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Research Article

Conventional DC-DC Converters Through Duality Approach for Current-Based Applications

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Abstract: This paper discusses the application of the principle of duality to conventional voltage-based DC-DC converters, such as buck, boost, fly-back, cuk, sepic, and zeta topologies, in order to obtain their current-based DC-DC converters. The duality approach involves finding the dual of a circuit, which is a circuit equivalent to the original circuit but with certain parameters swapped. Therefore, this paper presents a comprehensive study on achieving the most commonly used topologies of DC-DC current converters by applying the duality approach to their DC-DC voltage converters. This approach serves as a solution for applications where a current source is available and there is a need for output current control. An application of these current converters is to power current-based loads, such as light-emitting diodes (LEDs), and to provide conversion for current sources, such as photovoltaics (PV). As an advantage, these converters do not require additional inductors at their input or output terminals. Additionally, the paper provides a detailed explanation of the principle of operation and mathematical analysis of the conversion ratio for the discussed current converters. The proposed current converters and their application as an interface between a PV and a high-power LED were simulated using MATLAB to verify the mathematical equations. Overall, this paper provides a useful study guideline for understanding the principle of duality and the application of DC-DC current converters for current-based loads and sources.

Keywords: Duality approach, DC-DC current converters, current-based loads, current source.

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NOMENCLATURE

Symbol Variables	Description
D	Transistor ON duty cycle
T_s	Sampling period time
G	Current conversion ratio
TVS	Total voltage stress (V)
TCS	Total current stress (A)
V_{PV}	PV module voltage (V)
I_{PV}	PV module current (A)
r_d	Differential resistance (Ω)
C_j	Junction capacitance
C_{sc}	Space-charge capacitance
C_d	Diffusion capacitance
R_b	Series bonding resistance (Ω)
L_b	Series bonding inductance
C_b	Parallel bonding capacitance
Z_{LED}	Impedance of an LED
I_{ph}	Light current (A)
I_0	Diode reverse saturation current (A)
Q_d	Diode ideality factor
n_s	Number of cells in series
R_s	Series resistance (Ω)
R_p	Shunt resistance (Ω)
k	Boltzmann's constant
T_c	Cell temperature
q	Charge of an electron

1. INTRODUCTION

The classical switched-mode power converters (SMPCs) have been the dominant power converters for DC-DC power conversion in recent times [1-3]. Classical SMPCs typically use inductors and capacitors as energy storage components and are well-suited for providing DC power supplies and low-voltage DC drives [4, 5]. DC-DC converters with high-frequency switching devices are used to achieve the modulation or demodulation of output voltages at the same power levels [6, 7]. They are typically fed by a constant power source and can be divided into different types of structures [8-10]. These structures are obtained by making changes in the component configurations of basic converters, such as the buck and boost converters. Hence, new converter topologies have been developed, such as the fly-back, cuk, sepic, and zeta converters, which have different features and are suitable for different applications [11].

Another type of power converter has recently been introduced for current conversion applications. These converters are designed to control the output or load currents [12-21]. There are several methods to achieve the current converters, each coming with its own advantages and disadvantages, like those introduced in [17-21]. However, there is another way to access DC-DC current converters by making changes in DC-DC voltage converters. These changes are made by applying the principle of duality in the circuit of the voltage converters [12-16]. Some of the advantages of this method are its simplicity, applicability, and ease of implementation. Ref. [15] and [16] present a current DC-DC buck converter obtained by applying the principle of duality to the conventional voltage DC-DC buck converter. To conduct a comprehensive study and achieve conventional DC-DC current converters, this article was selected as the basis of our work. Furthermore, in addition to buck converter, other topologies of conventional DC-DC voltage converters were also examined. These DC-DC current converters are particularly well-suited for applications that require precise control of output current, such as powering current-based loads like light-emitting diodes (LEDs). The converters can also be used to convert current sources, such as photovoltaic (PV) cells, to produce multiple or fractional current outputs [22, 23]. Since the source and load currents that are connected to these DC-DC current converters are constant, so we need to obtain a constant current at the input and output terminals of the converters. However, the main difference between these proposed converters and other conventional current converters is that it does not need to use some equipment, such as inductors, at their input and output terminals to filter the current ripple. Actually, these proposed DC-DC current converters perform current filtering in their internal structure, and there is no need to use additional elements, which is their main advantage over other current converters.

Table 1: Duality relationship between components and wiring system.

Components/terms in the original circuit	Their Dual
Voltage source	Current source
Current source	Voltage source
Resistance	Conductance
Conductance	Resistance
Inductance	Capacitance
Capacitance	Inductance
Transistor	Transistor
Diode	Diode
Star wiring system	Delta wiring system
Delta wiring system	Star wiring system
Volt second balance of the inductors	Ampere second balance of the capacitors
Ampere second balance of the capacitors	Volt second balance of the inductors
Series connection	Parallel Connection
Parallel Connection	Series connection
Mesh	Node
Node	Mesh

In this paper, Section 2 first introduces the duality principle. Then, the structures of the conventional DC-DC current converters, including the buck, boost, fly-back, cuk, sepic, and zeta converters are proposed, and their semiconductor ratings are calculated. Also, the circuit models of a photovoltaic (PV) system and a high-power LED as examples of current sources and loads, respectively, which can be used with the proposed DC-DC current converters, are described. Section 3 verifies the feasibility of the proposed new type DC-DC current converters and the principle of duality by using simulation results obtained from MATLAB. Eventually, Section 4 presents the conclusions.

