

The 6th International Conference on Power and Energy Systems Engineering (CPESE 2019),
September 20–23, 2019, Okinawa, Japan

The development of a step-down switched-capacitor inverter without flying capacitors and full-bridge circuits

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Received 2 October 2019; accepted 22 November 2019

Abstract

Recently, an inductor-less inverter attracts many researchers' attention, because the inductor-less design can provide not only small size but also small electromagnetic interference (EMI). In this paper, we propose a novel step-down switched-capacitor (SC) inverter without flying capacitors. Unlike traditional single-phase inverters, the proposed single-phase inverter has the advantages, namely, inductor-less design, downsizing by omitting flying capacitors, no full-bridge circuit, and symmetrical topology. To achieve these features, the proposed SC inverter changes the connection order of series-connected capacitors alternately. By offering a simple circuit configuration, the proposed inverter can achieve not only small EMI but also small size and high power efficiency. Furthermore, by using pulse width modulation (PWM), the proposed inverter generates a sinusoidal output without flying capacitors and full-bridge circuits. The effectiveness of the proposed inverter is justified by comparing the proposed inverter with an existing single-phase SC inverter. The simulation program with integrated circuit emphasis (SPICE) simulations demonstrate that the proposed inverter outperforms the existing SC inverter in the points of power efficiency and component counts. Concretely, about 94% power efficiency can be achieved when the output power is 2kW. Furthermore, the proposed inverter can reduce two flying capacitors from the existing SC inverter.

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Peer-review under responsibility of the scientific committee of the 6th International Conference on Power and Energy Systems Engineering (CPESE 2019).

Keywords: Inductor-less inverters; Switched-capacitor techniques; Step-down inverters; No full-bridge inverters; Symmetrical topology

1. Introduction

For past few decades, voltage source DC/AC inverters have been used in non-isolated applications. For example, Babaei and Nahavandi [1] proposed a flexible multilevel boost DC-AC inverter, Debre et al. [2] developed a Z source based multilevel inverter, and so on. However, these existing inverters require magnetic components, although high

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<https://doi.org/10.1016/j.egy.2019.11.071>

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power efficiency can be achieved. Due to the existence of magnetic components, these existing inverters become heavy and bulky. For this reason, many attempts were undertaken to develop an inductor-less DC/AC inverter in recent years, because inductor-less design can offer not only small size but also small electromagnetic interference (EMI). The inductor-less design of DC/AC inverters is usually achieved by using the SC techniques [3].

The SC inverter can be divided into two types: the SC inverter with grounded inputs and the SC inverter with non-grounded inputs. For example, in order to reduce component counts, Gautam and Pakala et al. proposed multilevel inverter with non-grounded inputs [4,5]. The SC multilevel inverter has the strong points, namely, small and simple circuit configuration. However, the application of the existing SC multilevel inverter is limited, because non-grounded inputs, such as photovoltaic (PV) input, is necessary. On the other hand, unlike the SC inverter with non-grounded inputs, the SC inverter with grounded inputs has a variety of applications. In past studies, many attempts have been undertaken to develop the SC inverters with grounded inputs. For example, the series–parallel type SC inverter was proposed by Ueno et al. [6] and Oota et al. [7]. As far as the authors know, Ueno et al. invented the first inverter without magnetic components. Following these studies, the Fibonacci-type SC inverter [8,9], the flying capacitor-type step-down SC inverter without full-bridge circuits [10], etc. have been developed to improve power efficiency and hardware cost. However, these conventional SC inverters still suffer from a high component count and low power efficiency.

In this paper, a novel step-down inductor-less inverter is designed by using SC techniques. By changing the connection order of series-connected capacitors alternately, the proposed single-phase inverter provides a stepped-down ac voltage. The advantages of the proposed single-phase inverter are inductor-less design, downsizing by omitting flying capacitors, no full-bridge design, and symmetrical topology. Unlike existing SC inverters, the proposed single-phase inverter can provide a sinusoidal output without flying capacitors and full-bridge circuits. By reducing the number of circuit components, high power efficiency and small size can be achieved by the proposed inverter. The feasibility of the proposed inverter is investigated by simulation program with integrated circuit emphasis (SPICE) simulations, where the proposed inverter is compared with the state-of-the-art conventional SC inverter [10] using two flying capacitors.

2. Circuit configuration

2.1. Conventional inverter

The circuit configuration of the conventional inverter [10] is illustrated in Fig. 1, the switches S_1 and S_2 are driven by two-phase clock pulses. In the existing inverter, the voltages of the main capacitors C_1 and C_2 are averaged by connecting the flying capacitors C_3 and C_4 to C_1 or C_2 alternately. Thus, the existing inverter provides the stepped-down voltage $(1/2) \times V_{in}$ alternately to V_{o1} and V_{o2} without a full-bridge circuit. As shown in Fig. 1, the existing inverter offers a sinusoidal output by filtering the PWM signal by an LC filter. Although the existing inverter can eliminate a full-bridge circuit, there is still room for improvement to reduce the number of circuit components.

