CHAPTER 2

REVIEW OF A TIME VARYING d_0 CONTROLLED RECTIFIER

2.1 Introduction

For completeness, the important concept of the generalized zero voltage space vectors [12, 42] used for integrating the input three-phase AC subcircuit with the output DC subcircuit will first be repeated. Then, a time varying d_0 controlled boostbuck AC/DC converter [12, 42] is roughly reviewed. In fact, as mentioned in the first chapter, it is the main motivation of the dissertation to further improve the single stage high performance three-phase AC/DC converter. It will then become quite obvious after understanding the basic operation principle of this converter [12, 42] that there remains many drawbacks to improve. The new PWM strategies which are proposed to overcome the disadvantages will be presented in the following chapters.

2.2 Concept of Generalized Zero Voltage Space Vectors

The concept of the generalized zero voltage vectors was first proposed by Pan et al. [12] for integrating the three-phase step-up/down AC/DC converter to achieve a high performance single stage converter. As an illustration, first consider the input side AC subcircuit as shown in Fig. 2.1. As can be observed from Fig. 2.1, there are 64 combinations for the six-switch status as shown in Table 2.1. From Table 2.1 one can see that there are 37 combinations resulting in open circuit of line current. Hence, only 27 combinations can be used for practical converter control. The terminal voltages of the rectifier, namely V_k, k=1, 2, 3, with respect to node N in Fig. 2.1 can be expressed as follows:

$$V_k = f(W_k, W_{k+3}, V_{DC}), \quad k=1, 2, 3 \tag{2.1}$$

where V_k is expressed as a function of the switches status and the DC bus voltage, and W_i is defined as follows:

$$W_i \equiv \begin{cases} 1 \text{ when } S_i \text{ is turned on} \\ 0 \text{ when } S_i \text{ is turned off} \end{cases}, \quad i=1, 2, \ldots 6 \tag{2.2}$$

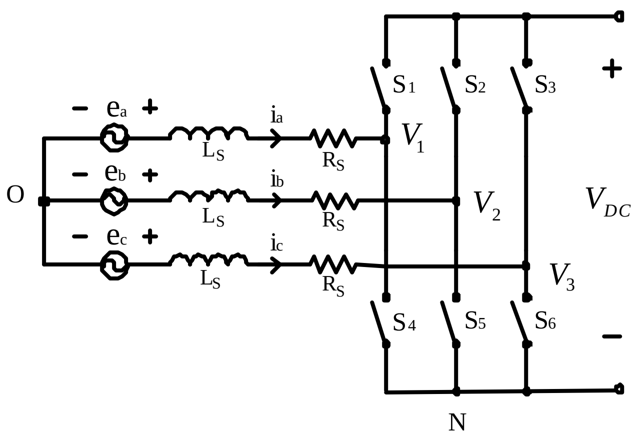

Fig. 2.1 Configuration of the conventional three-phase AC/DC rectifier

Table 2.1 Possible switch combination status of the six switches

S_1	S_2	S_3	S_4	S_5	S_6	State	S_1	S_2	S_3	S_4	S_5	S_6	State
0	0	0	0	0	0	Open	1	0	0	0	0	0	Open
0	0	0	0	0	1	Open	1	0	0	0	0	1	Open
0	0	0	0	1	0	Open	1	0	0	0	1	0	Open
0	0	0	0	1	1	Open	1	0	0	0	1	1	V_{43}
0	0	0	1	0	0	Open	1	0	0	1	0	0	Open
0	0	0	1	0	1	Open	1	0	0	1	0	1	Open
0	0	0	1	1	0	Open	1	0	0	1	1	0	Open
0	0	0	1	1	1	V_{07}	1	0	0	1	1	1	V_{47}
0	0	1	0	0	0	Open	1	0	1	0	0	0	Open
0	0	1	0	0	1	Open	1	0	1	0	0	1	Open
0	0	1	0	1	0	Open	1	0	1	0	1	0	V_{52}
0	0	1	0	1	1	Open	1	0	1	0	1	1	V_{53}
0	0	1	1	0	0	Open	1	0	1	1	0	0	Open
0	0	1	1	0	1	Open	1	0	1	1	0	1	Open
0	0	1	1	1	0	V_{16}	1	0	1	1	1	0	V_{56}
0	0	1	1	1	1	V_{17}	1	0	1	1	1	1	V_{57}
0	1	0	0	0	0	Open	1	1	0	0	0	0	Open
0	1	0	0	0	1	Open	1	1	0	0	0	1	V_{61}
0	1	0	0	1	0	Open	1	1	0	0	1	0	Open
0	1	0	0	1	1	Open	1	1	0	0	1	1	V_{63}
0	1	0	1	0	0	Open	1	1	0	1	0	0	Open
0	1	0	1	0	1	V_{25}	1	1	0	1	0	1	V_{65}
0	1	0	1	1	0	Open	1	1	0	1	1	0	Open
0	1	0	1	1	1	V_{27}	1	1	0	1	1	1	V_{67}
0	1	1	0	0	0	Open	1	1	1	0	0	0	V_{70}
0	1	1	0	0	1	Open	1	1	1	0	0	1	V_{71}
0	1	1	0	1	0	Open	1	1	1	0	1	0	V_{72}
0	1	1	0	1	1	Open	1	1	1	0	1	1	V_{73}
0	1	1	1	0	0	V_{34}	1	1	1	1	0	0	V_{74}
0	1	1	1	0	1	V_{35}	1	1	1	1	0	1	V_{75}
0	1	1	1	1	0	V_{36}	1	1	1	1	1	0	V_{76}
0	1	1	1	1	1	V_{37}	1	1	1	1	1	1	V_{77}

