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A Series of Exponential Step-Down Switched-Capacitor Converters and Their Applications in Two-Stage Converters

Song Xiong, Siu-Chung Wong Senior Member, IEEE, and Siew-Chong Tan Senior Member, IEEE

Abstract—There is a demand for low-power high-voltage-gain transformerless DC–DC converters. It is difficult to achieve this kind of conversion with good efficiency through a buck converter. The two-stage converter is proven to be an effective solution for such applications. In this paper, a series of exponential step-down switched-capacitor (ESC) converters that achieve the benefits of high-voltage-gain conversion, but comprise fewer switches than other switched-capacitor converter topologies, is proposed. The ESC converters are applicable as first-stage converters in the two-stage power conversion solution. Experimental results validating the idea are provided.

I. INTRODUCTION

It is common to use high-voltage-gain DC–DC converters in modern electronic products. A current application of such converters is targeted at converting a DC bus supply voltage of 12 V or higher into an ultra-low voltage level of less than 1 V [1]. At present, for such power conversions, the industry is using the buck-based topology, which is low in cost and simple in implementation [2]. As space and weight are limited in such electronic products, the buck converters are designed to operate at a high switching frequency to reduce the size of their magnetic components. To achieve a high-voltage-gain conversion, the buck converters are operated with a very small duty ratio \( D = \frac{V_{out}}{V_{in}} \), which limits the switching frequency and complicates the control implementation [3]. Besides, the converters inherit a deteriorated dynamic performance and poor efficiency due to the short turn-on time and the long freewheeling time of the switching actions. Converters with transformers would be a better choice for high-voltage-gain conversion if size and cost are not of concerns.

Nevertheless, confining to the size and weight requirements, an alternative candidate is the switched-capacitor (SC) DC–DC converters, which are known for their advantages of small size and light weight [4], [5]. As they comprise only power switches and capacitors, they are highly suitable for integrated circuit (IC) implementation which can be easily integrated in electronic products [4]. For these reasons, SC converters have been widely considered for the high-voltage-gain applications. However, SC converters cannot achieve a high efficiency if they are used for the purpose of voltage regulation, which limits their usefulness to voltage transformation applications [5].

The limitations of the single-stage converters have spurred the interests in developing a new kind of high-voltage-gain two-stage DC–DC converters [3], [6], [7], of which the converter is made up of a first-stage SC converter, followed by a second-stage buck converter. For this two-stage SC-buck converter, the first-stage SC converter steps down the input voltage to a low level (i.e., step-down voltage transformation) while the second-stage buck converter mainly performs the voltage regulation. The overall efficiency of this two-stage converter can be higher than a single buck converter for the reason that the first-stage SC converter provides a much lower input voltage for the buck and it runs at a higher efficiency state. It is obvious that if the energy saved by the second-stage buck converter is higher than the energy losses incurred by the first-stage converter, then the overall efficiency can be improved.

Even though existing SC converter products can achieve an efficiency as high as 98% (e.g. LTC1044, MAX1044, SI7660, GS7660 etc.), the rated powers are always very low. In addition, most SC converter topologies require a large number of switches in their circuitries when the voltage conversion is high [6]–[8]. This complicates their implementation and increase their cost. It is desired to have SC converters with fewer switches that can still attain high-voltage-gain conversion with high efficiency. In this paper, a series of exponential step-down switched-capacitor (ESC) converters which satisfy such requirements is proposed.

II. A SERIES OF ESC CONVERTERS

A. Second-Order ESC Converter: Topology and Operation

Fig. 1 shows the topology of the second-order step-down ESC converter and its timing control diagram. This converter steps down the input voltage to a quarter of its amplitude, that is \( V_o = \frac{1}{4} V_i \). Comparing with the basic series-charging-parallel-discharging SC converter, this converter uses fewer switches.