2. METHODOLOGY

2.1. Duality Principle

The principle of duality is a fundamental concept that states the existence of a correspondence between different circuit elements and variables. This principle allows for the transformation of a given circuit into an equivalent dual circuit by interchanging certain elements and variables while maintaining the same overall behavior and functionality. One common application of the principle of duality is in circuit analysis in which voltage and current sources are interchanged and elements and wiring connections are replaced with their dual counterparts. This dual circuit exhibits the same behavior and response as the original circuit but with different element configurations. Furthermore, the characterizing equations, e.g., Kirchhoff's laws and Ohm's law, remain the same in both circuits, but the roles of voltage and current are interchanged. Table 1 presents the duality relationships between components and wiring connections in electrical circuits.

By applying the principle of duality, the circuit analysis and design can be simplified. Complex circuits can be transformed into more manageable dual circuits, which may exhibit similar characteristics but in a different configuration. This enables researchers to leverage their understanding of circuit properties and behavior in one domain to analyze and solve problems in the corresponding dual domain.

2.2. Proposed Current-Type Converters

In DC-DC current converters, capacitor C is used to regulate the current conversion ratio, while inductor L is used as a filter for the output terminal. Unlike voltage-type converters, which operate based on volt-second balance, current-type converters operate based on the ampere-second balance of capacitor C. This means that to maintain a steady state, the quantity of charge flowing into capacitor C during one switching cycle should be equal to that flowing out of it. Or, the current integration of capacitor C should be equal to zero during one switching cycle.

Hence, the mentioned DC-DC current converters are proposed as follows, respectively.

2.2.1. Current DC-DC buck converter

By applying the principle of duality to the conventional voltage buck converter (Fig. 1), the proposed current buck converter is derived as depicted in Fig. 2. The proposed current buck converter operates in the following two modes, depending on whether switch S is ON or OFF:

$State\ 1\ [0 \le t \le DT_s]$: As shown in Fig. 3(a), in this interval, S is turned ON, and diode D is in reversed bias. Thus, capacitor C is discharged through inductor and load. The current flowing through inductor and load is equal and increases linearly.

$State\ 2\ [DT_s \le t \le T_s]$: According to Fig. 3(b), in this state, switch S is turned OFF when diode D is in forward bias. Hence, the current source charges capacitor C, and inductor L releases its energy into the output load.

By applying the ampere-second balance on C, we have:

$$DT_s(-I_{out}) + (1-D)T_s(I_{in} - I_{out}) = 0 \tag{1}$$

Hence, the current conversion ratio of the proposed converter is:

$$G_{Buck} = \frac{I_{out}}{I_{in}} = 1 - D \tag{2}$$

2.2.2. Current DC-DC Boost converter

Fig. 4 depicts the conventional voltage boost converter. By applying the duality principle to it, the proposed current boost converter is obtained as shown in Fig. 5. And its operation modes are as below:

$State\ 1\ [0 \le t \le DT_s]$: Based on Fig. 6(a), in this mode, S is turned ON and D is in reversed bias. Therefore, L is charged through the input current source and C.

$State\ 2\ [DT_s \le t \le T_s]$: As shown in Fig. 6(b), S is turned OFF where D is in forward bias. Thus, the input current source charges C, and L releases its energy into the output load.

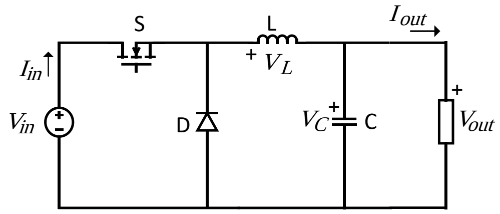


Fig. 1: The conventional voltage buck converter.

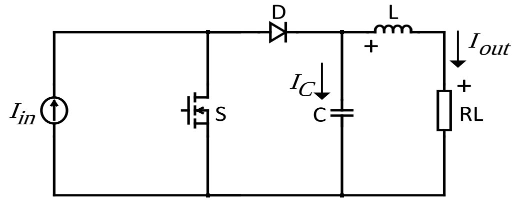


Fig. 2: The proposed current buck converter.

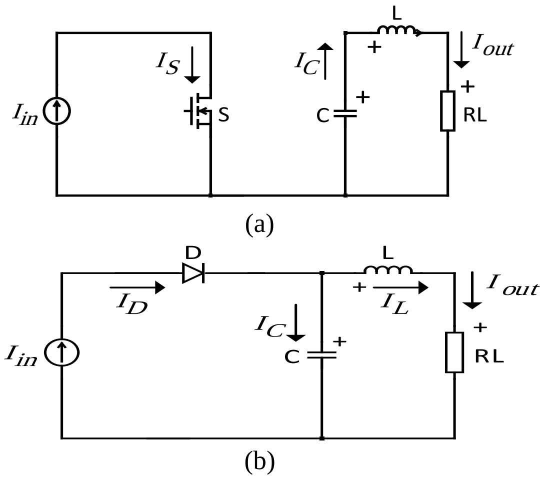


Fig. 3: The equivalent circuits of the proposed current buck converter: (a) ON state and (b) OFF state.

