A Single-Input Dual-Output Step-Up/Step-Down DC-DC Converter Designed by Switched Capacitor Techniques

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Abstract

In this paper, we propose a single-input dual-output (SIDO) DC-DC converter designed by switched capacitor (SC) techniques. Unlike conventional SC converters, the proposed converter can provide nine kinds of two stepped-up and/or stepped-down output voltages without changing circuit topology. This paper also presents a novel analysis method to estimate properties of the SC SIDO converters, because few studies have been done on the theoretical analysis of the multi-output SC converters. Unlike the traditional state-space averaging method, the proposed method can derive the power efficiency and output voltages without complex matrix calculations. The simulation program with integrated circuit emphasis (SPICE) simulation shows the following results: (1) more than 82% efficiency is obtained over a range of output power from 0.1W to 1W with conversion ratios of 1/2 and 3/2 and (2) the proposed analysis method will be helpful to estimate the power efficiency and output voltages of the SC SIDO converter, because theoretical results are in good agreement with SPICE simulated results. Furthermore, experiment on a breadboard shows the validity of the proposed SC SIDO topology.

Keywords: switched capacitor circuits, DC-DC converters, single-input dual-output, step-up/step-down converters.

1. Introduction

In mobile consumer products, power supplies at different voltage and/or current levels are required to drive some circuit units. To generate multiple outputs at different voltage levels from a single DC supply, several DC power distributed systems have been used: low dropped regulator

(LDO) arrays, single-input parallel-connected DC-DC converters, and so on. Among others, in order to reduce the number of external circuit components, single-inductor multi-output (SIMO) DC-DC converters have been developed in recent years. For example, Patra et al. and Deepti et al. suggested a step-down SIMO converter using a buck converter topology^(1,2). Owing to the single inductor topology, the step-down SIMO converter^(1,2) can achieve small hardware cost. However, the converter reported in references (1,2) offers only stepped-down voltages. Ray et al. proposed a multi-output DC-DC converter^(3,4) which can provide a step-up and multiple step-down outputs. Unlike the step-down SIMO converter^(1,2), the multi-output converter reported in references (3,4) can provide stepped-up and stepped-down voltages. However, the multi-output converter reported in references (3,4) requires a couple of inductors. To drive multi-color LEDs, Dietrich et al. suggested an SIMO converter using a buck-boost converter topology⁽⁵⁾. Unlike the conventional converters reported in references (1-4), the buck-boost SIMO converter⁽⁵⁾ can achieve step-up and step-down conversion by using only one inductor. However, the outputs are negative voltages though the buck-boost SIMO converter⁽⁵⁾ can drive multi-color LEDs effectively. Therefore, the applications field of the buck-boost SIMO converter is limited.

As distinct from above-mentioned DC-DC converters containing magnetic components, multi-output DC-DC converters designed by switched-capacitor (SC) techniques have been proposed recently. The SC DC-DC converter can be realized without the use of magnetic components. Therefore, the SC converter can reduce not only circuit size but also effects of the electromagnetic interference (EMI), though the conversion ratio of the SC converter is

predetermined by circuit topology. In previous studies, Suzuki et al. proposed a serial fix type DC-DC converter⁽⁶⁾ designed by SC techniques. However, the serial fix type converter provides only the stepped-down voltages, V_{in}/N ($N=1,2,3, \dots$). Of course, as reported in the reference [7], the conventional converter can generate stepped-up voltages by swapping the input and output terminals. However, the serial fix type converter cannot control conversion ratios without changing circuit topology. Hua et al. suggested a single-input dual-output (SIDO) DC-DC converter for energy harvesting applications⁽⁸⁾. By using a charge pump⁽⁹⁾, the SIDO converter reported in reference (8) can provide stepped-up voltages from a small input voltage. However, the conversion ratios of the conventional SIDO converter reported in reference (8) are only 2x and 3x. Chen et al. proposed an SC SIDO converter employing pseudo-three phase swap-and-cross control⁽¹⁰⁾. By connecting series-parallel type converters⁽¹¹⁾ in parallel, the conventional converter reported in reference (10) achieves step-up and step-down conversion. However, the circuit size becomes large, because two converters are required to achieve step-up/step-down conversion.

