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Triphase Cascaded Converters with Direct Synchronous Pulsewidth Modulation

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Original scientific paper

A novel method of direct synchronous pulsewidth modulation (PWM) is applied for control of modular multilevel converters consisting from three standard triphase inverter modules along with an 0.33 p.u. output transformer. The proposed method provides synchronisation of the voltage waveforms for both each module and the composed voltage at the output of the converter. Multilevel output voltage of the converter has quarter-wave symmetry during the whole range including the zone of overmodulation. Both continuous and discontinuous versions of synchronous PWM, based on a vector approach for determination of the pulse patterns, have been analysed and compared using simulations of the systems with low switching frequencies, which normally are used in high power systems.

Key words: converter control, modulation strategies, multilevel converters, variable speed drives

1 INTRODUCTION

Three-level and multilevel converters are a subject of increasing interest in the last years due to some advantages compared with standard three-phase inverters. One of the most perspective topology of multilevel converters for high power adjustable speed drive application is a novel triphase cascaded (modular) converter that uses three standard triphase inverter modules along with an 0.33 p.u. output transformer [1–3].

The multilevel output of these converters is synthesised in this case by adding of each inverter output voltage using a multi-winding transformer, with a relative phase shifting of the two-level voltage waveforms. At the same time problem of synchronisation of the voltage waveforms is important for converters with this topology. High-power switches of every inverter module have low switching frequency, so there are undesirable even harmonics and combined harmonics (sub-harmonics) in the spectrum of the output voltage of the modular converter during typical asynchronous control modes using standard techniques of vector PWM.

In order to avoid asynchronism of typical vector PWM schemes and to provide synchronous symmetrical voltage control with smooth pulses-ratio changing, a novel method of feedforward PWM for three-phase inverters has been recently proposed [4–5]. It is based on a new approach for determine the pulse patterns of the output voltage of the inverter, described in absolute values as a function of the fundamental and switching frequencies of the drive system. The method provides smooth symmetrical shock-less variation of the inverter output voltage due to special quasi-linear control of the signals, which are formed on the boundaries of the 60 clock-intervals.

This paper presents the development and application of the proposed methodology of PWM to high power modular converters with multilevel output voltage, which are characterised by low switching frequencies.

2 GENERAL STRUCTURE OF MODULAR CONVERTER

Figure 1 presents the basic topology of modular converter consisting from three standard three-phase voltage source inverters along with a 0.33 p.u. output transformer and an induction motor M as a load, especially useful for medium voltage application [1]. Between the main peculiarities and advantages of this topology there are [2–3]:

a) four-level line output voltage with low dv/dt and low total harmonic distortion factor;
b) balanced operation of all three inverter-modules, with no circulating current;
c) the effective switching frequency in each module is reduced to one third;
d) possible to use low cost switches like IGBT;
e) the modular construction yields an easier maintenance.

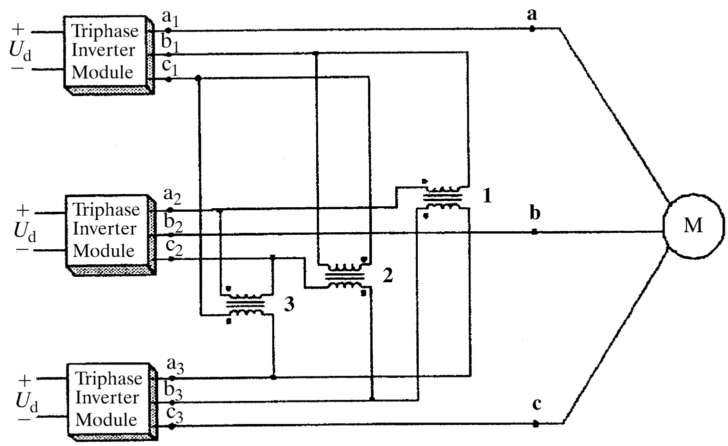

Fig. 1 Basic topology of modular converter consisting from three voltage source inverters, with an induction motor (M) as a load [1]

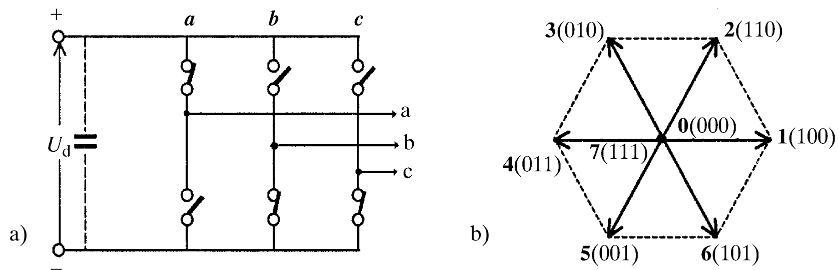

Fig. 2 Structure of one module (three-phase voltage source inverter) (a), and its output voltage vectors (b).

