

Chapter 2

Voltage-, Current-, and Z-source Converters

Some fundamental concepts are to be introduced in this chapter, such as voltage sources, current sources, impedance networks, Z-source, two-port network, impedance source converters, impedance networks converters.

2.1 Voltage Sources and Current Sources

A power converter processes energy flow between two sources, i.e. generally between a generator and a load, as illustrated in Fig. 2.1. An ideal static converter is assumed to transmit electric energy between the two sources with 100% efficiency. The conversion efficiency is the main concern in designing a converter. Therefore, in practice, power converter design aims at improving the efficiency.

There are two types of sources, namely voltage and current sources, any of which could be either a generator or a load.

A real voltage source can be represented as an ideal voltage source in series with a resistance r_{VS} , with the ideal voltage source having zero resistance, to ensure its output voltage to be constant. The voltage source is normally equivalent to a capacitor C with infinite capacitance, i.e. $C = \infty$, so that $r_C = Z_C = -j \frac{1}{\omega C} \approx 0$, where Z_C denotes the resistance of the capacitor.

Similarly, a real current source can be represented as an ideal current source in parallel with a resistance r_{CS} , with the ideal current source having infinite resistance, so that its output current is constant, which is normally equivalent to an inductor with infinite inductance, i.e. $L = \infty$, which implies also $r_L = Z_L = j\omega L \approx \infty$, where Z_L represents the resistance of the inductor.

Correspondingly, converters are classified into voltage source converters and current source converters.

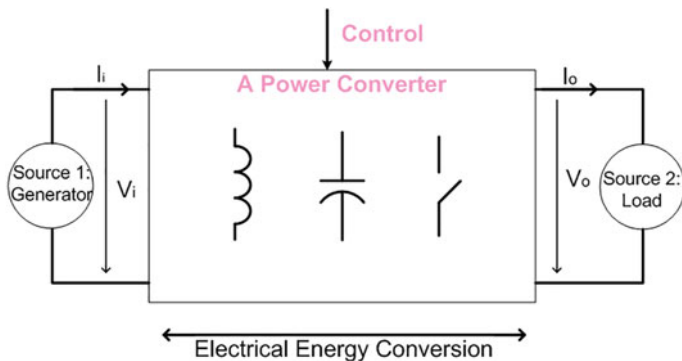


Fig. 2.1 A power converter

2.2 Impedance Network and Z-source

2.2.1 Impedance

The term, resistance, is just concerned with a DC circuit, which is extended to impedance in case of applying to both DC and AC circuits. Therefore, for DC circuits, resistance and impedance are equivalent. Unlike resistance, which has only magnitude and is represented as a *positive* real number (ohms (Ω)), impedance possesses both magnitude and phase and can be represented as a complex number with the imaginary part denoting the reactance and the real part representing the resistance.

Impedance is used to measure the opposition that a circuit presents to a current when a voltage is applied [1], and is defined as the frequency domain ration of the voltage to the current. For a sinusoidal current or voltage input, the polar form of the complex impedance relates the amplitude and phase of the voltage and current. In particular,

- the magnitude of the complex impedance is the ratio of the voltage amplitude to the current amplitude, and
- the phase of the complex impedance is the phase shift by which the current lags or leads the voltage.

2.2.2 Impedance Network and Two-Port Network

Like a resistor network, which is a collection of interconnected resistors in series or/and parallel, an impedance network in the context of power electronics, which involves nonlinear switches, is a network of impedance components like switches, sources, inductors, and capacitors, interconnected in series or/and parallel. An

Fig. 2.2 Two-port network

impedance network can be passive, if it is just composed of inductors and/or capacitors, or active, if it is constituted of switches and/or diodes, inductors and/or capacitors.

It is difficult, if not impossible, to analyse an impedance network using (linear) circuit theory due to the nonlinear switching components in the impedance network. It is, however, helpful to simplify the analysis of an impedance network by reducing the number of its components, which is then normally done by replacing the actual components with notional components of the same functions. Among existing analysis methods, such as Nodal and Mesh methods [2], the two-port network is well suited for the analysis of the impedance network [3].

