

Simplified five-level voltage source inverter with level-phase-shifted carriers based modulation technique

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ABSTRACT

A simplified circuit topology of the five-level inverter for DC-AC power conversion with non-insulated DC power sources along with reduced switching device count is introduced and discussed in this research paper. The inverter circuit is based on the three-level H-bridge inverter configuration. The developed five-level PWM inverter needs five controlled power switches and four isolated gate drive circuits. Furthermore, the proposed topology does not require bidirectional power semiconductor controlled switches, hence a conventional discrete power MOSFETs or IGBTs can be used to build the inverter circuits. To achieve a better quality AC output voltage, the level-phase-shifted carriers based sinusoidal pulse width modulation was applied to create a five-level PWM voltage waveform. The developed inverter circuit was examined by utilizing computer simulation with Power PSIM software. The basic principle operation of the inverter circuit was verified experimentally in laboratory applying two non-insulated DC input voltage sources as the inputs of the inverter's prototype circuit. Some analysis of inverter's output waveforms are provided and discussed.

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1. INTRODUCTION

The demand of high power and high quality power inverters for many utilizations as industrial motor drives and renewable energy conversions encourages the researchers to develop new converter topologies such as multilevel power inverters. Contrast to the traditional two-level power inverter, the multilevel power inverters possess some merits such as their potential to yield a higher output power, reduced voltage change (dv/dt), decreased gradient current change (di/dt), and preferable characteristic of AC voltage waveforms effecting in less electromagnetic noise. The multilevel power inverter can also reduce the output filter size by enhancing the inverter's level count [1-5].

The definition of multilevel power inverter circuits includes a three-level power inverter, and the inverters with higher level number. To date, a lot of inverter topologies especially voltage source inverter (VSI) circuits have been developed. Basically, there are four major topologies of multilevel VSI topologies have been presented [6]. They are the cascaded H-bridges multilevel VSI with disjunct DC power sources, the neutral clamped multilevel VSI, the flying capacitors VSI and the hybrid topology of multilevel VSI [7-12].

The topology of cascaded full-bridge power inverter with cloistered DC power sources has a great merit with its modularity. Even though, it has disadvantage such as the need of many disjunct DC voltage power sources, and the large number of controlled power switches. The more the controlled switches,

the more count of isolated driving circuits are requisite. The second topology i.e. the diode clamped multilevel VSI has been widely applied in modern AC motor drive application. The topology of flying capacitor VSI is another alternative. However, the number of capacitors required in this inverter circuits will cause another challenge such as the intermediate voltage control of the capacitor voltages. The fourth topology is the hybrid multilevel VSI. Basically, the hybrid topology is the topology of multilevel inverter developed to reduce some shortfalls in the three topologies of multilevel inverter circuits previously discussed. Still, the circuit complexity has become another issue of the multilevel power inverter circuits.

Circuit of a hybrid multilevel power inverter created from the H-bridge voltage source inverter and sub-multilevel circuits was discussed in [13]. The sub-multilevel circuit is constructed using capacitor and two bidirectional controlled switches. Another circuit topology of multilevel VSI created from a full-bridge inverter and an additional bidirectional active power switch as shown in Figure 1 was presented in [14]. Nevertheless, the additional bidirectional controlled power switches in inverter topologies described in reference [13] and [14] will cause some drawbacks of the inverter. The conventional bidirectional power semiconductor controlled switches constructed by combining two unidirectional power semiconductor controlled switches or a single controlled power switch with four diodes cause the total inverter power losses go up. Another structure of multilevel inverter circuits built from the three-level cell of H-bridge inverter was provided in [15]. Eight active switches are entailed in this inverter circuit. Circuit structure of a five-level multistring inverter was discussed in [16] and [17]. Two detached DC voltage sources with six active switches are demanded in this inverter circuit. The five-level multistring inverter structure is shown in Figure 2. The large quantity of controlled power switches and the requirement of separated DC voltage power sources will escalate the intricacy of inverter power circuits. Papers [18] described another multilevel voltage source power inverter constructed by H-bridge VSI and two-level voltage source modules. In this topology, six controlled power switches with five disjunct gate drive power supplies are entailed to operate the switches of inverter.