Figure 2 shows the structure of the power circuits of every module (three-phase voltage source inverter). The corresponding vectors (switching state sequences) of the output voltage of the inverter (six active vectors **1–6**, and two zero vectors **0** and **7**) are also presented here. The conventional definition for the switching state sequences (voltage vectors) for the switches of the phases of ***abc*** in the inverter is used: **1** – 100; **2** – 110; **3** – 010; **4** – 011; **5** – 001; **6** – 101; **7** – 111; **0** – 000 (»1« – switch-on state, »0« – switch-off state).

3 SYNCHRONISED PULSEWIDTH MODULATION FOR CONTROL OF MODULAR CONVERTERS

Voltage space vector modulation is one of the most suitable modulation method for use in adjustable speed ac drive systems fed by voltage source inverters [6–7]. In particular, it is easy to implement and it provides high quality of the output voltage and current in the inverters with high switching frequency. All varieties of voltage space vector PWM can be divided into two big classes: continuous vector PWM and discontinuous pulsewidth modulation [8]. At the same time it is known [9] that for power drive systems with a low ratio between the switching frequency and fundamental frequency it is necessary to provide synchronous voltage control to avoid undesirable combined harmonics of the fundamental frequency. For resolving this task, a novel PWM method [4] is used to control modular converters, providing synchronisation of the voltage waveforms for every module and a composed output voltage of the converter.

3.1 Continuous Synchronised PWM

Figure 3 shows the switching state sequence, gate signals of the switches of three phases, and the line output voltage of the inverter for quarter-period of the fundamental frequency, for the most popular (conventional) continuous version of voltage space vector modulation (CPWM) [6–8]. It is a typical scheme of continuous pulsewidth modulation, because the modulation principle is based on continuous operation of all switches of the inverter during every switching period (sub-cycle). The active switching states are situated in the centres of sub-cycles. Zero vector states (**0** and **7**) are changing step-by-step after every sub-cycle. The sequence of switchings is here **-7-2-3-0-3-2-7-**.. inside the first 60 -clock-interval.

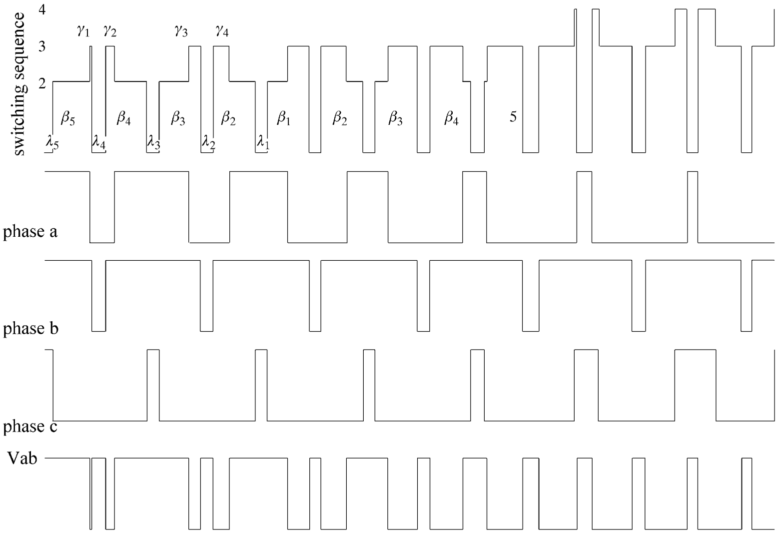

Fig. 3 Control and output signals for quarter-period of one inverter module with continuous pulsewidth modulation (CPWM)

In Figure 3 the signals βj represent the total switch-on durations during the switching period (sub-cycle) τ, signals γ_k (minor component of two parts of the β-signal) are generated on the boundaries of the corresponding β. Widths of notches λ_k represent the duration of zero state sequences.

Basic peculiarity of the proposed method of synchronised PWM is in step-by-step generation of the special signals $\lambda'(\lambda_5)$ (with the neighbouring $\beta''(\beta_5)$), which are formed in the clock-points (0 , 60 , 120 ...) of the output curve [4–5]. They are reduced simultaneously till zero at the boundary frequencies F_i, providing a continuous symmetrical adjustment of the output voltage with smooth pulses-ratio changing.

