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ONE-STAGE AND TWO-STAGE STRATEGIES OF THE FLEXIBLE DIGITAL PWM

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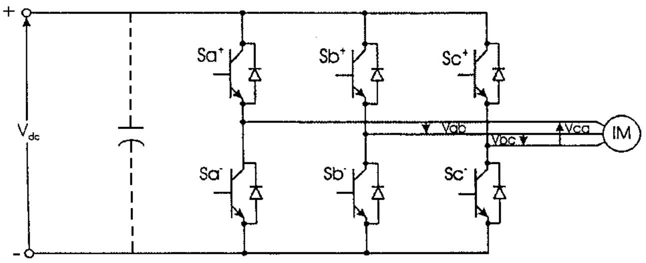
Abstract. *This paper presents detailed description of the one-stage and two-stage schemes of novel method of synchronous pulsewidth modulation (PWM) for voltage source inverters for ac drive application. The proposed control functions provide accurate realization of different versions of voltage space vector modulation with synchronization of the voltage waveforms of the inverter and with smooth pulses-ratio changing. Voltage spectra do not contain even harmonics and sub-harmonics (combined harmonics) during the whole control range including the zone of overmodulation. Examples of determination of the basic control parameters of the inverters with low switching frequency, as well as results of its simulations, are presented.*
Keywords: *voltage source inverters, control of adjustable speed drives, schemes of space-vector modulation.*

Introduction

Control of power converters feeding adjustable speed ac drives is based on the principle of modulation of pulse signals. Parameters and characteristics of power conversion systems are in dependence of the PWM methods and techniques used [1]-[3].
Voltage source inverters are nowadays the most widespread converters for different applications, especially for induction motor drives. Control of the output signals of three-phase inverters is mainly based on the corresponding schemes of voltage space vector modulation, which is the most suitable for adjustable speed drives [1].
Typical vector PWM of the output voltage of the inverters is based on asynchronous principle. It is accompanied by the non-symmetrical voltage waveforms, the spectra of which contain even harmonics and sub-harmonics (combined harmonics) which are very undesirable in most applications [1],[4]-[5]. So, synchronization of the output voltage of the inverters is an important practical problem, especially for the power systems with low switching frequency. Some techniques, providing symmetry of the voltage waveforms during PWM control, have been described in [5],[6], but they were based on undesirable abrupt pulses-ratio changing during transition between control sub-zones.
In order to provide synchronous symmetrical voltage control with smooth pulses-ratio changing, a novel method of feedforward PWM for drive inverters has been recently proposed with application to the one-stage scheme of algebraic discontinuous PWM with the 30^0 non-switching intervals [7],[8].
This paper presents a theoretical description and some simulation results of both one-stage and more flexible two-stage schemes of synchronous pulsewidth modulation. Control algorithms are based here on accurate trigonometric control functions.

One-stage scheme of synchronous PWM

Fig. 1a shows a simplified structure of three-phase voltage source inverter supplying the induction motor (*IM*) as a load. Fig. 1b presents 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** within six sectors **I-VI**). The conventional definition for the state sequences (voltage vectors) of 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). This vector form is very convenient for analysis and synthesis of voltage waveforms for 3-phase converters with different versions of PWM.



a)

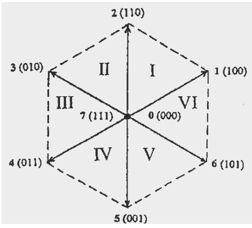


Fig. 1. Basic structure of three-phase voltage source inverter with an induction motor *IM* as a load (a), and its output voltage vectors (b).

Fig. 2 shows the switching state sequences, control signals for a three switches and line output voltage of the inverter for the one-stage scheme of direct synchronous PWM, applied to discontinuous symmetrical PWM with the 30^0-non-switching intervals (DPWM, Method 4 in [3]).

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 $\lambda^{'}$ (λ_4) (with the neighbouring signals $\beta^{''}$ (β_4)), its widths are reduced smoothly till close to zero values at the boundary frequencies F_i calculated in accordance with (1):

$$F_i = \frac{1}{6(2i-1.5)\tau}. \qquad (1)$$

Specific properties of discontinuous PWM allows providing a better quality of the output voltage of the inverter in comparison with continuous PWM at higher values of the fundamental frequency of the drive systems [1],[3],[8].

Symmetrical variation of the voltage waveform of the inverter with synchronous PWM is provided by a special algorithm [7]-[8]. It provides continuous adjustment of the voltage waveform with smooth pulses-ratio changing.