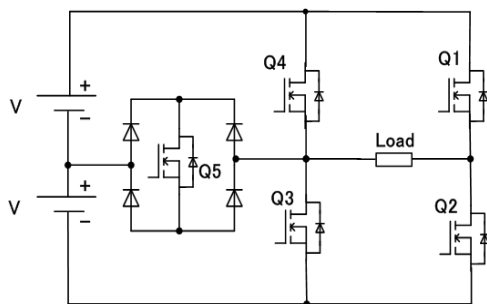


Figure 1. Five-level inverter employing H-bridge VSI and auxiliary bidirectional switch [14]

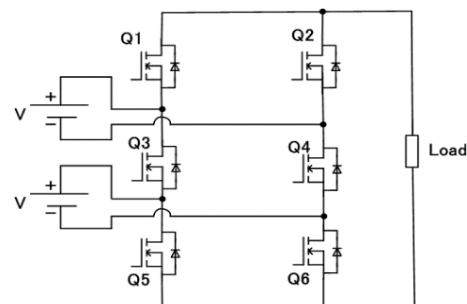


Figure 2. Five-level multistring inverter [16]

2. RESEARCH METHOD

In this research paper, a distinct topology of five-level VSI with non insulated DC voltage power sources and reduced switching device count is presented. Furthermore, the developed five-level VSI circuits need only four gate drive circuits for gating signal generation. In the developed inverter topology, the DC input power sources are non-insulated DC sources. Furthermore, all controlled power semiconductor switches are sole directional switches. The five-level VSI circuit was designed and tested through computer simulations utilizing Power PSIM Software. Furthermore, the basic principle operation of the inverter circuit was verified experimentally in laboratory of the inverter's prototype circuit.

2.1. Proposed Inverter Circuits and Its Basic Operation

Figure 3 is the new circuit of five-level power inverter. In this new topology, only five active power switches with four isolated gate drive power supplies and a single discrete diode are required. The less the active semiconductor switches, the simpler inverter circuits will be obtained. A low pass filter consists of inductor (L_f) and capacitor (C_f) is connected to the inverter. Table 1 indicates the switching conditions of the new five level VSI for five level voltage evocation. Moreover, Figure 4 presents the detailed operation modes for five-level PWM voltage waveform (V_{PWM}) evocation, specifically $+2V$, $+V$, 0 , $-V$ and $-2V$ output voltage levels. The load voltage waveform get near to a sinusoidal voltage, which is a five-level PWM voltage after filtering by the low pass filter.

