Chapter 1
Converter Topologies

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1.1 Introduction

Switching power converters are in existence for almost five decades. While their research and development have been extensively pursued, and their findings exhaustively applied to the modern world of electronics and industrial applications, the teaching and dissemination of their understandings in books and lecture notes are still confined to the most primitive types of converters known to engineers. These include the simplest and most fundamental types of topologies, namely the voltage buck, boost, and buck–boost converters and their transformer-isolated versions, namely, the forward and flyback converters. Discussions covering interesting aspects of the more complicated high-order converters, namely the Ćuk, SEPIC, and zeta converters have also been commonly furnished in the literature [1–3, 5].

In this chapter on "Converter Topologies", however, we will be a little more adventurous in our exploration by offering an exclusive coverage on a few less commonly known converters that can be derived using fundamental circuit theory and common engineering insights. We believe that these converters possess unique features that may give them a competitive edge in applications related to the emerging types of energy sources and loads. For example, the family of fundamental current converters that will be discussed may be useful for applications where the energy source and load behave like current sources and sinks. The family of cascaded

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quadratic converters that will be discussed would be useful for applications that require a wide conversion range, e.g. in ultra-low-voltage devices.

Concurrent to the objective of introducing some less-known types of converters, this chapter also provides from a circuit-theory perspective, how fundamental converters are derived, how they are related, and how they can be integrated to result in more complicated types of converters. In particular, we will start the chapter with how voltage buck, boost, and buck–boost converters can be derived from the reconfiguration of a switching-inductor cell with its input voltage source and output voltage sink. We will then move on to discuss how the less-known family of current buck, boost, and buck–boost converters can be derived from the reconfiguration of a switching-capacitor cell with its input current source and output current sink. The dual relationship between the family of voltage converters and current converters is then reviewed.

Following that, we move on to discuss how the family of fourth-order Ćuk, SEPIC, and zeta converters can be derived using a two-inductor–two-switch circuit cutset approach. In connection to this, we will also provide a glimpse at a missing circuit from this set of converters that has been absent from the literature. Next, on the topic of fourth-order converters, we will illustrate how the same family of converters can be derived from cascading two fundamental converters. From that, we demonstrate that using the same technique of cascading two fundamental converters, different types of quadratic converters with wide conversion ratio can be obtained [4]. Lastly, the family of fourth-order converters that are derived by adding filters to the second-order converters will be discussed. Before continuing our exploration, an overview of how the different converter topologies are related using our method of classification is shown in Fig. 1.1.

1.2 Minimum Configurable Switching Storage Structures

Switching power conversion encompasses two types of conversions, namely voltage conversion and current conversion. Power converters which electronically convert an energy source of one voltage level to another voltage level are known as voltage converters. In this respect, current converters are power electronics that convert an energy source of one current level to another current level. The basic mechanism of performing an ideally lossless voltage or current conversion involves the rapid repeated connection and disconnection of the voltage or current source to an appropriate storage device, namely an inductor or a capacitor, in a controlled manner via electronic switches, such that the energy is transferred at the appropriate voltage or current level before being released to the output load in the desired form. In configuring such power converters, it is important that voltage sources are never connected directly to a capacitor and that current sources are never connected directly to an inductor. From a theoretical viewpoint, there are two simplest configurable switching storage structures possible, namely a star-connected two-switch inductor cell and a delta-connected two-switch capacitor cell. We will next give a discussion on these storage cells and how they are configured to give the various possible types of power converters, some of which are already well known to us.

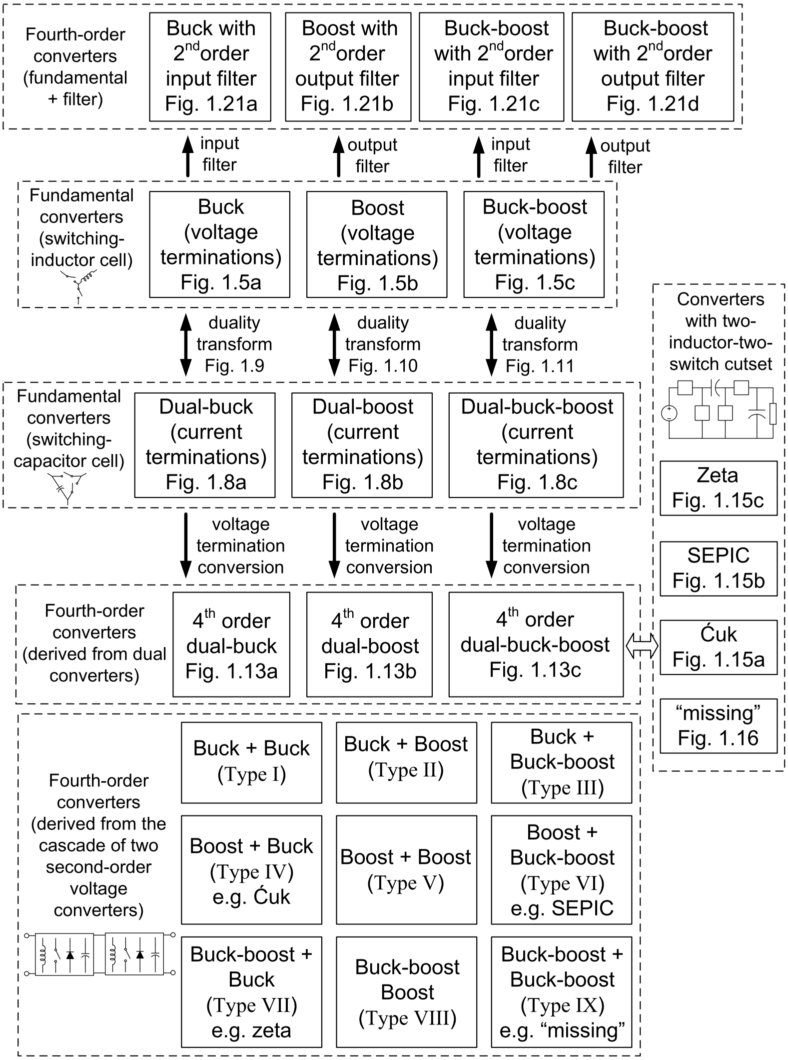


Fig. 1.1 Overview of the relationships of converter topologies

1.2.1 Switching-Inductor Cell

The *switching-inductor cell* comprises a storage inductor and two switches arranged in a star connection as depicted in Fig. 1.2. Since current flowing through an inductor must be continuous and cannot become zero instantaneously, the two switches must be designed to operate complementarily