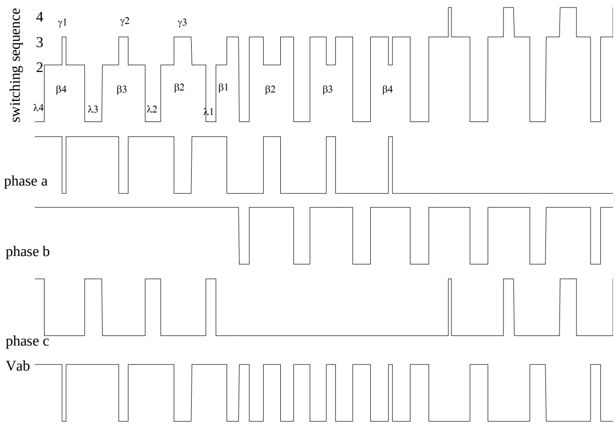


Fig. 2. Control and output signals for quarter-period of the inverter with DPWM.

Equations (2)-(7) present a set of accurate trigonometric control functions for determination of parameters for control and output signals of the inverter in absolute values (seconds) for standard scalar control mode of the drive system during the whole range including the zone of overmodulation:

for *j=2,...i-1:*

$$\beta_j = \beta_1 \cos[(j-1-K_3)\tau K_{ov1}] \qquad (2)$$

$$\gamma_j = \beta_{i-j+1}\{0.5-0.87\tan[(i-j-K_3)\tau]\}K_{ov2} \qquad (3)$$

$$\beta_i = \beta^{''} = \beta_1 \cos[(i-K_3-1)\tau K_{ov1}]K_s \qquad (4)$$

$$\gamma_1 = \beta^{''}\{0.5-0.87\tan[(i-K_3-2)\tau + (\beta_{i-1}+\beta_i+\lambda_{i-1})/2]\}K_s K_{ov2} \qquad (5)$$

$$\lambda_j = \tau - (\beta_j + \beta_{j+1})/2 \qquad (6)$$

$$\lambda_i = \lambda^{'} = \left(\tau - \beta^{''}\right)K_{ov1}K_s, \qquad (7)$$

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

Figure 3 illustrates the variation of the clock-point signals for scalar control mode of the drive sys-tem with DPWM with low switching frequency.

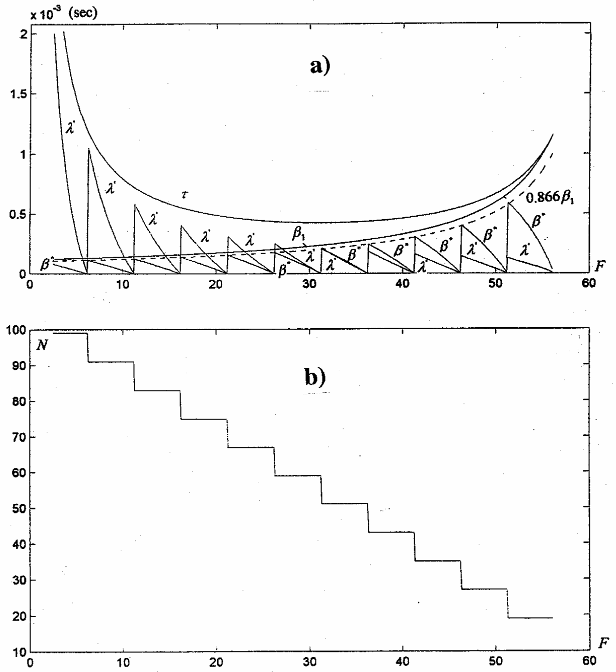


Fig. 3. Variation of the clock-point signals (a), and number of pulses in half-wave of line voltage (b) for discontinuous PWM with variable τ .

The curves in Fig. 3 correspond to the control mode with a non-linear dependence (8) on the duration of switching periods τ from the fundamental and maximum frequencies F and F_m (the speed ratio (diapason between the initial and maximum frequency of scalar control mode) is equal $D=24$ for this case):

$$\tau = \frac{F_m}{6F(DF_m + F_m - DF)} \tag{8}$$

The boundary frequencies are calculated in accordance with (9) for this PWM version:

$$F_i = \frac{F_m(D - 2i + 2.5)}{D} \tag{9}$$

Fig. 3a shows the width variation of $\tau, \beta_1, \lambda', \beta''$. There is a synchronous quasi-linear variation of λ' and β'' here. They are decreased simultaneously till close to zero width at the boundary frequencies. Fig. 3b presents the number of pulses in the half-wave of the output voltage of the inverter, which is changing by eight pulses after every boundary frequency for discontinuous one-stage versions of synchronous PWM.