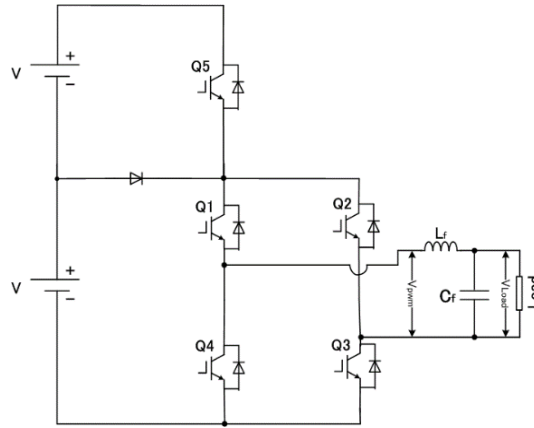


Figure 3. The circuit of proposed five-level VSI

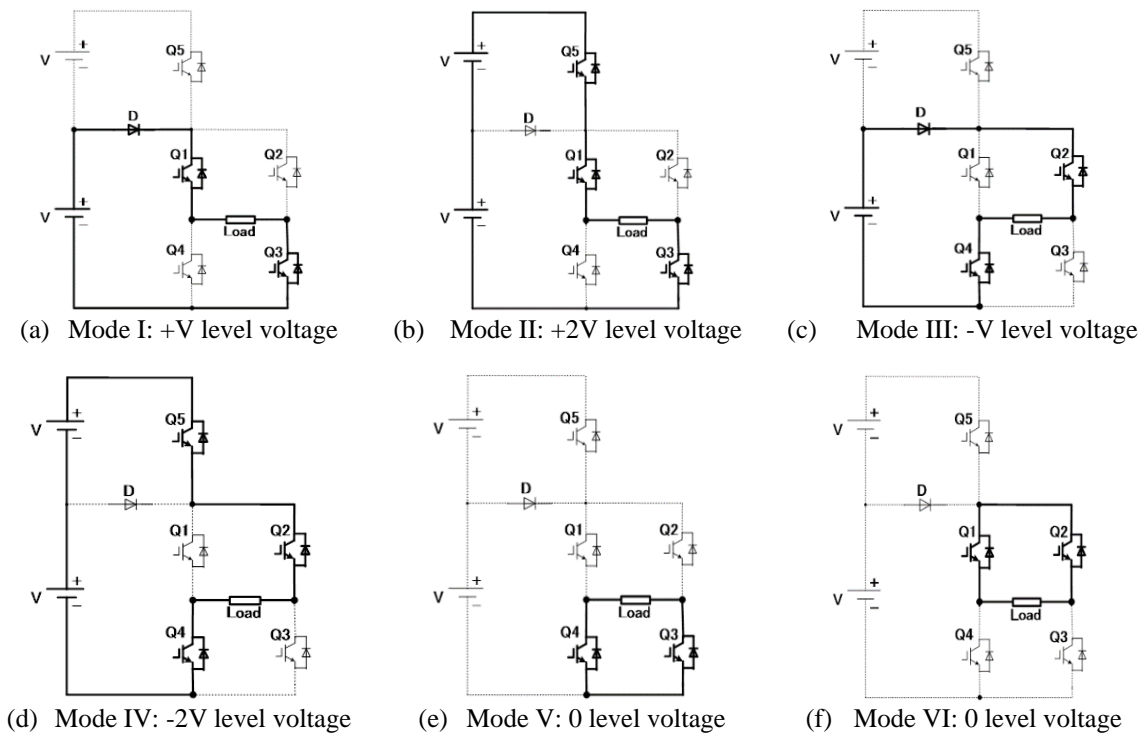


Figure 4. Operation modes of five-level VSI

Table 1. Switching Conditions of Five-Level VSI

Operation Modes	Q ₁	Q ₂	Q ₃	Q ₄	Q ₅	D	V _{PWM}
I	1	0	1	0	0	1	+V
II	1	0	1	0	1	0	+2V
III	0	1	0	1	0	1	-V
IV	0	1	0	1	1	0	-2V
V	0	0	1	1	0	0	0
VI	1	1	0	0	0	0	0

2.2. Inverter’s Modulation Technique

A pure sinusoidal waveform of current and voltage are ideal shape for almost all AC power load. Nevertheless, in real condition many factors affect the real shape of current and voltage. Because of voltage drop in the circuits and voltage ripple of the DC input voltage source, harmonic will appear in the AC voltage and current waveforms of a power inverter. In many inverter circuits some modulation strategies are applied

to achieve lower distortion of current and voltage [19, 20]. Furthermore, power filter circuits are also added to filter switching harmonics in order to obtain a closer sinusoidal waveforms. In this research, the level and phase shifted carriers based modulation was implemented for the driving signals generation of inverter's switches as displayed in Figure 5. Two carrier signals with an identical frequency but have contrary phase and different offset level were used together with a sinusoidal modulating signal as shown the figure. The basic frequency component of AC current and voltage waveforms is regulated by the sinusoidal modulating signal as the modulator waveform. Switching rapidity of the inverter's power semiconductor switches is the same with the frequency of triangular carrier signals [21, 22]. Gating signals of inverter are produced by the PWM generator controlling the ON/OFF condition of inverter's power semiconductor switches to output the desired five-level voltage shape. The gate drive circuits work as interface and isolation between the high power and control circuits.