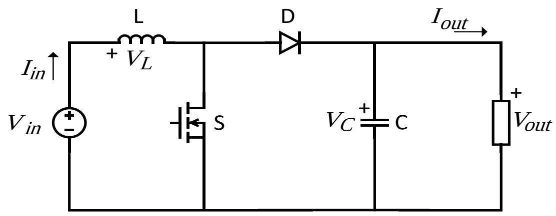


Fig. 4: The conventional voltage boost converter.

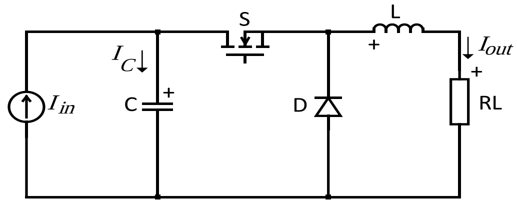


Fig. 5: The proposed current boost converter.

By applying the ampere-second balance on C, we have:

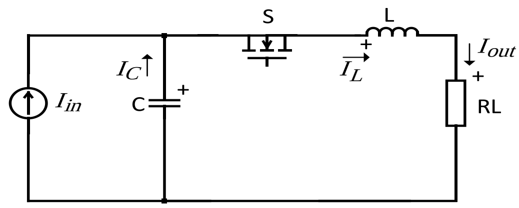
$$DT_s(I_{in} - I_{out}) + (1-D)T_s(I_{in}) = 0 \tag{3}$$

Thus, the current conversion ratio is obtained as:

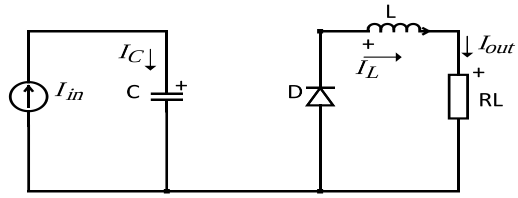
$$G_{Boost} = \frac{I_{out}}{I_{in}} = \frac{1}{D} \tag{4}$$

2.2.3. Current DC-DC Fly-back converter

The principle of duality is applied to the conventional



(a)



(b)

Fig. 6: The equivalent circuits of the proposed current boost converter: (a) ON state and (b) OFF state.

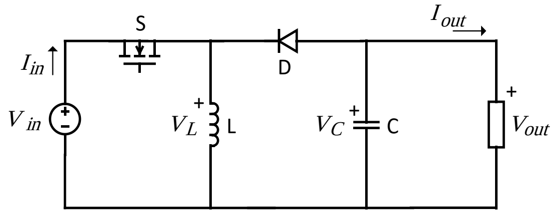


Fig. 7: The conventional voltage fly-back converter.

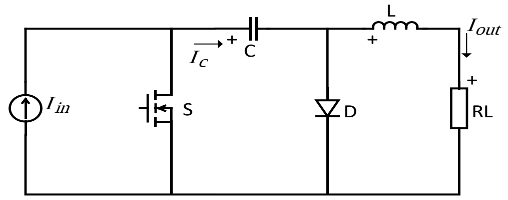
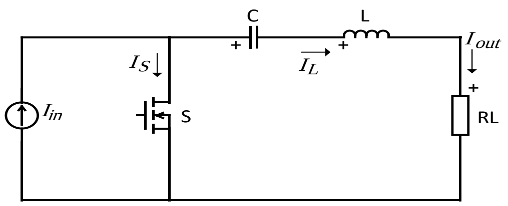
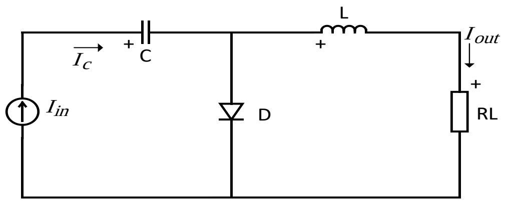


Fig. 8: The proposed current fly-back converter.



(a)



(b)

Fig. 9: The equivalent circuits of the proposed current fly-back converter: (a) ON state and (b) OFF state.

Voltage fly-back converter (Shown in Fig. 7). Hence, the proposed current fly-back converter is derived as exhibited in Fig. 8. Its two operation modes are as follows:

$State$ 1 $[0 \leq t \leq DT_s]$: In this state, switch S is turned ON, and D is in reversed bias, according to Fig. 9(a). Thus,

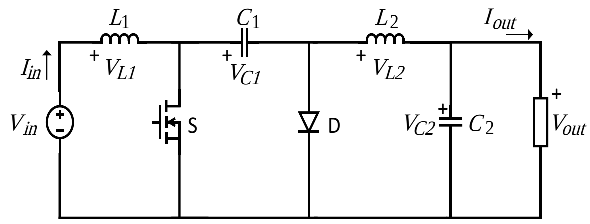


Fig. 10: The conventional voltage cuk converter.