Next, define the corresponding voltage space vectors for all switches status,

$$V_{mn} \equiv \sqrt{\frac{2}{3}}\left(V_1 + V_2 a + V_3 a^2\right) \tag{2.3}$$

where

$$a \equiv e^{j\frac{2p}{3}}$$

$$m \equiv W_1 \times 2^2 + W_2 \times 2^1 + W_3 \times 2^0$$

$$n \equiv W_4 \times 2^2 + W_5 \times 2^1 + W_6 \times 2^0 .$$

And the inverse formula is given as

$$\left[V_1 \quad V_2 \quad V_3\right] = \sqrt{\frac{2}{3}}\,\mathrm{Re}\{\,[1 \quad a^2 \quad a]\, V_{mn}\,\} + \frac{1}{3}\sum_{k=1}^{3} V_k \tag{2.4}$$

By using equation (2.3), one can obtain from Fig. 2.1 the corresponding space vectors. The above 27 qualified voltage space vectors are listed in Table 2.2. From Table 2.2 one can see that space vectors of class A and B correspond to the six nonzero voltage space vectors, $(V_{43}, V_{61}, V_{25}, V_{52}, V_{16}, V_{34})$, and the two conventional zero voltage space vectors, (V_{07}, V_{70}), respectively. However, there are 19 more zero voltage space vectors corresponding to class C, class D and class E, respectively in Table 2.2. The difference between class B zero voltage space vectors and other new zero space vectors, (class C, class D and class E), lies in the fact that the latter will result in short circuit of the V_{DC}.

In summary, the conventional two zero space vectors and 19 more new zero voltage space vectors are totally called generalized zero voltage space vectors,

V_{GZ} [12]. For reference, Fig. 2.2 shows the complete space vector set of the terminal voltages, V_i, $i = 1, 2, 3$, of Fig. 2.1. By applying the generalized zero voltage space vectors one can easily extend the DC/DC boostbuck converter to three-phase AC/DC boostbuck rectifier [12, 42].

Table 2.2 Qualified voltage vectors

Space Vector / Class	V_{mn}
Class A	V_{43}, V_{61}, V_{25}, V_{34}, V_{16}, V_{52}
Class B	V_{07}, V_{70}
Class C	V_{35}, V_{53}, V_{36}, V_{63}, V_{56}, V_{65}, V_{17}, V_{71}, V_{27}, V_{72}, V_{47}, V_{74}
Class D	V_{37}, V_{73}, V_{57}, V_{75}, V_{67}, V_{76}
Class E	V_{77}