Two-stage strategy of synchronous PWM

In order to provide more smooth variation of the number of pulses in half-wave of the output voltage of the inverter, a two-stage scheme of synchronous PWM can be used. In addition to the known one-stage scheme of PWM it is characterized by the specific second control stage during smooth step-by-step process of pulse-ratio changing. Fig. 4 illustrates this second stage for the mentioned above version of discontinuous PWM, which includes two novel parameters of the scheme of modulation: clock-point signals β' and the notches λ'' neighbouring with the clock-point signal.

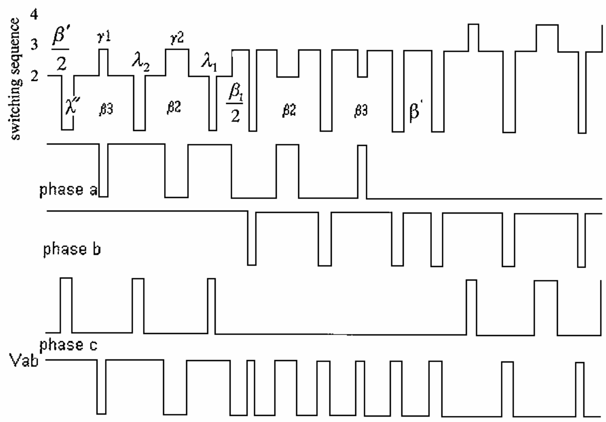


Fig. 4. Control and output signals for quarter-period of the second part of the two-stage scheme of DPWM.

Algorithm of the two-stage synchronous PWM is characterised by two control sub-zones, which are changing each other step-by-step during adjustment of the fundamental frequency. It is based on two threshold (boundary) frequencies F_i' and F_i'', determined for the discontinuous versions of modulation as a function of the number of notches *i* (10) inside a half of the 60^0 clock-intervals correspondingly in accordance with (11):

$$i = \frac{1/6F + 0.5\tau}{2\tau} \qquad (10)$$

$$F_i'' = \frac{1}{6(2i - 2.5)\tau}. \qquad (11)$$

In the first of two control sub-zones, when $F_i'' > F \geq F_i'$, the voltage waveforms for discontinuous PWM are like the presented in Fig. 2, and the basic set of control functions is the same too, but here are another value of the coefficient of synchronization, which is equal to

$$K_{s1} = [1 - (F - F_i')/(F_i'' - F_i')] \qquad (12)$$

for determination of λ' and γ_1, and

$$K_{s1}' = [1 - 0.75(F - F_i')/(F_i'' - F_i')] \qquad (13)$$

for determination of the β'' signal. So here is a linear decrease of duration of the β'' signal, and then the junction of two equal halves into one signal β', situated on the edges of the 60^0 clock-intervals, at the F_i'' boundary frequencies.

Control in the second sub-zones, when $F_i' > F \geq F_{i+1}''$, is based on the frame set of functions, described previously. It is also characterized by the linear variation of the β'-signal in accordance with (14), its width is close to zero at the next boundary frequency. Here is also smooth quasi-linear variation of the notches λ'' (15), neighboring with the β'-signal. The coefficient of synchronization K_{s2} is determined from (16) in these control sub-zones:

$$\beta' = \beta_{i+1} = 0.433\beta_1 K_{s2} \qquad (14)$$

$$\lambda'' = \lambda_{i+1} = 1/12F - (i - 1.25)\tau - \beta_i/2 - \beta'/2 \qquad (15)$$

$$K_{s2} = [1 - (F - F_{i+1}'')/(F_i' - F_{i+1}'')]. \qquad (16)$$

Fig. 5 shows the variation of the basic control signals for the two-stage scheme in discontinuous PWM until the zone of overmodulation. The parameters of the control process are the same as in the example presented in the previous part. Fig. 5a illustrates the variation of the clock-points signals λ' and β' which are changing each other step-by-step on the boundary frequencies. Fig. 5b presents variation of the signals λ'' and β'' which are the next with the corresponding clock-point signal. Fig. 5c shows pulse number N variation in the

