Research on commutation identity between matrix converter and three-level inverter

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Abstract. The commutation strategy is the important content of matrix converter industrial application, for it not only affects the converter safe operation, but also is closely related to the input and output performance. In this paper, the matrix converter and the three-level inverter are compared on the perspective of three-level, the relationship between them is studied, and the logical correspondence of switch tubes in two topologies is established. By analyzing the switching sequence of the three-level inverter and equivalent the clamping diode, the two-step voltage-controlled commutation strategy is obtained, which proves the equivalence between the matrix converter and three-level inverter.

1. Introduction
Matrix converter (MC) has become an important aspect of power electronics research for its many advantages, such as high power density, adjustable power factor and good input-output characteristics[1-3]. Among them, the commutation strategy is an important content which affects the safe operation of MC. Generally speaking, there are two basic principles for MC to realize the safe commutation:

1) Short circuit among the input phases is not allowed, otherwise it will cause over-current of switch tube;

2) Open circuit in the output phase is not allowed under the condition of inductive load, otherwise it will cause over-voltage of switch tube.

Based on the above two principles, domestic and foreign scholars have made a deep research on commutation strategy and proposed many methods. These methods can be roughly divided into two categories: one is based on the direction of the output current; the other is based on the input voltage. In addition, there are hybrid commutation method [4,5], overlap commutation method, dead-band commutation method and so on [6]. However, no matter what kind of commutation method is, its foundation is need to meet the two basic principles.

Compared with MC, switching between the tube of the three-level inverter (TLI) is simpler, the relevant theoretical research is also more mature. But in essence, the switching of TLI also follows two basic principles of "no short circuit" and "no open circuit". Because the TLI has three fixed input voltage: positive level, negative level and zero level, the state switching between the tube is relatively fixed. The input of MC is abc three phase voltage, whose amplitude is variable, so the state switching between tubes cannot be fixed, this increases the complexity of the MC commutation.

Considering the MC has three levels to choose at any time, the characteristic is similar to the TLI. We divide the MC input voltage into high, medium and low level, corresponding to the positive, zero level and negative level in TLI. Based on the "three-level" perspective, the MC and TLI are compared, and the commutation method is discussed and analyzed in this paper.
2. Comparative analysis of commutation between MC and TLI

2.1. Three level perspective of MC
The basic topology of TLI includes four main tubes, four freewheeling diodes, two clamping diodes, DC link buffer circuit, balance resistance and etc. The switching time of each tube is controlled by the dead time, and the instantaneous output level state is determined by the tube state and the output current direction.

MC is actually a direct AC-AC converter, which consists of three input phases and its output can be connected to any input phase, as shown in Figure.1. If we divide three-phase voltage into high-level Up, zero level Uo and low-level Un according to the magnitude, (the virtual rectifier in Figure.1), and consider the input level remains unchanged in each switching cycle, then the MC can be regarded as a TLI structure. In the figure, the virtual rectifier can automatically allocate voltage to p, o, n phases according to the magnitude of three-phase input voltage, while the subsequent circuit can refer to the TLI for modulation and commutation.

From above comparative analysis, it can be seen that the MC and TLI have some similarities. Next, we compare the commutation process of the two topologies, so as to deduce the general commutation law of MC from TLI.

2.2. Switching equivalence of MC and TLI
In order to simplify the analysis, this paper only makes a comparison between single leg of TLI and single-phase output of MC. Other cases can be referred to.

We assume the current flowing into the load is forward and the current flowing out of the load is reverse, such as shown in Figure.2(a). The four main switches are marked with Si1, Si2, Si3, Si4, the Di5 and Di6 are clamping diodes.