By neglecting the states in which very short dead-time occur, the number of operating states can be reduced to four as shown in Fig. 1(b). Fig. 2 gives the circuit representation of these states. In State 1 (Fig. 2(a)), flying capacitor \( C_{f1} \) is discharging while capacitor \( C_{f2} \) is charging. In State 2 (Fig. 2(b)), both capacitors \( C_{f1} \) and \( C_{f2} \) are charging. In State 3 (Fig. 2(c)), \( C_{f1} \) is charging and \( C_{f2} \) is discharging. In State 4 (Fig. 2(d)), both \( C_{f1} \) and \( C_{f2} \) discharges. From the timing diagram, the ESC converter is operated in the following sequence: State 1 - State 2 - State 3 - State 4 - State 1 and so on.
Fig. 1. Proposed ESC converter and its timing diagram.

(a) Topology
(b) Timing diagram

Fig. 2. Operating states of the proposed ESC converter.

(a) State 1
(b) State 2
(c) State 3
(d) State 4

III. ESC-BUCK CONVERTER

A comparison of the proposed topology in Fig. 1 with that given in [9] shows their difference being the additional structure given in Fig. 3(c). By adopting this structure (Fig. 3(c)), a series of higher-order ESC converters can be developed. Fig. 4 shows a third-order ESC converter.

1) Topologies of High-Order ESC converter: Figs. 3(a) and 3(b) give the basic structure of an ESC converter and its timing diagram. This structure gives an output voltage half of the input voltage. Here, $C_{f1}$ will parallel with $C_{11}$ during State 1, of which $C_{f1}$ will be charged to the voltage level of $C_{11}$. In State 2, $C_{f1}$ is paralleled with $C_{10}$, of which $C_{f1}$ discharges to $C_{10}$ and output load. As a whole, $C_{f1}$ automatically equalizes the voltage of the capacitors $C_{10}$ and $C_{11}$, which is half the input voltage. Figs. 3(c) and 3(d) are the extension structure of the ESC converters and its timing diagram. The operation of the extension structure is similar to the basic structure.

If the basic structure is cascaded with the extension structure, a second-order ESC converter as given in Fig. 1(a) is resulted. Likewise, a third-order ESC converter (output voltage being one eighth of its input voltage) can be derived by further cascading the second-order ESC converter with an additional extension structure, as given in Fig. 4. Similarly, an $n$-order ESC converter can be derived using the same approach. Its output voltage is

$$V_o = \frac{1}{2^n} \cdot V_{in}.$$  

2) Switching Intervals of High-Order ESC converter: The timing diagram is similar to that of the second-order ESC converter (see Fig. 1(b)). The switching interval is $\frac{1}{2^n}$ for the third-order ESC converter and $\frac{1}{2^n}$ for an $n$-order ESC converter.

Fig. 3. Structures of the generalized ESC converter.

B. Generalization of ESC converter

A series of ESC converters with fixed conversion ratio of $\frac{1}{2^n}$ have been introduced. The output voltage of these converters changes with the input voltage. If the required output voltage is not an exact multiple of $\frac{V_{in}}{2^n}$, the converter is inapplicable. This lack of voltage regulation function limits their applications. It has been demonstrated that a two-stage converter can give a better efficiency than a single buck converter in high-voltage-gain conversion operations [3], [6]. Here, the ESC converter fits well for this application.

In this paper, it is proposed that the ESC converter is used as the first-stage converter of the two-stage converter.
shows a topology of a second-order ESC-buck converter. The first stage is a second-order ESC converter which steps down the input voltage to 1/4, while the second-stage buck converter regulates the output voltage.

IV. EXPERIMENTAL RESULTS

Experimental prototypes are constructed for the verification of the proposed ESC-buck converter. The parameters of the buck converter are shown in Table I. The ESC converter is built with discrete elements using parameters shown in Table II.