A two-port network, as shown in Fig. 2.2, is an electrical network or a device with four terminals, which are arranged into two pairs called ports, i.e. each pair of terminals is one port. As shown in Fig. 2.2, the left port is usually regarded as the input port, while the right one is the output port. Therefore, a two-port network is represented by four external variables, i.e. voltage $U_1(s)$ and current $I_1(s)$ at the input port, and voltage $U_2(s)$ and current $I_2(s)$ at the output port, so that the two-port network can be treated as a black box modeled by the relationships between the four variables $U_1(s)$, $I_1(s)$, $U_2(s)$, and $I_2(s)$ [4–7].

The transmission equation of a two-port network is given by [8–11]

$$\begin{bmatrix} U_1(s) \\ I_1(s) \end{bmatrix} = \mathbf{A}(s) \cdot \begin{bmatrix} U_2(s) \\ -I_2(s) \end{bmatrix}, \quad (2.1)$$

where $\mathbf{A}(s)$ is the transmission matrix and written as

$$\mathbf{A}(s) = \begin{bmatrix} A_{11}(s) & A_{12}(s) \\ A_{21}(s) & A_{22}(s) \end{bmatrix}, \quad (2.2)$$

whose elements are defined as

$$\left\{ \begin{array}{l} A_{11}(s) = \left. \frac{U_1(s)}{U_2(s)} \right|_{I_2(s)=0}, \\ A_{12}(s) = \left. \frac{U_1(s)}{-I_2(s)} \right|_{U_2(s)=0}, \\ A_{21}(s) = \left. \frac{I_1(s)}{U_2} \right|_{I_2(s)=0}, \\ A_{22}(s) = \left. \frac{I_1(s)}{-I_2(s)} \right|_{U_2(s)=0}. \end{array} \right. \quad (2.3)$$

Therefore, (2.1) can be rewritten as

$$\left\{ \begin{array}{l} U_1(s) = A_{11}(s)U_2(s) + A_{12}(s)(-I_2(s)), \\ I_1(s) = A_{21}(s)U_2(s) + A_{22}(s)(-I_2(s)). \end{array} \right. \quad (2.4)$$

A two-port network model is a mathematical circuit analysis technique to represent a complex circuit into a simple notation. A two-port network is regarded as a “black box” with its properties specified by a matrix of numbers, which allows the response of the network to signals applied to the ports to be calculated easily, without solving all the internal voltages and currents in the network [7].

Impedance networks can have multiple ports connecting external circuits, but generally have two ports, and can thus be equivalent to a two-port network. In terms of Thevenin’s equivalent impedance theorem, the *input impedance* of a two-port network is the equivalent impedance of the two-port network with an open input port and an output port connecting a load; while the *output impedance* (also named as *source impedance* or *internal impedance*) is the equivalent impedance of the two-port network with a short-circuited input port and an open output port. Further in terms of Ohm’s law, the input impedance of a two-port network $Z_i(s)$ reads

$$Z_i(s) = \frac{U_1(s)}{I_1(s)} = \frac{A_{11}(s)Z_L(s) + A_{12}(s)}{A_{21}(s)Z_L(s) + A_{22}(s)}, \quad (2.5)$$

where $Z_L(s)$ is the load impedance of the two-port network’s output port.

Similarly, the output impedance of two-port network $Z_o(s)$ writes

$$Z_o(s) = \frac{U_2(s)}{I_2(s)} = \frac{A_{22}(s)Z_S(s) + A_{12}(s)}{A_{21}(s)Z_S(s) + A_{11}(s)}, \quad (2.6)$$

where $Z_S(s)$ is the source impedance of the two-port network’s input port.

2.2.3 Impedance Source Converters (Z-source Converters)

An impedance network together with a source constitute an *impedance source* (also named a Z-source), with its equivalent impedance $Z \in [0, +\infty)$. The impedance source is a general source in the sense that it includes voltage- and current sources as its extreme cases; that is, it becomes a voltage source for $Z = 0$; and a current source for $Z \rightarrow \infty$. It can then exhibit rich properties for $0 \leq Z < \infty$.

Correspondingly, an impedance source converter is thus coined, which possesses unique advantages over traditional voltage and current sources converters and can well meet more stringent requirements from today's industry. It is known that voltage source converters suffer from shoot-through problems, the inapplicability to a capacitive load, and limited gains of output voltages; while current source converters have open-circuit problems, the inapplicability to an inductive load, and limited gains of output currents. A well-designed impedance source converter can overcome those above-mentioned problems.

