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A Novel Multi-Level Inverter for Renewable Energy System Applications

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Abstract

This article proposes a new multi-level inverter using switched-capacitor structure which works based on switching capacitor on series/parallel in the circuit through the switches. This configuration reduces the number of components include semiconductor switches, diodes and input source than the traditional inverters, thereby reducing the cost and the size of the system. The proposed inverter uses two capacitors, two diodes and nine switches to create a nine-level output voltage. In this paper, the simulation results are implemented by PSIM 9.0 software and the experimental results are shown.

Keywords: *PWM, SPWM, multilevel inverter, switched-capacitor.*

Symbols

Symbols	Units	Description
S_1, P_1, S_{21}, S_{22}, P_2, T_1, T_2, T_3, T_4		Switches in circuit
C_1, C_2		Capacitors in circuit
D_1, D_2		Diodes in circuit
R		Resistor in circuit
L		Inductor in circuit
V_{in}	V	Input voltage
V_{AB}	V	Output voltage
V_{C1}	V	The voltage of C_1
V_{C2}	V	The voltage of C_2

Tóm tắt

Bài báo đề xuất một cấu hình nghịch lưu đa bậc mới hoạt động dựa trên nguyên tắc nạp/xả của tụ điện khi được mắc nối tiếp/song song với nguồn điện. Cấu hình đề xuất giảm số linh kiện bán dẫn trong mạch như diode, công tắc bán dẫn, nguồn ngõ vào so với các cấu hình truyền thống. Nhờ vậy cấu hình đề xuất làm giảm chi phí và kích thước của hệ thống, đồng thời làm giảm sự phức tạp trong điều khiển. Mạch nghịch lưu đề xuất tạo ra chín bậc ở ngõ ra sử dụng một nguồn ngõ vào, hai tụ điện, hai diode, chín công tắc bán dẫn. Trong bài báo, các kết quả mô phỏng được thực hiện bằng phần mềm PSIM 9.0, các kết quả thực nghiệm được thực hiện trên mô hình phần cứng.

1. Introduction

Nowadays, under the development of science, the renewable energy is becoming popularity to replace fossil fuel, which increases the high rate of pollution and depleted threat. Moreover, the renewable energies such as solar photovoltaic, wind energy, biomass, ocean energy, geothermal, ... are available in nature and almost does not populate, so it contributes to global climate development in the long term, bring more benefits to the ecosystem and ensure the sustainable development of the contemporary society. Therefore, green energy sources have a great potential in a broad range of applications like satellites, electric vehicle, charging system, and communications.

However, the power is generated from the solar panel, fuel cells, … are a direct current source, to be able to use this power supply for AC devices such as motors, machinery, equipment, this power should be converted into alternating current source. A component has an important role in converting DC power to AC power is inverters.

The multi-level inverter is the one of the important ingredients in the transformation of DC power to AC power source. Along with the development of technology, inverter is constantly improving in performance and quality. Therein, the multi-level inverter is an improvement of the inverter with output waveform is a ladder format that has high quality and reduced output filter circuit size.

In the field of motor control, in the storage of electricity, electric cars or the building electrical system... the inverter is widely used. The multi-level inverter configuration is commonly used as diode clamp configuration [1], Flying Capacitor [2], Cascade [3]. However, this configuration uses a large number of components (semiconductor switch, supply, capacitor, diode), which raises the cost of the inverter and the control becomes complicated.

To solve the problem in the traditional inverters, the multi-level inverter uses capacitor switching was developed. The switched-capacitor multi-level inverter uses charging and discharging characteristics of the capacitor to create a ladder waveform at the output and it does not need the auxiliary circuit in order to balance the voltage of the capacitor; so it economizes cost and reduces the complication control. In

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addition, the switched-capacitor inverter has ability to boost the input voltage without using magnetic elements. With dominance, the switched-capacitor inverter has attracted the attention of many researchers; many configurations had a good quality output waveform [4] - [9]; the works have optimized the performance or studied pulse width modulation algorithm for inverter [10] - [11].

This paper proposes a new switched-capacitor multi-level inverter. This topology reduces the cost, the size of the system and the complication of control method.

The rest of the letter is organized as follows: section 2 describes the characteristic of the switched - capacitor structure in circuit analysis and operation principle of the proposed inverter; the section 3 presents the simulation and experiment results for validating the operation of the proposed circuit; and finally, section 4 draws the conclusion.