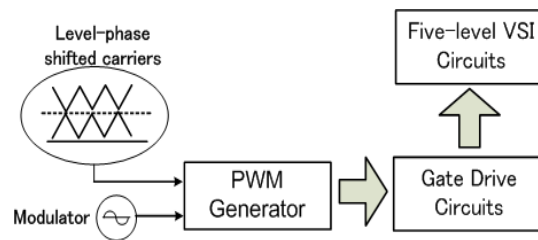


Figure 5. Modulation technique of the five-level VSI

3. RESULTS AND ANALYSIS

3.1. Computer Simulation Test Results

Computer simulations experiments were performed to verify and to prove the basic principle works of the developed five-level VSI circuits. Parameters of simulation test were indicated in Table 2. A five-level VSI circuit as displayed in Figure 3 was examined. A low-pass filter circuit with inductor $L_f = 1$ mH and capacitor $C_f = 5$ μ F was used. The five-level VSI circuit was connected with a resistive and inductive power load, i.e. power resistor 10 Ω , and power inductor 1 mH. The switching operation frequency of controlled power semiconductor switches was designed as 21 kHz to minimize the audible noise and to push the switching harmonics into higher frequency orders. The output voltage fundamental frequency was 50 Hz. Two non-isolated 12 V DC input voltage sources were used as the inverter's inputs.

Figure 6 indicates test results of computer simulation presenting the output voltage waveforms created by the five-level VSI circuit. A five-level voltage waveform has been confirmed. Furthermore, a sinusoidal voltage was applied to the power load after filtering by a low-pass filter. Figure 7 is harmonic profile of the generated five-level voltage waveform for frequency range up to 50 kHz. Switching harmonic components and its sidebands appeared around frequency 21 kHz and its multiples. Figure 8 presents the low harmonic orders of the produced five-level output voltage. The amplitudes of all low harmonic orders were less than 1%. Furthermore, Figure 9 displays a current waveform flowing thru the power load, power switch Q_5 and power diode D of inverter circuits. A sinusoidal current, I_{Load} , flowed supplying electric power to the load circuit. The currents flowing via the switch Q_5 and diode D were the PWM currents with frequency 21 kHz.

Table 2. Test Parameters

No.	Parameters	Values
1	DC input power source voltages	12 V
2	Switching operation frequency	21 kHz
3	Inductor power filters, L_f	1 mH
4	Capacitor power filter, C_f	5 μ F
5	Power load	$R = 10 \Omega$, $L = 1$ mH
6	Fundamental output frequency	50 Hz

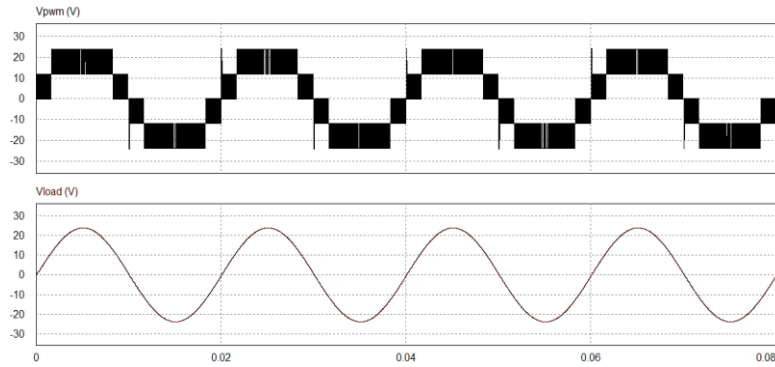


Figure 6. Five-level PWM AC voltage (V_{pwm}), and load voltage (V_{Load}) waveforms