Experiments are performed on three topologies of the converters. The first set of experiments are performed on the commercially available buck converter IC MAX8655. The second set of experiments are performed on a first-order ESC-buck converter (i.e., first-order ESC converter as the first-stage converter and MAX8655 as the second-stage converter). The third set of experiments are performed on a second-order ESC-buck converter (i.e., second-order ESC converter plus MAX8655). In all cases, the same buck converter settings are employed. The efficiency measurement given in this work is the overall system efficiency which includes the power consumed by the drivers and controller circuit of the ESC converter.

Fig. 6 shows the efficiency curves of the buck IC MAX8655. It can be seen that the efficiency for the buck converter is high at a low input voltage of 5 V and 10 V. Its efficiency is significantly lower for the same output power when input voltage is 20 V. Fig. 7(a) gives the efficiency comparison of the first-order and second-order ESC-buck converters. The second-order ESC-buck converter has a higher efficiency than the first-order ESC converter when the input voltage is higher than 26 V.

Fig. 7(b) shows that at an input voltage of 20 V, both the first-order and second-order ESC-buck converters give a higher efficiency than the MAX8655 buck converter operating on its own. This validates the use of ESC converters as the first-stage converter of a two-stage converter solution for high-voltage-gain applications. In this case, the first-order and second-order ESC-buck converter each excels at different load conditions. For output power higher than 6.5 W, the former gives a higher efficiency than the latter. For output power lower than 6.5 W, the latter gives a higher efficiency. However, as shown in Fig. 7(c), when both ESC converters are operated with an even higher input voltage of 30 V, which is over the input voltage rating of MAX8655, the efficiency of the second-order ESC-buck converter is higher than that of the first-order ESC-buck converter for the entire specified load range.

V. CONCLUSIONS

This paper presents a series of exponential switched-capacitor (ESC) converter topologies which can exponentially step-down the voltage input with fewer switches than con-

![Fig. 4. Third-order ESC converter.](image)

![Fig. 5. Second-order ESC-Buck converter.](image)

### Table I

<table>
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<tr>
<th>ESC Type</th>
<th>First-Order</th>
<th>Second-Order</th>
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<tr>
<td>Flying Capacitor $C_{f1}$</td>
<td>6 × 47 μF</td>
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<tr>
<td>Flying Capacitor $C_{f2}$</td>
<td>NA</td>
<td>6 × 47 μF</td>
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<tr>
<td>Capacitor $C_{10}$</td>
<td>1 × 47 μF</td>
<td>1 × 47 μF</td>
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<tr>
<td>Capacitor $C_{11}$</td>
<td>1 × 47 μF</td>
<td>1 × 47 μF</td>
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<tr>
<td>Capacitor $C_{12}$</td>
<td>NA</td>
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<td>Switch</td>
<td>NTMFS4897</td>
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### Table II

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<th>IC Type</th>
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<tr>
<td>Input Voltage</td>
<td>4.5–25 V</td>
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<tr>
<td>Output Voltage</td>
<td>1.2 V</td>
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<tr>
<td>Switching Frequency</td>
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<td>Filter Inductor</td>
<td>0.82 μH</td>
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<tr>
<td>Output Capacitor</td>
<td>4 × 47 μF</td>
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![Fig. 6 shows the efficiency curves of the buck IC MAX8655.](image)
tional switched-capacitor converters. While the prospect of the ESC converter is very good for voltage transformation application, without regulation capability, its application is limited. Knowing that there are numerous buck type ICs in the market which perform very well under normal condition but suffers from a poor efficiency when the input voltage is high, it is proposed in this paper that for high-voltage-gain conversion functions, the ESC converter is placed between the input power source and the buck IC to form a two-stage converter. Experimental results of the ESC-buck converters show that a higher efficiency compared with the single buck IC converter can be achieved.

REFERENCES

Fig. 6. Efficiency curves of MAX8655.

Fig. 7. Experimental results of ESC-buck converter using MAX8655 operating at a regulated output voltage of 1.2 V. The ESC converter operates at a switching frequency of 30 kHz.