2.2.4 Impedance Networks Converters

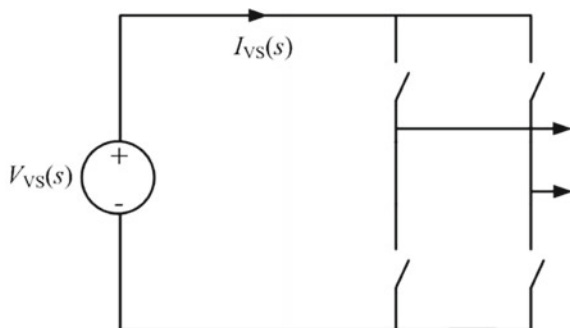
Extending from impedance source converters, an impedance network can be put in other positions of the converter but not only with the source, and these kinds of converters are named as impedance network converter. The impedance networks converter is a general one in the sense that it include impedance source converters when the impedance network is placed with a source.

2.3 Voltage-Source- and Current-Source-Inverters

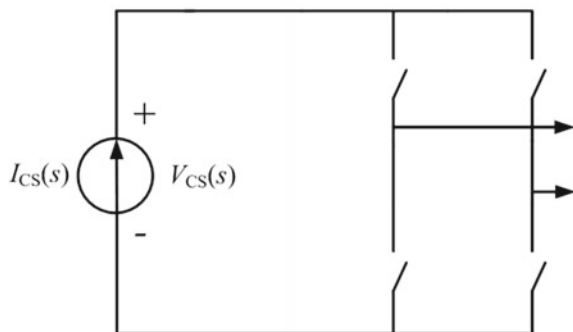
A converter is a general term for AC-DC rectifiers, DC-DC choppers, DC-AC inverters, and AC-AC converters. AC-DC rectifiers and AC-AC converters may have the problems of shoot-through, open-circuit and limited output gains; while DC-DC choppers may suffer from the shoot-through and open-circuit problems and inapplicability to a capacitive or inductive load, as well as DC-AC inverters may have all of the above-mentioned problems. For simplicity, voltage-source- and current-source-inverters are taken as examples to be qualitatively analysed from the perspective of impedance networks.

Voltage-source- and current-source-inverters are depicted in Fig. 2.3, where $V_{VS}(s)$ and $I_{VS}(s)$ in Fig. 2.3a represent the voltage and current of the voltage source; while $V_{CS}(s)$ and $I_{CS}(s)$ in Fig. 2.3b stand for the voltage and current of the current source, respectively. Furthermore, their equivalent circuits are drawn in Fig. 2.4, where $Z_{VS}(s)$ and $Z_L(s)$ are the equivalent source impedance and equivalent load impedance of the voltage source inverter in Fig. 2.4a, whose corresponding two-port

Fig. 2.3 Voltage source and current source inverters



(a) Voltage source inverters



(b) Current source inverters

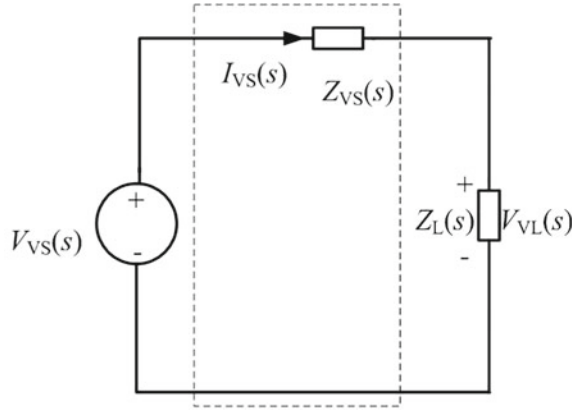
network is indicated in the dashed box in Fig. 2.4a, where $Z_{VS}(s)$ is the unique component in the two-port network; while $Y_{CS}(s)$ and $Y_L(s)$ are the equivalent source admittance and load admittance of the current source inverter in Fig. 2.4b, whose corresponding two-port network is shown in the dashed box in Fig. 2.4b, where $Y_{CS}(s)$ is also the unique component in the two-port network.