2. Proposed switched-capacitor nine-level inverter

2.1. Circuit Analysis

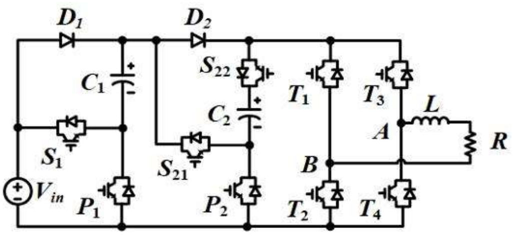

Figure 1: Circuit topology of the switched-capacitor nine-level inverter.

In Figure 1, the proposed inverter includes five switches to switch two capacitors in the series and in parallel, combining four switches in H-bridge to create positive voltage and negative voltage, beside the circuit also uses two diodes and a single source. In the operation status, the capacitor C_1 is charged when connecting parallel with the input source through P_1 ($V_{C1} = V_{in}$), whereas it is discharged with the input source in series through S1. Likewise, the capacitor C_2 is charged in parallel with input source through P_2 and S_{22} ($V_{C2} = 2V_{in}$) whereas it is discharged in series through S_{21} and S_{22}.

2.2. Operation Principle

There are two periods in the operation principle of the proposed inverter is negative and positive period. The difference between the two periods is the switches of H-bridge. In the positive period, the switches T_1 and T_4 are ON states while T_2 and T_3 are OFF states; and the states of these switches change when the period alters. All the operation state of switches is shown in table I.

Figure 2 shows the five operation states of the proposed inverter consists of states 0 (Figure 2(a)) which is the value of output voltage is zero along with four states (Figure 2(b) to 2(e)) in the positive period of output voltage:

+ State 0 (Figure 2.a): the switches S_1, S_{21}, S_{22}, T_2, T_4 are in the OFF state, while the switches P_1, P_2, T_1, T_3 are in the ON state. The diode D_1 is forward-biased. The C_1 capacitor is charged from the input voltage, and $V_{C1} = V_{in}$. The circuit output voltage is defined:

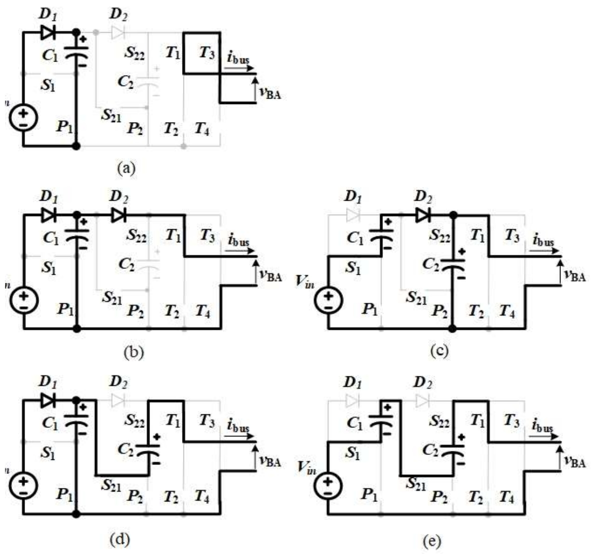

Figure 2: Operation states of the proposed inverter in the positive period.

$$V_{AB} = 0\ V \tag{1}$$

+ State 1 (Figure 2.b), the switches S_1, S_{21}, S_{22}, T_2, T_3 are maintained in the OFF state, while the switch P_1, P_2, T_1, T_4 are maintained in the ON state. The diode D_1 and D_2 are forward-biased. The C_1 capacitor is charged from the input voltage, and $V_{C1} = V_{in}$. The circuit output voltage:

$$V_{AB} = V_{in} \tag{2}$$

+ State 2 (Figure 2.c): the switches P_1, S_{21}, S_{22}, T_2, T_3 are kept in the OFF state, the switch S_1, P_2, T_1, T_4 are kept in the ON state. The diode D_1 is reverse-biased and the diode D_2 is forward-biased. The C_1 capacitor is discharged, whereas the C_2 capacitor is charged from the input voltage and C_1 voltage, and $V_{C2} = V_{in} + V_{C1} = 2V_{in}$. The circuit output voltage is defined:

$$V_{AB} = V_{in} + V_{C1} = 2V_{in} \tag{3}$$

+ State 3 (Figure 2.d): the switches S_1, P_2, T_2, T_3 are maintained in the OFF state, while the switch P_1, S_{21}, S_{22}, T_1, T_4 are maintained in the ON state. The diode D_1 is forward-biased and the diode D_2 is reverse -biased. The C_1 capacitor is charged from the input voltage, and $V_{C1} = V_{in}$, whereas the C_2 capacitor is discharged. The output voltage of the circuit is defined:

