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Article

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An inductor-less step-up/step-down multilevel inverter with a single input source

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Abstract

This paper presents a step-up/step-down multilevel inverter with a single input source. To achieve inductor-less design, the proposed multilevel inverter is designed by switched-capacitor (SC) techniques. In the proposed inverter, the voltage of series-connected main capacitors is averaged by shifting the connection of flying capacitors alternately. At the same time, a multilevel output is generated by connecting some of the series-connected main capacitors to an output terminal via transfer switches. Unlike existing SC multilevel inverters with a single input source, the proposed SC multilevel inverter can provide small component counts, step-up/step-down conversion, and flexible conversion ratio. Concerning the proposed SC 5-level inverter, theoretical analysis, simulation program with integrated circuit emphasis (SPICE) simulations, and breadboard experiments are conducted to investigate the circuit characteristics. The results of these analysis demonstrate that 1. The proposed inverter can achieve step-down conversion as well as step-up conversion by converting a single input voltage; 2. The proposed inverter can reduce three circuit components from the series-parallel type inverter; and 3. When the output power is 200W, the proposed inverter can achieve about 83% and 93% efficiency in the step-up mode and the step-down mode respectively.

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Keywords: Multilevel inverters; Step-up/step-down inverters; Inductor-less inverters; Switched-capacitor techniques; Full-bridge circuits

1. Introduction

Recently, the demand for dc/ac power supplies with small size and light weight is increasing in electric products. However, due to the presence of inductors or transformers, traditional dc/ac converters with magnetic components [1] becomes bulky. To meet these requirements, the switched-capacitor (SC) technique is one of the best solutions. Among others, it is known that SC multilevel inverters can provide small electromagnetic interference (EMI), lower switching loss, high power quality, high voltage capability, and so on [2]. The SC inverter can be divided into

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two types, namely, the SC inverter with multiple input sources and the SC inverter with a single input source. In this research, we focused on the SC multilevel inverter with a single input source, because the SC inverter with multiple input sources [3] is useful for photovoltaic or fuel cell applications only. In previous studies, many researchers undertook to design the SC multilevel inverters with a single input source, such as flying-capacitor-clamped SC inverter [2], series-parallel type SC inverter [4], cascaded SC inverter [5], Fibonacci-type SC inverter [6,7]. These SC multilevel inverters can offer small size, light weight, and small EMI. However, the conversion ratio of these conventional SC inverters is predetermined by its circuit topology. Therefore, due to the lack of flexibility in conversion ratio, the application of the conventional inverters is limited.

In this paper, we propose a step-up/step-down multilevel inverter with a single input source, where the SC technique is employed to achieve inductor-less design. In the proposed inverter, the following two processes are operated at the same time: 1. By shifting the connection of flying capacitors alternately, the proposed inverter averages the voltage of series-connected main capacitors; 2. A multilevel output is generated by connecting some of the series-connected main capacitors to an output terminal via transfer switches. Unlike existing SC multilevel inverters with a single input source, the proposed inverter can achieve step-up/step-down conversion, small component counts, and flexible conversion ratio. To clarify the performance, we conduct theoretical analysis, SPICE simulations, and breadboard experiments.

2. Circuit configuration

The circuit configuration of the proposed SC multilevel inverter is illustrated in Fig. 1. Unlike existing SC multilevel inverters, the proposed inverter can achieve not only step-up conversion but also step-down conversion by changing the position of input terminals. Furthermore, no full-bridge circuit is required to achieve step-up/step-down conversions. To help readers' understanding, the simplest case, namely, 5-level inverter, is discussed in this section. Fig. 2 demonstrates the proposed SC 5-level inverter. To connect C_{f1} in parallel with C_1 or C_2 alternately, the switches S_1 and S_2 are driven by 2-phase clock pulses. Thus, in the case of $2\times$ step-up mode, the voltage of C_1 and C_2 becomes V_{in} . On the other hand, in the case of $(1/2)\times$ step-down mode, the voltage of C_1 and C_2 becomes $(1/2)V_{in}$. According to the amplitude of an output wave, S_{pj} and S_{mj} are controlled as shown in Table 1.