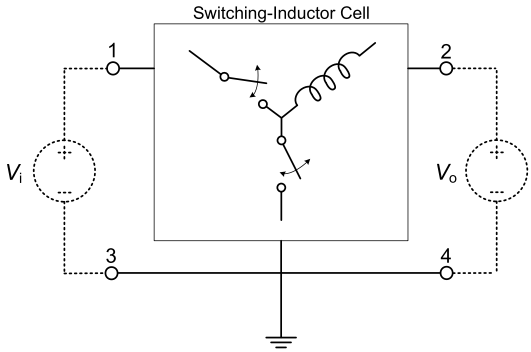
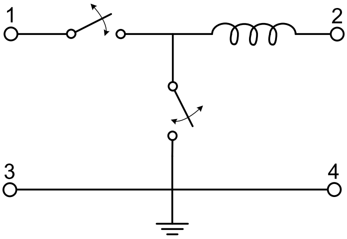


Fig. 1.2 DC–DC voltage converter using the switching-inductor cell

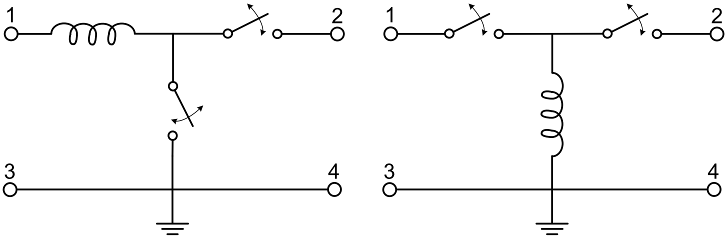
such that a closed-circuit continuous path will always exist for the flow of the inductor current. For this reason, this switching-inductor cell represents the minimum configurable switching-inductor structure possible. To qualify for a lossless conversion process, the switching-inductor cell must be implemented with an input voltage source together with an output voltage sink (see Fig. 1.2), which forms the basis for a voltage-to-voltage converter.

As illustrated in Fig. 1.3, there are three possible ways of configuring the switching-inductor cell while still maintaining the star-connection structure. Each can be realised by swapping the positions of any two of the three circuit elements. For proper operation of such a configuration with its input source and output sink, there should be no instance when the two switches are concurrently turned on. This will cause a direct short circuit of either the source, the sink, or the source with the sink for the respective configurations given in Fig. 1.3a–c. Additionally, when there is current flowing in the inductor, there should be no instance when both the switches are simultaneously turned off.

By replacing the voltage sink in Fig. 1.2 with a more realistic and practical circuit representation in the form of a resistor–capacitor sink as illustrated in Fig. 1.4, and by considering the three possible configurations of the switching-inductor cell given in Fig. 1.3, three fundamental types of voltage converters can be obtained. They are the voltage *buck*, *boost*, and *buck–boost converters*, which represent the fundamental topologies of the voltage converters. The schematics of these converters are given in Fig. 1.5a–c. For economical reasons, one of the two switches is replaced by a diode. The primary difference between the topologies is that each converter has a different voltage conversion ratio M such that $M(D) = V_o/V_i$, where D is the duty cycle and is a function of the turn-on time T_{ON} and the period T which is the sum of turn-on and turn-off time periods, $T_{\mathrm{ON}} + T_{\mathrm{OFF}}$, of the active switch S, i.e. $D = T_{\mathrm{ON}}/(T_{\mathrm{ON}} + T_{\mathrm{OFF}})$. For example, the voltage conversion ratios $M(D)$ for the respective converters when they are operating in the continuous inductor conduction



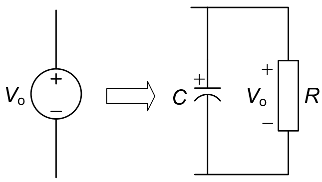
(**a**) Structure 1



(**b**) Structure 2 (**c**) Structure 3

Fig. 1.3 The three possible configurations of the switching-inductor cell

Fig. 1.4 Voltage sink replaced by resistor–capacitor sink



mode (current flow of the inductor never falls to zero) are

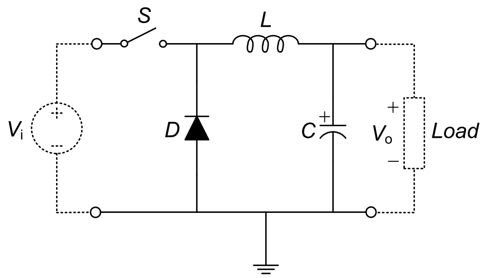
$$\frac{V_o}{V_i} = D \qquad \text{(voltage buck converter)}, \tag{1.1}$$

$$\frac{V_o}{V_i} = \frac{1}{1-D} \qquad \text{(voltage boost converter)}, \tag{1.2}$$

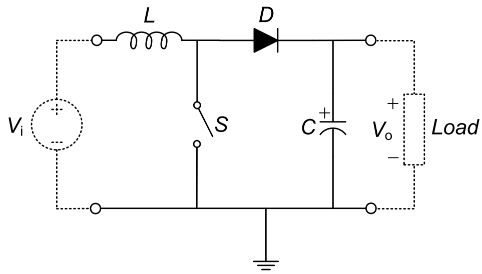
$$\frac{V_o}{V_i} = \frac{D}{1-D} \qquad \text{(voltage buck–boost converter)}. \tag{1.3}$$

From these equations, one can expect that since the duty ratio is confined as $0 < D < 1$, the voltage buck converter can only produce an output voltage smaller than the input voltage, i.e. $V_o < V_i$; a voltage boost converter can only produce an output voltage bigger than the input voltage, i.e. $V_o > V_i$; whereas a voltage buck–boost converter will have $V_o < V_i$ when $0 < D < 0.5$ and $V_o > V_i$ when $0.5 < D < 1$. In the case of discontinuous inductor conduction mode, the converters inherit a different set of conversion ratios. Nevertheless, their properties of stepping up or stepping down voltage levels remain the same regardless of the conduction

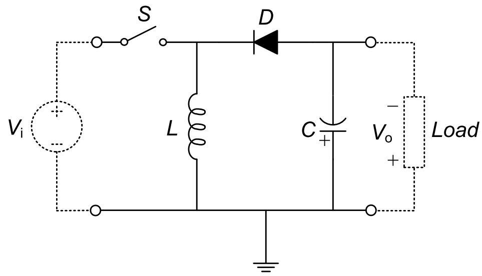
Fig. 1.5 The three fundamental DC–DC voltage converters



(a) Voltage buck converter



(b) Voltage boost converter



(c) Voltage buck–boost converter

mode. Finally, since the family of fundamental converters are well known, the details of their operations will not be further discussed. We move on to the switching-capacitor cell and its family of current converters.