In this paper, we propose an SIDO step-up/step-down converter designed by SC techniques. The proposed SIDO converter consists of 15 transistor switches and 3 capacitors. Unlike conventional SC converters⁽⁶⁻¹¹⁾, the proposed converter can offer nine kinds of two stepped-up/stepped-down outputs: $V_{in}/3$ and $2V_{in}/3$, $V_{in}/3$ and V_{in} , $2V_{in}/3$ and V_{in} , $V_{in}/2$ and V_{in} , V_{in} and $3V_{in}/2$, $V_{in}/2$ and $3V_{in}/2$, V_{in} and $2V_{in}$, V_{in} and $3V_{in}$, and $2V_{in}$ and $3V_{in}$. This paper also presents a novel analysis method to estimate properties of the SC SIDO converters, because few studies have been done on the theoretical analysis of the SC SIDO converters. In the traditional theoretical analysis of SC DC-DC converters, the state-space averaging method has been commonly used^(12, 13). However, the state-space averaging method requires complex matrix calculations. By assuming a five-terminal equivalent circuit, the proposed method derives the power efficiency and output voltages without complex matrix calculations. To confirm the validity of the proposed converter, simulation program with integrated circuit emphasis (SPICE) simulations, theoretical analysis, and experiments are performed.

The rest of this paper is organized as follows. In Section 2, the circuit configuration of the conventional SC SIDO converter and the proposed SC SIDO converter is presented. In Section 3, the property of the proposed converter is analyzed by the proposed analysis method. Simulation

results and experimental results are shown in Sections 4 and 5, respectively. Finally, conclusion and future work are drawn in Section 6.

Fig. 1. Conventional dual-output SC DC-DC converter.

2. Circuit Configuration

2.1 Conventional Converter

Figure 1 shows an example of the conventional multi-output SC converter. The converter of figure 1 is based on the serial fix type converter⁽⁶⁾ proposed by Suzuki et al. The conventional converter consists of six transistor switches and four capacitors, where transistor switches $S_{1,j}$, $S_{2,j}$, and $S_{3,j}$ ($j=1, 2$) are driven by non-overlapped three phase clock pulses. By controlling these transistor switches, the conventional converter of figure 1 offers the following stepped-down voltages:

$$V_{out1} = \left(\frac{1}{3}\right)V_{in} \quad \text{and} \quad V_{out2} = \left(\frac{2}{3}\right)V_{in}. \quad (1)$$

In the conventional converter, a fly-capacitor C_4 shuttles electric charge among the three voltage regions: $V_{in}/3$, $2V_{in}/3$ and V_{in} . Of course, by swapping the input and output terminals, the conventional converter can generate stepped-up and/or stepped-down voltages. However, the conversion ratios of the conventional multi-output SC converter are predetermined by the circuit topology. For this reason, the application filed of the conventional converter is limited.

2.2 Proposed Converter

Figure 2 shows the proposed SC SIDO converter. The proposed SIDO converter provides stepped-up and/or

stepped-down voltages as follows:

$$V_{out1} = \left(\frac{s_1}{r}\right)V_{in} \quad \text{and} \quad V_{out2} = \left(\frac{s_2}{r}\right)V_{in}, \quad (2)$$

where $s_1 \neq s_2$ ($r, s_1, s_2 = \{1, 2, \dots, N\}$).

(a) General form.

(b) Three stages ($N=3$).

Fig. 2. Proposed SC SIDO converter.

