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Impedance Networks Matching Mechanism for Designing Power Converters

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Abstract—In this paper, a profound analysis of voltage sources inverters is first conducted for understanding their disadvantages. It follows with the explanations of the advantages of Z-source inverters. Based on these analysis, this paper proposes the impedance network matching mechanism, which forms the basis of a systematic methodology of designing power converters.

1. Introduction

In 1882, the first power grid, which is a DC and short-distance distribution system, was invented by T. Edison. Then, the problem was how to transfer energy over a long distance [1]. It is now well known that electricity must be transmitted at AC high voltages because DC voltage cannot be increased or decreased at that time [2] until the invention of transformers in 1885 [3]. Transformers played a vital rôle in electricity transmission, especially in the energy conversion. However, transformers can only increase or decrease AC voltage (AC-AC) at the same frequency [4]. In practical applications, electric energy was expected to convert from one form to another, e.g. between AC and DC, or just into different voltages or frequencies, or some combinations of those, which cannot be fully fulfilled by transformers. With the developments of semiconductor switches, power electronics appeared and has developed to be a discipline [5].

With rapid development of modern industry, more severe problems are faced by power electronics [6]. In order to solve these problems, some advances were witnessed in the semiconductor switches in power converters, for example, integrated gate-commutated thyristors (IGCT) were invented to have lower conduction loss. However, due to high switching losses, typical operating frequency is normally set up to 500 Hz. Accordingly, control strategies were also improved in algorithms with higher accuracy and speed [7].

To design a new power electronics converter, one can, on the one hand, develop a new control strategy. On the other hand, one can design a novel power converter topology, so as to obtain specific outputs and better features. In fact, a control strategy is specified to a certain topology, and the topology determines the control system. Therefore, it is of great significance to coin new power converter topologies to fulfill various requirements in applications.

It is known that voltage-source converters suffer from shoot-through problems, the incapability of loading a capacitive load, and limited gains of output voltages, while current-source converters have open-circuit problems, the incapability of loading an inductive load, and limited gains of output currents. In order to solve these problems, Z-source converters were firstly proposed by Peng in 2002 [8, 9]. Z-source can be regarded as a general source, including the current source and the voltage source as two extreme cases. Like traditional converters, the design of specific Z-source converters is still an art, lacking of a systematic design methodology.

In this paper, it is thus motivated to profoundly analyze voltage sources converters and understand why impedance-source converters have the unique features over traditional ones based on the two-port network theory. Then, a deep understanding of the impedance network matching mechanism will lead to a systematic methodology of designing power converters.

2. Preliminaries: Two-port Network

A two-port network, as shown in Fig. 1, is an electrical network with two ports, where the left port is considered as the input port, while the right one is the output port, representing by four 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.

The transmission equation of a two-port network is given by

$$\begin{bmatrix} U_1(s) \\ I_1(s) \end{bmatrix} = \mathbf{A}(s) \cdot \begin{bmatrix} U_2(s) \\ -I_2(s) \end{bmatrix}, \tag{1}$$

Figure 1: Two-port networks

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

$$\begin{cases} A_{11}(s) = \left.\dfrac{U_1(s)}{U_2(s)}\right|_{I_2(s)=0} \\ A_{12}(s) = \left.\dfrac{U_1(s)}{-I_2(s)}\right|_{U_2(s)=0} \\ A_{21}(s) = \left.\dfrac{I_1(s)}{U_2}\right|_{I_2(s)=0} \\ A_{22}(s) = \left.\dfrac{I_1(s)}{-I_2(s)}\right|_{U_2(s)=0} \end{cases} . \tag{2}$$

Therefore, an impedance network can be equivalent to a two-port network, and whose input and output impedances read

$$Z_{\mathrm{i}}(s) = \frac{U_1(s)}{I_1(s)} = \frac{A_{11}(s)Z_{\mathrm{L}}(s) + A_{12}(s)}{A_{21}(s)Z_{\mathrm{L}}(s) + A_{22}(s)}, \tag{3}$$

and

$$Z_{\mathrm{o}}(s) = \frac{U_2(s)}{I_2(s)} = \frac{A_{22}(s)Z_{\mathrm{S}}(s) + A_{12}(s)}{A_{21}(s)Z_{\mathrm{S}}(s) + A_{11}(s)}, \tag{4}$$

where $Z_{\mathrm{L}}(s)$ and $Z_{\mathrm{S}}(s)$ are the load and source impedances of the two-port network's output and input ports, respectively.