Similarly, the current direction of MC is shown in Figure.2(b). The current flowing into the load is forward and the current flowing out of the load is reverse. In the figure, SP, So and Sn are the main switches of input positive level, zero level and negative level phase respectively, where subscript f is the forward tube and r is the reverse tube.
Under the steady state conditions, both converter can output three levels. The specific switch states of the two topologies are shown in Table 1.

| Converter topology | Output positive level | Output zero level | Output negative level |
|--------------------|-----------------------|------------------|-----------------------|
| TLI                | $S_{i1}, S_{i2}$ on   | $S_{i2} \& S_{i3} \& D_{i5} \& D_{i6}$ are switched according to the current direction | $S_{i3}, S_{i4}$ on |
| MC                 | $S_{pf}, S_{pr}$ on   | $S_{of}, S_{or}$ on | $S_{nf}, S_{nr}$ on |

If we consider the diode as a semi controlled device whose turn-on and turn-off are determined by the direction of load current, the TLI contains four fully controlled switches and two half controlled switches, while the MC contains six fully controlled switches. Therefore, the two topologies are equivalent in both output state and number of devices, which lays a foundation for the study of their identity.

Take the forward current as an example: when the system outputs positive level, $S_{i1}$ and $S_{i2}$ tubes of TLI are on, $S_{i3}$ must be turned off, $S_{i4}$ can be turned on or off, $D_{i5}$ and $D_{i6}$ are both turned off, while MC only needs $S_{pf}$ tube on, $S_{pr}$ can be turned on or off, other two phase reverse tubes can not be on, and the forward tube can be turned on or off.

When the output is negative level, $S_{i1}$ tube of TLI is on or off, $S_{i2}$ must be turned off, $S_{i3}$ and $S_{i4}$ are on state, but the current flows through its anti parallel diodes $D_{i3}$ and $D_{i4}$, and both $D_{i5}$ and $D_{i6}$ are turned off, while the MC corresponds to $S_{nf}$ on, $S_{nr}$ can be turned on or off, the other two phase forward tube can not be turned on, and the reverse tube can be turned on or off. In this way, analogizing the other four case, we can establish the corresponding relationship between the two topological switch states under steady state conditions as follows:

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\begin{align*}
S_{pf} &= S_{i1} \& S_{i2} \& S_{i3} \& D_{i5} \& D_{i6} \\
S_{pr} &= \overline{S_{i1}} \& D_{i5} \& D_{i6} \\
S_{of} &= S_{i1} \& S_{i2} \& S_{i3} \& D_{i5} \& D_{i6} \\
S_{or} &= \overline{S_{i1}} \& S_{i2} \& S_{i3} \& D_{i5} \& D_{i6} \\
S_{nf} &= S_{i2} \& D_{i5} \& D_{i6} \\
S_{nr} &= \overline{S_{i2}} \& S_{i3} \& S_{i4} \& D_{i5} \& D_{i6}
\end{align*}
\]

(1)

where, $S$ represents the state of the controlled switch, 1 is on, 0 is off; $D$ represents the state of diode, 1 is on, 0 is off; $\&$ is logical and; $\overline{}$ is logical negation.

3. Dynamic analysis of commutation between MC and TLI

A dead time is usually set in the inverter to prevent direct through, so the level switching has a dynamic process. By using formula (1), we transplant the dynamic process to MC and obtain the corresponding commutation sequence.

3.1. Positive level to zero level, load current forward

The dynamic process of TLI and MC from positive level to zero level is shown in Figure 3. In each picture, TLI is on the left and the MC is on the right, the dotted line represents the load current direction, the blue represents the current flow path, the red represents the switch tube in the on state but without current, and the yellow represents the switching tube in the commutation.
The commutation process of two converters is described in detail below.

1. Initial state 1: TLI outputs positive level, Si1 and Si2 are on, Si3 and Si4 are off, Di5 and Di6 are off; at this time, according to formula (1), the initial state 1 of MC can be obtained, Spf is on, Spr is on but no current.