1.2.2 Switching-Capacitor Cell

The *switching-capacitor cell* comprises a storage capacitor and two switches arranged in a delta connection as depicted in Fig. 1.6. The voltage of a capacitor has to be maintained continuous and cannot become zero instantaneously. The presence of the two switches is important in the sense that they must be

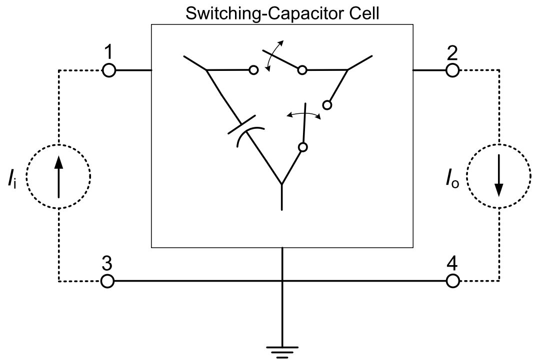


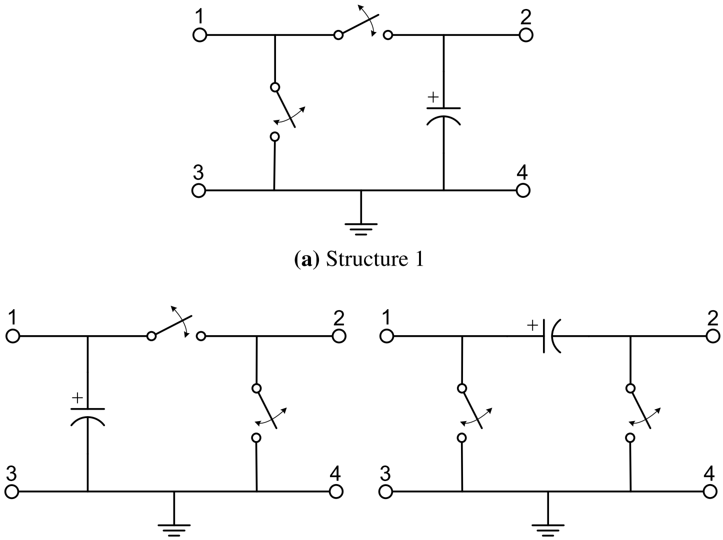
Fig. 1.6 DC–DC current converter using the switching-capacitor cell

synchronised to operate complementarily to ensure that there is no circumstance that the capacitor has a direct short circuit. This gives the minimum configurable switching-capacitor structure. For lossless energy transfer, the switching-capacitor cell must be implemented with an input current source and an output current sink. This forms the basis for the current-to-current converters.

As illustrated in Fig. 1.7, there are three possible ways of configuring the switching-capacitor cell while still maintaining the delta-connection structure. Each can be realised by swapping the positions of any two of the three circuit elements. For proper operation of such a configuration with its input source and output sink, there should be no instance when the two switches are concurrently turned off. This will cause a direct open circuit of either the source (in case (a)) or the sink (in case (b)), or a short circuit between the current source and the current sink (in case (c)) for the respective configurations given in Fig. 1.7a–c. Additionally, when there is stored charge in the capacitor, there should be no instance when both the switches are simultaneously turned on, thus avoiding a capacitor short circuit.

By considering the three possible configurations of the switching-capacitor cell given in Fig. 1.7, three fundamental types of current converters can be obtained. They are the current buck, boost, and buck–boost converters, which are in reality the dual counterparts of the voltage converters given in Fig. 1.5a–c. These converters represent the fundamental topologies in the family of current converters. The schematics of these converters are given in Fig. 1.8a–c. For economical reasons, one of the two switches can be replaced by a diode. Here, each of these topologies possesses a different current conversion ratio M, such that $M(D') = I_o/I_i$, where $D' = 1 - D$ and $D = T_{\mathrm{ON}}/(T_{\mathrm{ON}} + T_{\mathrm{OFF}})$ represents the duty cycle of S. The current conversion ratios $M(D')$ for the respective converters when they are operating in the continuous voltage conduction mode (voltage of the capacitor never falls to zero) are

$$\frac{I_o}{I_i} = D' \qquad \text{(current buck converter)}, \tag{1.4}$$



(**a**) Structure 1

(**b**) Structure 2 (**c**) Structure 3

Fig. 1.7 The three possible configurations of the switching-capacitor cell

$$\frac{I_o}{I_i} = \frac{1}{1 - D'} \quad \text{(current boost converter)}, \tag{1.5}$$

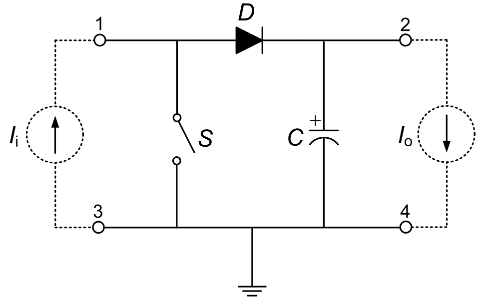
$$\frac{I_o}{I_i} = \frac{D'}{1 - D'} \quad \text{(current buck–boost converter)}. \tag{1.6}$$

It is clear from the equations that for a buck current converter, the output current is always smaller than its input current, i.e. $I_o < I_i$; for the current boost converter, output current is always bigger than the input current, i.e. $I_o > I_i$; and for the current buck–boost converter, $I_o < I_i$ when $0 < D' < 0.5$ and $I_o > I_i$ when $0.5 < D' < 1$.

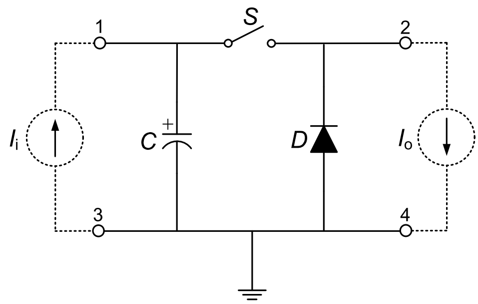
1.2.3 Duality of Voltage and Current Converters

The family of current converters are basically the dual counterparts of the voltage converters. So far, we have demonstrated the formulation of these converters from basic circuit rules and framework of a switching-inductor cell and a switching-capacitor cell. Interestingly, using the principle of circuit duality, it is possible to extract the same family of current converters from the voltage converters, and conversely, the family of voltage converters from the current converters.

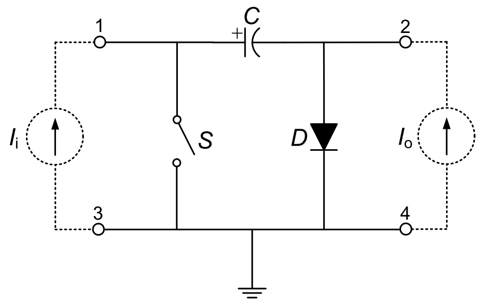
Fig. 1.8 The three fundamental DC–DC current converters



(a) Current buck converter



(b) Current boost converter



(c) Current buck–boost converter

A pictorial illustration of the transformation of the family of voltage DC–DC converters into the family of current DC–DC converters are given in the following figures, Figs. 1.9, 1.10, 1.11. Here, the converters drawn in dotted lines are the family of voltage converters and those drawn in solid lines are the family of current converters. To understand the process of the transformation, we recall that in circuit duality, a voltage source would be replaced by a current source and vice versa, an inductor would be replaced by a capacitor and vice versa, a resistor by a conductance and vice versa, a closed switch by an open switch and vice versa, a turn-on signal by a turn-off signal and vice versa. The process involves the applications of these rules.

