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MULTILEVEL INVERTERS FOR UNCONVENTIONAL ENERGY CONVERSION SYSTEMS

BY

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Abstract. In view to decrease the natural fuel reserves and in order to reduce pollution, it was and it is still necessary to develop new types of energy sources. Wind energy sources are among the most efficient unconventional energy sources and, therefore, this paper presents a comparative analysis and an optimal implementation solution of high power inverters within these systems.

Key words: multilevel inverter; unconventional energy; switching cells; wind energy.

1. Introduction

The inverter aims to transform direct electrical energy into alternating electrical energy. According to the inverter performances, filters can also be connected in order to get alternating voltages as close to the sinusoidal wave as possible. If it is fitted out with thyristors, along with the filters, we can also use reactive power compensation circuits. For IGBT inverters, compensation of reactive power is no longer necessary with an adequate control technique, and the filtering circuits are smaller in size.

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Fig. 1 presents a complete wind energy conversion system, which allows the connection of alternating energy consumers at its output (Ullah & Thiringer, 2007).

Using such systems at high powers supposes a special architecture of the converters within these systems, therefore of inverters too. Static power converters for high voltages generally need switches (semiconductor devices) that can function at these voltages. If these switches are not available, different converter topologies must be developed, where only a voltage fraction is applied to each switch. An optimal solution, that fulfils quite well these requirements, consists in using multilevel voltage inverters with imbricated switching cells. These inverters bring about certain advantages, such as: the decrease of the total harmonic distortion factor, limiting the du/dt stress due to reducing the switched voltage, output waveforms close to sinusoidal wave, etc.

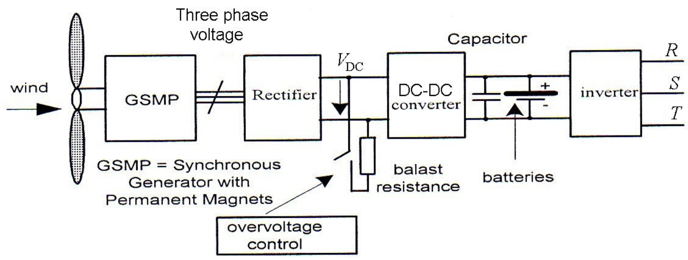


Fig. 1 – Wind energy conversion system.

2. Strategies for Multilevel Inverter Control

The control of multilevel switching cells must fulfill simultaneously two important requirements

a) compatibility with voltage $U_{Ck} = kU_d/n$ = const., (k = 1,...,n);

b) optimization of the harmonic spectrum.

Each capacitor, C_k, is connected between the pairs of switches k and $k+1$ (Fig. 2).

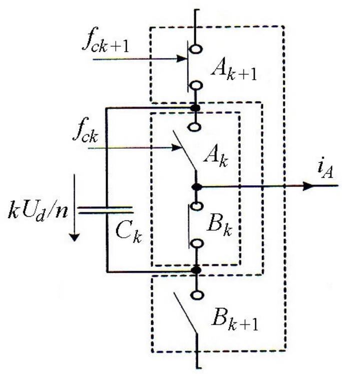


Fig. 2 – Connecting capacitor, C_k.

According to their state, the current through the capacitor can be: $-I_A$, 0 or $+I_A$ (we assumed $I_A = i_A$ = const. for the duration of a switching period, T_p). Thus, the current through the capacitor can be expressed as

$$i_{Ck} = (f_{Ck} - f_{Ck+1})I_A, \tag{1}$$

where f_{Ck} and f_{Ck+1} stand for the connection functions for A_k and A_{k+1} switches and can only have two values: 0 or 1 (according to the state of the switches) (Floricau, 1997). For instance, f_{Ck} = 1 when the A_k switch is off and f_{Ck} = 0 when the A_k switch is on. Starting from eq. (1), we can define the permanent stability condition for the voltage on the capacitors, U_{Ck}, (k = 1,...,n)

$$\overline{I}_{Ck} = 0 \text{ therefore } \int_0^{T_p} (f_{Ck} - f_{Ck+1})\mathrm{d}t = 0. \tag{2}$$

The obvious solution of eq. (2) corresponds to the classic structure of switches connected in series, where the control systems are identical. If there is one control signal for all switches, the current through the capacitor will permanently be null (in theory), therefore they are no longer necessary. More generally, the stability condition is fulfilled if control signals f_{Ck}, f_{Ck+1} have the same conduction duration during a switching period, even if they are out of phase.