3.2 Discontinuous Synchronised PWM

In contrast with continuous PWM the schemes of discontinuous pulsewidth modulation are characterised by the 60 - or 30 -non-switching intervals for every switch of the inverter module during the period of the output voltage. The schemes of discontinuous PWM with the 60 -non-switching intervals can be symmetrical or asymmetrical. The most famous scheme of discontinuous pulsewidth modulation has symmetrical output voltage and it is characterised by the 60 -non-switching intervals [8].

At the same time it is known, that a better quality of the output voltage of the inverter is provided by the scheme of discontinuous symmetrical PWM with the 30 -non-switching intervals [4, 5, 8]. Figure 4

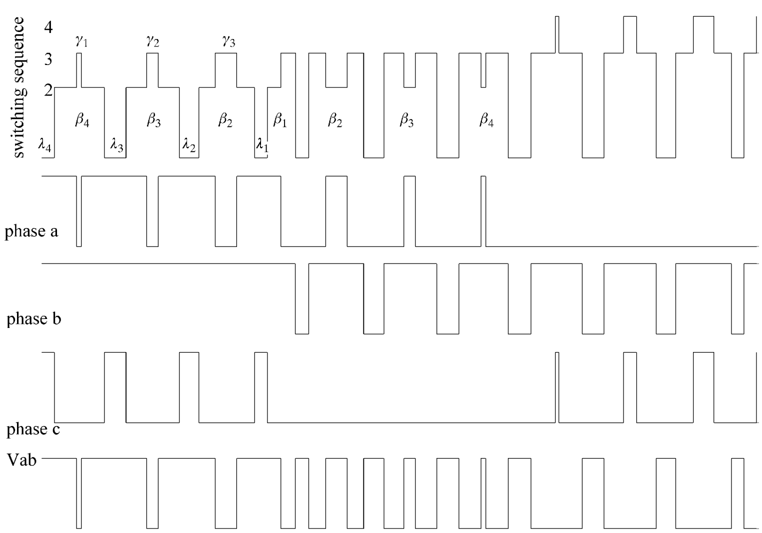

Fig. 4 Control and output signals for quarter-period of one inverter module with discontinuous pulsewidth modulation (DPWM)

shows the switching state sequences, control signals for three switches and line output voltage of the inverter for one-stage scheme of direct synchronised PWM, applied to discontinuous symmetrical pulse-width modulation with these 30 -non-switching intervals (DPWM, Method 4 in [8]). The general switching state sequence is **-2-3-2-7-2-3-2-7-2-3-0-3-2-3-0-..** in this case. Here are also clock-point signals $\lambda'(\lambda_4)$ (with the neighbouring $\beta''(\beta_4)$), its widths are reduced smoothly till close to zero values at the boundary frequencies F_i, transient between control sub-zones.

3.3 Basic Control Correlations

Continuous symmetrical variation of the voltage waveforms of the inverter modules is provided by a special algorithm. It is based on a step-by-step control of specialised parameters of the schemes of synchronised PWM between the boundary frequencies F_i, situated on the axis of the fundamental frequency F of the drive system [4–5]. It provides a continuous adjustment of the voltage waveform with smooth pulse-ratio changing until the maximum fundamental frequency F_m. F_i is calculated in a general form as a function of the width of switching periods (sub-cycles) τ in accordance with (1), and the neighbouring F_{i-1} – from (2). The modulation index is $m=F/F_m$ in this case. Index i is equal to the numbers of notches inside a half of the 60 clock-intervals, and it is determined from (3), where fraction is rounded off to the nearest higher integer:

$$F_i = \frac{1}{6(2i - K_i)\tau} \tag{1}$$

$$F_{i-1} = \frac{1}{6(2i - K_2)\tau}, \tag{2}$$

$$i = \frac{1/6F + \tau K_1}{2\tau}, \tag{3}$$

where $K_1=1$, $K_2=3$ for CPWM, and $K_1=1.5$, $K_2=3.5$ for DPWM.

The relative durations of the active switching states and pulses of the output voltage of the inverter for these symmetrical schemes of PWM can be written in accordance with the principle of voltage space vector modulation [4]:

$$\frac{\beta_j}{\beta_1} = \sin(60° - \alpha_j) + \sin(\alpha_j), \tag{4}$$

$$\frac{\gamma_k}{\beta_{i-j+1}} = \frac{\sin(\alpha_k)}{\sin(60° - \alpha_k) + \sin(\alpha_k)}, \tag{5}$$

where: α – angle position of the centre of the corresponding β-signal from the beginning of the 60 clock-intervals; β_1 – the signal, which is formed in the centres of the 60 clock-intervals, where $\alpha=30$; $j=2,\dots\ i-1$; $k=i-j+1$.