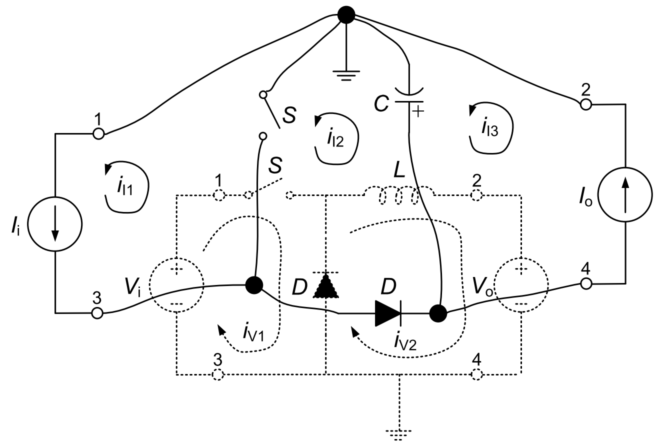


Fig. 1.9 Dual transformation of a buck converter

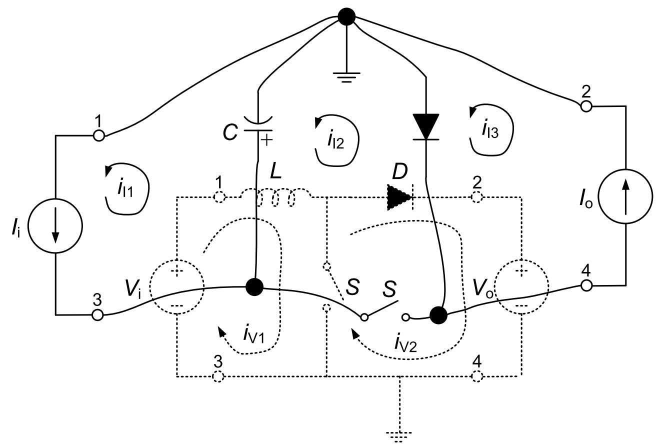


Fig. 1.10 Dual transformation of a boost converter

1.2.4 Practical Current DC–DC Converters

While the reported family of current DC–DC converters in Fig. 1.8a–c are theoretically feasible, in reality, it is uncommon that practical current source and current sink are readily available. Hence, a more practical scenario would be to replace the current sources and current sinks with their circuit equivalent of voltage sources and sinks, which are respectively shown in Fig. 1.12a–b. This will result in an interesting family of current buck, boost, and buck–boost converters that are based on voltage sources and sinks, as depicted in Fig. 1.13a–c. Note that the derived converters possess two inductors and two capacitors and they must be operated only in the continuous inductor conduction mode such that the currents of both the induc-

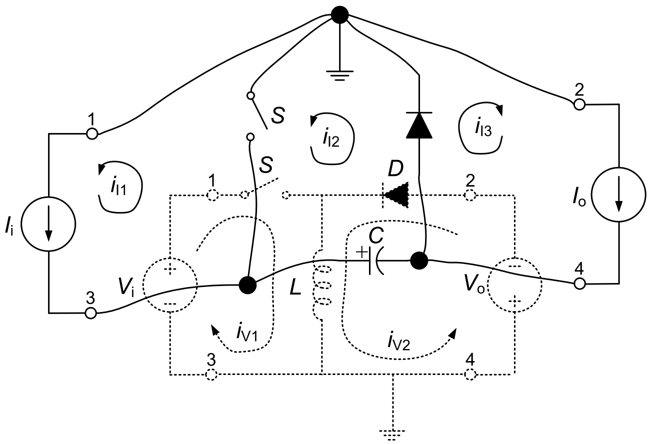
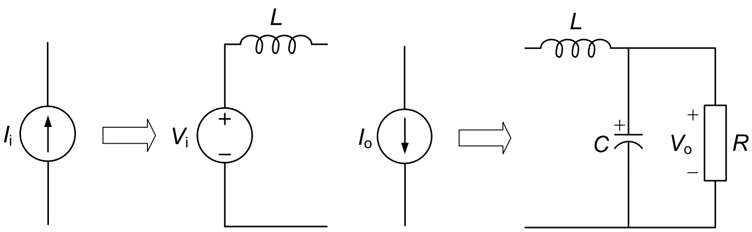


Fig. 1.11 Dual transformation of a buck–boost converter

tors are always continuous (to preserve the original property of a current source and current sink). The presented current buck and boost converters and their modified versions, as illustrated in Figs. 1.8a–c, 1.13a–b, are relatively unknown topologies which may be interesting for new emerging applications. Coincidentally, the modified buck–boost converter given in Fig. 1.13c happens to be the well-known Ćuk converter, which will be discussed in the following.

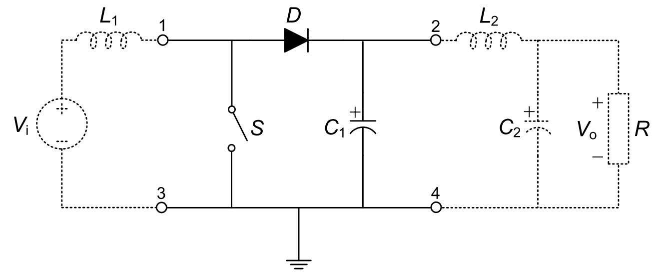
1.3 Fourth-Order Converters

The Ćuk, SEPIC, and zeta converters are a family of fairly interesting fourth-order converters that were introduced in the 1980s. They have been classified as fourth-order converters for the reason that each of these converters comprises four independent storage elements involving two inductors and two capacitors that are interactively configured with the voltage source and sink via a switch and a diode.