For multilevel converters, in order to obtain equal conduction durations for all the cells of an arm, it is necessary to use n carrier waves dephased by T_p/n and, thus, stability for capacitors C_1, ...,C_n is realized.

The power circuit of the three-level inverter with imbricated cells and the control strategy are presented in Fig. 3.

The PWM control strategy adopted for an arm consists in comparing a reference (sinusoidal) wave to two carrier (triangular symmetric) waves having a phase difference of 180° (Hava *et al.*, 1997). These comparisons lead to two connection functions for arm, f_{c1} and f_{c2}, defined as follows:

$$\begin{cases} v_u > v_{p1}, \text{ therefore } f_{c1} = 1; \ v_u > v_{p2}, \text{ therefore } f_{c2} = 1; \\ v_u < v_{p1}, \text{ therefore } f_{c1} = 0; \ v_u < v_{p2}, \text{ therefore } f_{c2} = 0. \end{cases} \tag{3}$$

The power circuit of the four-level inverter with imbricated cells and the control strategy are presented in Fig. 4.

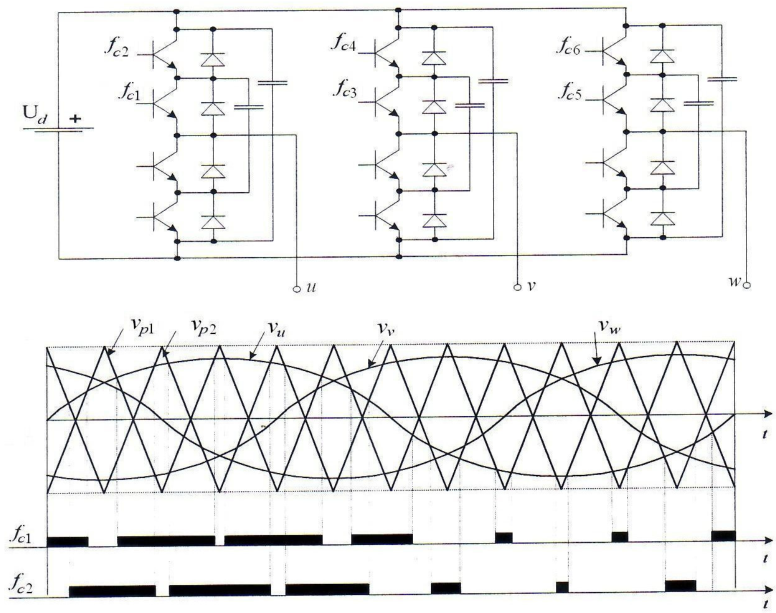


Fig. 3 – Three-phase voltage inverter with three-level imbricated switching cells and sinusoidal PWM control strategy.