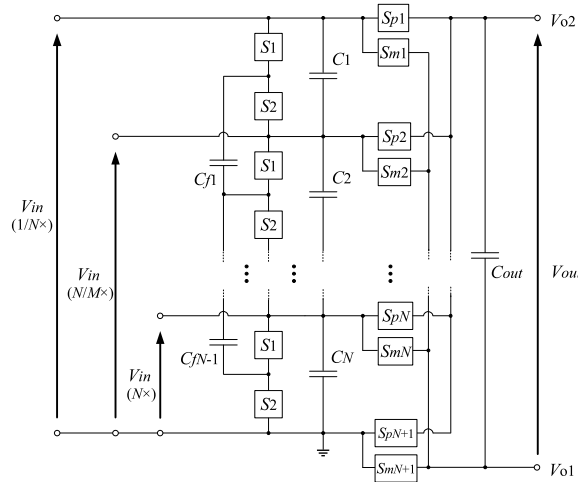


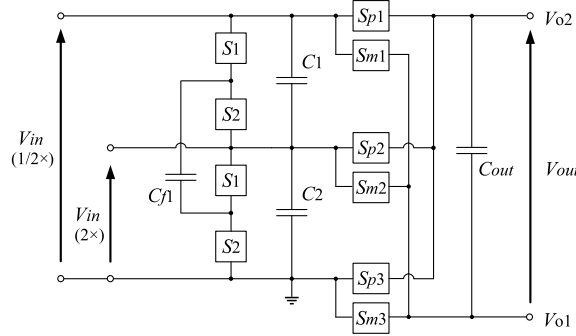
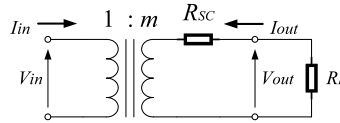
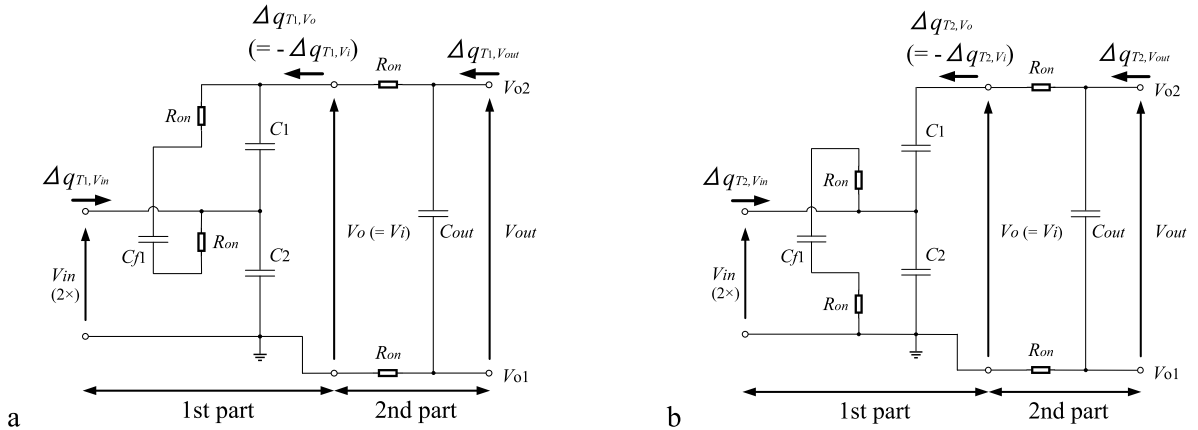
Fig. 1. Circuit configuration of the proposed SC multilevel inverter.

3. Theoretical analysis

In this section, the characteristics of the 5-level step-up inverter is analyzed theoretically by using the four-terminal equivalent model [7,8] shown in Fig. 3, where m is the turn ratio of an ideal transformer, R_{SC} is the internal resistance of the power converter, and R_L is the output load. To simplify the theoretical analysis, we assumed that 1. On-resistance of all switches is the same, 2. Parasitic elements are negligibly small, and 3. Period of clock pulses for S_1 and S_2 is much smaller than time constant.

Table 1. Control of S_{pj} and S_{mj} .