3. Analysis of Voltage-Source Inverters

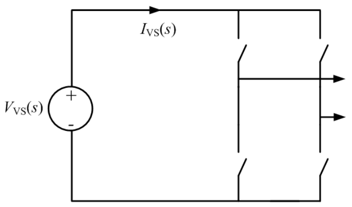
This section explains why voltage-source inverters have the problems mentioned as a typical example.

A voltage-source inverter and its equivalent circuit are drawn in Fig. 2, where $Z_{\mathrm{VS}}(s)$ and $Z_{\mathrm{L}}(s)$ are the equivalent source impedance and equivalent load impedance of the voltage-source inverter, whose corresponding two-port network is indicated in the dashed box in Fig. 2(b), where $Z_{\mathrm{VS}}(s)$ is the unique component in the two-port network.

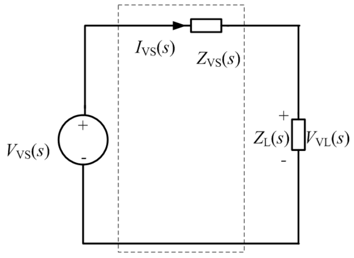
(1) Shoot-through

In terms of (2), the transmission matrix of the voltage-source inverter in Fig. 2(b) reads

$$\begin{cases} A_{\mathrm{V}11}(s) = 1 \\ A_{\mathrm{V}12}(s) = Z_{\mathrm{VS}}(s) \\ A_{\mathrm{V}21}(s) = 0 \\ A_{\mathrm{V}22}(s) = 1 \end{cases} . \tag{5}$$



(a) Voltage-source type



(b) Voltage-source type

Figure 2: Voltage-source inverter and its equivalent circuit with two-port network.

Substituting (5) into (3) results in the input impedance of the voltage-source inverter

$$Z_{\mathrm{i}}(s) = Z_{\mathrm{L}}(s) + Z_{\mathrm{VS}}(s), \tag{6}$$

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

$$I_{\mathrm{VS}}(s) = \frac{V_{\mathrm{VS}}(s)}{Z_{\mathrm{L}}(s) + Z_{\mathrm{VS}}(s)}. \tag{7}$$

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

(2) Limited output voltage

In terms of Fig. 2(b), submitting $Z_{\mathrm{S}}(s) = 0$ and (5) into (4) results in the output impedance of voltage-source inverter as

$$Z_{\mathrm{o}}(s) = Z_{\mathrm{VS}}(s). \tag{8}$$

Obviously, the voltage of the load can be expressed as

$$V_{\mathrm{VL}}(s) = V_{\mathrm{VS}}(s) - I_{\mathrm{VS}}(s)Z_{\mathrm{VS}}(s). \tag{9}$$

According to (9), because of the existence of the source impedance $Z_{\mathrm{VS}}(s)$ in the two-port network, the output impedance $Z_{\mathrm{o}}(s)$ leads that the load voltage $V_{\mathrm{VL}}(s)$ is lower than the source voltage $V_{\mathrm{VS}}(s)$.

(3) Incapability of loading capacitive loads

Further by analyzing (9), the impedance $Z_{\mathrm{VS}}(s)$ in the two-port network is equivalent to a capacitor with very large capacitance, if the load impedance $Z_{\mathrm{L}}(s)$ is capacitive, it is easy to find that a capacitive source offer energy to a capacitive load resulting in that $V_{\mathrm{VL}}(s) = V_{\mathrm{VS}}(s)$ finally in steady states, which implies that the voltage-source inverter is incapability of loading capacitive loads.