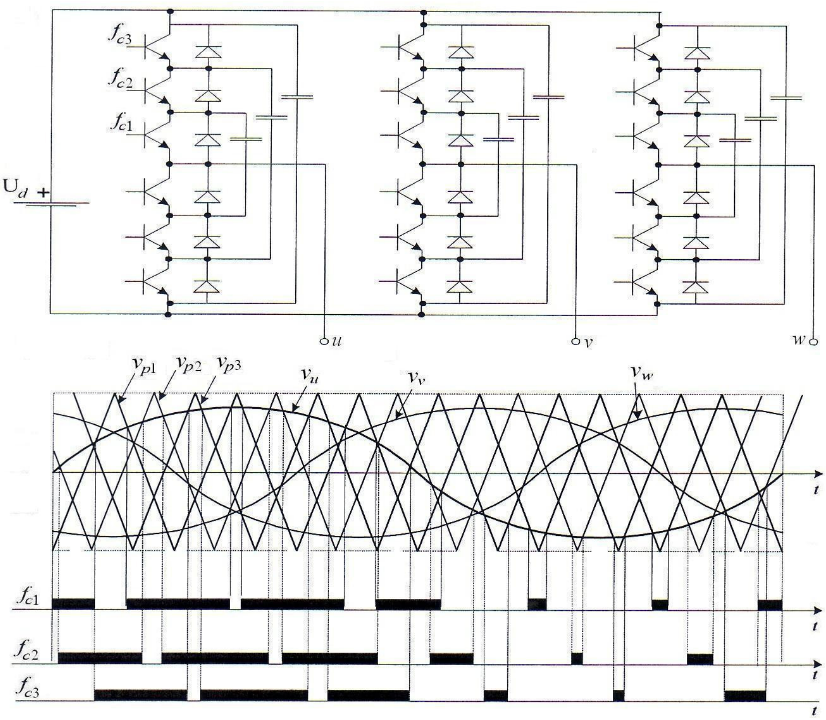


Fig. 4 – Three-phase voltage inverter with four-level imbricated switching cells and PWM control strategy.

The PWM control strategy adopted for an arm consists in comparing a reference (sinusoidal) wave to three carrier (triangular symmetrical) waves having a phase difference of 120°. These comparisons lead to two connection functions for arms f_{c1}, f_{c2} and f_{c3}, defined as follows:

$$\begin{cases} v_u > v_{p1} \text{ therefore } f_{c1} = 1;\; v_u > v_{p2} \text{ therefore } f_{c2} = 1;\; v_u > v_{p3} \text{ therefore } f_{c3} = 1; \\ v_u < v_{p1} \text{ therefore } f_{c1} = 0;\; v_u < v_{p2} \text{ therefore } f_{c2} = 0;\; v_u < v_{p3} \text{ therefore } f_{c3} = 0. \end{cases} \quad (4)$$

The control strategies presented above, destined to three-phase inverters with imbricated switching cells, are well known in the specialty literature. Moreover, studies were performed which have highlighted the benefits and drawbacks of their use. We shall now focus on studying the functioning of these inverters if, as part of the control strategy, the reference sinusoidal wave is replaced by a modified sinusoidal wave (discontinuous command techniques, DPWM) (Meynard & Foch, 1993), described by eq.

$$s_1 = \begin{cases} 1; & 0 \le \omega_m t \le \pi/6, \\ \sqrt{3} m_a \cos\omega_m t + m_a \sin\omega_m t - 1; & \pi/6 \le \omega_m t \le \pi/2, \\ \sqrt{3} m_a \cos\omega_m t - m_a \sin\omega_m t + 1; & \pi/2 \le \omega_m t \le 5\pi/6, \\ -1; & 5\pi/6 \le \omega_m t \le 7\pi/6, \\ \sqrt{3} m_a \cos\omega_m t - m_a \sin\omega_m t + 1; & 7\pi/6 \le \omega_m t \le 3\pi/2, \\ \sqrt{3} m_a \cos\omega_m t + m_a \sin\omega_m t - 1; & 3\pi/2 \le \omega_m t \le 11\pi/6, \\ 1; & 11\pi/6 \le \omega_m t \le 2\pi. \end{cases} \quad (5)$$

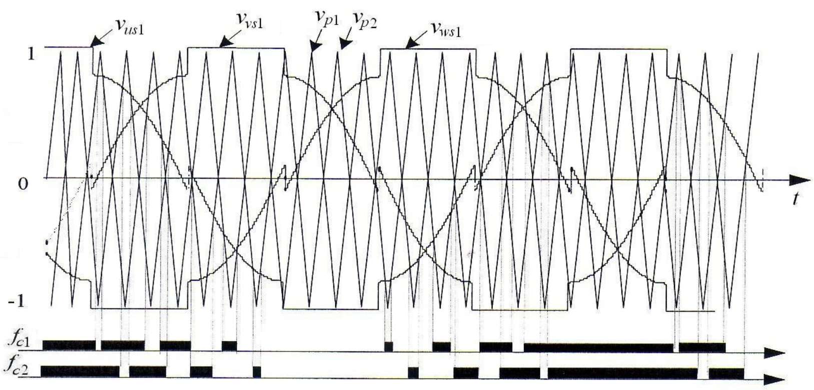
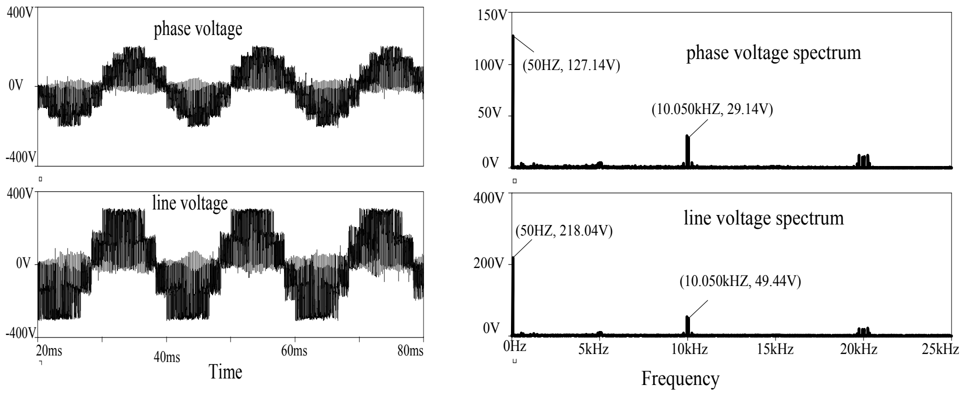