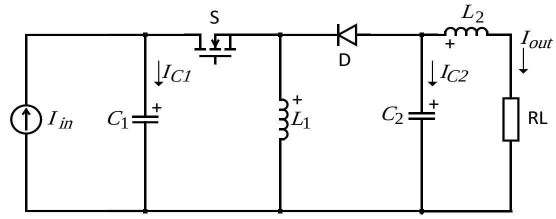
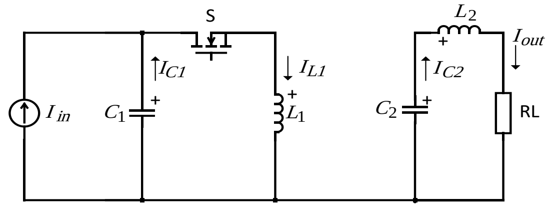
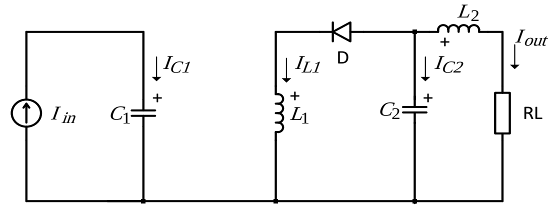


Fig. 11: The proposed current cuk converter.



(a)



(b)

Fig. 12: The equivalent circuits of the proposed current cuk converter: (a) ON state and (b) OFF state.

The input current source and C are charging inductor L and output load in series.

$State$ 2 $[DT_s \leq t \leq T_s]$: Fig. 9(b) shows this interval. So, S is turned OFF and D is in forward bias. The input current source charges capacitor C.

To obtain the current conversion ratio, the ampere-second balance on C is applied as:

$$DT_s(I_{out}) + (1 - D)T_s(I_{in}) = 0 \qquad (5)$$

Hence, the current conversion ratio is:

$$G_{Fly-back} = \frac{I_{out}}{I_{in}} = -\frac{1-D}{D} \qquad (6)$$

2.2.4. Current DC-DC Cuk converter

Fig. 10 shows the conventional voltage cuk converter. By applying the principle of duality to it, the proposed current cuk converter is derived (Fig. 11) whose ON and OFF operation modes are as follows:

$State$ 1 $[0 \leq t \leq DT_s]$: In this interval, S in ON and D is in reversed bias as shown in Fig. 12(a). Hence, C_1 charges L_1, and C_2 charges L_2, which is in series with the output load. So, the currents of all inductors increase linearly.

$State$ 2 $[DT_s \leq t \leq T_s]$: Based on Fig. 12(b), in this operation mode, switch S is turned OFF and diode D is in forward bias. Thus, the input current source charges C_1 and the inductors release their energy into C_2.

By applying the ampere-second balance on C_1, C_2, we have:

$$\begin{cases} DT_s(I_{in} - I_{L_1}) + (1-D)T_s(I_{in}) = 0 \\ DT_s(-I_{out}) + (1-D)T_s(-I_{L_1} - I_{out}) = 0 \end{cases} \quad (7)$$

Thus, the average current across L_1 is determined as:

$$I_{L_1} = \frac{1}{D} I_{in} \quad (8)$$

and, the current conversion ratio is obtained as:

$$G_{Cuk} = \frac{I_{out}}{I_{in}} = -\frac{1-D}{D} \quad (9)$$

2.2.5. Current DC-DC Sepic converter

The principle of duality is applied to the conventional voltage sepic converter as shown in Fig. 13. Then, the proposed current sepic converter is obtained as displayed in Fig. 14. The operation modes of the proposed circuit are as below:

$State$ 1 $[0 \le t \le DT_s]$: As shown in Fig. 15(a), in this mode, S is turned ON, and D is in reversed bias. Therefore, L_1 and L_2 are charged by C_1 and C_2, respectively, where the output load is in series with L_2.

$State$ 2 $[DT_s \le t \le T_s]$: S is turned OFF, and D is in forward bias, according to Fig. 15(b). Hence, the input current source charges C_1, and C_2 is fed by L_1.

If the amp-second balance is applied on C_1 and C_2, we will have:

$$\begin{cases} DT_s(I_{out}) + (1-D)T_s(-I_{L_1}) = 0 \\ DT_s(I_{in} - I_{L_1} - I_{out}) + (1-D)T_s(I_{in}) = 0 \end{cases} \quad (10)$$

Hence, the current across L_1 is calculated as:

$$I_{L_1} = \frac{D}{1-D} I_{out} \quad (11)$$

Therefore, the current conversion ratio of the proposed converter is as follows:

$$G_{Sepic} = \frac{I_{out}}{I_{in}} = \frac{1-D}{D} \quad (12)$$

2.2.6. Current DC-DC Zeta converter

By applying the principle of duality to the conventional voltage zeta converter which is shown in Fig. 16, the proposed current zeta converter is derived as shown in Fig. 17. Its two states of operation modes are described as follows:

$State$ 1 $[0 \le t \le DT_s]$: According to Fig. 18(a), in this operation mode, S is turned ON, and D is in reversed bias. Subsequently, C_1 charges L_1, and L_2, which is in series combination with the output load, is fed by C_2.