For easy understanding, let's discuss the simplest example of the proposed SIDO converter. Figure 2 shows an example of the proposed SIDO converter. In figure 2 (b), clock pulses for the transistor switch $S_{1,j}$ ($j=1, 2, 3$) are non-overlapped three phase pulses and clock pulses for $S_{2,j}$ are set to inverted pulses of $S_{1,j}$. According to the conversion ratios s_1/r and s_2/r in (2), the transistor switches $S_{3,j}$, $S_{4,j}$, and $S_{5,j}$ are driven by clock pulses obtained by shifting the clock pulse of $S_{1,j}$ cyclically. In other words, by

controlling $S_{3,j}$, $S_{4,j}$, and $S_{5,j}$, the conversion ratios s_1/r and s_2/r are determined. Concretely, the proposed SIDO converter of figure 2 (b) can offer the output voltages, V_{out1} , $V_{out2} = \{V_{in}/3, V_{in}/2, 2V_{in}/3, V_{in}, 3V_{in}/2, 2V_{in}, 3V_{in}\}$, without changing circuit topology.

Fig. 3. Proposed equivalent circuit.

3. Theoretical Analysis

To save space, the property of the proposed SIDO converter is analyzed in conversion ratios of 1/2 and 3/2 theoretically. By assuming a five-terminal equivalent circuit as shown in figure 3, the proposed analysis method is performed, because it is known that the general equivalent circuit of the single-input single-output SC DC-DC converter can be expressed by a four-terminal circuit⁽¹⁴⁾. In figure 3, R_{sc1} , R_{sc2} , and R_{sc3} are called the SC resistance and m_1 and m_2 are the conversion ratio of ideal transformers. Unlike the state-space averaging method^(12, 13), the proposed analysis method derives these parameters from instantaneous equivalent circuits of the SC SIDO converter without complex matrix calculations.

Figure 4 shows the instantaneous equivalent circuits of the proposed SIDO converter of figure 2 (b). In figure 4, R_{on} denotes the on-resistance of the transistor switch. In the steady state, the differential value of electric charges in C_k ($k=1, 2, 3$) satisfies the following equations:

$$\sum_{i=1}^3 \Delta q_{T_i}^k = 0, \quad (3)$$

where $\Delta q_{T_i}^k$ ($(i=1, 2, 3)$ and $(k=1, 2, 3)$) denotes the electric charge of the k -th capacitor in the case of State- T_i . The interval of State- T_i satisfies the following conditions:

$$T = \sum_{i=1}^3 T_i \quad \text{and} \quad T_1 = T_2 = T_3, \quad (4)$$

where T is a period of the clock pulse and T_i ($i=1, 2, 3$) is

the interval of State- T_i . In State- T_1 , the differential values of electric charges in the input V_{in} and the outputs V_{out1} and V_{out2} , $\Delta q_{T1,Vin}$, $\Delta q_{T1,Vout1}$ and $\Delta q_{T1,Vout2}$, are expressed as

$$\begin{aligned}\Delta q_{T1,Vin} &= \Delta q_{T1}^2 - \Delta q_{T1}^3, \\ \Delta q_{T1,Vout1} &= \Delta q_{T1}^1 - \Delta q_{T1}^2, \\ \text{and} \quad \Delta q_{T1,Vout2} &= \Delta q_{T1}^3.\end{aligned}\quad (5)$$

(a) State- T_1 .

(b) State- T_2 .

(c) State- T_3 .

Fig. 4. Instantaneous equivalent circuits with conversion ratios of 1/2 and 3/2.

In State- T_2 , the differential values of electric charges in the input V_{in} and the outputs V_{out1} and V_{out2} , $\Delta q_{T2,Vin}$, $\Delta q_{T2,Vout1}$ and $\Delta q_{T2,Vout2}$, are expressed as

$$\begin{aligned}\Delta q_{T2,Vin} &= \Delta q_{T2}^3 - \Delta q_{T2}^1, \\ \Delta q_{T2,Vout1} &= \Delta q_{T2}^2 - \Delta q_{T2}^3,\end{aligned}\quad (6)$$

$$\text{and} \quad \Delta q_{T2,Vout2} = \Delta q_{T2}^1.$$

In State- T_3 , $\Delta q_{T3,Vin}$, $\Delta q_{T3,Vout1}$ and $\Delta q_{T3,Vout2}$, are expressed as

$$\begin{aligned}\Delta q_{T3,Vin} &= \Delta q_{T3}^1 - \Delta q_{T3}^2, \\ \Delta q_{T3,Vout1} &= \Delta q_{T3}^3 - \Delta q_{T3}^1,\end{aligned}\quad (7)$$

$$\text{and} \quad \Delta q_{T3,Vout2} = \Delta q_{T3}^2.$$

Furthermore, the following conditions are satisfied, because the instantaneous equivalent circuits have symmetrical structure as shown in figure 4.

