverters should be decreased correspondingly, in order to provide close to constant amplitude of the phase voltage during solar irradiance fluctuations. Analysis of operation of photovoltaic system on the base of cascaded inverters with simplified algorithms of synchronized PWM has been done in [12].

In order to increase effectiveness of operation of dual three-phase systems on the base of two inverters supplied by isolated DC sources (with equal or different voltages), it is rational to adjust continuously switching frequency of each modulated inverter in function of voltage magnitude of DC sources (under condition of similar switching losses of two inverters). In particular, inverters supplied by the higher DC-voltage should be operated at lower switching frequency (at the rated switching frequency of the corresponding switches of inverters), and if inverters are supplied by the lower DC-voltage, their switching frequency can be increased correspondingly.

In the case of different voltages of two DC sources, the inverter supplied by the higher voltage V_H should be operated at lower switching frequency F_{s2} , and the inverter supplied by the lower voltage V_L should be operated at higher switching frequency F_{s1} :

$$F_{s1} V_L = F_{s2} V_H. \quad (5)$$

Properties of the Method of Synchronized PWM. In order to avoid asynchronous operation of systems with conventional space-vector modulation, novel space-vector-based method of synchronized PWM [8], can be used for control of each inverter in a dual-inverter system for photovoltaic application. Fig. 2, *a, b* presents switching state sequences and basic voltage waveforms of standard three-phase inverter inside the interval 0° – 90° . It illustrates schematically basic continuous (Fig. 2, *a*) and discontinuous (Fig. 2, *b*) versions of space-vector pulsewidth modulation.