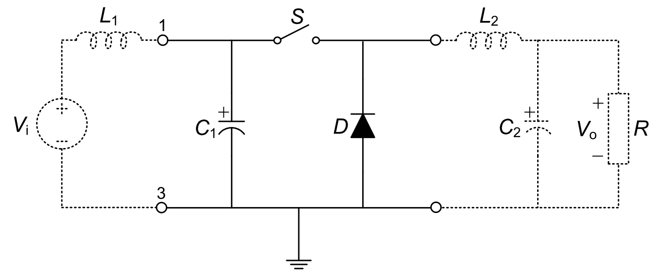


(**a**) Current source (**b**) Current sink

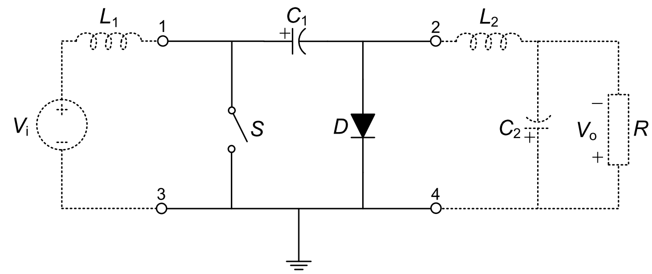
Fig. 1.12 (**a**) Current source replaced by an equivalent of voltage source and series inductor and (**b**) current sink replaced by a resistor–capacitor sink and series inductor



(a) Modified current buck converter



(b) Modified current boost converter



(c) Modified current buck–boost converter

Fig. 1.13 The three fundamental DC–DC current converters with their input current sources and output current sinks replaced by equivalent voltage source and sink circuits

From a topological viewpoint, fourth-order converters have twice the number of storage elements and are more complicated than the fundamental voltage buck, boost, and buck–boost converters, which are primarily second-order converters. Nevertheless, the fourth-order converters possess unique features which renders them preferential in certain applications over the second-order converters.

Next, we will illustrate how this family of fourth-order converters can be obtained from a two-inductor–two-switch circuit cutset. We will also reveal the identity of a "missing" fourth-order converter that has been absent from the literature.

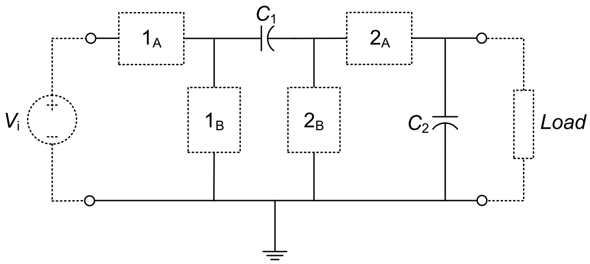


Fig. 1.14 Generic fourth-order converter with two-inductor–two-switch cutset

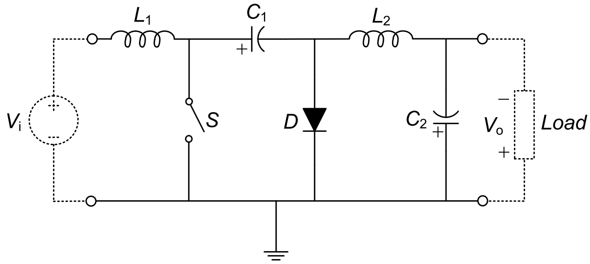
1.3.1 Two-Inductor–Two-Switch Circuit Cutset

Based on the two-inductor–two-switch cutset, the family of fourth-order converters can be portrayed in the generic structure as depicted in Fig. 1.14. In this diagram, the four boxes in dotted lines which are labelled as 1_A, 1_B, 2_A, and 2_B represent either an inductor or a switch. The structure itself is known as the two-inductor–two-switch circuit cutset. To ensure that there will be no short-circuit operation of the voltage source and the voltage sink, the cutset must be configured such that if component 1_A is a switch, then component 1_B must be an inductor, and vice versa. Likewise, if component 2_A is a switch, then component 2_B must be an inductor, and vice versa. With these constraints, there exist only four possible configurations in this two-inductor–two-switch circuit cutset. One of these possible configurations is: 1_A is an inductor, 1_B is a switch, 2_A is an inductor, and 2_B is a diode. This makes the *Ćuk converter* given in Fig. 1.15a. A second configuration is to assign 1_A as an inductor, 1_B as a switch, 2_A as an inductor, and 2_B as a diode. This gives the *SEPIC converter*, which is shown in Fig. 1.15b. The third configuration is to assign 1_A as a switch, 1_B as an inductor, 2_A as an inductor, and 2_B as a diode, to give what is known as the *zeta converter*, as depicted in Fig. 1.15c. For all the three topologies, the voltage conversion ratios $M(D)$ for the continuous inductor conduction mode are exactly that of a buck–boost converter, i.e.

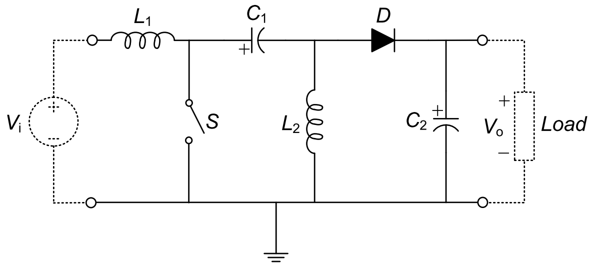
$$\frac{V_o}{V_i} = \frac{D}{1-D}. \tag{1.7}$$

The difference between these converters and the voltage buck–boost converter is that for the latter, both the input current and the output current are pulsating in nature. However, for the Ćuk converter, both the input current and the output current are non-pulsating. For the SEPIC converter, the input current is non-pulsating but the output current is pulsating. For the zeta converter, the input current is pulsating but the output current is non-pulsating.

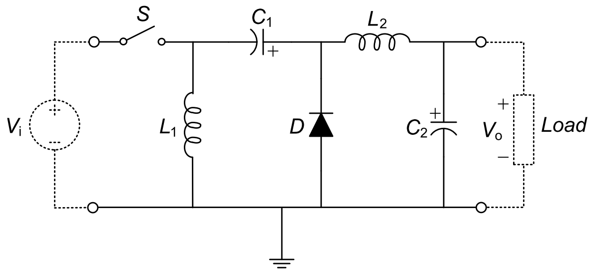
Fig. 1.15 Known types of fourth-order converters with the two-inductor–two-switch cutset



(a) Ćuk converter



(b) SEPIC converter



(c) Zeta converter

The three converters described above are the only known types of fourth-order converters with this cutset. A "missing" fourth-order converter that can be derived from the same cutset has been absent from the literature. This "missing" converter would be the remaining configuration of the cutset which is to set 1_A as a switch, 1_B as an inductor, 2_A as a diode, and 2_B as an inductor. Figure 1.16 shows the "missing" converter. Since this converter is rarely mentioned, a simple discussion of its operation will be provided.