$$V_{AB} = V_{in} + V_{C2} = 3V_{in} \tag{4}$$

+ State 4 (Figure 2.e): the switches P_1, P_2, T_2, T_3 are kept in the OFF state, the switches S_1, S_{21}, S_{22}, T_1, T_4 are kept in the ON state. The diode D_1 and D_2 is reverse -biased. The C_1 and C_2 capacitor is discharged. The output voltage of the circuit is defined:

$$V_{AB} = V_{in} + V_{C1} + V_{C2} = 4V_{in} \tag{5}$$

Table 1: The Switches State in The Proposed Inverter

	S_1	P_1	S_{2x}	P_2	T_1	T_2	T_3	T_4	C_1	C_2	V_{AB}
9	1	0	1	0	1	0	0	1	D	D	4Vin
8	0	1	1	0	1	0	0	1	C	D	3Vin
7	1	0	0	1	1	0	0	1	D	C	2Vin
6	0	1	0	1	1	0	0	1	C	-	Vin
5	0	1	0	1	1	0	1	0	C	-	0
4	0	1	0	1	0	1	1	0	C	-	-Vin
3	1	0	0	1	0	1	1	0	D	C	-2Vin
2	0	1	1	0	0	1	1	0	C	D	-3Vin
1	1	0	1	0	0	1	1	0	D	D	-4Vin

1 is ON state, 0 is OFF state, C is Charged, D is Discharged.

3. Simulation and experimental results

To confirm the operation of the proposed inverter, a simulation and experiment are performed with the circuit schematic as the figure 1. The parameters of the proposed inverter topology are listed in Table 2.

Table 2: Parameters of Proposed Inverter

C_1, C_2	2200 µF
L	30 mH
R	80 Ω
V_{in}	48 V
$f_{carrier}$	5000 Hz
f_{ref}	50 Hz

The proposed inverter produce 50-Hz sinusoidal voltage waveform with the maximum output voltage is 192 V. The inverter is filtered by R, L load at the output.

3.1. Simulation results

The simulation is carried out by using PSIM 9.0 software with 2 cases: resistive load and inductive load using the parameters in table II.

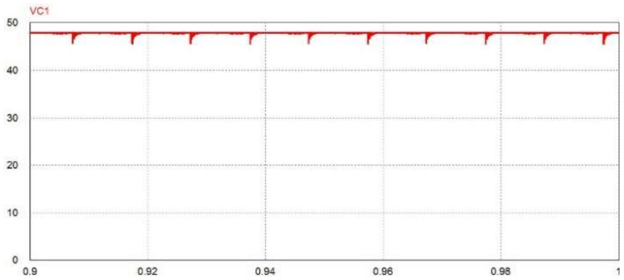

Figure 3: Voltage waveform of the C_1 capacitor.

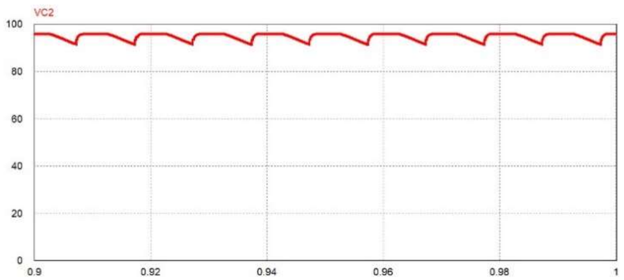

Figure 4: Voltage waveform of the C_2 capacitor.

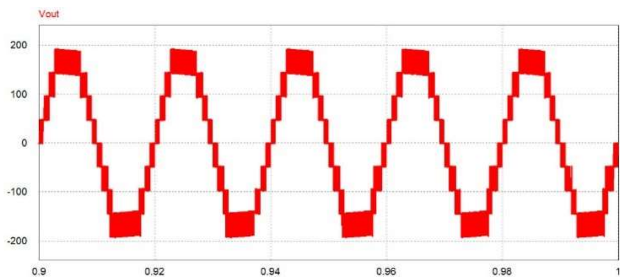

Figure 5: Output voltage waveform with the resistive load R =80 Ω.