Step-up mode						Step-down mode					
Gain	$2\times$	$1\times$	0	$-1\times$	$-2\times$	Gain	$1\times$	$1/2\times$	0	$-1/2\times$	$-1\times$
Turn on	S_{p1}, S_{m3}	S_{p2}, S_{m3}	S_{p3}, S_{m3}	S_{p3}, S_{m2}	S_{p3}, S_{m1}	Turn on	S_{p1}, S_{m3}	S_{p2}, S_{m3}	S_{p3}, S_{m3}	S_{p3}, S_{m2}	S_{p3}, S_{m1}
Turn off	Others	Others	Others	Others	Others	Turn off	Others	Others	Others	Others	Others

**Fig. 2.** Circuit configuration of the 5-level inverter.**Fig. 3.** Four-terminal equivalent model.**Fig. 4.** Instantaneous equivalent circuits of the first converter block: (a) state- T_1 ; (b) state- T_2 .

First, in the case of $2\times$ step-up mode, the relation between the input and the output is obtained by using the instantaneous equivalent circuits shown in Fig. 4. In Fig. 4, R_{on} is the on-resistance of switches, $\Delta q_{T_i, v_{in}}$ ($i = 1, 2$) is the electric charge of V_{in} in State- T_i , and $\Delta q_{T_i, v_{ol}}$ ($l = 1, 2$) is the electric charge of V_{ok} in State- T_i .

At a steady state, the differential value of electric charges, $\Delta q_{T_i}^k$ ($k = 1, 2, cf1, out$), satisfies

$$\Delta q_{T_1}^k + \Delta q_{T_2}^k = 0, \quad (1)$$

because the overall change in electric charges of C_k is zero. In Eq. (1), the period of State- T_1 and State- T_2 satisfies

$$T_1 + T_2 = T \quad \text{and} \quad T_1 = T_2 = T/2. \quad (2)$$

By using Kirchhoff's current law, we have the following relations:

$$\begin{aligned} \Delta q_{T_1, v_{in}} &= -\Delta q_{T_1}^1 + \Delta q_{T_1}^2 - \Delta q_{T_1}^{cf1}, \quad \Delta q_{T_2, v_{in}} = -\Delta q_{T_2}^1 + \Delta q_{T_2}^2 + \Delta q_{T_2}^{cf1}, \\ \Delta q_{T_1, v_o} &= \Delta q_{T_1}^1 + \Delta q_{T_1}^{cf1}, \quad \text{and} \quad \Delta q_{T_2, v_o} = \Delta q_{T_2}^1. \end{aligned} \quad (3)$$

Since the overall change in the electric charges, $\Delta q_{T_i, v_{in}}$ and $\Delta q_{T_i, v_{out}}$, is zero at the steady state, we have the average currents, I_{in} and I_o , from Eq. (3):

$$I_{in} = \frac{\Delta q_{v_{in}}}{T} = \frac{\Delta q_{T_1, v_{in}} + \Delta q_{T_2, v_{in}}}{T}, \quad \text{and} \quad I_o = \frac{\Delta q_{v_o}}{T} = \frac{\Delta q_{T_1, v_o} + \Delta q_{T_2, v_o}}{T}. \quad (4)$$

By using Eqs. (1)–(3), Eq. (4) can be rewritten as

$$I_{in} = -2I_o \quad \text{and} \quad m = 2, \quad (5)$$

because voltage conversion is not performed in the 2nd part.

Next, the consumed energy of Fig. 4 is discussed to derive the internal resistance R_{SC} . The total consumed energy of the 1st part, W_T^1 , can be expressed as

$$W_T^1 = W_{T_1}^1 + W_{T_2}^1 = 2R_{on} \frac{(\Delta q_{T_1}^{cf1})^2}{T_1} + 2R_{on} \frac{(\Delta q_{T_2}^{cf1})^2}{T_2} = (8R_{on}) \frac{(\Delta q_{v_o})^2}{T}, \quad (6)$$

where $W_{T_1}^1$ and $W_{T_2}^1$ denote the consumed energy in State- T_i . On the other hand, the total consumed energy of the 2nd part, W_T^2 , can be given by

$$W_T^2 = W_{T_1}^2 + W_{T_2}^2 = 2R_{on} \frac{(\Delta q_{T_1, v_{out}})^2}{T_1} + 2R_{on} \frac{(\Delta q_{T_2, v_{out}})^2}{T_2} = (2R_{on}) \frac{(\Delta q_{v_{out}})^2}{T}, \quad (7)$$

where $W_{T_1}^2$ and $W_{T_2}^2$ denote the consumed energy in State- T_i . Therefore, from Eqs. (6) and (7), the internal resistances for the 1st part and 2nd part, R_{SC1} and R_{SC2} , can be obtained as