There are three possible operating states for this "missing" converter. The equivalent circuit diagrams of the converter for the various operating states are given in Fig. 1.17a–c. During ON state (see Fig. 1.17a) when switch S is turned on, L_1 will be energised by voltage source V_1 and the energy stored in C_1 will be transferred to L_2. Diode D is turned off and C_2 will supply the load. There are two possible oper-

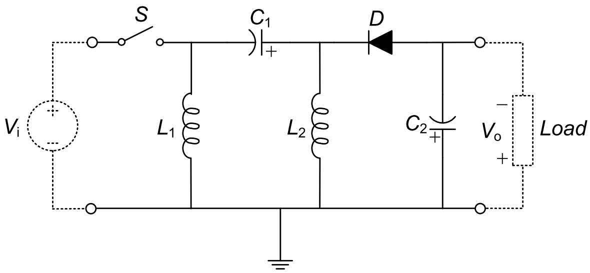
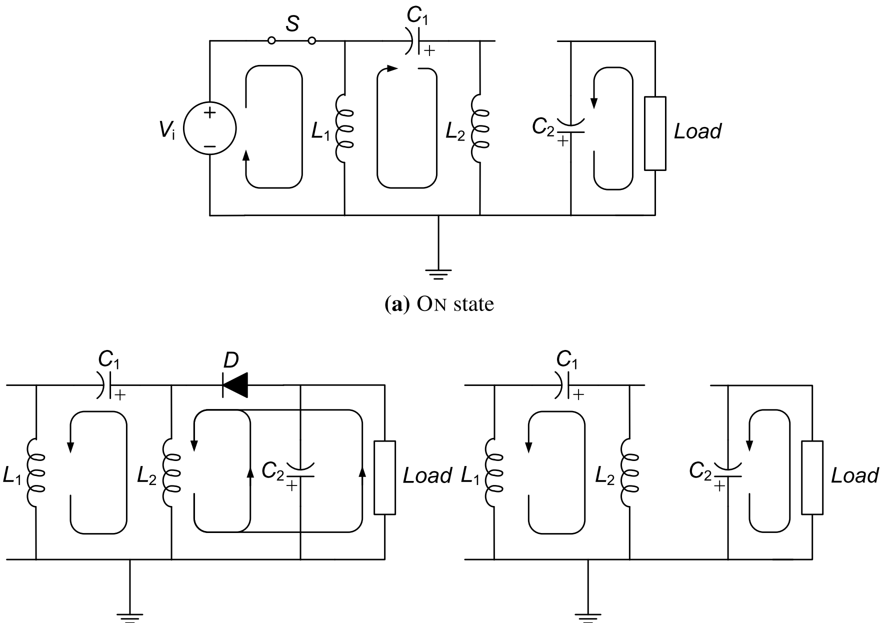


Fig. 1.16 The “missing” fourth-order converter

ating states when switch S is turned off. At the instance S is turned off, the converter enters the OFF state (see Fig. 1.17b). Here, the energy stored in L_1 is transferred to C_1 and the energy stored in L_2 will be transferred to C_2 and the load via diode D. This process will continue until the next ON state or when there is no more energy stored in L_2, i.e. the current of L_2 reaches zero. When this happens, a third operating state with L_2 being reversely energised by L_1 takes place. From Fig. 1.17c, in this state, L_1 will concurrently charge C_1 while reversely energising L_2. The diode D is turned off and the load is supplied by C_2. Similar to the other three topologies in the cutset, the voltage conversion ratio $M(D)$ of the “missing” converter in the continuous inductor conduction mode is the same as that of a buck–boost converter,



(a) ON state

(b) OFF state with L_2 de-energising

(c) OFF state with L_2 energising

Fig. 1.17 The three possible operating states of the “missing” fourth-order converter

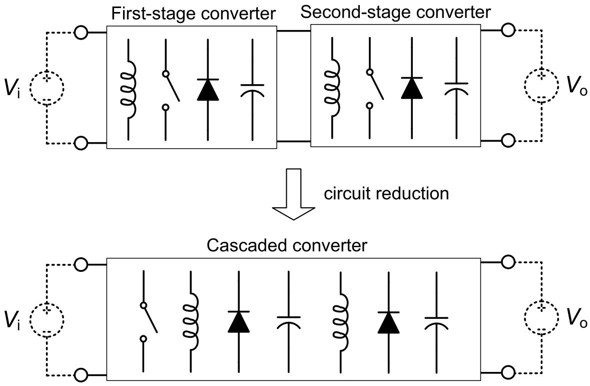


Fig. 1.18 Fourth-order voltage converter derived from the cascade of two second-order voltage converters

i.e.

$$\frac{V_o}{V_i} = \frac{D}{1-D}. \tag{1.8}$$

In fact, this converter behaves exactly like a fundamental voltage buck–boost converter with pulsating input and pulsating output currents. This may explain its redundancy in the family of buck–boost converters since unlike the three other topologies, the "missing" converter does not actually solve the issue of pulsating current at the input or output.

1.3.2 Cascading of Two Second-Order Converters

In the previous part, it is illustrated that by using the two-inductor–two-switch cutset, a family of four fourth-order converters can be derived. Interestingly, the same family of fourth-order converters can be obtained by combining two fundamental second-order converters in cascade and then doing a circuit reduction to result in a cascaded converter with only one active switch S, as shown in Fig. 1.18. For example, the Ćuk converter is essentially an equivalent of a first-stage boost converter that is cascaded with a second-stage buck converter. The SEPIC converter is an equivalent of a first-stage boost converter that is cascaded with a second-stage buck–boost converter. The zeta converter is an equivalent of a first-stage buck–boost converter that is cascaded with a second-stage buck converter. The "missing" converter is an equivalent of a first-stage buck–boost converter that is cascaded with a second-stage buck–boost converter.

Since there are three fundamental voltage converters, namely the buck, boost, and buck–boost converters, there will be in all nine possible types of cascaded fourth-order converters, which are hereby labelled as Types 1–9, that can be obtained from the cascading of two converters (refer to Fig. 1.1):

1 First-stage buck plus second-stage buck;
2 First-stage buck plus second-stage boost;
3 First-stage buck plus second-stage buck–boost;
4 First-stage boost plus second-stage buck (e.g. Ćuk);
5 First-stage boost plus second-stage boost;
6 First-stage boost plus second-stage buck–boost (e.g. SEPIC);
7 First-stage buck–boost plus second-stage buck (e.g. zeta);
8 First-stage buck–boost plus second-stage boost;
9 First-stage buck–boost plus second-stage buck–boost (e.g. "missing").

Figure 1.19 illustrates how the Ćuk converter can be derived from the Type 4 configuration of a first-stage boost and a second-stage buck converter. As shown in the figure, the diode and capacitor of the boost converter are first interchanged and the buck converter is vertically flipped before both the converters are integrated. The points where the two converters are cascaded remain the same with A connecting A' and B connecting B'. Since the active switches S_{Buck} and S_{Boost} share a common driving signal and their positions are overlapped when the two converters are integrated, only one switch S will be required. For the same reason, one of the diodes D_{Buck} or D_{Boost} can be removed. Using the same approach of swapping component's positions and eliminating a redundant switch and diode, the other three converters, namely SEPIC, zeta, and the "missing" converter can also be derived. In fact, with such an approach, all other types of fourth-order converters, including the quadratic converters, can be derived.

