Development of a Fibonacci Switched-Capacitor DC-AC Inverter

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Abstract

In previous studies, we proposed the circuit topology of the Fibonacci SC DC-AC inverter and analyzed its characteristics theoretically. Unlike a common DC-AC inverter containing inductors or transformers, the SC inverter requires no magnetic components by using SC techniques. Furthermore, unlike conventional SC DC-AC inverters based on a series-parallel type converter, the proposed inverter can provide the staircase AC waveform by a smaller number of capacitors. In this paper, the experimental circuit of the Fibonacci SC DC-AC inverter is built with commercially available components and is evaluated its real behavior. In the experimental circuit, a bootstrap circuit is employed to drive bidirectional switches effectively. The effectiveness and feasibility of the proposed inverter are demonstrated through experiments.

Keywords: DC-AC inverter, switched capacitor circuits, inductor-less circuits.

1. Introduction

For cigarette socket in vehicles, DC-AC inverters have been marketed. The DC-AC inverter can generate AC waveform from the input DC voltage of a cigarette socket. However, the output waveform of the marketed DC-AC inverters is almost square wave which is far from a sine wave. Furthermore, the DC-AC inverters are heavy and bulky due to magnetic components. Therefore, in recent years, a switched-capacitor (SC) DC-AC inverter has been proposed by many researchers. Unlike the common DC-AC inverter containing magnetic components, the SC DC-AC inverter can generate an AC voltage without the use of magnetic components. Therefore, the SC inverter can reduce not only circuit size but also effects of the

electromagnetic interference (EMI).

In 1993, Ueno et al. suggested the voltage equation type SC DC-AC inverter⁽¹⁾. Following this, Oota proposed a bidirectional SC DC-AC inverter⁽²⁾. By using a series-parallel type inverter⁽³⁾, these inverters can generate a staircase AC waveform. However, many circuit components are required in order to provide big number of steps of the staircase waveform. That is because the steps of the staircase waveform are proportional to the number of capacitors. To improve this drawback, Eguchi et al. suggested the DC-AC converter using ring-type converter⁽⁴⁾. The ring-type converter can provide flexible output voltages by changing connection-types of series capacitors. However, the ring-type converter cannot realize high voltage ratio unless many capacitors exist. To reduce the number of capacitors, Chang proposed the multistage switched-capacitor-voltage-multiplier (SCVM) DC-AC inverter⁽⁵⁾. The SCVM inverter can generate a staircase AC waveform by the small number of capacitors due to series-connected SC cells. However, all capacitor voltages of these conventional DC-AC inverters are the same. Therefore, in order to provide a staircase AC waveform formed by many steps, we proposed the circuit topology of the Fibonacci SC DC-AC inverter⁽⁶⁾ and analyzed its characteristics theoretically. In the proposed inverter, the voltage ratio of capacitors is the ratio of the Fibonacci number. By combining some of these capacitors in series, the proposed inverter generates the staircase AC waveform by a small number of capacitors, because the voltage of the charged capacitors of the proposed inverter is higher than that of the conventional SC DC-AC inverter.

In this paper, the experimental circuit of the Fibonacci SC DC-AC inverter is built with commercially available components and is evaluated its behavior. In the experimental circuit, a bootstrap circuit is employed to drive bidirectional switches effectively. The effectiveness

and feasibility of the proposed inverter are demonstrated through experiments.

Fig. 1. Conventional SC DC-AC inverter.

2. Circuit Configuration

2.1 Conventional Inverter

Figure 1 shows the conventional SC DC-AC inverter⁽²⁾. The conventional inverter is based on the series-parallel type converter. As figure 1 shows, there is no magnetic components. In the conventional inverter, all the capacitor voltages are V_{in} . To generate a staircase AC waveform, the bi-direction switches are controlled like a step-up DC-DC converter. The output voltage V_o of each step is expressed by

$$V_o = mV_{in}, \quad (1)$$

$$\text{where } m = \{1, 2, \dots, N+1\}$$

In Eq. 1, N is the number of main capacitors. Concretely, the conventional inverter generates the staircase waveform formed by 8 $((3+1) \times 2)$ steps in the case of 3 stages. The staircase waveform V_{out} is obtain through the full bridge circuit. When bi-directional switches e are turned on, each capacitor of the sub circuit-1 are charged, and the sub circuit-2 generates stepped-up voltage. At that time, the output voltage is selected by controlling bi-directional switches e_n . On the other hand, when bi-directional switches o are turned on, each capacitor of the sub circuit-2 are charged, and the sub circuit-1 generates stepped-up voltage. At that time, the output voltage is selected by controlling bi-directional switchers o_n . In the conventional inverter, two capacitors and eight bi-directional switches are required for every additional one stage.

Fig. 2. Proposed SC DC-AC inverter.

Table 1. Operations during one cycle.

State	Inverter Block -1	Inverter Block -2
T_1	Charging process	Transferring process
T_2	Transferring process	Charging process
T_3	Averaging process	Transferring process
T_4	Transferring process	Averaging process

2.2 Proposed Inverter

Figure 2 shows the proposed Fibonacci SC DC-AC inverter⁽⁶⁾. Unlike the conventional SC DC-AC inverter, the voltage ratio of capacitors becomes the ratio of a Fibonacci number. Concretely, the voltage of i -th ($i = 1, 2, 3$) capacitor is $i \times V_{in}$ in the case of 3 stages. In the proposed inverter, the output voltage V_o of each step is expressed as

$$V_o = nV_{in}, \quad (2)$$

$$\text{where } n = \{1, 2, \dots, 7\}$$

As Eq. 2 shows, the proposed inverter can generate the staircase waveform formed by 14 $(=7 \times 2)$ steps in the case of 3 stages. Therefore, the proposed inverter can provide the staircase AC waveform by a smaller number of capacitors. Table 1 shows the timing of the operation process. As table 1 shows, the proposed inverter has three processes: 1) charging process; 2) transferring process; and 3) averaging process. By repeating these three processes mutually, the voltage ratio of each capacitors becomes the

ratio of a Fibonacci number.