Realisation of (4)–(5) can be based on either simplified pure algebraic control functions [4], or precise trigonometric ones [5]. Eqs. (6)–(11) present a set of accurate trigonometric control functions, based on some transformation of (4)–(5), for determination of parameters for control and output signals of every module (three-phase inverter) in absolute values (seconds). It is available in this case for standard scalar control mode of the drive system during the whole range including the zone of overmodulation:

for $j=2,\dots\ i-1$:

$$\beta_j = \beta_1 \cos\left[(j - 1 - K_3)\tau K_{ov1}\right] \tag{6}$$

$$\gamma_j = \beta_{i-j+1}\left\{0.5 - 0.87\tan\left[(i - j - K_3)\tau\right]\right\}K_{ov2} \tag{7}$$

$$\beta_i = \beta'' = \beta_1 \cos\left[(i - K_3 - 1)\tau K_{ov1}\right]K_s \tag{8}$$

$$\gamma_1 = \beta''\left\{0.5 - 0.87\tan\left[(i - K_3 - 2)\tau + \frac{\beta_{i-1} + \beta_i + \lambda_{i-1}}{2}\right]\right\}K_s K_{ov2} \tag{9}$$

$$\lambda_j = \tau - \frac{\beta_j + \beta_{j+1}}{2} \tag{10}$$

$$\lambda_i = \lambda' = (\tau - \beta'')K_{ov1}K_s, \tag{11}$$

where: $\beta_1 = 1.1\,\tau m$ until $F_{ov1} = 0.907\,F_m$, and $\beta_1 = \tau$ after F_{ov1}; $K_s = 1 - \frac{F - F_i}{F_{i-1} - F_i}$ – coefficient of synchronisation; coefficient of overmodulation $K_{ov1}=1$ until F_{ov1}, and $K_{ov1} = 1 - \frac{F - F_{ov1}}{F_{ov2} - F_{ov1}}$ between F_{ov1} and $F_{ov2}=0.952\,F_m$; coefficient of overmodulation $K_{ov2}=1$ until F_{ov2}, and $K_{ov2} = 1 - \frac{F - F_{ov2}}{F_m - F_{ov2}}$ in the zone between F_{ov2} and F_m; $K_3=0$ for CPWM and $K_3=0.25$ for DPWM.

3.4 Rational Phase Shifting between Inverter Modules

A phase shifting parameter is an important parameter for control of a modular converter. In order to provide high quality multilevel output voltage of the inverter, a relative shift between voltage waveforms of every three-phase inverter has to be generated. It is known [3] that for n-cascaded converter consisting from n voltage source inverters the most rational value of this shift can be determined as a

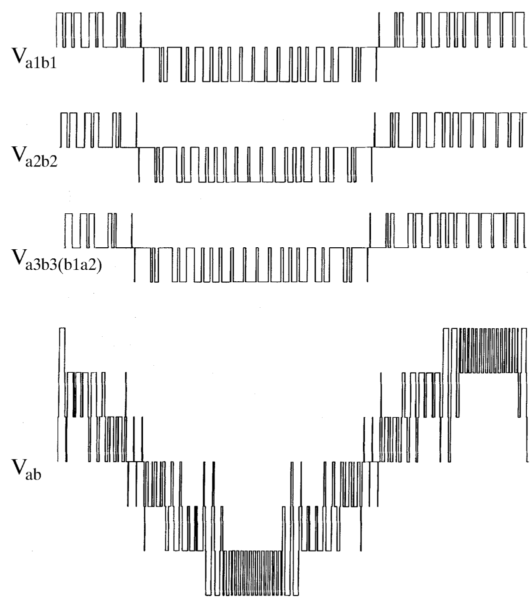

Fig. 5 Line-to-line voltage of every module and of the converter with continuous PWM (CPWM, F=40 Hz, m=0.8)

