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Reduction in Harmonic Contents for Single-Phase Five-Level PWM Inverter

Amit Kumar Sharma[1], Gaurav Rajoria[2], Ravinder Singh Chauhan[2] and Sawan Sharma[1]

[1]Department of Electrical Engineering, Govt. Women Engineering College, Ajmer, India
[2] Department of Electrical Engineering, Jaipur National University, Jaipur, India
amy.sharma@gmail.com

ABSTRACT

A single-phase five-level PWM inverter is presented to alleviate harmonic components of the output voltage and the load current. Operational principles with switching functions are analyzed. Two reference signals identical to each other with an offset equivalent to the amplitude of the triangular carrier signal were used to generate PWM signals for the switches. The inverter offers much less total harmonic distortion and can operate at near-unity power factor. The proposed system is verified through simulation and is implemented in a prototype.

Key words: Five-Level Inverter, PWM Inverter, THD, Load Currents and Load Voltages

INTRODUCTION

PWM inverter can control their output voltage and frequency simultaneously. And also they can reduce the harmonic components in load currents. These features have made them power candidate in many industrial applications such as variable speed drives, uninterruptible power supplies, and other power conversion systems. the popular single-phase inverters adopt the full-bridge type using approximate sinusoidal modulation technique as the power circuits. The output voltage of them has three values: zero, positive and negative supply dc voltage levels. Therefore, the harmonic components of their output voltage are determined by the carrier frequency and switching functions. Moreover, the harmonic reduction of them is limited to a certain degree. Under these technical backgrounds, this paper presents a single-phase five level PWM inverter whose output voltage has five values: zero, half and full supply dc voltage levels (positive and negative, respectively), so called a five-level single-phase PWM inverter. The proposed inverter can reduce the harmonic components compared with that of traditional full-bridge three-level PWM inverter under the condition of identical supply dc voltage and switching frequency. Operational principles and switching functions are analyzed.