As table 1 shows, by shifting the timing of each process of the inverter block-2 against that of the inverter block-1, the transferring process can be appeared at all timings. Table 2 shows an example of the timing of clock pulses in the case of the 7x step-up. As table 1 indicates, in the inverter block-1, T_1 is the charging process, T_2 and T_4 are the transferring process, and T_3 is the averaging process. On the other hand, in the inverter block-2, T_2 is the charging process, T_1 and T_3 are the transferring process, and T_4 is the averaging process. In the transferring process, the n ($n = \{1, 2, \dots, 7\}$) $\times$ stepped-up voltage is obtained by combing some of main capacitors in series. Concretely, to obtain the 7x stepped-up voltage, C_1^j , C_2^j , C_3^j ($j = 1, 2$), and the input voltage are connected in series. In the proposed inverter, two capacitors, two diodes and six bi-directional switches are added to the proposed inverter for every additional one stage.

Table 3 shows comparison of the number of circuit components between the conventional inverter and the proposed inverter in the case of 7x step up. As table 3 shows, the conventional inverter needs 78 circuit components because the conventional inverter must be expanded to 7 stages to generate the 7 stepped-up voltage. On the other hand, the proposed inverter requires 38 circuit components. The number of the circuit components of the proposed the inverter is smaller than that of conventional

Table 2. Setting of clock pulses in the case of the 7x step-up.

State	On	Off
T_1	$S_{g1}^1, S_{s2}^1, S_{g3}^1, S_{s1}^2, S_{s2}^2, S_{s3}^2, S_{o4}^2$	Others
T_2	$S_{s1}^1, S_{s2}^1, S_{s3}^1, S_{o4}^1, S_{g1}^2, S_{s2}^2, S_{g3}^2$	Others
T_3	$S_{s1}^1, S_{g2}^1, S_{s3}^1, S_{s1}^2, S_{s2}^2, S_{s3}^2, S_{o4}^2$	Others
T_4	$S_{s1}^1, S_{s2}^1, S_{s3}^1, S_{o4}^1, S_{s1}^2, S_{g2}^2, S_{s3}^2$	Others

Table 3. Comparison of the number of components.

The number of components	Conventional inverter (7 stages)	Proposed inverter (3 stages)
Voltage gain	7x step-up	7x step-up
Capacitor	16	8
switch	62	24
Diode	0	6
Total	78	38

inverter. Therefore, the number of circuit components can be reduced by the proposed inverter.

3. Experiment

To clarify the operation principle of the proposed inverter, experiments are performed. In the experiment, the number of stages of the proposed inverter was set to three stages. The experimental conditions of the proposed inverter with three stages are as follows: $V_{in} = 12V$ and $T = 2\mu s$. Table 4 shows circuit components of the experimental inverter. As you can see from table 4, to control the bi-directional switches, an AVR micro controller ATMEGA 164P is used in the experimental inverter. However, the signals generated by the AVR micro controller cannot control the bi-directional switches because power of the AVR micro controller is too small. Therefore, to drive the bi-directional switches, bootstrap circuits are attached to each switch. The bootstrap circuit consists of high-low side driver ICs, diode switches and a pumping-up capacitors so it does not require magnetic component. The bootstrap circuit is controlled by the signal of the AVR micro controller and drives the gate terminal of the bi-directional switches by using a voltage of the pumping-up capacitor.

Figure 3 shows the experimental inverter. To charge the pumping-up capacitor of the bootstrap circuit, a charging time of the pumping-up capacitor is required. Therefore, the circuit for charging is added as shown in figure 3. To turn on the switch S_d during the charging process and the transferring process, the pumping-up capacitors of the bootstrap are charged.

Figure 4 shows the photograph of the experimental inverter. As table 4 shows, the experimental inverter of figure 4 was built with commercially available components on a print board. Figure 5 shows the measured output waveform of the proposed inverter.

Fig. 3. One experimental inverter.

Fig. 4. Experimental inverter.

Table 4. Circuit components of the experimental inverter.

Parts	Components	Models
Clock pulse generator block	Micro controller	AVR ATMEGA 164P
Bootstrap circuit block	High-low side driver IC	IR2110
	Diode switches	1N4007
	Capacitors	2.2 μ F
Inverter block	Power switch	TK40E06N1
	Capacitor	100 μ F
Full-bridge block	Power switch	TK100E10N1
	Load	10 k Ω

Fig. 5. Output staircase AC waveform.

As figure 5 shows, the proposed inverter can generate a staircase AC waveform, where the maximum output voltage is 72.2 V. From this result, the experimental inverter can realize the high voltage ratio with the small number of capacitors because 72.2 V is about six times the input

voltage despite the fact that the number of the capacitor is only three. From figure 4, the effectiveness and feasibility of the proposed inverter have been verified.

4. Conclusions

The experimental circuit of the Fibonacci SC DC-AC inverter was built with commercially available components and was evaluated its behavior in this paper. To investigate the operation principle of the proposed inverter, the experiment was performed. The results of this study are as follows: (1) circuit components can be reduced by the proposed inverter and (2) the effectiveness and feasibility of the proposed inverter has been verified by the experiment.

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