Figure 3 shows the voltage of the capacitor C_1 with the maximum voltage of 48 V and the minimum voltage of 45.6 V. While Figure 4 shows the voltage of capacitor C_2 with the maximum voltage of 96 V and the minimum voltage of 91.3 V. The ripple voltage waveform of C_1 and C_2 do not change in both cases (resistive load and inductive load).

For resistive load of 80 Ω, the output voltage waveform is shown in Figure 5 that has a ladder waveform with 9-level includes 4-level at positive period (corresponding to states 1 to 4 in figure 2), 4-level at negative period and 1-level at output voltage is 0 (corresponding to states 0 in figure 2). The maximum value of output voltage is 192 V and the total harmonic distortion is about 13.95 % as Figure 6.

Turing into inductive load of R =80 Ω and L=30 mH, Figure 7 shows the R voltage waveform that filtered by inductor; thus,

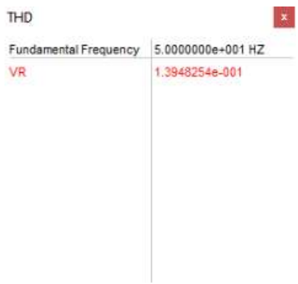

Figure 6: The total harmonic distortion (THD) of the output waveform with the resistive load R =80 Ω.

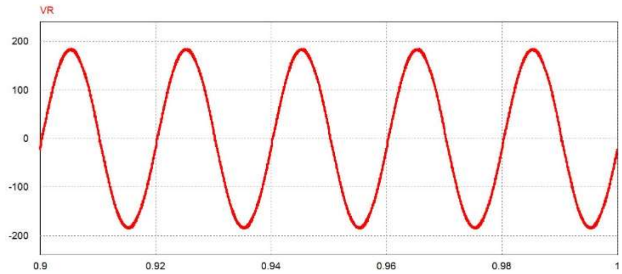

Figure 7: The R voltage waveform with an inductive load of R =80 Ω and L=30 mH.

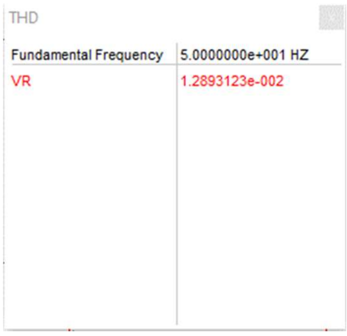

Figure 8: The total harmonic distortion (THD) of the R voltage waveform with an inductive load of R =80 Ω and L=30 mH.

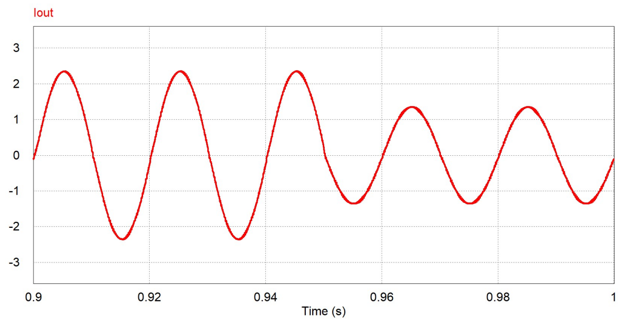

Figure 9: The output current when load change from 80 Ω to 140 Ω.

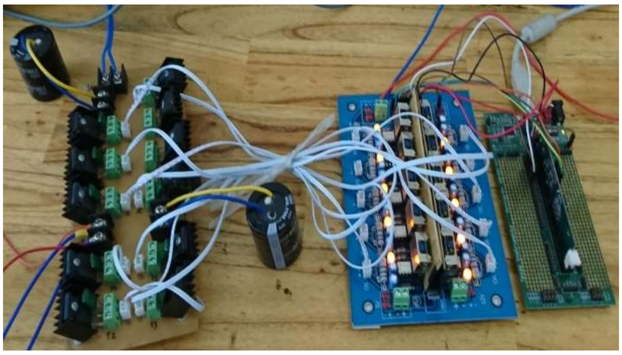

Figure 10: The prototype model of the proposed SC inverter.

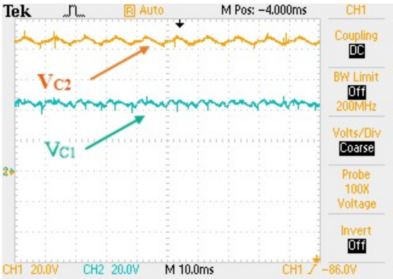

Figure 11: The voltage waveform of C_1 and C_2.