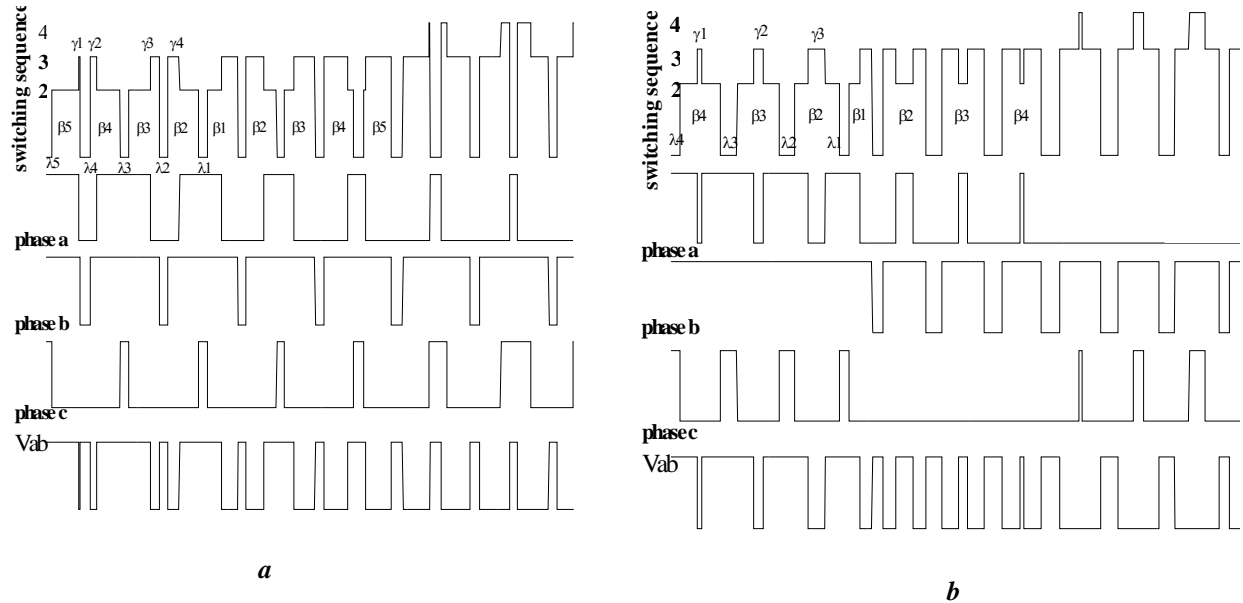


Fig. 2

Control (modulation) parameter	Conventional schemes of vector PWM	Proposed 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	$T_{ak} = 1.1mT[\sin(60^\circ - \alpha_k) + \sin \alpha_k]$ $t_{ak} = 1.1mT \sin \alpha_k$ $t_{bk} = 1.1mT \times \sin(60^\circ - \alpha_k)$	Algebraic PWM	Trigonometric PWM
		$\beta_k = \beta_1[1 - A \times (k-1)\tau FK_{ov1}]$ $\gamma_k = \beta_{i-k+1}[0.5 - 6(i-k)\tau F]K_{ov2}$ $\beta_k - \gamma_k$	$\beta_k = \beta_1 \times \cos[(k-1)\tau K_{ov1}]$ $\gamma_k = \beta_{i-k+1}[0.5 - 0.9m(i-k)\tau]K_{ov2}$ $\beta_k - \gamma_k$
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		$\beta'' = \beta_1[1 - A \times (k-1)\tau FK_{ov1}]K_s$ $\lambda' = (\tau - \beta'') \times K_{ov1}K_s$	$\beta'' = \beta_1 \times \cos[(k-1)\tau K_{ov1}]K_s$ $\lambda' = (\tau - \beta'') \times K_{ov1}K_s$

The upper traces in Fig. 2 are switching state sequences (in accordance with conventional designation [8]), then – the corresponding phase voltages of each inverter. The lower traces in Fig. 2, *a, b* show the corresponding quarter-wave of the line-to-line output voltage of inverters. Signals β_j represent total switch-on durations during switching sub-intervals τ , signals γ_k are generated on the borders (Fig. 2, *a*) or in the centres (Fig. 2, *b*) of the corresponding β -signals. Widths of notches λ_k represent duration of zero sequences [8].

So, one of the basic ideas of the proposed PWM method is in continuous synchronisation of the positions of all central signals β_1 in the centres of the 60° -clock-intervals (to fix positions of β_1 in the centres of the cycles), and then – to generate symmetrically all other active β - and γ -signals, together with the corresponding

notches. Table presents generalized properties and basic control correlations for the proposed method of synchronized PWM [9]. It is also compared here with conventional asynchronous space-vector modulation. In particular, for dual-inverter photovoltaic system with constant switching frequency of inverters it is possible to use simplified algorithm of synchronized PWM [12], but for the systems with controlled switching frequencies of inverters it is necessary to provide full-scale dissemination (like for AC drives) of the method of synchronized PWM [8].

Synchronous Operation of the System with Controlled Switching Frequency of Dual Inverters.

Synchronous control of the output voltage of each inverter of dual-inverter-based system in accordance with algorithms of synchronized PWM provides synchronous symmetrical regulation of the phase voltages V_1 , V_2 and V_3 of the system. Rational phase shift between output voltage waveforms of the two inverters in the case of equal DC-links voltages ($V_H=V_L$) is equal to one half of the switching interval (sub-cycle) [15], and in the case of different DC-links voltages (and different switching frequencies of two inverters) this shift should be equal to average value of the halves of the corresponding switching intervals.

To illustrate processes in photovoltaic system on the base of cascaded inverters with controlled switching frequencies, supplied by two isolated DC sources with equal voltages ($V_L=V_H$), Fig. 3 – Fig. 4 present results of MATLAB-based simulation of the system with both continuous (Fig. 3) and discontinuous (Fig. 4) versions of synchronized PWM.

Fig. 3, *a* shows basic voltage waveforms of the system with continuous synchronized PWM with high DC-links voltage ($V_L=V_H=V_{dc-high}$) during period of the fundamental frequency $F=50$ Hz (switching frequency $F_s=1.2$ kHz and modulation index $m=0.45$ are relatively low here). Fig. 3, *b* presents basic voltage waveforms for the 60° -interval of the period of the fundamental frequency, and, in particular, it shows more in details the corresponding phase shift $\tau/2$ between waveforms of the two inverters, and the corresponding signals $\gamma_1, \gamma_2, \gamma_3, \gamma_4$ (see Fig. 2, *a* and Table) on the boundaries of line voltage waveform. Fig. 3, *c* presents phase voltage spectrum for this control mode.