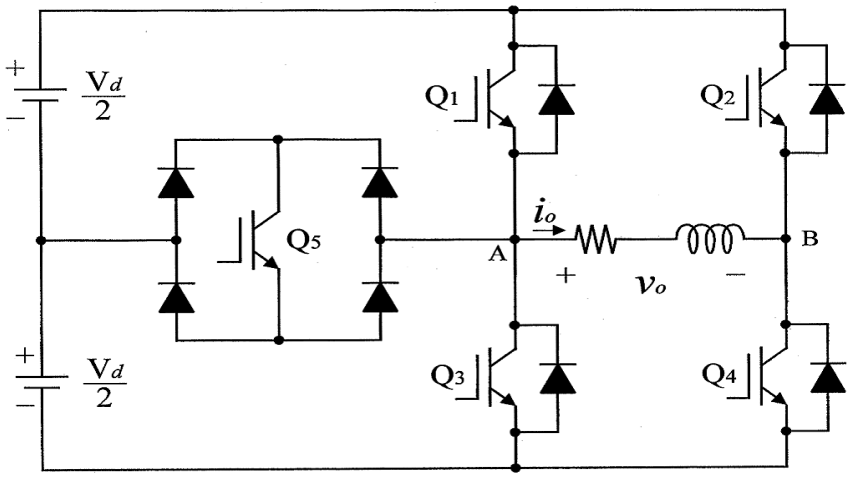

Fig.1 Configuration of the proposed single-phase five-level PWM inverter

THE CONFIGURATION AND OPERATIONAL PRINCIPLE OF PROPOSED INVERTER

Fig. 1 shows a configuration of the proposed single-phase five-level PWM inverter. One switching element and four diodes added in the conventional full-bridge inverter are connected to the center-tap of dc power supply. Proper switching control of the auxiliary switch can generate half level of dc supply voltage. The operation of proposed inverter can be divided into 10 switching states. The additional switch must be properly switched considering the direction of load current. The switching patterns adopted in the proposed inverter are illustrated in Fig. 3, and the output voltage levels according to the switch on off conditions are shown in Table I. Basic principle of the proposed switching strategy is to generate gate signals by comparing the reference signal with the two carrier waves having same frequency and in phase, but different offset voltages. Largely, there are two switching methods according to the output voltage levels. If the required output voltage for a certain load can be produced using only the half of dc bus voltage, only the lower carrier wave is compared with the reference signal the lower dc bus voltage is used to generate the output voltage. Namely, the modulation index is equal or less than 0.5, the behavior of proposed inverter is similar to the conventional full-bridge three-level PWM inverter, and the distribution of harmonic components in output voltage is similar to that of the conventional inverter having the values of two times the modulation index. The mentioned above is the first operational mode. On the other hand, if the required output voltage is increased beyond the modulation index 0.5, it comes into the second mode using the upper bank of capacitor. In this case, the switching function produced by upper carrier wave is prior to that of the lower. According to the amplitude of the voltage reference, the operational interval of each mode varies within a certain period. The modes are separated as

$$\begin{aligned}&\text{Mode A: } 0 < \text{wt} \le \theta_1, \quad \theta_2 < \text{wt} < \pi\\ &\text{Mode B: } \theta_1 < \text{wt} \le \theta_2\\ &\text{Mode C: } \pi < \text{wt} \le \theta_3, \quad \theta_4 < \text{wt} < 2\pi\\ &\text{Mode D: } \theta_3 < \text{wt} \le \theta_4\end{aligned} \tag{1}$$

The phase angle depends on the modulation index. The modulation index M_a of the proposed five-level PWM inverter is defined as [5]

$$\mathrm{M_a} = \frac{\mathrm{A_M}}{2\mathrm{A_c}} \tag{2}$$

Where $\mathrm{A_M}$ is peak value of voltage referenceV_{ref}, and $\mathrm{A_c}$ is peak-to-peak value of carrier. When the modulation index is less than 0.5, the phase angle displacement is equal to

$$\begin{aligned}&\theta_1 = \theta_2 = \frac{\pi}{2},\\ &\theta_3 = \theta_4 = \frac{3\pi}{2}\end{aligned} \tag{3}$$

On the other hand, when the modulation index is greater than 0.5, the phase angle displacement is determined by

$$\begin{aligned}&\theta_1 = \sin^{-1}\left(\frac{\mathrm{A_C}}{\mathrm{A_M}}\right)\\ &\theta_2 = \pi - \theta_1\\ &\theta_3 = \pi + \theta_1\\ &\theta_4 = 2\pi - \theta_1\end{aligned} \tag{4}$$

The control signals are generated by the signals $\mathrm{C_A}$ and $\mathrm{C_B}$ come from the comparators, which compare the respective carrier signals with the voltage reference , the gate signals $\mathrm{Q_1}-\mathrm{Q_5}$are produced by the phase angle displacement. The switching functions of proposed inverter are then given by the use of logical AND, OR, NOT gates.

$$\begin{aligned}&\mathrm{Q_1} = \overline{\mathrm{C_A}} * \mathrm{P_2} + \overline{\mathrm{C_B}} * \mathrm{P_4} + \overline{\mathrm{C_B}} * \mathrm{P_6}\\ &\mathrm{Q_2} = \mathrm{P_4} + \mathrm{P_5} + \mathrm{P_6}\\ &\mathrm{Q_3} = \overline{\mathrm{C_B}} * \mathrm{P_2} + \overline{\mathrm{C_B}} * \mathrm{P_3} + \overline{\mathrm{C_A}} * \mathrm{P_5}\\ &\mathrm{Q_4} = \mathrm{P_1} + \mathrm{P_2} + \mathrm{P_3}\\ &\mathrm{Q_5} = \mathrm{C_B} * \mathrm{P_1} + \mathrm{C_A} * \ \mathrm{C_B} * \mathrm{P_2} + \mathrm{C_B} * \mathrm{P_3} + \mathrm{C_B} * \mathrm{P_4} + \mathrm{C_B} \quad * \mathrm{C_A} * \mathrm{P_5} + \mathrm{C_B} * \mathrm{P_6}\end{aligned} \tag{5}$$