Therefore, due to the impedance of two-port network between the voltage-source and the inverter bridges, there are some disadvantages in the voltage-source inverter listed as above.

4. Analysis of Z-Source Inverters

The equivalent circuit of Z-source inverter with two-port network is shown as Fig. 3, therein, define $L_1 = L_2 = L$, $C_1 = C_2 = C$, and the impedance of diode D as $Z_{\mathrm{ZS}}(s)$.

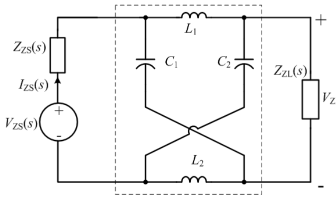


Figure 3: Equivalent circuit of Z-source inverter with two-port network.

In terms of (2), one can obtain the transmission matrix of Z-network and obtain its elements

$$\begin{cases} A_{\mathrm{Z11}}(s) = \dfrac{s^2LC+1}{1-s^2LC} \\ A_{\mathrm{Z12}}(s) = \dfrac{2sL}{1-s^2LC} \\ A_{\mathrm{Z21}}(s) = \dfrac{2sC}{1-s^2LC} \\ A_{\mathrm{Z22}}(s) = \dfrac{s^2LC+1}{1-s^2LC} \end{cases} . \tag{10}$$

Submitting $Z_{\mathrm{S}}(s) = Z_{\mathrm{VS}}(s)$, $Z_{\mathrm{L}}(s) = Z_{\mathrm{ZL}}(s)$ and (10) into (3) and (4) results in the input and output impedances of Z-network as

$$Z_{\mathrm{Zi}}(s) = \begin{cases} \dfrac{2sL}{s^2LC+1} & \text{Shoot}-\text{through states} \\ \dfrac{s^2LC+1}{2sC} & \text{Open}-\text{circuit states} \\ \dfrac{(s^2LC+1)Z_{\mathrm{Z}}(s)+2sL}{2sCZ_{\mathrm{Z}}(s)+s^2LC+1} & \text{Normal states} \end{cases} , \tag{11}$$

and

$$Z_{\mathrm{Zo}}(s) = \begin{cases} \dfrac{2sL}{s^2LC+1} & \text{When } D \text{ on} \\ \dfrac{s^2LC+1}{2sC} & \text{When } D \text{ off} \end{cases} . \tag{12}$$

(1) Immunity to shoot-through

The input current of the Z-source inverter is

$$I_{\mathrm{ZS}}(s) = \frac{V_{\mathrm{ZS}}(s)}{Z_{\mathrm{Zi}}(s)} , \tag{13}$$

therein, the input impedance $Z_{\mathrm{Zi}}(s)$ is not equal to 0 in any conditions according to (11) indicating that the Z-source inverter is immune to the shoot-through problems.

(2) High output voltage gain

Assume the duty cycle of the diode D as $d \in [0, 1]$. In terms of (12), one can obtain the average output impedance as

$$Z_{\mathrm{Zo}}(s) = \frac{(1-d)L}{2} \left(\frac{s^4 + s^2\left(\dfrac{2(1+d)}{(1-d)LC}\right) + \dfrac{1}{L^2C^2}}{s^3 + s\dfrac{1}{LC}} \right) , \tag{14}$$

while the output voltage of Z-source inverter $V_{\mathrm{ZL}}(s)$ is

$$V_{\mathrm{ZL}}(s) = V_{\mathrm{ZS}}(s) - I_{\mathrm{ZL}}(s)Z_{\mathrm{Zo}}(s). \tag{15}$$

It is obvious that $Z_{\mathrm{Zo}}(s)$ is the function of the duty d in terms of (14). Adjusting $Z_{\mathrm{Zo}}(s)$ via d one can obtain $V_{\mathrm{ZL}}(s) > V_{\mathrm{ZS}}(s)$, which implies that the Z-source inverters can overcome the limited voltage problems of voltage-source inverters.