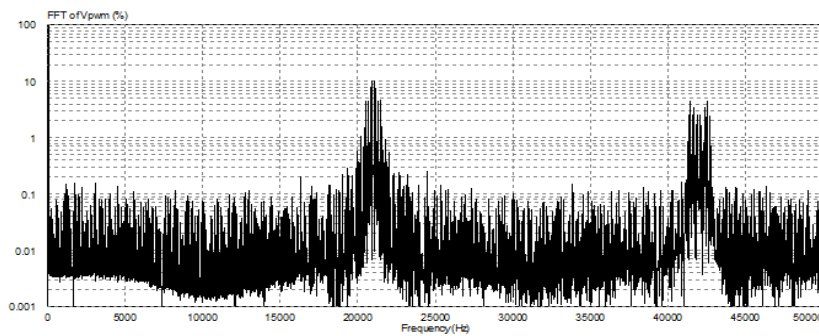


Figure 7. Harmonic profile of five-level voltage with the switching harmonics constituents

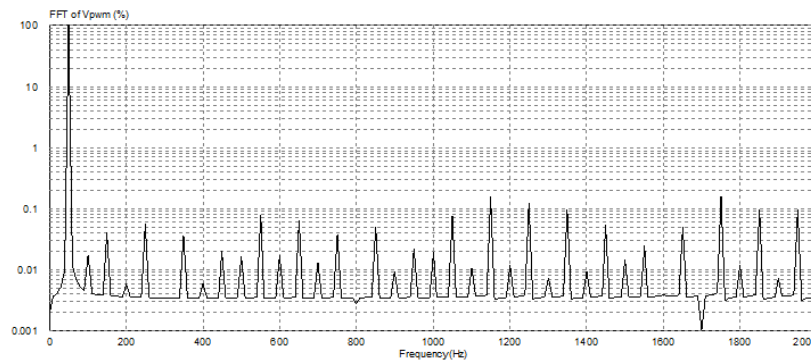


Figure 8. Profile of the low harmonic components

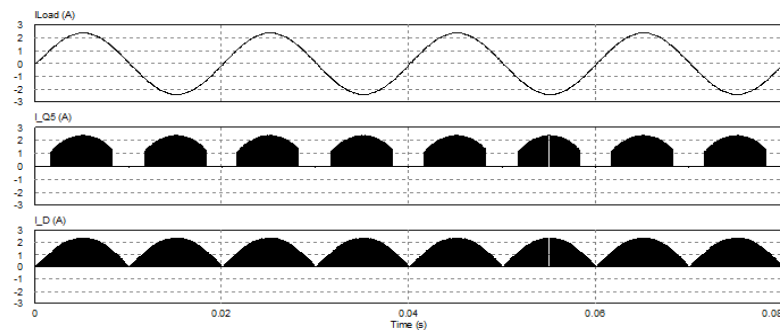


Figure 9. Waveforms of currents flowing thru the load, switch Q_5 and diode D

3.2. Laboratory Prototype Test Results

In order to examine the five-level VSI circuits experimentally, a five-level inverter prototype was made using five power MOSFETs FK30SM-6, and a single power diode VS-30ETH06PBF. The level-phase shifted carriers based PWM technique was applied. The DC input power sources were acquired from the two adjustable DC voltage sources connected in series. Figure 10 shows the laboratory experimental set-up of the prototype five-level inverter.

Figure 11 presents the firing signals of the MOSFETs switches Q_2 and Q_3 obtained from the PWM circuits after passing the driver IC TLP 250. Figure 12 is the gating signals of switches Q_1 and Q_4 . The gating signal of MOSFET switch Q_5 is presented in Figure 13. These signals were used to control the operation of five-level inverter circuits to generate a five-level PWM voltage waveform.

Figure 14 shows the experimental waveform of a five-level PWM output voltage generated by the inverter when the modulation index 0.9. A five level PWM AC voltage was experimentally confirmed. The harmonic spectrum of this waveform is shown in Figure 15. The switching harmonics component and its sidebands appeared around the frequency 21 kHz and its multiples. This frequency is the switching frequency of the power MOSFETs used in inverter. Furthermore, the measured load voltage waveform is shown in Figure 16. A sinusoidal voltage was obtained after filtering the five-level PWM voltage waveform. The laboratory test results agreed with the computer simulations.