The harmonic components of output voltages in the proposed and the conventional inverter will be presented in the following. From the two carrier waves and output voltage, the analysis of harmonic components in the proposed inverter can be performed. The output voltage produced by comparisons of the reference signal and two carrier waves can be expressed as

$$\mathrm{V_o}(\theta) = \mathrm{A_o} + \sum_{\mathrm{n}=1}^{\infty}(\mathrm{A_n}\cos \mathrm{n}\theta + \mathrm{B_n}\sin \mathrm{n}\theta) \tag{6}$$

If there are P pulses per a quarter period, and it is an odd number, the coefficients $\mathrm{B_n}$ and $\mathrm{A_O}$ would be a zero where is an even number. Therefore, the equation (6) can be rewritten as

$$\mathrm{V_o}(\theta) = \sum_{\mathrm{n}=1,3,\ldots}^{\infty} \mathrm{A_n}\cos \mathrm{n}\theta \tag{7}$$

$$\mathrm{A_n} = -\frac{2\mathrm{V_{dc}}}{\mathrm{n}\pi}\sum_{\mathrm{m}=0}^{\mathrm{P}}\sum_{\mathrm{i}=1}^{4}[(-1)^{\mathrm{int}(\mathrm{i}/2)}\sin(\mathrm{n}\alpha_{\mathrm{m+i}})] \tag{8}$$

Where m is a pulse number, The Fourier series coefficient of the conventional single-phase full- bridge inverter by sinusoidal PWM is given as

$$A_n = \frac{4V_{dc}}{n\pi}\sum_{m=1}^{P}\ [(-1)^m \sin(n\alpha_m)] \quad (9)$$

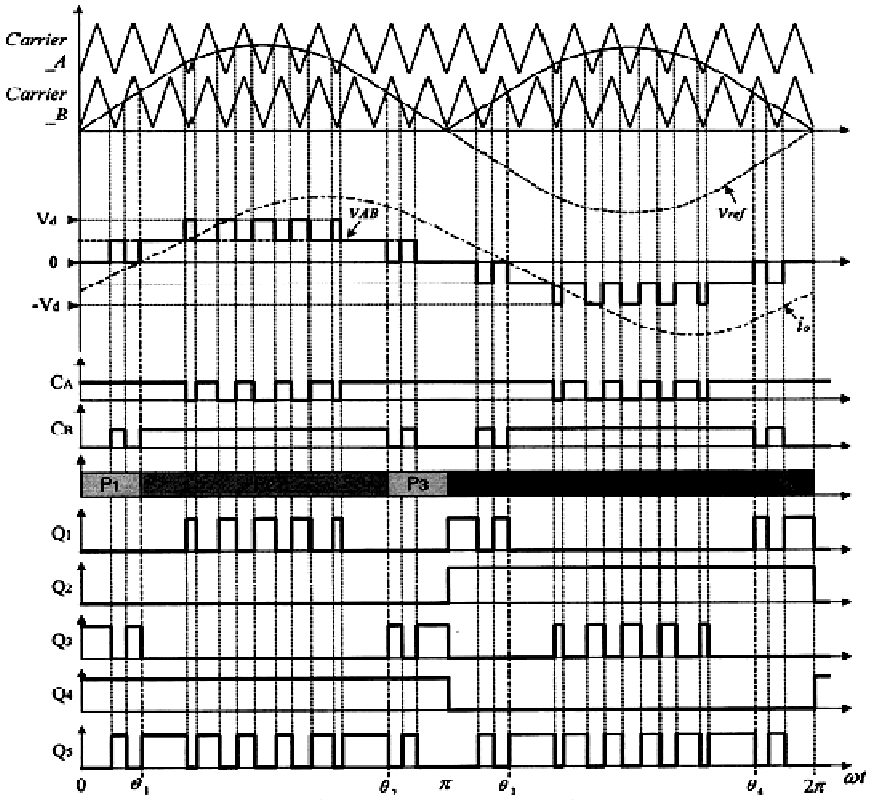

Fig.2 Switching patterns of the proposed single-phase five-level PWM inverter

Output Voltage According to the Switch ON-OFF Condition

Table -1 Switch On-Off Condition

On Switches	Node A Voltage	Node B Voltage	Output Voltage (V_{AB} - V_o)
Q_1,Q_4	V_d	0	$+V_d$
Q_5,Q_4	$V_{d/2}$	0	$+V_{d/2}$
(Q_3,Q_4) OR (Q_1,Q_2)	0(V_d)	0(V_d)	0
Q_2,Q_5	0	$V_{d/2}$	$-V_{d/2}$
Q_2,Q_3	0	V_d	$-V_d$