2. Initial state 2: at the next moment of TLI, Si1 tube will be turned off, Di5 will automatically turn on the freewheeling current; correspondingly, MC will switch between Spf and Sof tube. However, due to the uncontrollable turn-on and turn-off time, the current may be cut off in the process of commutation. So the Sof tube should be turned on in the initial state 2 to simulate the natural commutation characteristics of the diode in the TLI.

3. Transition state: the TLI turns off Si1 and causes the natural freewheeling of Di5; in MC, since the initial state 2 has opened a forward switch Sof in advance, the switching off of Spf will cause its natural freewheeling.

4. End state: the TLI turns on Si3 according to the modulation law; the MC should turn off Spr and turn on Sor at the same time, the circuit is not affected.

3.2. Positive level to zero level, load current reverse
When the load current reverse, the dynamic process of TLI and MC from positive level to zero level is shown in Figure.4. In each picture, TLI is on the left and the MC is on the right.

The commutation process of two converters is described in detail below.

1. Initial state: TLI output positive level, Si1 and Si2 is on state but the current freewheeling by the reverse parallel diode, Si3 and Si4 are off, Di5 and Di6 are off; at this time, according to formula (1), the initial state of MC can be obtained, Spr tube is on state, Spf tube is on but no current.

2. Transition state: TLI turns off the Si1 tube; correspondingly, the MC turns off the Spf and turns on the Sof tube. For this step has no effect on the circuit, the two steps can be carried out at the same time.

3. End state 1: TLI turns on Si3 and causes the natural freewheeling of Di6; in the MC, due to the uncontrollable turn-on and turn-off time of the corresponding Spr and Sor tubes, in order to prevent current interruption, the Sor tube turn on in advance to complete the natural commutation.

4. End state 2: at this time, TLI has completed the commutation, while the MC needs to turn off Spr corresponding to formula (1).
Figure 4. Converter state when positive level to zero level, load current reverse
(a) initial state (b) transition state (c) end state 1 (d) end state 2

Other cases can be analyzed according to examples and will not be repeated.

4. Commutation characteristics of MC

From the above dynamic process, it can be seen that the switching of TLI can be transplanted to MC, while the latter needs to use full control devices instead of clamping diodes in the inverter. But this substitution will reduce the natural commutation degree of the converter, which inevitably requires a more secure control strategy, that result in the more complex commutation.

Based on the above analysis, we can get several characteristics of MC.

1. In essence, the voltage difference is used for the state switching in TLI, so the corresponding MC commutation also belongs to voltage type commutation.
2. TLI commutation needs dead time, and MC also needs a certain time limit.
3. The switching of some state in TLI has no effect on the system, in this case, it can be deduced that the switching can be carried out simultaneously in some cases of MC;
4. By imitating the natural commutation characteristics of clamped diodes in TLI, the freewheeling tubes of switching phase are turned on in the main state in advance, which is beneficial to the reduction of commutation time. Then the four-step commutation can be simplified to the two-step commutation. Figure 5 shows the commutation state of two-step commutation method, the six digits represent the state of three-phase forward and reverse tube, 1 is on, 0 is off. From the above analysis and the states in the figure, we can see that the essence of this method is an analog equivalent to the clamping diode in TLI.

Figure 5. States of two-step commutation
With the two-step commutation method, we can get the MC simulation waveform for input current and the output voltage in Figure 6. As can be seen from the figure, the method can realize the safe operation of MC.

![Simulation waveform of MC](image)

Figure 6. Simulation waveform of MC

5. Conclusion
The output voltage of MC has three levels to choose at any time. If it is divided according to the voltage magnitude, the output characteristics of the converter are very similar to TLI. Based on this three-level perspective, this paper compares MC with TLI, studies the relationship between two topologies. Based on the output state, the logical correspondence of switch tubes is established. By analyzing the switching sequence of TLI, we transplante it into MC and obtain the four-step commutation method. Using the equivalent of MC to clamping diode, we get a simplified two-step commutation method.

Acknowledgments
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