$$R_{SC1} = 8R_{on} \quad \text{and} \quad R_{SC2} = 2R_{on}, \quad (8)$$

because the total consumed energy of Fig. 3 is given by

$$W_T \triangleq \left(\frac{q_{v_{out}}}{T} \right)^2 R_{SC} T. \quad (9)$$

From Eqs. (5) and (8), the equivalent circuit of the proposed inverter can be expressed as

$$\begin{bmatrix} V_{in} \\ I_{in} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 2 & 2 \end{bmatrix} \begin{bmatrix} 1 & 8R_{on} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} V_o \\ -I_o \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} V_i \\ I_i \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 2R_{on} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} V_{out} \\ -I_{out} \end{bmatrix}. \quad (10)$$

Therefore, in the case of $2 \times$ step-up mode, we have the four-terminal equivalent model of the proposed inverter as shown in Fig. 5. Finally, from Fig. 5, we get the power efficiency and the output voltage of the proposed inverter as

$$\eta = \frac{R_L}{R_L + 10R_{on}} \quad \text{and} \quad V_{out} = 2V_{in} \times \left\{ \frac{R_L}{R_L + 10R_{on}} \right\}. \quad (11)$$

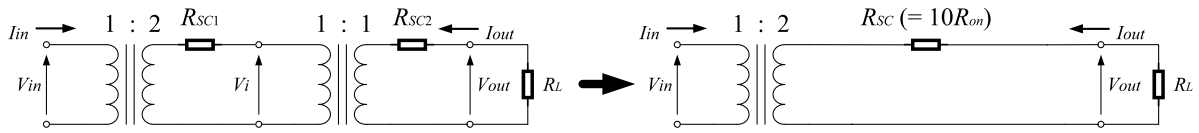
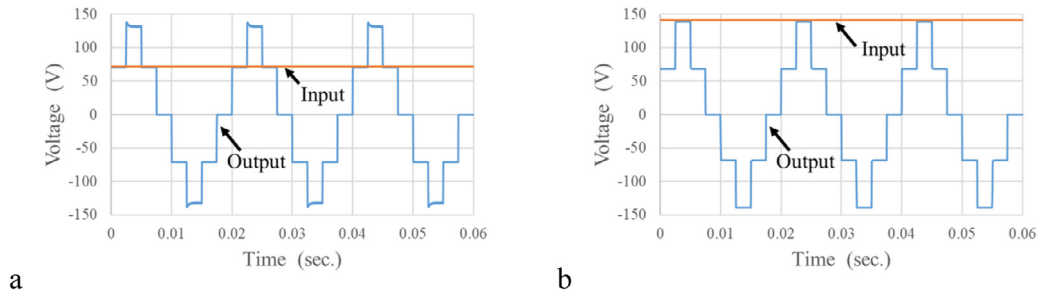
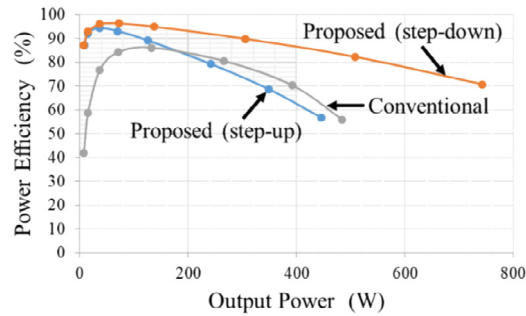
In the same way, other conversion modes can be analyzed. Table 2 shows the summary of the theoretical analysis. The characteristics of the proposed 5-level inverter can be obtained by Table 2. Of course, the characteristics of the proposed inverter depend on the shape of output waves.

4. Computer simulation

To evaluate the characteristics of the proposed SC 5-level inverter, we conducted SPICE simulations under the conditions that $R_{on} = 0.83 \, \Omega$, $f = 10 \, \text{kHz}$, $C_1 = C_2 = C_{f1} = 33 \, \mu\text{F}$, and $C_{out} = 1 \, \mu\text{F}$. Fig. 6 shows the

Table 2. Internal resistance of the proposed SC 5-level inverter.