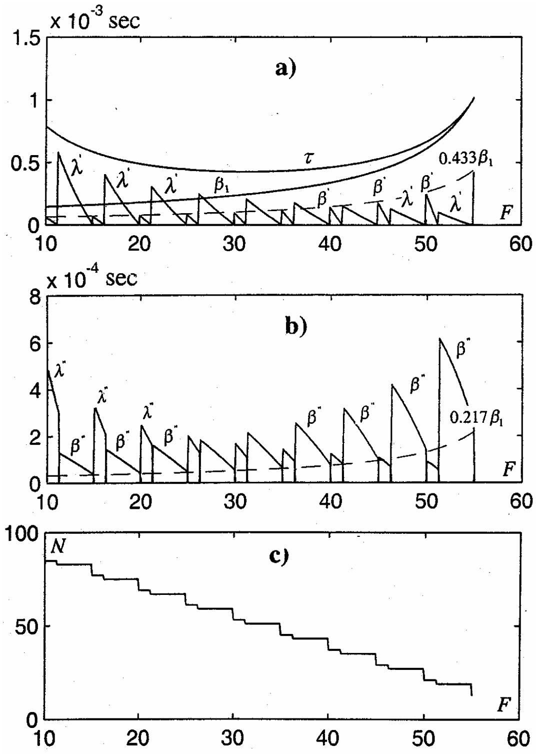


Fig. 5. Variation of the clock-point signals (a), the signals neighbouring with the clock-point signal (b), and number of pulses in half-wave of the line output voltage of the inverter (c).

half-wave of inverter output voltage. It is charac-terized by more flexible smooth pulses-ratio changing compared with the ratio changing of the one-stage scheme, presented in Fig. 3b. Here is non-uniform step-by-step changing the number of pulses (by 6 pulses, by 2, by 6, and so on).

Fig. 6 shows more in details line output voltage of the inverter which corresponds to the boundary part of the 60^0 clock-intervals with the clock-point signals β' and λ'. Control mode corresponds here to the non-linear variation of sub-circles τ during control of the fundamental frequency F from *5 Hz* until *60 Hz* in accordance with (9) where speed ratio $D=12$. In particular, for the left curves in Fig. 6, which correspond to control between the boundary frequencies $F_4'' = 35$ *Hz* and $F_3' = 40$ *Hz*, here is

smooth decrease of the clock-point signal β' until zero at the $F_3{}'$ frequency, with reduction of the number N of pulses in voltage half-wave from 21 to 19.
If the fundamental frequency lies between $F_3{}' = 40\ Hz$ and $F_3{}'' = 45\ Hz$ (right curves in Fig. 6),

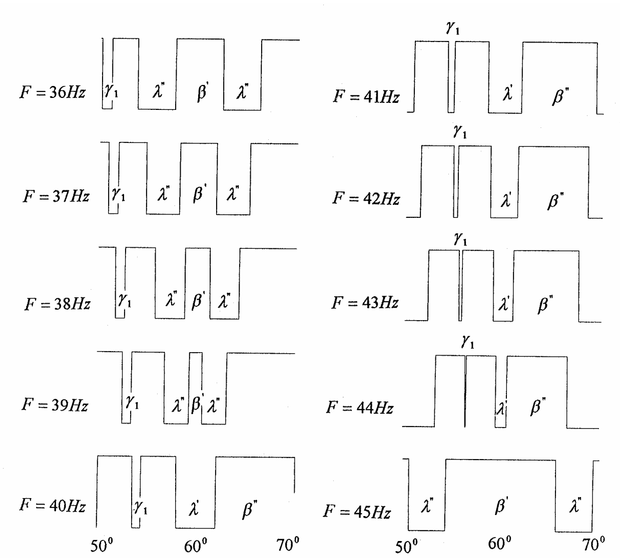


Fig. 6. Part of the line output voltage of the inverter with the two-stage scheme of DPWM.

smooth simultaneous decrease the widths of the signals λ' and γ_1 until zero is in this sub-zone. Number of pulses in voltage half-wave is reduced after the $F_3{}''$ frequency from 19 to 13.

Quality of the output voltage and current

The basic peculiarity of the voltage waveforms for inverters with both one-stage and two stage schemes of synchronous PWM, both continuous and discontinuous, is their quarter-wave symmetry during the whole control range including the zone of overmodulation [7],[8]. So, their spectra include only odd voltage harmonics (without triple harmonics) for any non-integer ratios F_s/F between the switching and fundamental frequencies and for any values of modulation index m. Even harmonics and combined harmonics (of the fundamental frequency) are eliminated from the voltage spectrum in the inverters with synchronous PWM, and it is especially important for power drive systems with low switching frequency.