SIMULATION OF SINGLE-PHASE FIVE-LEVEL PWM INVERTER

Fig. 2 shows the single-phase five-level PWM inverter circuits implemented with MATLAB/SIMULINK (using the Sym Power Systems block set) circuit models work perfectly and may be used in the simulation of power electronics converters for photovoltaic systems

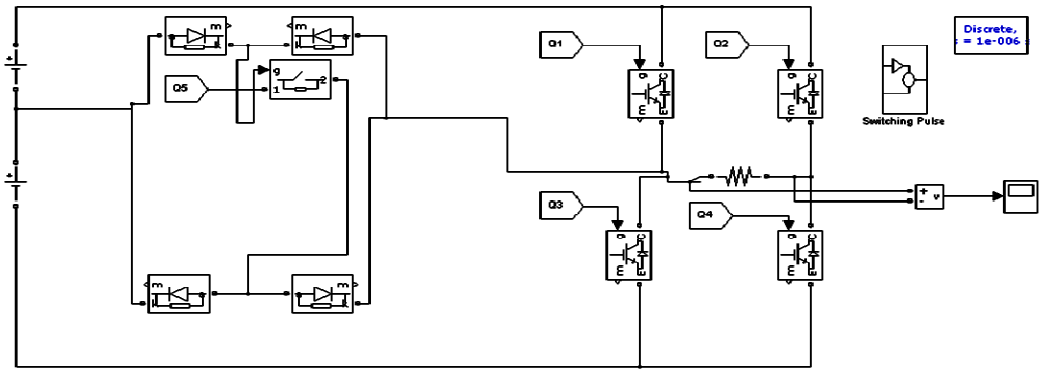

Fig.2 Simulink Model of Single-phase Five-level PWM inverter