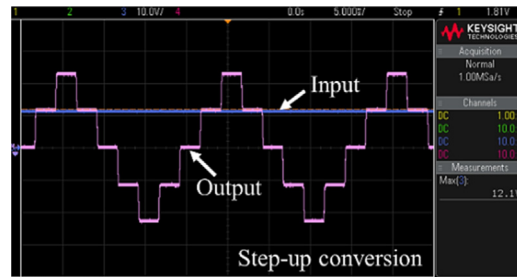
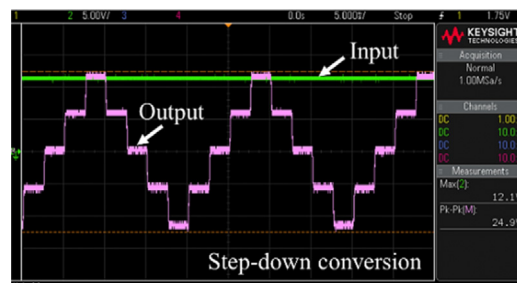
Step-up mode						Step-down mode					
Gain	$2\times$	$1\times$	0	$-1\times$	$-2\times$	Gain	$1\times$	$1/2\times$	0	$-1/2\times$	$-1\times$
R_{SC}	$10R_{SC}$	$2R_{SC}$	0	$2R_{SC}$	$10R_{SC}$	R_{SC}	$2R_{SC}$	$4R_{SC}$	0	$4R_{SC}$	$2R_{SC}$

**Fig. 5.** Four-terminal equivalent model of the proposed 5-level inverter in the case of $2\times$ step-up mode.**Fig. 6.** Simulated output voltage: (a) step-up; (b) step-down.**Fig. 7.** Simulated power efficiency as a function of output power.

simulated output voltage of the proposed inverter. In Fig. 6(a), the output load R_L is $100\ \Omega$ and the input voltage V_{in} is 72 V. On the other hand, the output load R_L is $100\ \Omega$ and the input voltage V_{in} is $100\sqrt{2}$ V in Fig. 6(b). As Fig. 6 shows, the proposed inverter can provide a stepped-down voltage as well as a stepped-up voltage. Fig. 7 demonstrates the comparison of power efficiency between the proposed SC 5-level inverter and the conventional SC 5-level inverter [4]. Due to the switching noise, the power efficiency decreases at full-load case. As Fig. 7 shows, the power efficiency of the proposed inverter is higher than that of the conventional inverter when the output power is less than 170 W. When the output power is 200 W, the proposed inverter can achieve about 83% and 93% efficiency in the step-up mode and the step-down mode respectively. Table 3 illustrates the comparison result. As Table 3 shows, unlike the conventional inverter, the proposed inverter can provide not only stepped-up voltage but also stepped-down voltage. Furthermore, the proposed inverter is smaller than the conventional inverter, because no full-bridge circuit is necessary in the proposed inverter. Therefore, the proposed inverter can reduce fabrication cost.

Table 3. Number of circuit components.

Inverter name	Conversion type	Number of switches	Number of capacitors	Component counts
Proposed inverter	Step-up/Step-down	10	4	14
Conventional inverter [4]	Step-up	14	3	17

**Fig. 8.** Measured output voltage of the 5-level step-up inverter.**Fig. 9.** Measured output voltage of the 5-level step-down inverter.

5. Breadboard experiment

In this section, the feasibility of the proposed topology is confirmed by breadboard experiments. In the experiments, we assembled the experimental circuit by using the commercially available ICs, namely, photo MOS relays AQV 217, darlington sink drivers TD62004APG. Fig. 8 depicts the measured output voltage of the 5-level step-up inverter, where $V_{in} = 12\text{ V}$ and $R_L = 100\text{ k}\Omega$. On the other hand, Fig. 9 shows the measured output voltage of the 5-level step-down inverter, where $V_{in} = 12\text{ V}$ and $R_L = 100\text{ k}\Omega$. As these figures show, the experimental circuit can achieve step-up/step-down conversion. The feasibility of the proposed topology can be confirmed by Figs. 8 and 9.

6. Conclusion

An inductor-less step-up/step-down multilevel inverter with a single input has been proposed in this paper. The results of this work are as follows: 1. The proposed inverter can achieve step-down conversion as well as step-up conversion by converting a single input voltage; 2. The proposed inverter can reduce three circuit components from the series–parallel type inverter; and 3. When the output power is 200 W, the proposed SC 5-level inverter can achieve about 83% and 93% efficiency in the step-up mode and the step-down mode respectively. The detailed experimental investigation of the proposed inverter is left to a future study.

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