Fig. 4 presents detailed (inside the 60° -interval) voltage waveforms (Fig. 4, *a*) and spectrum of the phase voltage (Fig. 4, *b*) for the system with discontinuous synchronized PWM (Fig. 2, *b*), operating under low DC-links voltage ($V_L=V_H=V_{dc-low}$ ($V_{dc-low}=0,5V_{dc-high}$)), in particular, it can corresponds to low level of solar irradiance). And this control regime is characterized by relatively high values of switching frequency $F_s=2,4$ kHz and modulation index $m=0,9$. So, phase voltage waveforms of the system are characterized in this case

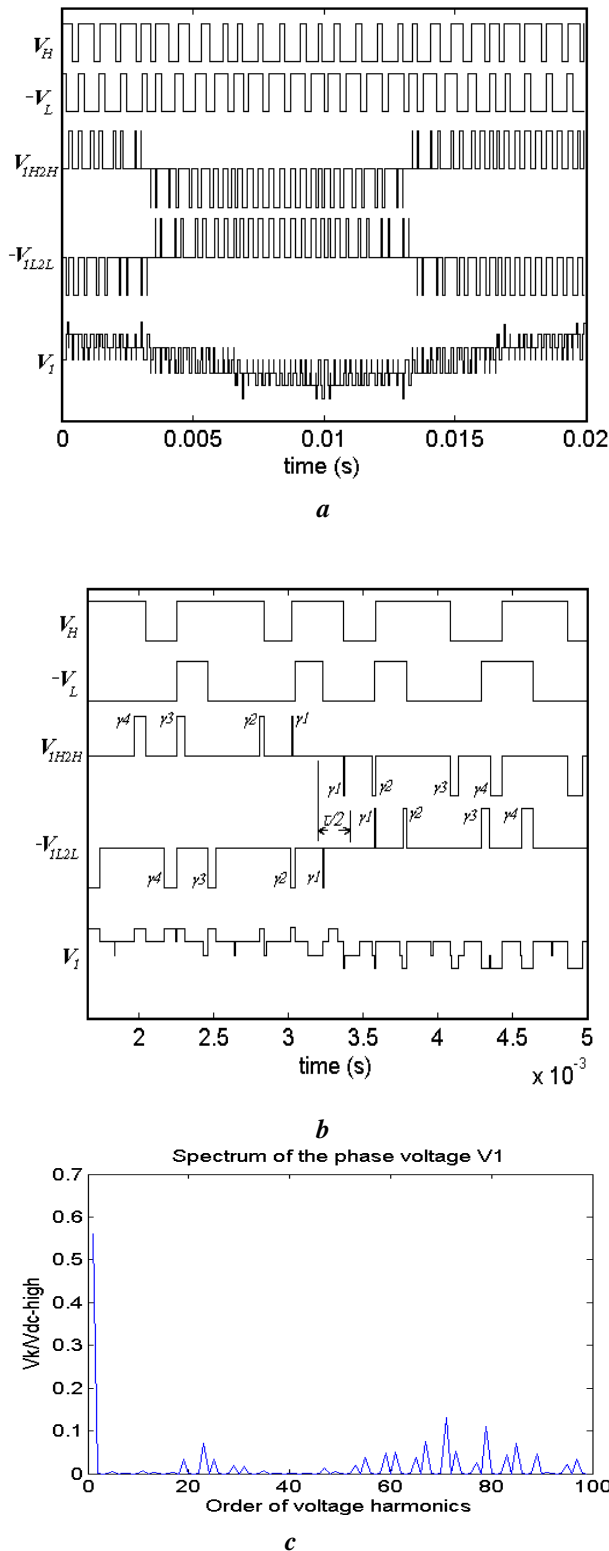


Fig. 3

much better spectral composition than for the systems with relatively high DC-voltages and lower switching frequencies of inverters (see the corresponding phase voltage spectra presented in Fig. 3, *c* (high DC-voltage and low switching frequency of the system, voltage spectrum is not very good here), and in Fig. 4, *b* (low DC-voltage and higher switching frequency of the system, and voltage spectrum almost does not contain low-order harmonics in this case).