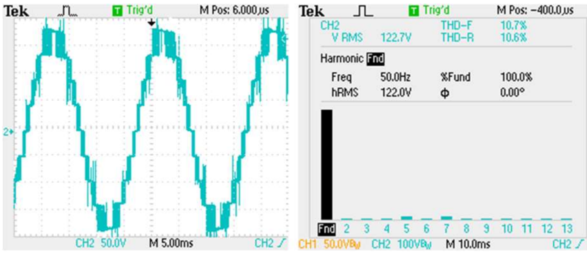

Figure 12: The output voltage waveform, THD value and the harmonics of the output voltage waveform with the resistive load R=80 Ω.

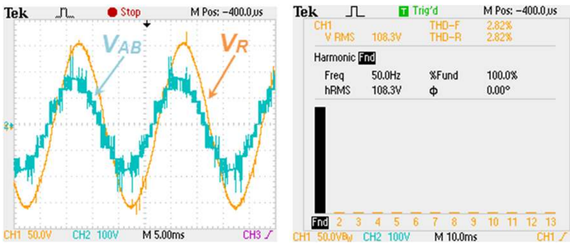

Figure 13: The output value with R=80 Ω, L=30 mH: (a) The output voltage waveform, R voltage waveform, (b) THD value and the harmonics of the R voltage waveform.

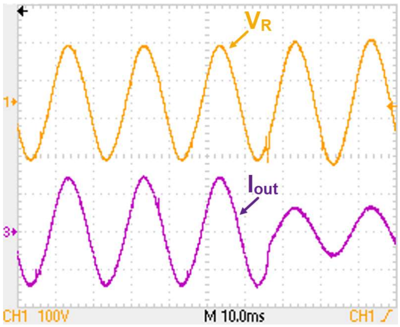

Figure 14: The R voltage waveform and the output current when load change from 80 Ω to 140 Ω.

it has the sine waveform with the total harmonic distortion is about of 1.29 % at the frequency is 50 Hz as Figure 8. The maximum voltage of the R voltage waveform is 188 V.

Figure 9 illustrates the output current waveform when the load changes from 80 Ω to 140 Ω. During the transition time, the frequency of output current does not transform, while the amplitude of output current declines.

3.2. Experimental Results

In order to verify the operation of proposed switched-capacitor multilevel inverter, the prototype model (Figure 10) was built with the parameters in Table II.

The experiment results are captured by Tektronix TPS 2024B. Figure 11 shows the output voltage waveform of C_1 and C_2. The maximum and minimum voltages of the C_1 capacitor is 47.4 V and 43.0 V, respectively. Therefore, the ripple voltage of C_1 is 4.44 V. Whereas, the voltage of C_2 capacitor fluctuates within the range of 83.7 (V) – 90.4 (V) and the deviation between highest and lowest values is 6.76 V. These results do not change in both cases (resistive load and inductive load).

For resistive load of 80 Ω, Figure 12 shows the output voltage waveform and the RMS value of the output voltage waveform of 122 V along with its THD value of 10.7 %.

Figure 13 shows the R voltage waveform of inductive load (R =80 Ω and L=30 mH) is a sinusoidal waveform has the RMS value of 108.3 V. Moreover, the harmonic of the output voltage waveform is filtered by inductor to create the R voltage waveform with good quality which is expressed through the measured frequency of the waveform is 50 Hz, and the total harmonic distortion (THD) = 2.82 %.

Figure 14 illustrates the R voltage waveform and output current waveform when load change from 80 Ω to 140 Ω. During the transition time, the frequency of both R voltage waveforms and output current waveforms, along with the amplitude of the R voltage does not transform, while the amplitude of output current declines. As a result, the proposed circuit can be stably operated with variable load.

4. Conclusion

This paper proposes a new switched-capacitor multilevel inverter which using the capacitor characteristic when it connects in series/parallel with the input source. Moreover, the proposed inverter has the output voltage is bigger than the input voltage. This paper presents the theory and principle of operation of the switched-capacitor nine-level inverter circuit configuration. Based on theory, inverter model was simulated by the PSIM 9.0 software and operability of the circuit is also proven by the fact pattern. Overall, the proposed inverter has the number of components significantly reduced compared with traditional inverter circuits resulting in saving cost and reducing complexity in control.

Besides, the inverter can be used for low-power applications of renewable energy systems. In addition, the proposed inverter uses an H-bridge circuit at the load output, so if connecting inverters as cascaded topology, it can be used for high power applications.

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