$$\Delta q_{T1,Vin} = \Delta q_{T2,Vin} = \Delta q_{T3,Vin},$$

$$\Delta q_{T1,Vout1} = \Delta q_{T2,Vout1} = \Delta q_{T3,Vout1},$$

$$\Delta q_{T1,Vout2} = \Delta q_{T2,Vout2} = \Delta q_{T3,Vout2},$$

$$\Delta q_{T1}^2 = \Delta q_{T2}^3 = \Delta q_{T3}^1, \quad (8)$$

$$\Delta q_{T1}^3 = \Delta q_{T2}^1 = \Delta q_{T3}^2,$$

$$\text{and} \quad \Delta q_{T1}^1 = \Delta q_{T2}^2 = \Delta q_{T3}^3.$$

Using (5)-(7), the average input current and the average output currents can be expressed as

$$\overline{I_{in}} = \frac{\Delta q_{Vin}}{T} = \sum_{i=1}^3 \frac{\Delta q_{Ti,Vin}}{T},$$

$$\overline{I_{out1}} = \frac{\Delta q_{Vout1}}{T} = \sum_{i=1}^3 \frac{\Delta q_{Ti,Vout1}}{T}, \quad (9)$$

$$\text{and} \quad \overline{I_{out2}} = \frac{\Delta q_{Vout2}}{T} = \sum_{i=1}^3 \frac{\Delta q_{Ti,Vout2}}{T}.$$

In (9), Δq_{Vin} , Δq_{Vout1} , and Δq_{Vout2} are electric charges in V_{in} , V_{out1} , and V_{out2} , respectively. Substituting (3)-(8) into (9), we have the relation between the average input current and the average output currents as follows:

$$\overline{I_{in}} = -\frac{1}{2}\overline{I_{out1}} - \frac{3}{2}\overline{I_{out2}}. \quad (10)$$

From (10), the conversion ratios in figure 3 are obtained as $m_1=1/2$ and $m_2=3/2$.

Next, in order to derive the SC resistances R_{SC1} , R_{SC2} ,

and R_{SC3} , the consumed energy in one period is discussed. From figure 4 (a), the consumed energy W_T can be expressed as

$$W_T = \sum_{i=1}^3 W_{T_i} = 3W_{T_1},$$

$$\begin{aligned} \text{where } W_{T_1} = & \frac{(\Delta q_{T_1}^1)^2}{T_1} R_{on} + \frac{(\Delta q_{T_1}^2)^2}{T_1} R_{on} \\ & + \frac{2(\Delta q_{T_1}^3)^2}{T_1} R_{on} + \frac{(\Delta q_{T_1, V_{out1}})^2}{T_1} R_{on} \\ & + \frac{(\Delta q_{T_1, V_{in}})^2}{T_1} R_{on}. \end{aligned} \quad (11)$$

Using (3)-(8), (11) is rewritten as

$$\begin{aligned} W_{T_1} = & \frac{7(\Delta q_{V_{out1}})^2}{4T} R_{on} + \frac{19(\Delta q_{V_{out2}})^2}{4T} R_{on} \\ & + \frac{3(\Delta q_{V_{out1}} \cdot \Delta q_{V_{out2}})}{4T} R_{on}. \end{aligned} \quad (12)$$