1.3.3 Quadratic Converters

The *quadratic converters* are a class of single-switched cascaded converters that have a wide output-to-input conversion range and their conversion ratios $M(D)$ have a quadratic dependence on the duty cycle D.

For example, a Type 1 topology in quadratic form, which is a buck converter in cascade with a second buck converter, will have a conversion ratio $M(D)$ comprising the multiplication of the conversion ratio of the first-stage buck converter of $M_1(D_1) = D_1$ and the second-stage buck converter of $M_2(D_2) = D_2$, i.e. $M(D) = M_1(D_1) \times M_2(D_2) = D_1 D_2$. Figure 1.20a shows an example of a Type 1 passive-buck active-buck quadratic converter. With only one active switch, this Type 1 buck–buck quadratic converter has a conversion ratio $M(D) = D^2$. Functionally, with a driving signal operating with duty cycle of 0.5, a conversion

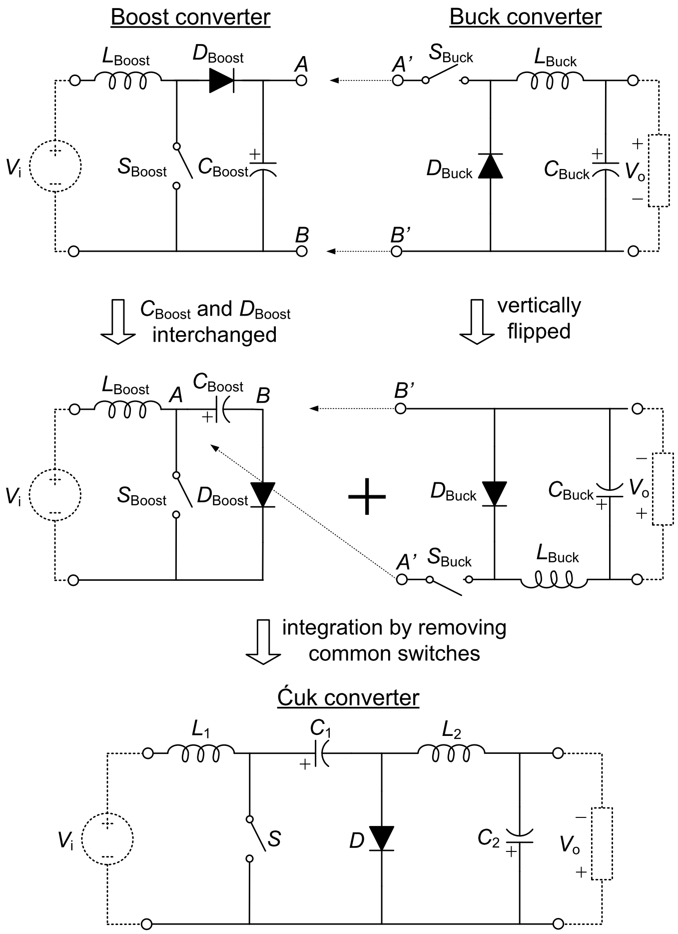
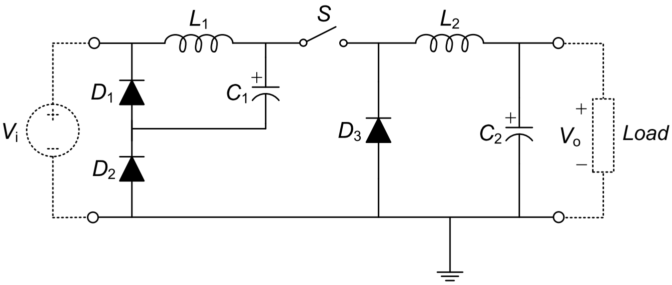


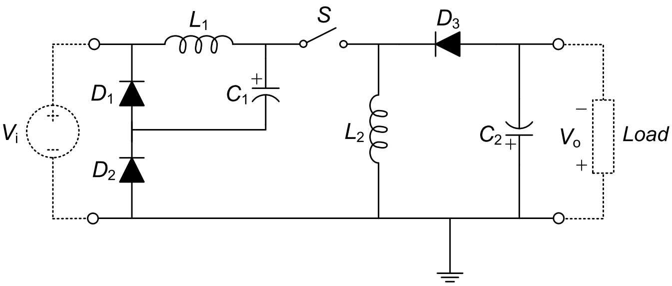
Fig. 1.19 Ćuk converter derived from the cascade of a boost and a buck converter

ratio of 0.25 can be achieved with this converter. Such kind of quadratic effect on the duty cycle significantly extends the conversion range of a converter without the use of a transformer.

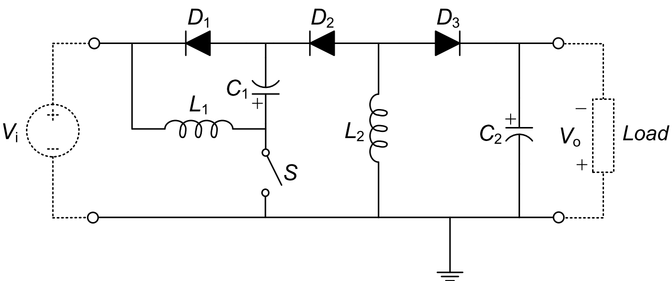
Similarly, by combining a buck and a buck–boost converter, a Type 3 passive-buck active-buck–boost quadratic converter can be obtained as depicted in Fig. 1.20b. The conversion ratio of a Type 3 quadratic converter is $M(D) = D^2/(1-D)$. By combining two buck–boost converters, a Type 9 passive-buck–boost active-buck–boost quadratic converter can be obtained as shown in Fig. 1.20c. The conversion ratio of a Type 9 quadratic converter is $M(D) = D^2/(1-D)^2$. Out of the nine available types of cascaded converters, there are seven types which can possibly become quadratic converters, if properly configured, as given in Table 1.1. The remaining two, namely Types 2 and 4, are non-quadratic converters with a conversion ratio that is similar to a buck–boost converter.