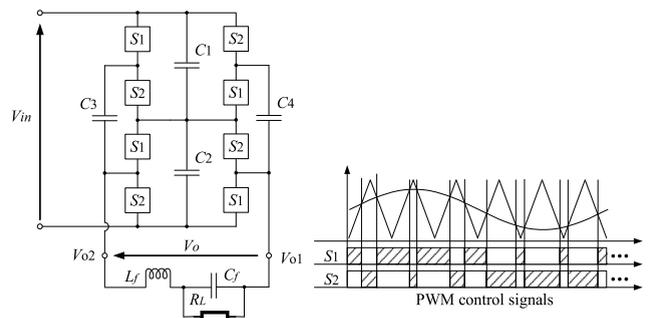


Fig. 1. Circuit configuration of the conventional inverter proposed by Santos et al. [10].

2.2. Proposed inverter

Fig. 2 depicts the circuit configuration of the proposed inverter. Unlike the existing converter, the proposed inverter has no flying capacitor. In the proposed inverter, two-phase clock pulses are used to drive the switches S_1

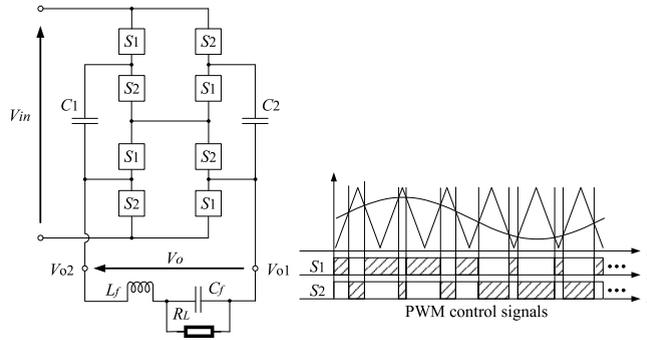


Fig. 2. Circuit configuration of the proposed inverter.

and S_2 as shown in Fig. 3. Fig. 3 shows the instantaneous equivalent circuits of the proposed SC inverter, where R_{on} is the on-resistance of S_i ($i = 1, 2$), $\Delta q_{T_i, v_{in}}$ is the electric charge of V_{in} in State- T_i , and $\Delta q_{T_i, v_{oj}}$ ($j = 1, 2$) is the electric charge of V_{oj} in State- T_i . As you can see from Fig. 3, the proposed inverter does not require full-bridge circuits as well as flying capacitors. Unlike the conventional inverter of Fig. 1, the voltages of C_1 and C_2 are averaged by changing the connection order of C_1 and C_2 as shown in Fig. 3. Therefore, the voltage of C_1 and C_2 becomes $(1/2)V_{in}$. The voltages V_{o1} and V_{o2} are given by

$$V_o = V_{o2} - V_{o1} = \begin{cases} \frac{1}{2}V_{in} & \text{if } S_1 = On \\ -\frac{1}{2}V_{in} & \text{if } S_2 = On, \end{cases} \quad (1)$$

where

$$V_{o1} = \begin{cases} 0 & \text{if } S_1 = On \\ \frac{1}{2}V_{in} & \text{if } S_2 = On \end{cases} \quad \text{and} \quad V_{o2} = \begin{cases} \frac{1}{2}V_{in} & \text{if } S_1 = On \\ 0 & \text{if } S_2 = On, \end{cases} \quad (2)$$

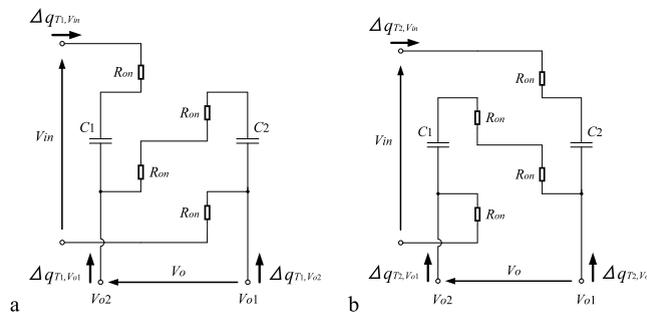


Fig. 3. (a) instantaneous equivalent circuit in state- T_1 ; (b) instantaneous equivalent circuit in state- T_2 .

If parasitic elements are negligibly small. To offer a sinusoidal wave, a PWM signal is generated by V_o . Using an LC filter, a sinusoidal wave is provided by filtering the PWM signal. As shown in Fig. 2, the PWM method of the proposed inverter is the same as that of the existing inverter shown in Fig. 1.

3. Comparison of performance

The characteristics of the proposed inverter were evaluated by SPICE simulations, where the parameters of the SPICE simulation were set to $V_{in} = 800$ V, $R_{on} = 0.83$ Ω , $f = 10$ kHz, $C_1 = C_2 = 800$ μ F, $L_f = 900$ μ H, and $C_f = 100$ μ F. In the SPICE simulations, the proposed inverter was compared with the state-of-the-art conventional inverter [10] in order to clarify the effectiveness of the proposed inverter. The simulation conditions are the same between the proposed SC inverter and the existing SC inverter.