2.4 Voltage Source Inverters

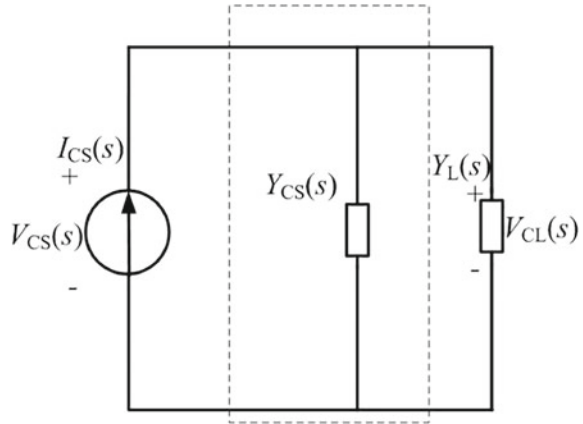
2.4.1 Shoot-Through

In terms of (2.3), the transmission matrix of the voltage source inverter in Fig. 2.4a reads

Fig. 2.4 Equivalent circuits of voltage-source- and current-source-inverters with two-port networks



(a) Voltage source inverters



(b) Current source inverters

$$\begin{cases} A_{V11}(s) = 1, \\ A_{V12}(s) = Z_{VS}(s), \\ A_{V21}(s) = 0, \\ A_{V22}(s) = 1. \end{cases} \quad (2.7)$$

Substituting (2.7) into (2.5) results in the input impedance of the voltage source inverter as

$$Z_i(s) = \frac{A_{V11}(s)Z_L(s) + A_{V12}(s)}{A_{V21}(s)Z_L(s) + A_{V22}(s)} = Z_L(s) + Z_{VS}(s), \quad (2.8)$$

while the input current of the voltage source is thus obtained as

$$I_{VS}(s) = \frac{V_{VS}(s)}{Z_i(s)} = \frac{V_{VS}(s)}{Z_L(s) + Z_{VS}(s)} . \quad (2.9)$$

It is obvious that $Z_L(s) = 0$ in case that the switches of the voltage source inverter on a bridge are turned on simultaneously. Moreover, the source impedance $Z_{VS}(s)$ is normally very small, i.e. $Z_{VS}(s) \approx 0$. Therefore, $Z_i(s) = Z_L(s) + Z_{VS}(s) \approx 0$, which implies $I_{VS}(s) \rightarrow \infty$. Thus, the voltage source is shorted and a very large current will break down the switches. This is the so-called **shoot-through problem**.

In order to prevent the occurrence of shoot-through, the dead-time compensation technique has often been adopted to prevent switches from turning on simultaneously [12].

2.4.2 Limited Output Voltage Gain

In terms of Fig. 2.4a, substituting $Z_S(s) = 0$ and (2.7) into (2.6) results in its output impedance as

$$Z_o(s) = \frac{A_{V22}(s)Z_S(s) + A_{V12}(s)}{A_{V21}(s)Z_S(s) + A_{V11}(s)} = Z_{VS}(s) . \quad (2.10)$$

Obviously, the voltage of the load can be expressed as

$$V_{VL}(s) = V_{VS}(s) - I_L(s)Z_{VS}(s) . \quad (2.11)$$

It is straightforward from (2.11) that $Z_{VL}(s) \leq V_{VS}(s)$ due to $Z_{VS}(s) \geq 0$ and $I_L(s) \geq 0$; namely, the load voltage $V_{VL}(s)$ is lower than or equal to the source voltage $V_{VS}(s)$.

In order to fulfill the high output voltage gain requirements in industrial applications like solar energy applications, DC-DC boost front stage converters can be cascaded to boost the output voltage, which has actually changed its output impedance features [13–16].

2.4.3 Inapplicability to Capacitive Loads

It is known that the electrical loads can be classified into resistive, capacitive, and inductive ones. A capacitive load is an AC electrical load, in which the current reaches its peak before the voltage; while an inductive load is a load that pulls a large amount of current when first energised, for example, motors, transformers, and wound control gear, and a resistive load is a load which consumes electrical energy

in a sinusoidal manner. This means that the current flow is in time with and directly proportional to the voltage, such as incandescent lighting and electrical heaters.