$State$ 2 $[DT_s \le t \le T_s]$: As the circuitry of this state is shown in Fig. 18(b), switch S is turned OFF, and D is in forward bias. Thus, the input current source charges C_1, and inductor L_1 is discharged into C_2.

Similarly, by applying the ampere-second balance on C_1 and C_2, we have:

$$\begin{cases} DT_s(I_{L_1}) + (1-D)T_s(I_{in}) = 0 \\ DT_s(-I_{out}) + (1-D)T_s(I_{in} - I_{L_1} - I_{out}) = 0 \end{cases} \quad (13)$$

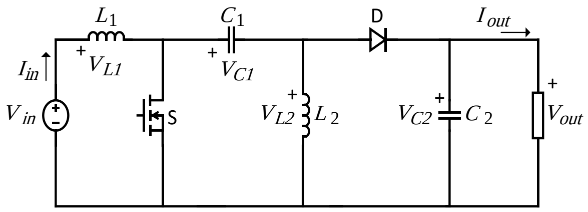


Fig. 13: The conventional voltage sepic converter.

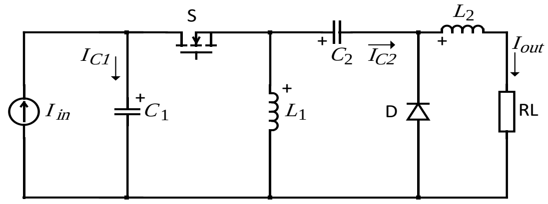
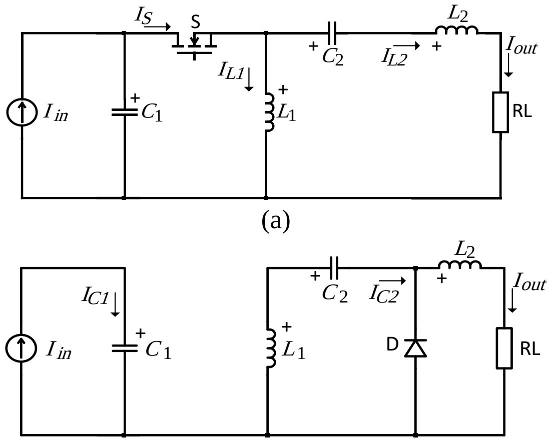


Fig. 14: The proposed current sepic converter.



(a)

(b)

Fig. 15: The equivalent circuits of the proposed current sepic converter: (a) ON state and (b) OFF state.

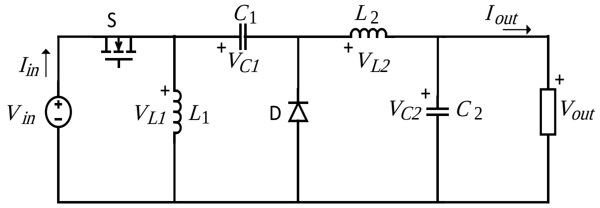


Fig. 16: The conventional voltage zeta converter.

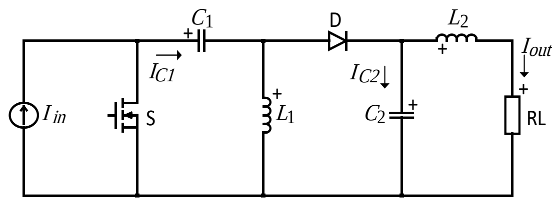


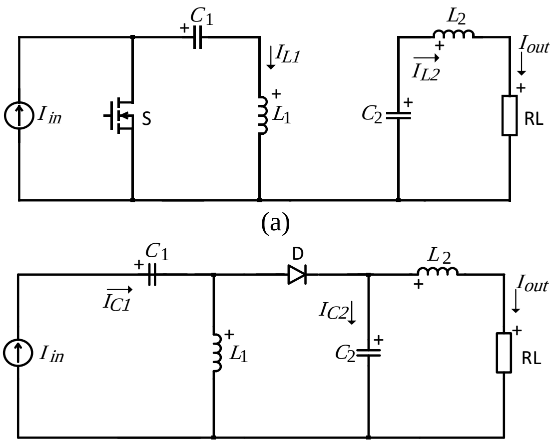
Fig. 17: The proposed current zeta converter.

And, the average current across L_1 is:

$$I_{L_1} = -\frac{1-D}{D} I_{in} \quad (14)$$

Hence, the current conversion ratio is obtained as:

$$G_{Zeta} = \frac{I_{out}}{I_{in}} = \frac{1-D}{D} \quad (15)$$



(b)

Fig. 18: Equivalent circuits of proposed Current Zeta converter: (a) ON state and (b) OFF state.