Fig. 5 – Control strategy of the three-phase voltage inverter with three-level imbricated switching cells, using signal s_1.

Fig. 5 presents the control strategy applied to the inverter illustrated in Fig. 4, using the modified sinusoidal wave, s_1, and its waveform, v_{us1}, v_{vs1}, v_{ws1}, for the given situation.

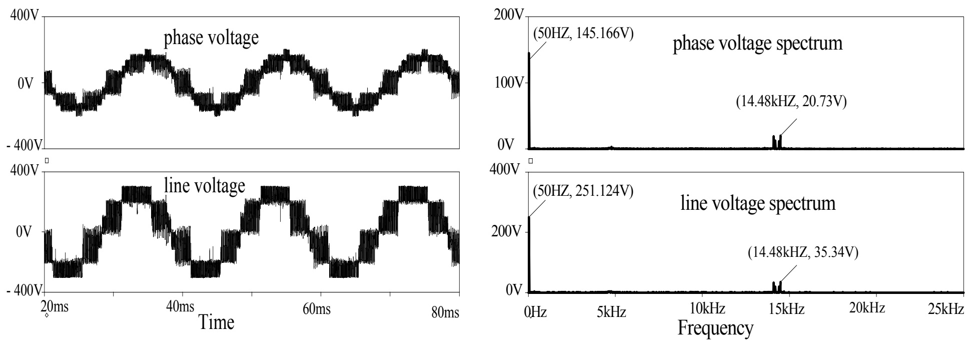
3. Simulation Results

Starting from the performed study and using the simulation environment Pspice, we shall present a comparative analysis of the functioning of the three-level three-phase inverter and of the four-level three-phase inverter, respectively. For the simulation of the three-level inverter we used the sinusoidal PWM and the DPWM control strategies; on the other hand, for the simulation of the four-level inverter we used only the PWM control strategy. In all situations, we took into account the following values: inductive load, R = 10 Ω, L = 10 mH, amplitude modulation index, m_a = 0.95, carrier wave frequency, 50 Hz, switching frequency, 5 kHz, and supply voltage amplitude U_d = 310 V.



a *b*

Fig. 6 – Three-level inverter: *a* – phase- and line voltage waveforms using PWM sinusoidal control; *b* – phase- and line-voltage spectrum using sinusoidal PWM control.



a *b*

Fig. 7 – Four-level inverter: *a* – phase- and line voltage waveforms using PWM sinusoidal control; *b* – phase- and line-voltage spectrum using sinusoidal DPWM control.

Figs. 6 *a* and 6 *b* present the main waveforms resulting from the simulation of the three-level inverter using the sinusoidal PWM strategy.

Figs. 7 *a* and 7 *b* present the main waveforms resulting from the simulation of the four-level inverter using the sinusoidal PWM control strategy, the phase voltage, the line voltage, their spectral diagram and the load current.

The results of the simulation of three- and four-level inverters controlled by sinusoidal PWM show their main benefits and drawbacks. Although, in the last topology, the waveform is much closer to the sinusoidal waveform and the harmonic spectrum due to commutations shifts to high frequencies, with reduced amplitudes, these inverters are difficult to implement, at both power and control level, and they also involve high costs.