Comparison of integral (averaged) spectral characteristics of the output voltage of inverters with the one-stage and two-stage schemes of synchronous PWM shows its practical identity for the both schemes.

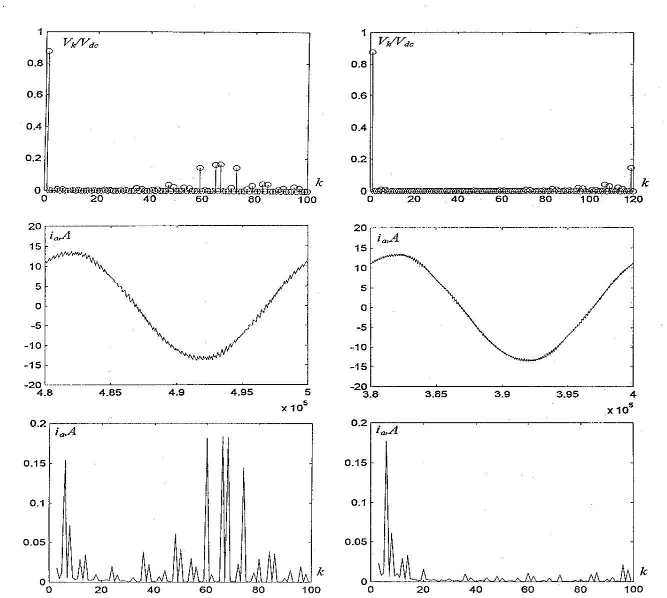


Fig. 7. Spectrum of the line voltage, phase current and its spectrum for the system with synchronous discontinuous two-stage PWM.

Fig. 7 presents results of simulation of adjustable speed drive system with the 5-hp 4-pole 60-Hz induction motor fed by the inverter with the two-stage scheme of synchronous discontinuous PWM. Here are spectrum of the line voltage (amplitudes of its harmonics divided to dc-link voltage), phase current i_a of the induction motor and its spectrum (in amperes, without the first harmonic). Fundamental frequency of the system is $50\ Hz$, modulation index $m=0.866$. Left curves correspond to PWM with average switching frequency $2.25\ kHz$, right curves – to switching frequency is equal to $4.5\ kHz$.
Fig. 8 shows the averaged weighted total harmonic distortion factor of line voltage of the inverter (*WTHD*, [8]) for synchronous one-stage scheme of continuous PWM (solid line) and standard asynchronous continuous PWM ([2], dotted line). *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 [8].

Figure 8 illustrates an advantage of synchronous PWM for the inverters with low switching frequencies, until frequency ratio is equal to about 100.

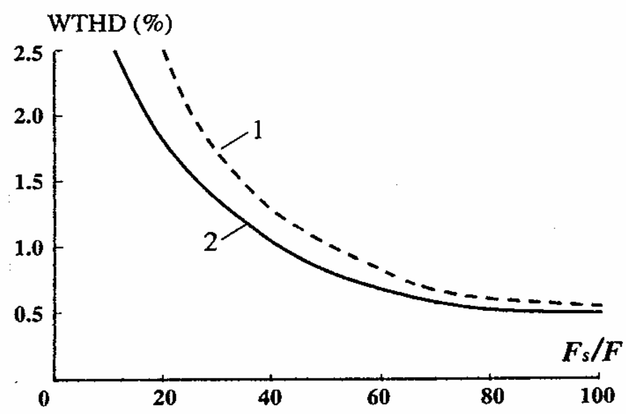


Fig. 8. *WTHD* of line voltage for asynchronous (1) and synchronous (2) PWM.

Conclusions

Both one-stage and two-stage strategies of direct synchronous PWM for three-phase inverters have been proposed and analysed in this paper. It allows providing synchronisation of the output voltage of the inverter during the whole control range including overmodulation, with quarter-wave symmetry of the voltage waveforms, the spectra of which do not contain even harmonics and sub-harmonics (combined harmonics), with flexible shock-less pulses-ratio changing.

The two-stage schemes of synchronous PWM provide smoother pulses-ratio changing compared with the one-stage ones. Analysis and comparison of the average *WTHD* factor for the one-stage and two-stage schemes of synchronous PWM show its practical identity for the both schemes. Both analysed strategies of synchronous PWM provide better spectral composition of the output voltage at low switching frequencies, until frequency ratio is equal to about 100.

The method, strategies and schemes proposed can also be disseminated to other topologies of inverters and converters.

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