Here, the consumed energy W_T of the five-terminal equivalent circuit shown in figure 3 is obtained as

$$\begin{aligned} W_T = & R_{SC1} (\overline{I_{out1}})^2 T + R_{SC2} (\overline{I_{out2}})^2 T \\ & + R_{SC3} (\overline{I_{out1}} + \overline{I_{out2}})^2 T, \\ = & (R_{SC1} + R_{SC3}) \frac{(\Delta q_{V_{out1}})^2}{T} \\ & + (R_{SC2} + R_{SC3}) \frac{(\Delta q_{V_{out2}})^2}{T} \\ & + 2R_{SC3} \frac{(\Delta q_{V_{out1}} \cdot \Delta q_{V_{out2}})}{T}. \end{aligned} \quad (13)$$

Therefore, from (12) and (13), we have the SC resistances as follows:

$$R_{SC1} = R_{on}, \quad R_{SC2} = 4R_{on}, \quad \text{and} \quad R_{SC3} = \frac{3}{4}R_{on}. \quad (14)$$

By combining (10) and (14), the equivalent circuit of the proposed SIDO converter can be expressed by figure 5, where R_{L1} and R_{L2} are output loads.

From figure 5, the power efficiency and the output voltages of the proposed SIDO converter can be derived. By using a principle of superposition, we have the output voltages V_{out1} and V_{out2} as follows:

$$V_{out1} = V_{out1,1} + V_{out2,1}, \quad (15)$$

$$\text{where } V_{out1,1} = \frac{(V_{in}/2 - V_{x1})R_{L1}}{R_{SC1} + R_{L1}},$$

$$V_{out2,1} = \frac{(V_{in}/2 - V_{x1})R_{L2}}{R_{SC2} + R_{L2}},$$

$$\text{and } V_{x1} = \frac{(V_{in}/2)R_{SC3}}{R_{SC3} + (R_{SC1} + R_{L1}) // (R_{SC2} + R_{L2})}$$

and

$$V_{out2} = V_{out1,2} + V_{out2,2}, \quad (16)$$

$$\text{where } V_{out1,2} = \frac{-V_{x2}R_{L1}}{R_{SC1} + R_{L1}},$$

$$V_{out2,2} = \frac{(V_{in} - V_{x2})R_{L2}}{R_{SC2} + R_{L2}},$$

$$\text{and } V_{x2} = \frac{\{(R_{SC1} + R_{L1}) // R_{SC3}\}V_{in}}{(R_{SC2} + R_{L2}) + (R_{SC1} + R_{L1}) // R_{SC3}}.$$

Furthermore, the power efficiency η of the proposed SIDO converter is obtained as

$$\eta = \frac{R_{L1} + R_{L2}\alpha^2}{(R_{SC1} + R_{L1}) + (R_{SC2} + R_{L2})\alpha^2 + R_{SC3}(1 + \alpha)^2}, \quad (17)$$

$$\text{where } \alpha = \frac{3(R_{SC1} + R_{L1}) + 2R_{SC3}}{R_{SC2} - 2R_{SC3} + R_{L2}}.$$

Fig. 5. Equivalent circuit of the SC SIDO converter with conversion ratios of 1/2 and 3/2.

4. Simulations

To confirm the validity of theoretical analysis,

properties of the proposed SIDO converter are investigated by SPICE simulations. The SPICE simulations are performed under conditions that $V_{in} = 3.7V$, $C_1 = C_2 = C_3 = C_{out1} = C_{out2} = 1\mu F$, $R_{on} = 1\Omega$, $T = 1.5\mu s$ and $R_L = R_{L1} = R_{L2}$, where C_{out1} and C_{out2} are output capacitors connecting the output terminals. In the SPICE simulations, the property of the proposed converter is compared with that of the conventional serial fix type converter shown in figure 1.

(a) Output voltages as a function of the output load.

(b) Output voltages as a function of the output power.

Fig. 6. Output voltages of the proposed SIDO converter.

Table 1. Timing of clock pulses for conversion ratios of 1/2 and 3/2.