(3) Capability of loading capacitive loads

Further by analyzing (12), assume the load impedance capacitive as $Z_{\mathrm{Z}}(s) = 1/(sC_{\mathrm{L}})$, where C_{L} is the capacitance of the load.

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

Based on the analysis above, there are some improved performances in Z-source inverters due to the inserted Z-network compared to the traditional one, i.e. immunity to shoot-through, high output voltage gain, and capability of loading all loads.

5. Impedance Networks Matching Mechanism

Impedance matching in linear circuits is to match the parameters of the load impedance and source impedance to realize specific purposes. A power converter is essentially a nonlinear switching circuit different from the linear electronics circuits, and its performances obviously can be improved by the impedance matching method, which can be extended to three aspects, i.e. input impedance matching, output impedance matching and load phase matching.

(1) Input impedance matching

Submitting $s = j\omega$ and $Z_{\mathrm{L}}(j\omega) = 0$ (shoot-through states) into the input impedance of the two-port network in (3) results in the input impedance as

$$Z_{\mathrm{i}}(j\omega) = \mathrm{Re}\left(\frac{A_{12}(j\omega)}{A_{22}(j\omega)}\right) + j\mathrm{Im}\left(\frac{A_{12}(j\omega)}{A_{22}(j\omega)}\right), \quad (16)$$

Assume the input impedance in (16) inductive, it is obvious that the converter can restrain the short-circuit current due to the inherent characteristic of inductive component hindering the current change, and this condition is expressed as

$$\mathrm{Im}\left(\frac{A_{12}(j\omega)}{A_{22}(j\omega)}\right) > 0. \quad (17)$$

(2) Output impedance matching

Similarly, submitting $s = j\omega$ into (4), the output voltage of the two-port network is

$$V_{\mathrm{L}}(j\omega) = V_{\mathrm{S}}(j\omega)\frac{Z_{\mathrm{L}}(j\omega)}{Z_{\mathrm{L}}(j\omega) + Z_{\mathrm{o}}(j\omega)}\,. \quad (18)$$

It is obvious that $|V_{\mathrm{L}}(j\omega)| > |V_{\mathrm{S}}(j\omega)|$ when the voltage gain M satisfies the condition $M > 1$, which results in

$$\begin{aligned}&\mathrm{Re}(Z_{\mathrm{L}}(j\omega))\mathrm{Re}(Z_{\mathrm{o}}(j\omega)) + \mathrm{Im}(Z_{\mathrm{L}}(j\omega))\mathrm{Im}(Z_{\mathrm{o}}(j\omega))\\ &< -\frac{|Z_{\mathrm{o}}(j\omega)|^2}{2} < 0\ ,\end{aligned} \quad (19)$$

when two factor formulars in (19) all smaller than 0, and their sum is smaller than 0, then (19) holds, which indicats that the output impedance exhibits negative impedance features; otherwise, the output impedance exhibits positive impedance features.

(3) Load phase matching

In order to improve the load ability of the converter, i.e. the converter is capable of all kinds of loads, the output impedance phase of the converter should be matched to be capacitive or inductive to reduce the total impedance phase. Therein, the best operation condition is that its total impedance phase is 0°, which can be expressed as similarly

$$\mathrm{Im}\left(Z_{\mathrm{L}}(j\omega)\right) = -\mathrm{Im}\left(Z_{\mathrm{o}}(j\omega)\right). \quad (20)$$

(4) Matching optimization

According to the analysis above, input impedance matching is to increase the input impedance in short-circuit case to make it inductive and then to restrain the input current; output impedance matching is to connect an impedance network or adjust the impedance networks parameters to match the output impedance being positive or negative for increasing or decreasing output voltage; and load phase matching is to match output impedance with the load impedance to realize total impedance phase being close to 0°. Therefore, to design a reasonable and feasible power converter, the parameters conditions of these three matchings should be overall considered in the design to realize matching optimization.

6. Conclusion

A profound analysis of voltage sources inverters and Z-source inverters is first conducted for understanding their disadvantages and advantages, respectively. It follows with the conclusions from these analysis and then an impedance network matching mechanism is proposed for designing power converters.

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