The impedance $Z_{VS}(s)$ in a two-port network is equivalent to a capacitor with very large capacitance, which implies that $Z_{VS}(s) = -j \frac{1}{\omega C} \approx 0$. In term of (2.11), one has $V_{VL}(s) = V_{VS}(s)$. It is remarked if the load impedance $Z_L(s)$ is capacitive, a capacitive source offers energy to a capacitive load, while $V_{VL}(s) = V_{VS}(s)$ at a steady state implies that the voltage source inverter does not function, and is thus inapplicable to capacitive loads.

It is concluded that, due to the impedance of a two-port network between the voltage source and the inverter bridges, the voltage source inverter has the problems of the shoot-through, limited output voltage gains, and inapplicability to capacitive loads, which restrain its wide applications.

2.5 Current Source Inverters

2.5.1 Open-Circuit

In terms of (2.3), the transmission matrix of the current source inverter in Fig. 2.4b reads

$$\begin{cases} A_{C11}(s) = 1, \\ A_{C12}(s) = 0, \\ A_{C21}(s) = Y_{CS}(s), \\ A_{C22}(s) = 1, \end{cases} \quad (2.12)$$

where $Y_{CS}(s)$ is the source admittance of the current source inverter, which is reciprocal to its source impedance.

Substituting (2.12) into (2.5) results in the input admittance of the current source inverter

$$Y_i(s) = \frac{1}{Z_i(s)} = \frac{A_{C21}(s) \frac{1}{Y_L(s)} + A_{C22}(s)}{A_{C11}(s) \frac{1}{Y_L(s)} + A_{C12}(s)} = Y_L(s) + Y_{CS}(s), \quad (2.13)$$

where $Y_L(s)$ and $Y_{CS}(s)$ are the load and source admittances, respectively, as shown in Fig. 2.4b, while the input voltage of the current source is thus obtained as

$$V_{CS}(s) = \frac{I_{CS}(s)}{Y_L(s) + Y_{CS}(s)}, \quad (2.14)$$

where $I_{CS}(s)$ is the current of current source, as shown in Fig. 2.4b.

An inverter normally includes at least one inverter bridge, while one inverter bridge is normally composed of one upper switch and one lower switch. On each bridge, either the upper switch or the lower switch must be kept on; otherwise, one has $Y_L(s) = 0$. Moreover, the source admittance $Y_{CS}(s)$ is normally very small, i.e. $Y_{CS}(s) \approx 0$. Therefore, $Y_i(s) = Y_L(s) + Y_{CS}(s) \approx 0$, which implies $V_{CS}(s) \rightarrow \infty$. Thus, the current source is open-circuit and a very large voltage will break down the switches.

In order to prevent the open-circuit problem, the overlapped time technique on upper and lower switches has been normally utilized to ensure at least one of the upper switches and one of the lower switches to be on at any time [12].

2.5.2 Limited Output Current Gain

In terms of (2.6), one can obtain the output admittance of the current source inverter as

$$Y_o(s) = \frac{1}{Z_o(s)} = \frac{A_{C21}(s) \frac{1}{Y_{CS}(s)} + A_{C11}(s)}{A_{C22}(s) \frac{1}{Y_{CS}(s)} + A_{C12}(s)} = Y_{CS}(s), \quad (2.15)$$

while the output current is

$$I_{CL}(s) = I_{CS}(s) - V_{CS}(s)Y_{CS}(s). \quad (2.16)$$

For $V_{CS}(s) \geq 0$ and $Y_{CS} \geq 0$, one has $I_{CL} \leq I_{CS}$, namely, the load current $I_{CL}(s)$ is lower than or equal to the source current $I_{CS}(s)$.

2.5.3 Inapplicability to Inductive Loads

The admittance $Y_{CS}(s)$ in a two-port network is equivalent to an inductor with very large inductance, which implies that $Y_{CS}(s) = -j \frac{1}{\omega L} \approx 0$. It is remarked if the load admittance $Y_L(s)$ is inductive, an inductive source offers energy to an inductive load, while $I_{CL}(s) = I_{CS}(s)$ at a steady state implies that the current source inverter does not work and is thus inapplicable to inductive loads.

It is concluded that, due to the admittance of the two-port network between the current source and the inverter bridges, the current source inverter has the problems of open-circuit, limited output current gains, and inapplicability to inductive loads.