Our alternative, namely using a DPWM-controlled three-level inverter with imbricated switching cells, represents an optimal solution. The simulation results are presented below.

Figs. 8 *a* and 8 *b* present the main waveforms resulting from the simulation of the three-level inverter using the DPWM control strategy.

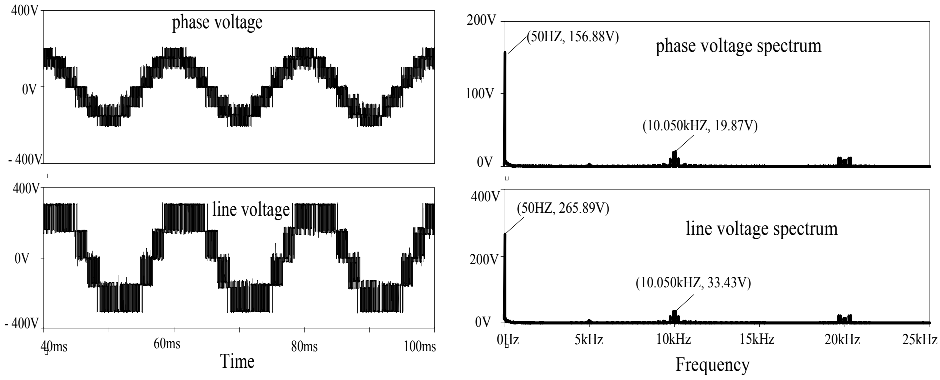


Fig. 8 – *a* – Phase- and line-voltage waveforms using DPWM control; *b* – phase- and line-voltage spectrum using DPWM control.

Fig. 9 presents the evolution of THD% (i_{load}) function when control strategy is implemented.

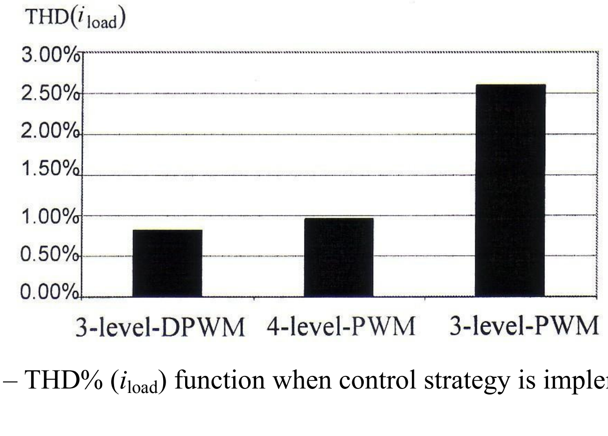


Fig. 9 – THD% (i_{load}) function when control strategy is implemented.

4. Conclusions

Analysing the simulation results we can make the following remarks:

1° Although each switch (transistor) is controlled under a switching frequency of 5 kHz, no harmonics occur around this frequency in the phase- and line-voltage spectrum; they appear at a double switching frequency (10 kHz) for the three-level inverter and at a triple switching frequency (15 kHz) for the four-level inverter.

2° The use of the DPWM control strategy allows the increase of the fundamental harmonic amplitude and the decrease in amplitude of the harmonics that occur at a double switching frequency.

3° The output voltage waveform of the DPWM-controlled three-level inverter is much closer to the sinusoidal waveform; it resembles the four-level inverter waveform, but it is much easier to implement and involves lower costs.

4° THD% has the lowest value for the DPWM-controlled inverter.

Based on these remarks, we can conclude that our solution, namely using DPWM-controlled multilevel inverters with imbricated switching cells, is viable and adequate for solving the problem of designing a wind energy conversion system with improved performances (Ursaru *et al.*, 2010).

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CONVERTOARE MULTINIVEL UTILIZATE ÎN SISTEMELE DE CONVERSIE A ENERGIEI NECONVENȚIONALE

(Rezumat)

Se analizează funcționarea invertoarelor multinivel cu celule de comutație imbricate, utilizate în sistemele de conversie a energiei eoliene. Utilizând o nouă strategie de comandă DPWM, în comparație cu strategia de comandă PWM sinusoidală, sunt scoase în evidență, cu ajutorul simulărilor, principalele avantaje conferite de această tehnică de comandă.