Fig. 4 demonstrates the simulated output voltage as a function of output load, where the output load R_L was set to 100 Ω . As you can see from Fig. 4, the proposed inverter can provide a stepped-down ac voltage from 800 V DC

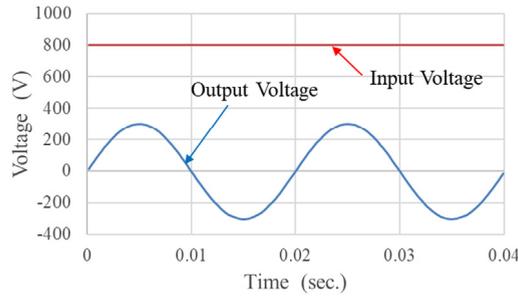


Fig. 4. Simulated output voltage as a function of time.

input. In Fig. 4, the total harmonic distortion (THD) of the proposed inverter was 2.5%. Fig. 5 shows the comparison of output voltages as a function of output power. As Fig. 5 shows, the proposed inverter can achieve higher output voltage than the existing inverter when the output power is more than 2 kW. Fig. 6 illustrates the comparison result of power efficiency as a function of output power. As you can see from Fig. 6, the power efficiency of the proposed inverter is higher than that of the conventional inverter. Concretely, about 94% power efficiency can be achieved by the proposed inverter when the output power is 2 kW. As Figs. 5 and 6 show, the proposed SC inverter outperforms the existing converter owing to the reduction of two flying capacitors. Fig. 7 depicts the comparison result of input power factor as a function of output power. As Fig. 7 shows, the input power factor of the existing inverter is slightly higher than that of the proposed inverter. The input power factor of the proposed inverter is about 0.43 when the output power is 2 kW.

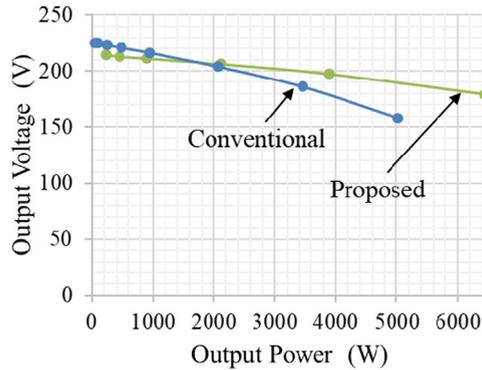


Fig. 5. Simulated output voltage.

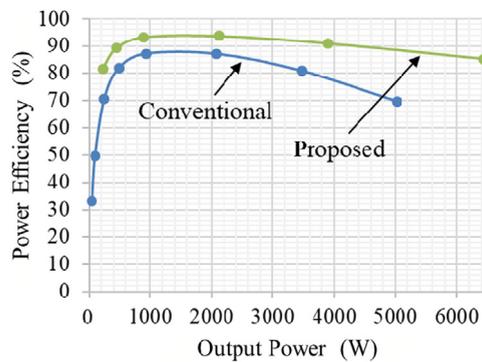


Fig. 6. Simulated power efficiency.

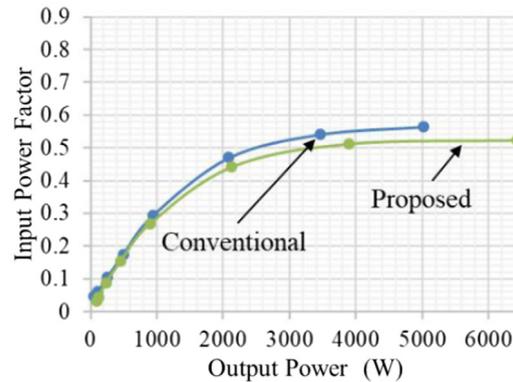


Fig. 7. Simulated input power factor.

Concerning the proposed SC inverter and the existing SC inverter, the comparison of the component count is shown in Table 1. As you can see from Table 1, the proposed inverter is smaller than the conventional inverter, because the proposed inverter requires no flying capacitor. This will lead to not the reduction of fabrication cost as well as improvement of circuit performance.

Table 1. Number of circuit components.

Topology	Gain	Number of switches	Number of capacitors	Total number of circuit components
Proposed inverter	$1/2 \times$	8	2	10
Conventional inverter [10]	$1/2 \times$	8	4	12

4. Conclusion

An inductor-less step-down DC/AC inverter has been designed by using SC techniques. By eliminating flying capacitors, the proposed novel topology realizes not only inductor-less design but also small size and high-power efficiency. The performance comparison between the proposed inverter and the existing SC inverter using flying capacitors was conducted by using SPICE simulations. The results of the SPICE simulation revealed that the proposed inverter outperforms the existing SC converter in terms of power efficiency. The proposed inverter achieved about 94% power efficiency with 2 kW output power. Furthermore, the proposed inverter can reduce the number of circuit components from the existing SC inverter. Concretely, the proposed technique enables that two flying capacitors can be reduced from the existing SC inverter.

The experimental evaluation and its analysis should be the subject of a future study.

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