Figure 10. Experimental set-up of the laboratory prototype

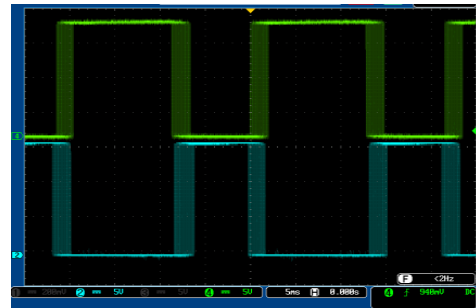


Figure 11. Gating signals of switches Q_2 and Q_3

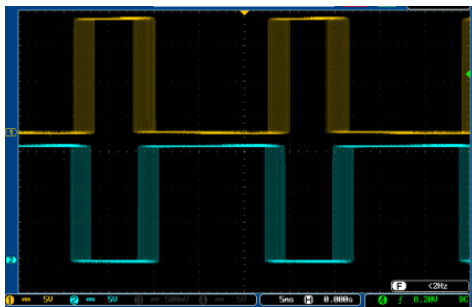


Figure 12. Gating signals of switches Q_1 and Q_4

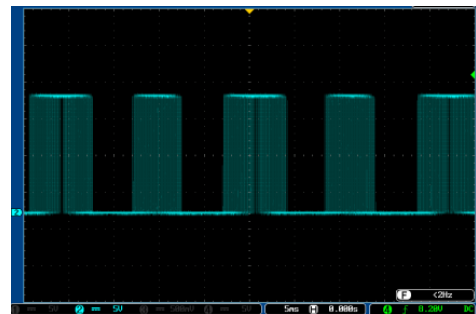


Figure 13. Gating signal of switch Q_5

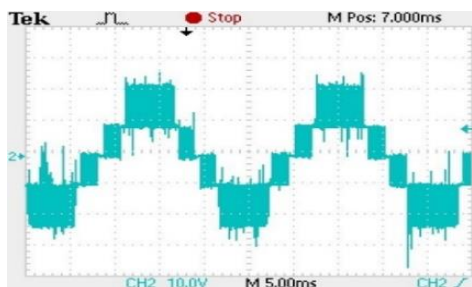


Figure 14. Experimental test result of five-level voltage

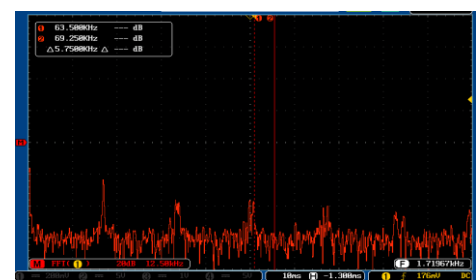


Figure 15. Harmonic profile of five-level voltage

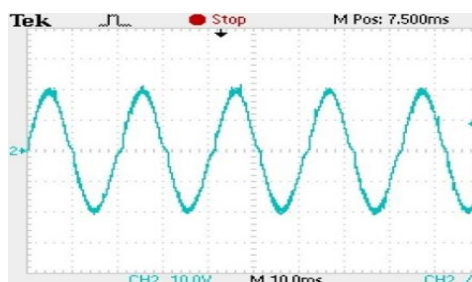


Figure 16. Experimental test result of the load voltage waveform

4. CONCLUSION




A simplified circuit structure of five-level voltage source inverter is being developed. Principle works of the inverter circuits have been presented and discussed. The presented five-level voltage source inverter needs five controlled power switches and a single discrete diode only, to generate a five-level PWM voltage waveform with non insulated dc power sources. Nethermost quantity of controlled power semiconductor switches needed to create this five-level VSI circuit is the main feature of this power inverter. Some data obtained by using computer simulations and laboratory prototype test have confirmed that the developed inverter circuits worked producing a five-level output voltage waveform. Using the installed low pass filter, this PWM waveform was filtered become a sinusoidal voltage with lower distortion.

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