2.3. Semiconductor Rating

The expressions for the average ON-state current and the average OFF-state voltage across the switch and diode for each of the proposed current converters are as follows:

$$\text{Boost structure: } \begin{cases} V_S = V_{in} \\ I_S = \frac{3-2D}{D} I_{in} \end{cases} \tag{16}$$

$$\text{Buck and fly-back structures: } \begin{cases} V_S = \frac{1}{1-D} V_{in} \\ I_S = \frac{1}{D} I_{in} \end{cases} \tag{17}$$

$$\text{Cuk, sepic, and zeta structures: } \begin{cases} V_S = \frac{1}{1-D} V_{in} \\ I_S = \frac{1}{D^2} I_{in} \end{cases} \tag{18}$$

Therefore, the values of the total current stress (TCS) and total voltage stress (TVS) of each current DC-DC converter semiconductor device are listed in Table 2.

2.4. Equivalent Circuit Model of Photovoltaic (PV)

The simple equivalent circuit model for a PV cell includes a real diode in parallel with an ideal current source. The diode represents the non-linear I-V characteristic of the cell, where the current is proportional to the solar flux, and the voltage is limited by the built-in potential of the cell. However, in the case of shading, the simple model is not sufficient to accurately predict the behavior of the PV cell. To account for this issue, a more complex equivalent circuit model is required, which includes resistive elements such as the parallel leakage resistance R_p and series resistance R_s [24]. Such a circuit is depicted in Fig. 19. By applying the current balance equation with the Shockley diode equation to a point to the left of R_s, we can obtain an equation that relates the current through the diode and the current through the resistor as:

$$I_{PV} = I_{ph} - I_d - I_p = I_{ph} - I_0\left(e^{\frac{V_{PV}+R_s I_{PV}}{n_s V_t Q_d}} - 1\right) - \frac{V_{PV}+R_s I_{PV}}{R_p} \tag{19}$$

Table 2: The value of the total voltage and current stress.

Current DC-DC Converter	TVS	TCS
Buck	$V_{in}/(1-D)$	I_{in}/D
Boost	V_{in}	$(3-2D)I_{in}/D$
Fly-back	$V_{in}/(1-D)$	I_{in}/D
Cuk	$V_{in}/(1-D)$	I_{in}/D^2
Sepic	$V_{in}/(1-D)$	I_{in}/D^2
Zeta	$V_{in}/(1-D)$	I_{in}/D^2

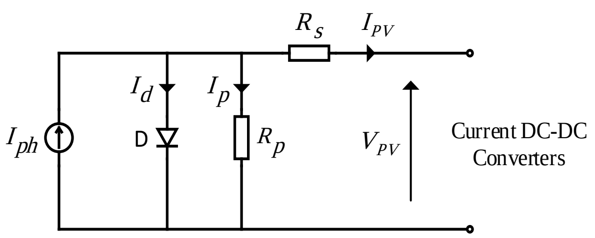


Fig. 19: The single-diode electrical PV module equivalent circuit.

where

$$V_t = kT_c/q \tag{20}$$

While a single PV cell may not produce enough voltage to power most household appliances or electronic devices, multiple cells can be connected in series to produce a higher voltage. A module consisting of several prewired cells connected in series is commonly used as the basic building block for PV applications. So, one of the most important considerations in PV system design is the configuration of the PV modules, specifically how many modules should be connected in series and how many in parallel to meet the energy requirements of the system. [25].

2.5. Equivalent Circuit Model of High-power LED

Packaging is an important consideration for high-power LEDs with large areas to ensure good heat dissipation and a longer lifetime. One important component in LED packaging is the electrostatic discharge (ESD) protection diode. The ESD protection diode, typically a Zener diode, is used to shunt the ESD current away from the LED chip and prevent damage [26]. In LED packaging, the ESD protection diode is often modeled as a single capacitor for simplicity, even though its accurate model cannot be obtained due to its integration into the package. Fig. 20 shows the equivalent circuit for high-power LEDs [27]. The impedance of an LED can be expressed as below:

$$Z_{LED} = R_b + j\omega L_b + \frac{1}{j\omega C_b} // (R_s + \frac{1}{j\omega C_j} // r_d) \tag{21}$$

in which $C_j = C_{sc} + C_d$ is the junction capacitance.

3. Test Results

Fig. 21 provides the input and output current waveforms

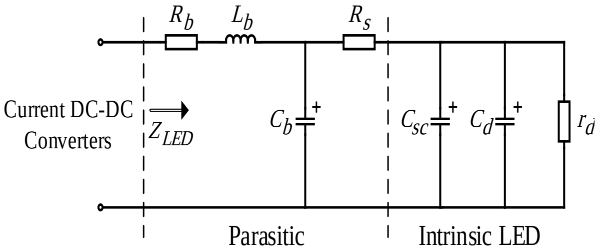


Fig. 20: The equivalent circuit model for the high-power LED.

of all proposed DC-DC current converters used as an interface between a PV cell and a high-power LED load.

The simulation parameters for the PV system, high-power LED, and proposed DC-DC current converters are consistent, except for some, which have been listed below:
In order to produce the required electrical output power in the PV system, the module has 36 cells in series, except for the fly-back topology whose module requires 50 cells in series. Another PV parameter is $I_{ph} = 5\ A$ for all topologies, except for the fly-back and zeta structures which is $I_{ph} = 7\ A$. Also, $R_p = 1000\ \Omega$ and $R_{s\_PV} = 0.3\ \Omega$.