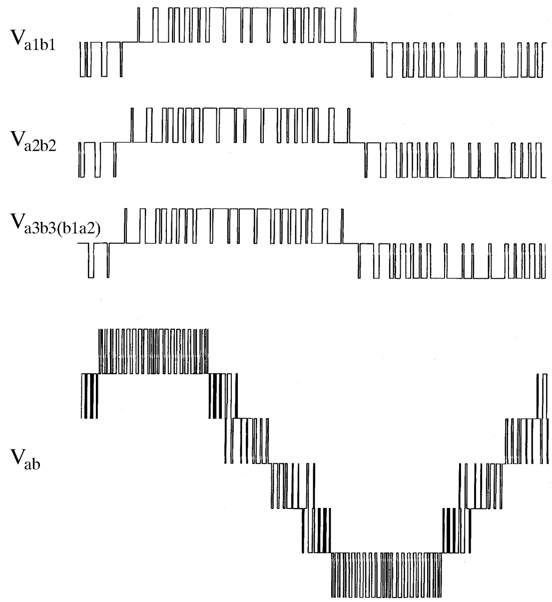

Fig. 6 Line-to-line voltage of every module and of the converter with discontinuous PWM (DPWM, F=40 Hz, m=0.8)

corresponding fixed part of the switching period. In accordance with the specific properties of continuous and discontinuous PWM schemes, the rational value of this phase shift is equal to one third of the duration of the switching period τ for discontinuous PWM, and two thirds of τ for continuous pulse-width modulation.

Figure 5 and Figure 6 show a period of the line voltage of every inverter and the composed line-to-line voltage of the converter with an ideal transformer. It corresponds to synchronised continuous (Figure 5) and discontinuous (Figure 6) PWM, with the fundamental frequency $F = 40$ Hz and modulation index $m = 0.8$. The phase shifting between the inverter modules is equal to $\frac{1}{3}\tau$ for DPWM, and equal to $\frac{2}{3}\tau$ for CPWM. The average switching frequency is equal to 700 Hz for the presented PWM versions.

Every module voltage and the composed line-to-line voltage have quarter-wave symmetry here, the spectra of which do not contain even harmonics and sub-harmonics (combined harmonics). This scheme provides also smooth pulses ratio changing at the whole control range including the zone of overmodulation. During control of the modulation index m, the number of levels in the line-to-line output voltage of the converter decreases automatically here from four to three at $m = 0.67$, and it is equal to three when the modulation index $0.33 < m < 0.67$ (Figure 7). Then, at $m = 0.33$, the number of levels decreases smoothly from three to two levels, and it is equal to two levels if $m < 0.33$ (Figure 8). This reduces strongly a motor voltage stress at lower fundamental frequencies in the drive system.

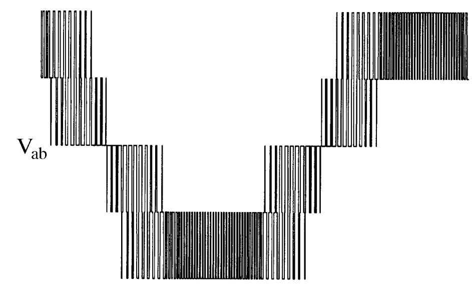

Fig. 7 Line-to-line voltage of the converter with continuous PWM (CPWM, F=25 Hz, m=0.5)

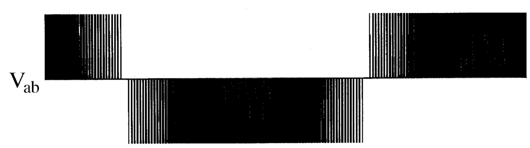

Fig. 8 Line-to-line output voltage of the converter with continuous PWM (CPWM, F=12.5 Hz, m=0.25)

All presented voltage waveforms are characterised by quarter-wave symmetry, and its spectrum does not contain even harmonics and combined harmonics (sub-harmonics) of the fundamental frequency, that is especially important for power systems with low switching frequencies.

3.5 Spectral Assessement of the Output Voltage

To analyse spectral composition of the output voltage of the converter, a weighted total harmonic distortion factor *WTHD* is used (12), which is determined by the means of a FFT algorithm with $n = 500$:

$$WTHD = \frac{\sqrt{\sum_{k=2}^{n}\left(\frac{V_k}{k}\right)^2}}{V_1}, \tag{12}$$

where V_1 and V_k – amplitudes of the fundamental and k-harmonics of the line voltage of the modular converter.