2.6 Z-source Inverters

Peng [17] has proposed to use an impedance network (named as Z-network) in 2002, as shown in Fig. 2.6, to couple with a DC source to form a novel source, as shown in the rectangles in Fig. 2.7, including voltage- and current-type Z-source inverters. Applying this Z-source technology in other converters results in Z-source DC-DC converters (Fig. 2.5a), Z-source AC-DC rectifiers (Fig. 2.5b), and Z-source AC-AC converters (Fig. 2.5c).

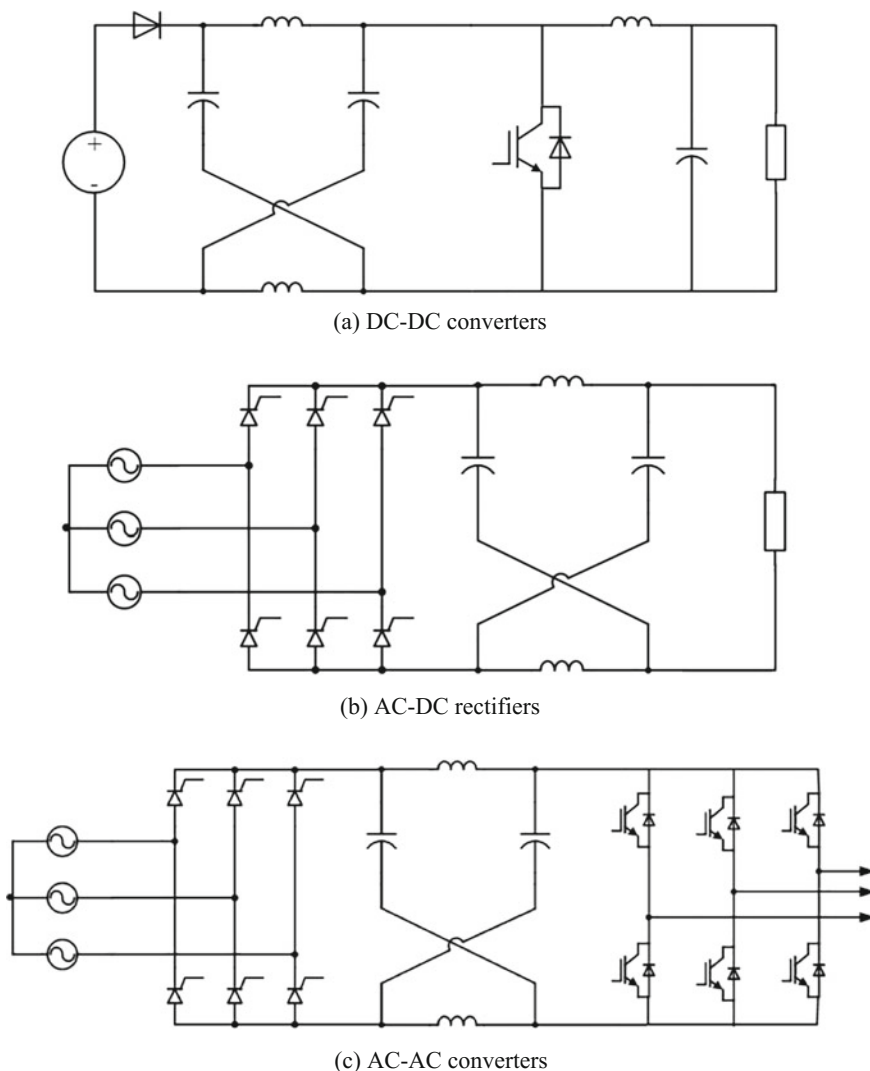
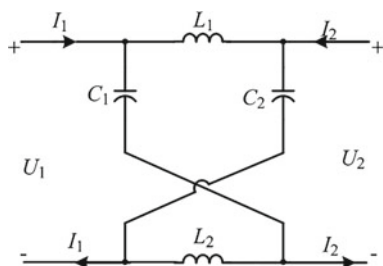
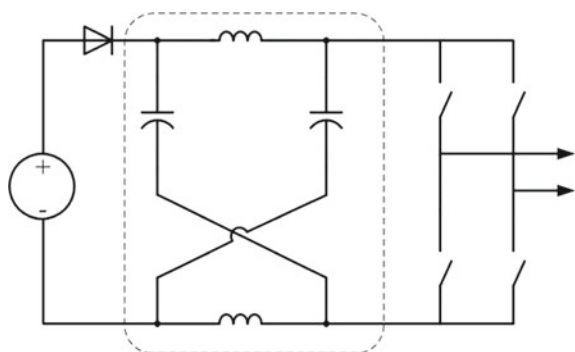
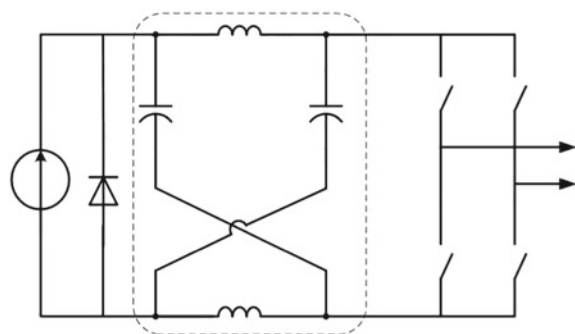