(a) Passive-buck-active-buck-quadratic converter



(b) Passive-buck active-buck–boost quadratic converter



(c) Passive-buck–boost active-buck–boost quadratic converter

Fig. 1.20 Three quadratic converters derived from the cascade of two second-order converters

Importantly, the aforementioned quadratic converters resulted from the cascade of two fundamental converters are possible only if the integration of the converters is done so that the individual converters in cascade still retain their respective power conversion properties after being cascaded. In other words, the overall conversion ratio of the cascaded converter must be a full cascade (multiplication) of the original conversion ratio of the two individual converters, i.e. $M(D) = M_1(D)M_2(D)$. Otherwise, a quadratic power conversion cannot be achieved with the cascaded converter. For example, in the case of the SEPIC, zeta, and the "missing" converter, which are of Types 6, 7, and 9, respectively, the conversion ratios are of non-quadratic form, i.e. $M(D) = D/(1 - D)$, which makes them effectively a buck–boost/boost–buck converter. The reason for this is that the integration of these con-

Table 1.1 Conversion ratio and description of the nine cascaded converters

Classification	Converters in Cascade	Conversion Ratio $M(D)$	Description
Type 1	buck + buck	D^2	quadratic
Type 2	buck + boost	$D/(1-D)$	non-quadratic
Type 3	buck + buck–boost	$D^2/(1-D)$	quadratic
Type 4	boost + buck	$D/(1-D)$	non-quadratic
Type 5	boost + boost	$1/(1-D)^2$	quadratic
Type 6	boost + buck–boost	$D/(1-D)^2$	quadratic
Type 7	buck–boost + buck	$D^2/(1-D)$	quadratic
Type 8	buck–boost + boost	$D/(1-D)^2$	quadratic
Type 9	buck–boost + buck–boost	$D^2/(1-D)^2$	quadratic

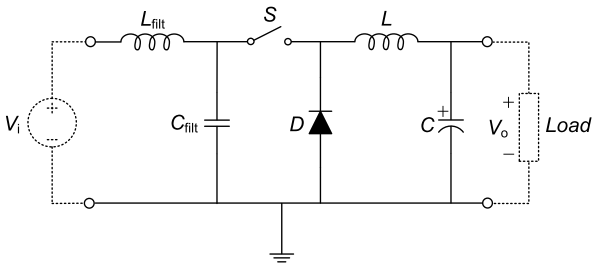
verters has been performed to the extent that the circuit reduction has resulted in the distortion of the original conversion property of the individual converters in cascade. For the SEPIC converter, which is derived from the cascade of boost and buck–boost converters, the supposed conversion ratio would be in the quadratic form of $M(D) = D^2/(1-D)$. However, circuit integration and simplification lead to an overall cascaded (SEPIC) converter that has lost one component of its step-down property D, making its conversion ratio of $M(D) = D/(1-D)$. The same explanation applies to the zeta and the “missing” converters.

Finally, it is worth emphasising that the quadratic converters are useful in applications where the difference between the input source and the output sink is too significant for the required power conversion to be achieved by a conventional converter, and when the use of transformer-based converter is not preferred. For details of the quadratic converters, readers are referred to the work in [4].

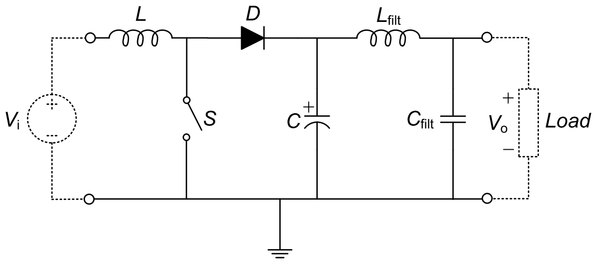
1.3.4 Adding of Second-Order Filter to Fundamental Converters

Lastly, we will introduce another kind of fourth-order converters that can be obtained from fundamental converters through the addition of second-order inductive-capacitive $L_{\text{filt}}C_{\text{filt}}$ filters. The function of $L_{\text{filt}}C_{\text{filt}}$ in these converters is for filtering and not energy storage. Hence, these components are typically small in capacity and size relative to the main inductor L and capacitor C of the converter. Consequently, $L_{\text{filt}}C_{\text{filt}}$ tackles only the filtration of high-frequency signals. They do not have any real effect on the actual process of power conversion. However, their addition to second-order converters would still mean that the converters possess four independent storage elements. Therefore, they are still technically classified as fourth-order converters.

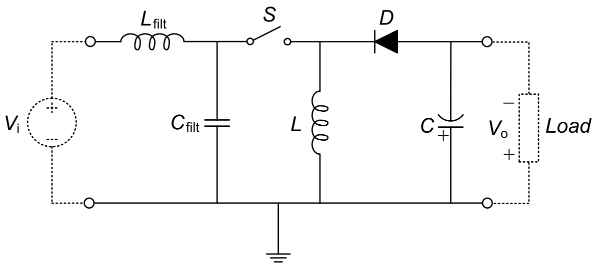
In any case, the placement of second-order filters is strategically conducted to minimise the pulsating flow of currents. For the voltage buck converter, which has a pulsating input current, a second-order filter is placed at the input side of the



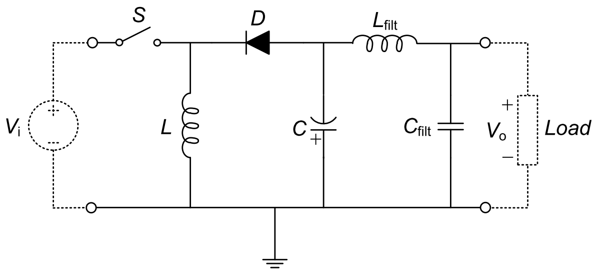
(a) Buck voltage converter with input filter



(b) Boost voltage converter with output filter



(c) Buck-boost voltage converter with input filter



(d) Buck–boost voltage converter with output filter

Fig. 1.21 Fourth-order converters derived from the adding of second-order filter to fundamental converters converter, as shown in Fig. 1.21a, to reduce the high-frequency current flow from the source. For the voltage boost converter, which has a pulsating output current, the second-order filter is placed at the output side of the converter, as shown in Fig. 1.21b, to reduce the high-frequency current flow to the sink. For the voltage buck–boost converter, which has both its input and output currents pulsating, the second-order filter can exist at either the input or output side of the converter, as shown in Fig. 1.21c–d, respectively, to reduce either high-frequency current flow from the source or to the sink.

1.4 Summary

Some relatively unknown, but interesting, DC–DC power converter topologies have been discussed in this chapter. The derivation of such converters and their relationships with fundamental converters have been discussed from a circuit-theoretic viewpoint. It is illustrated that current converters that may be useful for applications requiring current sources and sinks are derivable from fundamental voltage converters by using the principle of circuit duality or by using a proposed framework of a switching-capacitor cell. Based on a systematic procedure of deriving fourth-order Ćuk, SEPIC, and zeta converters from a two-inductor–two-switch-circuit cutset, we show that there is actually a missing topology from this family of fourth-order converters. We have also shown that there are nine possible types of fourth-order converters that can be obtained from the cascading of two fundamental converters. Out of these nine types of cascaded converters, seven types can be configured as quadratic converters. Finally, we have demonstrated that fourth-order converters can be obtained from fundamental converters by inserting second-order inductive-capacitive filters.

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