A 50-W and approximately 18-V high-power LED is considered the load and its parameters are $R_b = 0.27\ \Omega$, $R_{s\_LED} = 2.61\ \Omega$, $R_d = 7.07\ \Omega$, $L_b = 2.45\ nH$, $C_b = 14.4\ nF$, and $C_j = 0.2\ mF$.

The parameters for the proposed DC-DC current converters are $L = L_2 = 1\ mH$, $L_1 = 0.04\ mH$, $C = C_2 = 50\ \mu F$, $f_s = 10\ KHz$, and $C_1 = 10\ \mu F$, except for the zeta topology in which we have $C_1 = 6\ \mu F$. Besides, in order to implement the control system on these current converters, the PWM method is used by applying specific pulse signals with defined amplitudes to the switches. So, its details are as follows: the ON time duty cycle is considered 40% for all topologies, except for the boost and fly-back topologies, in which it is considered 90% and 70% to avoid working at DCM mode, respectively.

According to Figs. 21(c) and 21(d), the fly-back and cuk converters have equal negative output currents as their equal negative current conversion ratio are calculated by Eq. (6) and (9), respectively. Furthermore, based on Eq. (12) and Fig. 21(e), the sepic topology has the same current conversion ratio and output current as the fly-back and cuk topologies but in a reversed direction.

Also, based on Eq. (12) and (15) and Figs. 21(e) and 21(f), respectively, the sepic and zeta topologies have the same current conversion ratio and output currents.

To show the stability of the new topologies in a wide range of operations, there are some other results about input voltages of the proposed DC-DC current converters, which are shown in Fig. 22.

Furthermore, the graph of the proposed converters' current gain versus their OFF time duty cycle is depicted in Fig. 23. It is shown that the buck topology has a positive

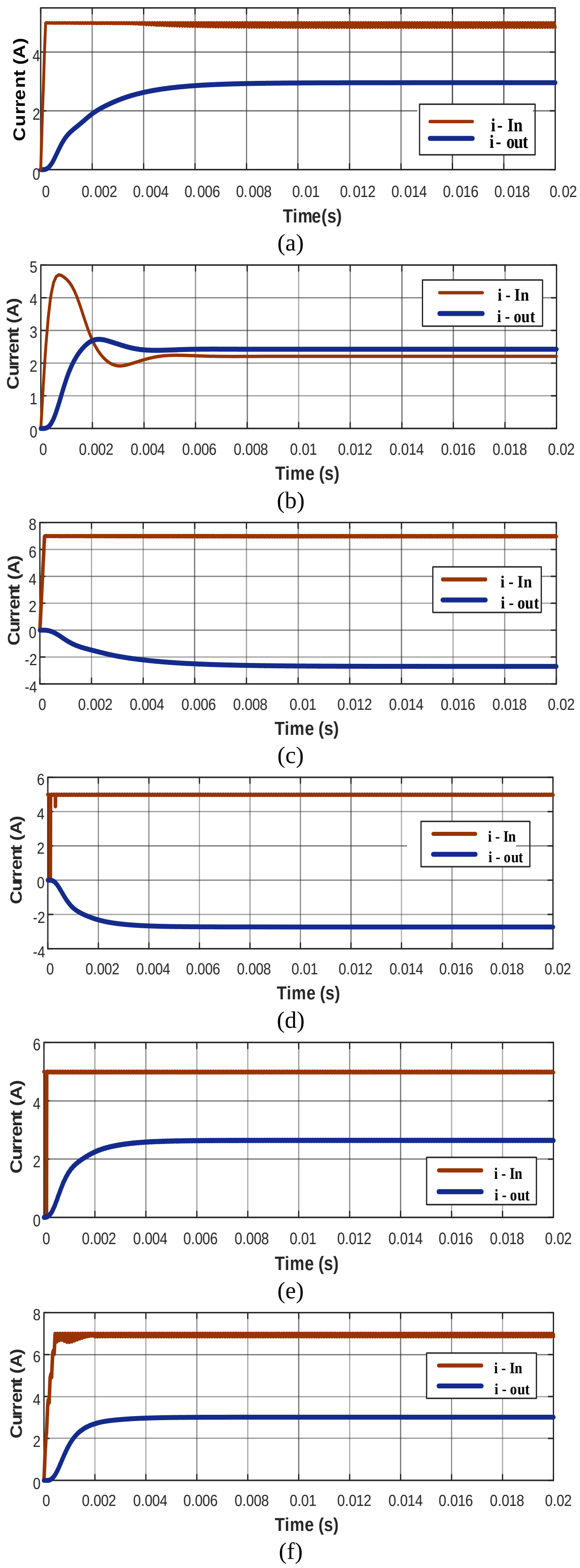


Fig. 21: The input and output currents of the proposed current DC-DC converters: (a) buck, (b) boost, (c) fly-back, (d) cuk, (e) sepic, and (f) zeta.