Figure 9 shows the variation of the averaged weighted total harmonic distortion factor (*WTHD*) of the line output voltage of every inverter (dotted curves) and of the converter (solid curves) from the modulation index m, calculated for the analysed variants of synchronous continuous (CPWM) and discontinuous (DPWM) modulation for the average switching frequency F_s, equal to 700 Hz and 1.1 kHz, for the scalar control mode. A typical tendency in variation of *WTHD* of the inverter modules (dotted curves) is here, showing a better performance of continuous PWM techniques until the modulation index m is equal to 0.55–0.6. But this difference is not shown strongly for the output voltage of the converter (solid lines), which has pulsating character of *WTHD* between the boundary frequencies F_i during the whole zone of the linear control.

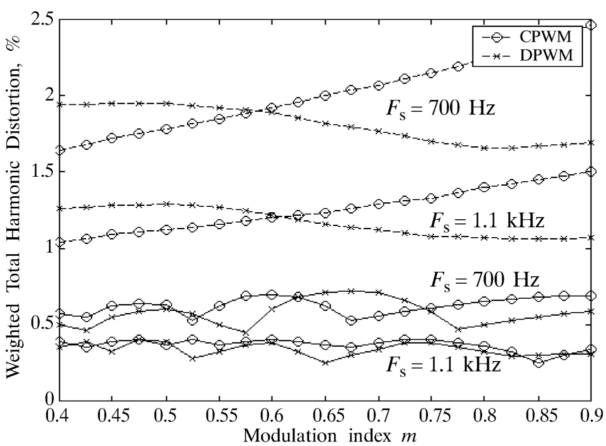

Fig. 9 WTHD of the line-to-line voltage for synchronised PWM (— V_{ab}, - - V_{a1b1})

Figure 10 shows the averaged *WTHD* of the line-to-line voltage of the modular converter between synchronised (solid line) and standard asynchronous

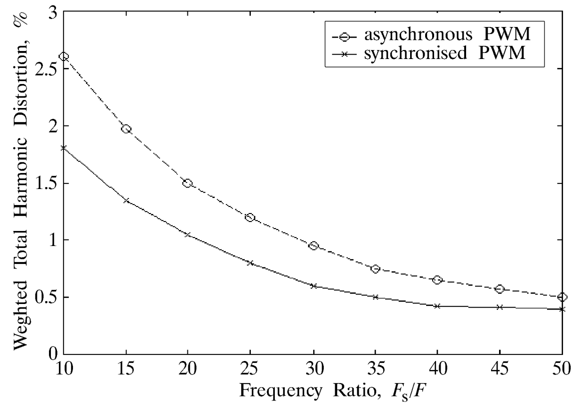

Fig. 10 WTHD of the line-to-line voltage for synchronous and asynchronous CPWM

([6], dotted line) continuous pulsewidth modulation (CPWM). *WTHD* has been determined as a function of the ratio F_s/F between the switching and fundamental frequencies, for $F = 30$ Hz, $m = 0.6$, in accordance with the averaging approach [5]. Figure 10 shows an advantage of synchronised PWM for low frequency ratio, available for high power systems.

4 CONCLUSIONS

A novel method of digital synchronised PWM, based on direct representation of the pulse patterns as a function of the fundamental and switching frequencies of the drive system, is applied to modular converters consisting of three standard inverters and multi-winding transformer. It allows to provide synchronisation of the output voltage for both every inverter module and of the converter during the whole control range including overmodulation, with smooth pulses-ratio changing. The output voltage waveforms have quarter-wave symmetry, and its spectra do not contain even harmonics and sub-harmonics (combined harmonics) of the fundamental frequency, which is especially important for high power drive systems.

The proposed method can also be disseminated to other topologies of three-level and multi-level power converters [10].

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Trofazni kaskadni pretvarači s izravnom sinkronom širinsko-impulsnom modulacijom. Primijenjena je nova metoda izravne sinkrone šironsko-impulsne modulacije za upravljanje višerazinskim pretvaračima koji se sastoje od tri standardna trofazna izmjenjivačka modula te 0,33 p.u. izlaznog transformatora. Predložena metoda osigurava sinkronzaciju valnih oblika izlaznog napona za svaki izmjenjivački modul i za cjeli pretvarač. Izlazni napon višerazinskog pretvarača ima četvrtvalnu simetričnost u čitavom području vrijednosti, uključivo i područje nadmodulacije. Analizirane su i simulacijski uspoređene kontinuirane i diskontinuirane inačice sinkrone širinsko-impulsne modulacije, zasnovane na vektorskom načelu određivanja impulsnog niza. Simulirani su sustavi s niskom sklopnom frekvencijom, kakvi su standardno sustavi velike snage.

Ključne riječi: upravljanje pretvaračima, modulacijske strategije, višerazinski pretvarači, elektromotorni pogoni promjenljive brzine

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