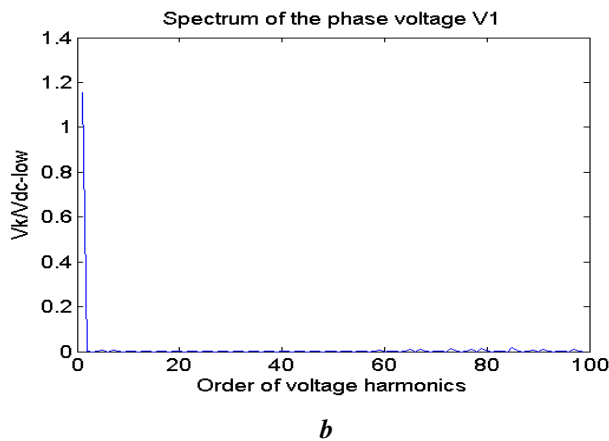
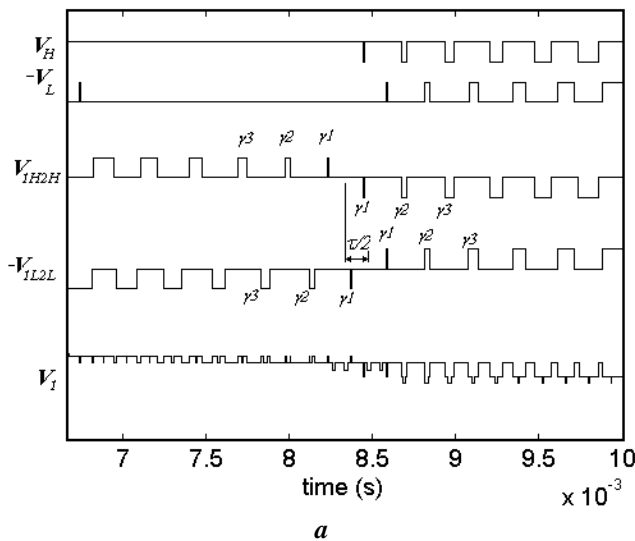


Fig. 4

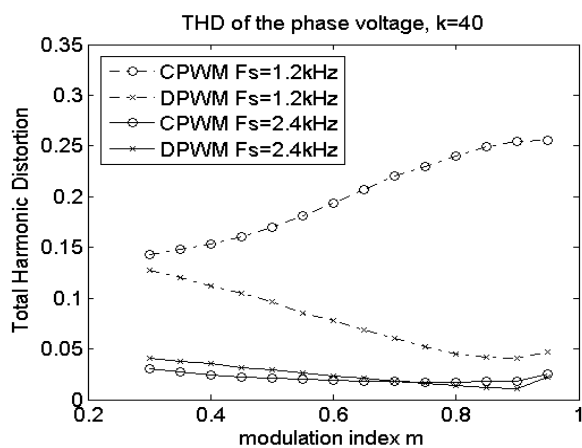


Fig. 5

photovoltaic application can provide effective variation of switching frequency of inverters under condition of equivalence of switching losses in each inverter. In particular, the proposed continuous control of

Analysis of voltage waveforms and spectral characteristics of the phase voltage of photovoltaic systems on the base of cascaded inverters with controlled switching frequency shows that for any control modes the algorithms of synchronized PWM (both of continuous and discontinuous synchronized PWM) provide symmetry of the phase voltage, and its spectra do not contain even harmonics and sub-harmonics for any operating conditions of the systems.

Spectral Assessment of Quality of the Phase Voltage of Photovoltaic System. Total Harmonic Distortion (*THD*) factor of voltage and current is one of the most suitable criteria for analysis of power quality in grid-connected photovoltaic systems. In particular, in accordance with the majority of standards for 50-Hz power systems, total voltage harmonic distortion has to be calculated up to the 40th voltage harmonic [1]. Fig. 5 presents the calculation results of Total Harmonic Distortion factor (*THD*) for the phase voltage V_1 in the function of modulation index $m=m_1=m_2$, of the dual-inverter system on the base of dual inverters with equal DC-links voltages ($V_H=V_L$), controlled by algorithms of continuous (CPWM) and discontinuous (DPWM) schemes of synchronized modulation. The *THD* factor

$$(THD = (1/V_1) \sqrt{\sum_{k=2}^{40} V_{1k}^2})$$

has been calculated until the 40-th low-order (*k*-th) voltage harmonic. The fundamental frequency of the system is $F=50$ Hz, and the *THD* factor has been calculated for two values of the average switching frequency of each modulated inverter: $F_s=1.2$ kHz and $F_s=2.4$ kHz.

The presented in Fig. 5 calculation results show big dependence of the *THD* factor on switching frequency of inverters. So, the proposed flexible control of switching frequency of dual inverters in function of DC-links voltages (voltages of two strings of photovoltaic panels) during fluctuation of solar irradiance can improve strongly effectiveness of processes of photovoltaic generation.

Conclusion. It has been shown, that a full-scale dissemination of a novel method of synchronized PWM for control of dual inverters for

switching frequency of dual inverters as function of DC-links voltages (voltages of two strings of photovoltaic panels) during fluctuation of solar irradiance can improve effectiveness of processes of photovoltaic generation. The spectra of the phase voltages of dual-inverters-based photovoltaic system with synchronized PWM do not contain in this case even harmonics and sub-harmonics for any operating conditions.

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