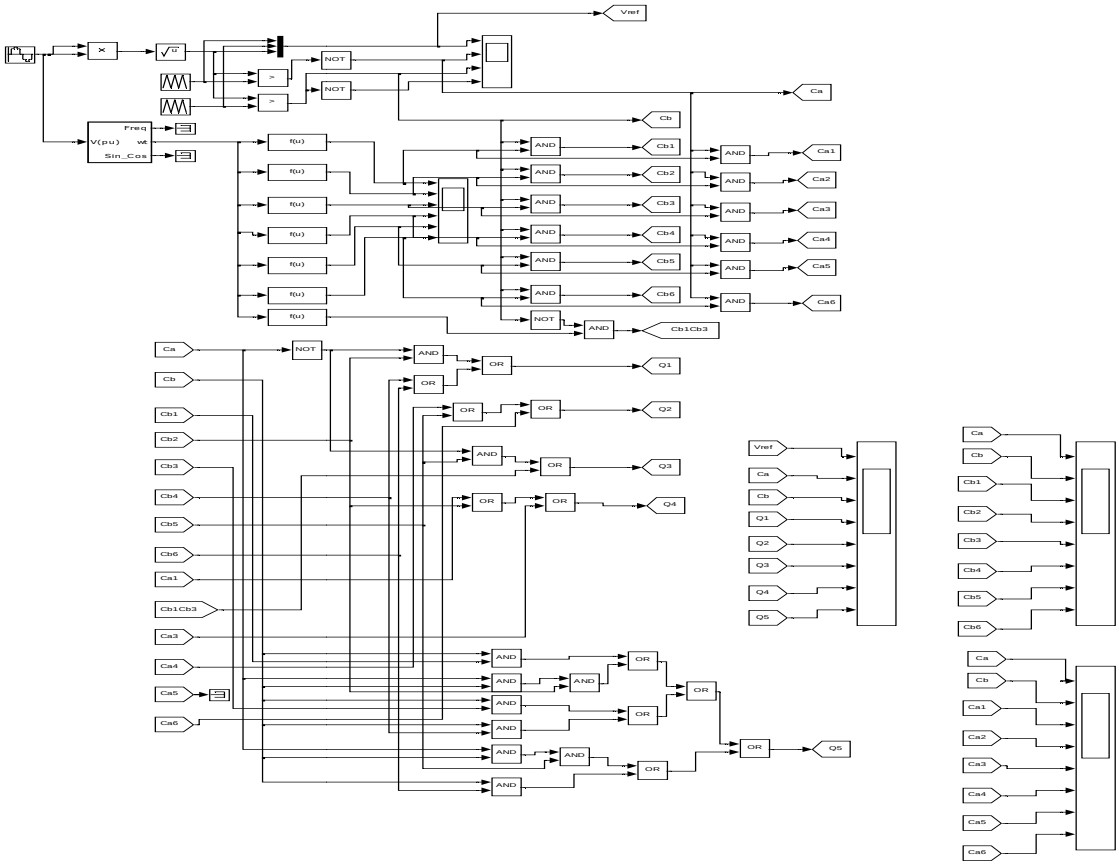

Fig.4 Switching Pulse of Single-phase Five-level PWM inverter

RESULTS AND DISCUSSION

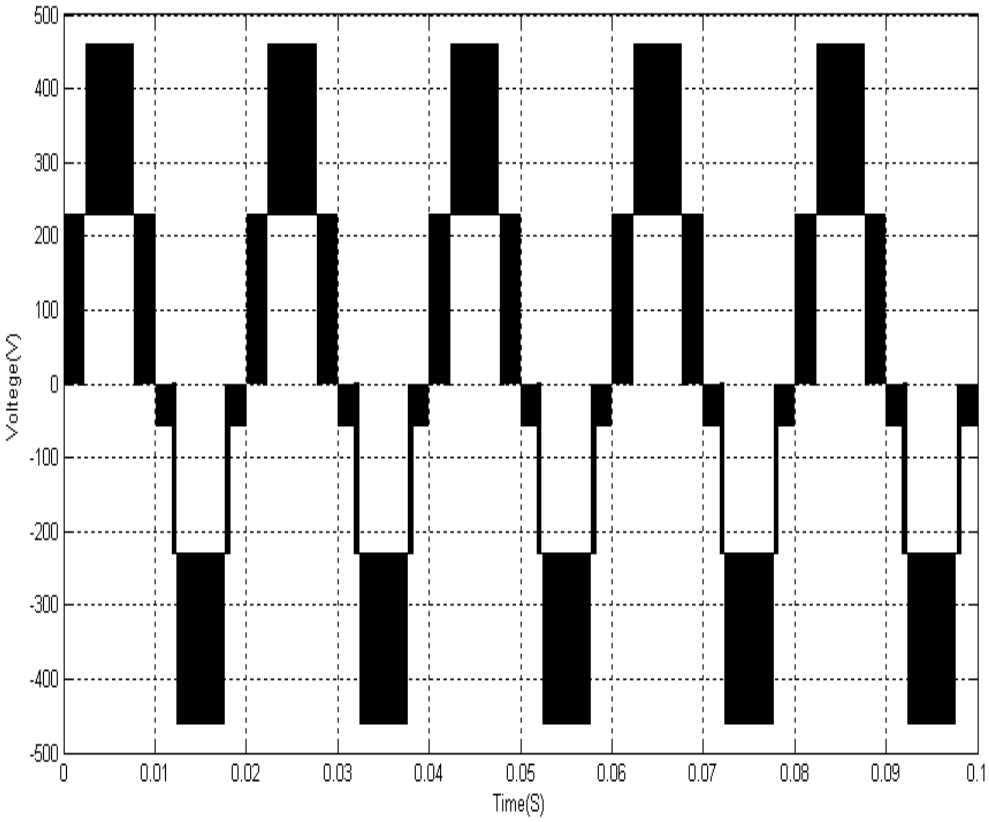

Fig.5 Inverter Output Voltage for Single-phase Five-Level PWM Inverter

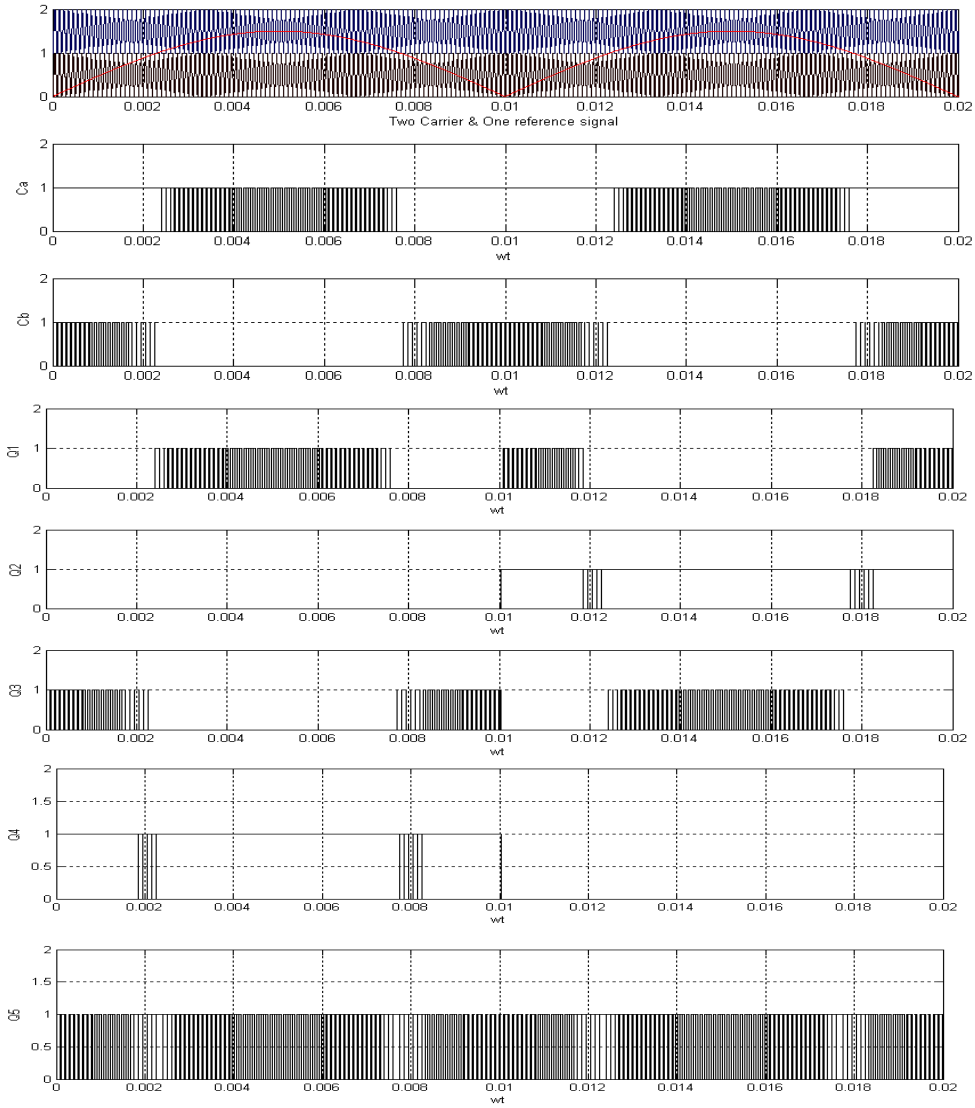

Fig.5 Switch patterns of the proposed single-phase five-level PWM inverter

CONCLUSION

This paper presents a single-phase five-level PWM inverter to reduce the harmonic components of output voltage and load current. The operational principles and the switching functions are analyzed in detail. It utilizes two carrier signals and one reference signal to generate PWM switching signals. The circuit topology, modulation law, and operational principle of the proposed inverter were analyzed in detail.

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