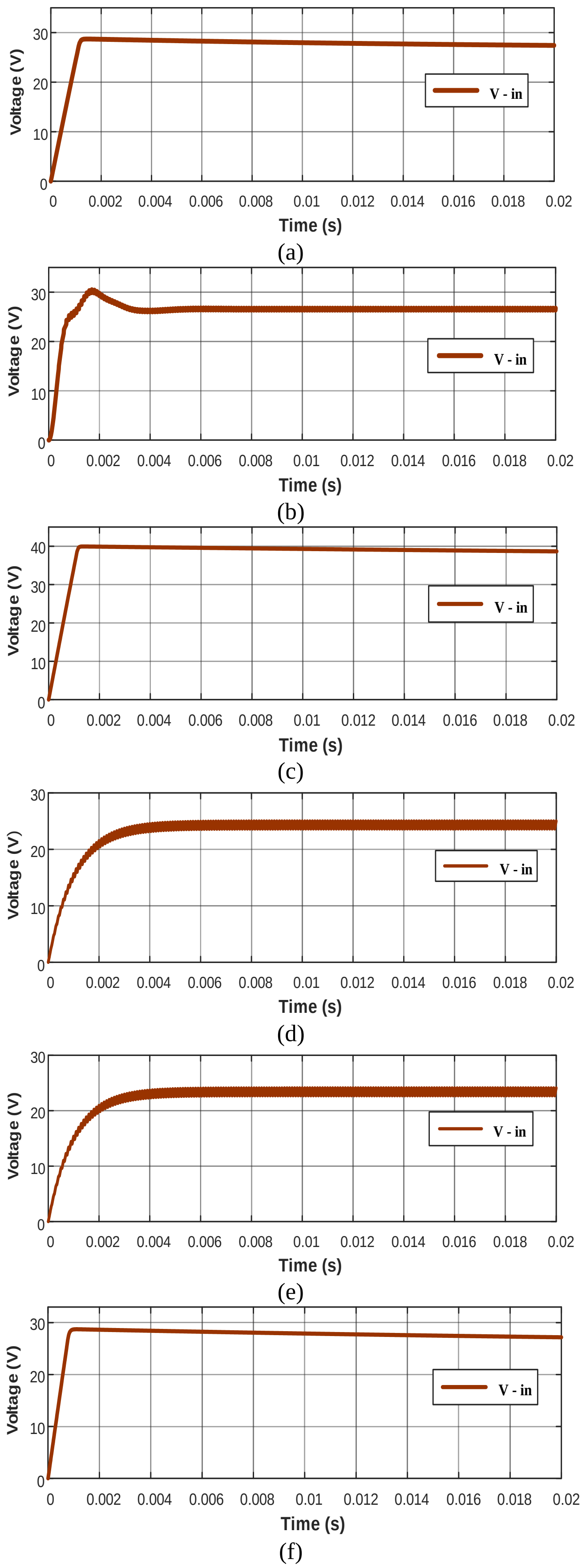


Fig. 22: The input voltages of the proposed DC-DC current converters: (a) buck, (b) boost, (c) fly-back, (d) cuk, (e) sepic, and (f) zeta.

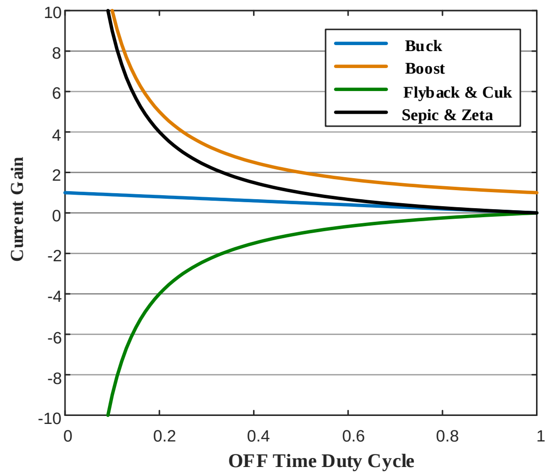


Fig. 23: The graph of the current gain versus duty cycle.

limited current gain, the boost, sepic, and zeta topologies have positive unlimited current gains, and the fly-back and cuk topologies have negative unlimited current gains. However, it is notable that these results are obtained theoretically based on their calculated current gain equations.

4. Conclusions

This paper explained several current-based DC-DC converters, including buck, boost, flyback, cuk, sepic, and zeta topologies, as viable solutions for applications that require current control. The proposed converters were derived using the principle of duality, which allows for the conversion of a voltage-based circuit into a current-based circuit. A detailed analysis of the circuit configurations and operation principles of the proposed current conversion circuits, and also mathematical equations for the proposed converters were presented. Besides, the semiconductor rating and the values of the total current stress (TCS) and the total voltage stress (TVS) were calculated for each current DC-DC converter's semiconductor device. In addition, the paper described a practical case study in which the proposed current converters were applied to a photovoltaic system and a high-power LED load. The circuit models of the PV system and LED load were described in detail, and simulations were provided in MATLAB to demonstrate the feasibility of the proposed converters in this application and the principle of duality and to verify the mathematical equations of the proposed DC-DC current converters.

Credit Authorship Contribution Statement

Zahra Gholami: Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Writing - original draft, Writing - review & editing. **Rahim Ildarabadi**: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Supervision, Validation, Visualization, Writing - review & editing. **Hamed Heydari-Doostabad**: Validation, Visualization, Writing - review & editing.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The ethical issues; including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy has been completely observed by the authors.

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