Fig. 2.5 Other typical Z-source converters

Fig. 2.6 A Z-network**Fig. 2.7** Z-source inverters

(a) Voltage-type

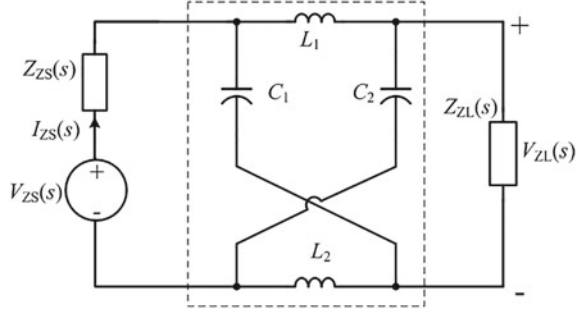


(b) Current-type

Similarly, voltage-type Z-source inverters are also taken as examples, for simplicity, to explain the reasons that Z-source converters can overcome the problems of voltage source and current source converters. The diagram of a voltage-type Z-source inverter is drawn in Fig. 2.7a, whose equivalent two-port network is illustrated in the dashed box in Fig. 2.8.

Assume $L_1 = L_2 = L$ and $C_1 = C_2 = C$, and denote the impedance of diode D by $Z_{DS}(s)$.

Fig. 2.8 Equivalent circuit of voltage-type Z-source inverters with two-port network



In terms of (2.2), one can obtain the transmission matrix of the Z-network as follows

$$\mathbf{A}_Z(s) = \begin{bmatrix} A_{Z11}(s) & A_{Z12}(s) \\ A_{Z21}(s) & A_{Z22}(s) \end{bmatrix}, \quad (2.17)$$

where, in terms of (2.3), the elements write

$$\begin{cases} A_{Z11}(s) = \frac{1 + s^2 LC}{1 - s^2 LC}, \\ A_{Z12}(s) = \frac{2sL}{1 - s^2 LC}, \\ A_{Z21}(s) = \frac{2sC}{1 - s^2 LC}, \\ A_{Z22}(s) = \frac{1 + s^2 LC}{1 - s^2 LC}. \end{cases} \quad (2.18)$$

Substituting $Z_S(s) = Z_{ZS}(s)$, $Z_L(s) = Z_{ZL}(s)$ and (2.18) into (2.5) and (2.6) results in the input and output impedances of the Z-network as

$$\begin{cases} Z_{Zi}(s) = \frac{A_{Z11}(s)Z_{ZL}(s) + A_{Z12}(s)}{A_{Z21}(s)Z_{ZL}(s) + A_{Z22}(s)} = \frac{(s^2 LC + 1)Z_{ZL}(s) + 2sL}{s^2 LC + 2sC Z_{ZL}(s) + 1}, \\ Z_{Zo}(s) = \frac{A_{Z22}(s)Z_{ZS}(s) + A_{Z12}(s)}{A_{Z21}(s)Z_{ZS}(s) + A_{Z11}(s)} = \frac{(s^2 LC + 1)Z_{ZS}(s) + 2sL}{s^2 LC + 2sC Z_{ZS}(s) + 1}, \end{cases} \quad (2.19)$$