State	On	Off
T_1	$S_{1,1}, S_{2,2}, S_{2,3}, S_{3,2}, S_{4,1}, S_{5,3}$	Others
T_2	$S_{1,2}, S_{2,3}, S_{2,1}, S_{3,3}, S_{4,2}, S_{5,1}$	Others
T_3	$S_{1,3}, S_{2,1}, S_{2,2}, S_{3,1}, S_{4,3}, S_{5,2}$	Others

(a) Power efficiency as a function of the output load.

(b) Power efficiency as a function of the output power.

Fig. 7. Power efficiency of the proposed SIDO converter.

Figure 6 shows the simulated output voltages with conversion ratios of 1/2 and 3/2. In figure 6, the clock pulse of the proposed converter was set to as shown in Table 1. On the other hand, in the conventional converter of figure 1,

the input terminal V_{in} and the output terminals V_{out1} and V_{out2} are set to the terminal b , a , and c , respectively. In figures 6 (a) and (b), the solid lines show the theoretical results obtained by (15) and (16). As figure 6 shows, the theoretical results are in good agreement with the SPICE simulated results. Therefore, the validity of (15) and (16) can be confirmed. Furthermore, unlike the conventional SIDO converter shown in figure 1, the proposed SIDO converter can provide not only a stepped-down voltage but also a stepped-up voltage without changing circuit topology.

Figure 7 shows the simulated power efficiency with conversion ratios of 1/2 and 3/2. In figures 7 (a) and (b), the solid lines show the theoretical results obtained by (17). As figure 7 shows, theoretical results agree well with SPICE simulated results. From figures 6 and 7, the validity of the theoretical analysis can be confirmed. The derived theoretical equations will be helpful to estimate the properties of the proposed SC SIDO converter. Furthermore, as figure 7 shows, the proposed converter can improve the power efficiency more than 3% from the conventional converter when the output load is 100Ω. The proposed converter can achieve more than 82% efficiency over a range of output power from 0.1W to 1W.

Fig. 8. Experimental circuit.

5. Experiment

Figure 8 shows the photograph of the experimental circuit. The experimental circuit of figure 8 was built with commercially available ICs AQV212 and TD62004APG on a bread board, where $V_{in} = 3.7V$, $C_1 = C_2 = C_3 = C_{out1} = C_{out2} = 10\mu F$, $T = 1.5ms$ and $R_{L1} = R_{L2} = 10k\Omega$. In the experiments, we focused on the verification of the circuit topology, because the experimental circuit was built with commercially available ICs on a bread board.

Figure 9 shows the measured output voltages of the proposed SC SIDO converter, where the 1/2x and 3/2x conversion ratios are realized. In figure 9, the measured output voltages are 1.84V and 5.53V, where the ideal outputs are 1.85V and 5.55. Figure 10 shows the measured output voltages with conversion ratios of 1/3 and 2/3. In figure 10, the measured output voltages are 1.23V and 2.46V, where the ideal outputs are 1.23V and 2.47. As figures 9 and 10 shows, the proposed converter can control conversion ratios without changing circuit topology. From figures 9 and 10, the validity of the proposed SC SIDO topology can be confirmed.

Fig. 9. Measured outputs with conversion ratios of 1/2 and 3/2.

Fig. 10. Measured outputs with conversion ratios of 1/3 and 2/3.

6. Conclusions

An SC SIDO DC-DC converter and its analysis method have been proposed in this paper. Concerning the proposed converter, SPICE simulations, theoretical analysis, and experiments were performed to confirm the validity of the circuit design.

The results of this study are as follows: (1) Without changing circuit topology, not only a stepped-down voltage but also a stepped-up voltage was offered by the proposed SIDO converter; (2) the proposed converter improved power efficiency more than 3% from the serial fix type converter when the output load was 100Ω. Furthermore, more than 82% efficiency was obtained over a range of output power from 0.1W to 1W with conversion ratios of 1/2 and 3/2; and (3) handy theoretical equations to estimate properties of the proposed SIDO converter were obtained by using a five-terminal equivalent circuit. The theoretical results were in good agreement with SPICE simulated results.

The detailed experiment of the proposed converter is left to a future study.

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