where $Z_{ZS}(s)$ is the source impedance of the input port of the Z-network and $Z_{ZL}(s)$ is the load impedance of the output port of the Z-network, described as

$$Z_{ZS}(s) = \begin{cases} 0, & \text{if } D \text{ is on,} \\ \infty, & \text{otherwise,} \end{cases} \quad (2.20)$$

and

$$Z_{ZL}(s) = \begin{cases} 0, & \text{at a shoot-through state,} \\ \infty, & \text{at an open-circuit state,} \\ Z_Z(s), & \text{at a normal state,} \end{cases} \quad (2.21)$$

where $Z_Z(s)$ is the load impedance of the inverter bridge.

Substituting (2.20) and (2.21) into (2.19) leads to the input and output impedances as

$$Z_{Zi}(s) = \begin{cases} \frac{2sL}{s^2LC + 1}, & \text{at a shoot-through state,} \\ \frac{2sC}{(s^2LC + 1)Z_Z(s) + 2sL}, & \text{at an open-circuit state,} \\ \frac{(s^2LC + 1)Z_Z(s) + 2sL}{2sCZ_Z(s) + s^2LC + 1}, & \text{at a normal state,} \end{cases} \quad (2.22)$$

and

$$Z_{Zo}(s) = \begin{cases} \frac{2sL}{s^2LC + 1}, & \text{if } D \text{ is on,} \\ \frac{s^2LC + 1}{2sC}, & \text{otherwise.} \end{cases} \quad (2.23)$$

2.6.1 Immunity to the Shoot-Through

The input current of the Z-source inverter is expressed as

$$I_{ZS}(s) = \frac{V_{ZS}(s)}{Z_{Zi}(s)}, \quad (2.24)$$

where $Z_{ZL}(s) = 0$ if the switches on a bridge are turned on simultaneously. It is obvious that $Z_{Zi}(s) \neq 0$ holds in all cases in terms of (2.22). Therefore, the Z-source inverter can operate at shoot-through states. Compared to the voltage source inverter, Z-source inverter is immune to the shoot-through problem, so that the short-circuited phenomenon at the source can be avoided because the Z-network increases the input impedance.

2.6.2 High Output Voltage Gains

Denote the duty cycle of the diode D as d and assume $d \in [0, 1]$. In terms of (2.23), one can obtain the average output impedance as

$$Z_{Zo}(s) = \frac{(1-d)L}{2} \left(\frac{s^4 + s^2 \left(\frac{2(1+d)}{(1-d)LC} \right) + \frac{1}{L^2 C^2}}{s^3 + s \frac{1}{LC}} \right), \quad (2.25)$$

while the output voltage of the Z-source inverter, $V_{ZL}(s)$, is expressed as

$$V_{ZL}(s) = V_{ZS}(s) - I_{ZL}(s)Z_{Zo}(s). \quad (2.26)$$

It is obvious that $Z_{Zo}(s)$ is the function of the duty d in terms of (2.25). Adjusting $Z_{Zo}(s)$ to be negative or positive via d , one can obtain either $V_{ZL}(s) > V_{ZS}(s)$ or $V_{ZL}(s) < V_{ZS}(s)$, which implies that the Z-source inverters can overcome the limited voltage gains of traditional voltage source inverters.

2.6.3 Applicability both to Capacitive and Inductive Loads

Assume that $Z_Z(s)$ is capacitive. Then, in terms of (2.23), one has

$$Z_Z(s) = \frac{1}{sC_L}, \quad (2.27)$$

where C_L is the capacitance of the load.

By adjusting the duty d , and the inductance L , capacitance C of the Z-network, the output impedance of the Z-network can exhibit the inductive feature, implying that the Z-source inverter is applicability of a capacitive load.

Similarly, assume that $Z_Z(s)$ is inductive and one can also prove that the Z-source inverter is also applicability of an inductive load.

It is thus concluded that due to the embedded Z-network, Z-source inverters have unique advantages over traditional ones, i.e. immunity to the shoot-through, higher output voltage gains, and applicability of both capacitive and inductive loads, which have a great potential in renewable energy applications.

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