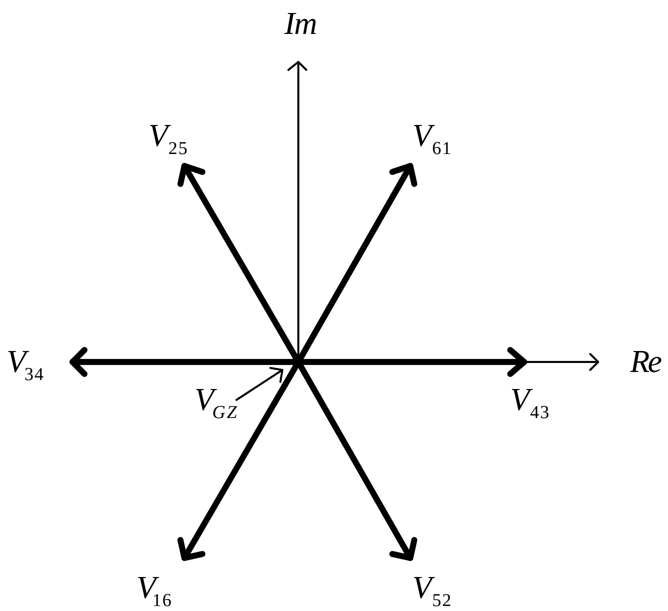

Fig. 2.2 Complete space vectors of terminal voltages on the complex plane

2.3 Operation Principle [12, 42]

Fig. 2.3 and Fig. 2.4 show the three-phase AC/DC boostbuck rectifier and an ideal three-phase input line current commands [12, 42]. From Fig. 2.4 one can see that, in each time interval, none of the input line current changes sign and one current has

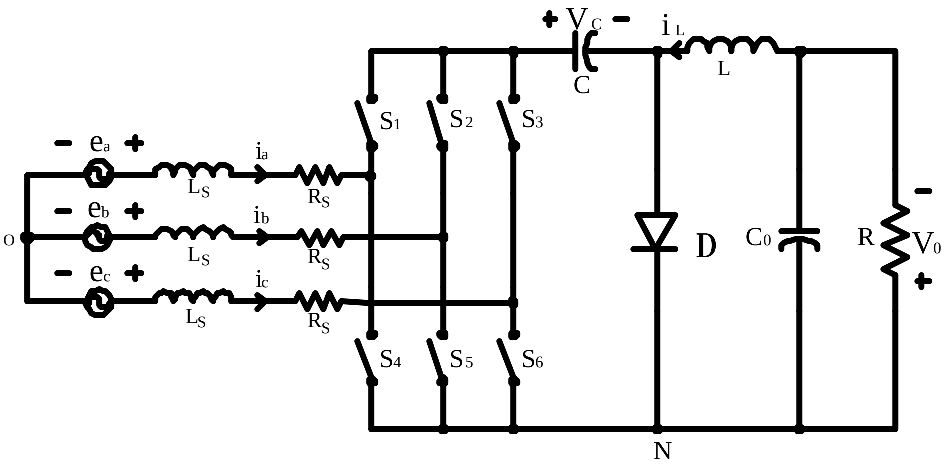

Fig. 2.3 Three-phase AC/DC boostbuck rectifier

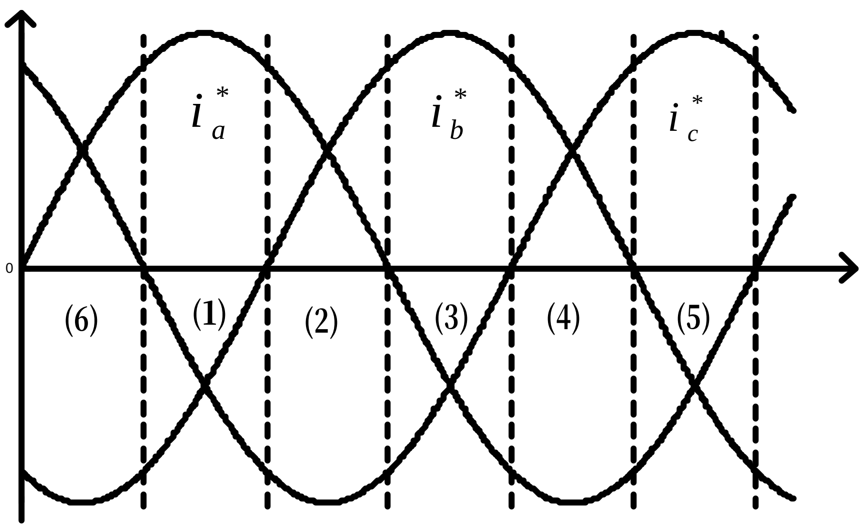

Fig. 2.4 An ideal three-phase input current waveform

the largest absolute value with two other currents having smaller magnitude and opposite sign. Due to the symmetry of a three-phase system, only interval one of Fig. 2.4 is explained here. During the whole 60^0 interval, phase-a current command is the largest and can be conducted through body diode of S_1 or S_4. To select appropriate space vectors for controlling the proposed converter, the complex plane of Fig. 2.2 is divided into six sectors. When the input current lies in interval one of Fig. 2.4, then the corresponding nonzero voltage space vectors V_{52}, V_{43} and V_{61} are chosen and zero voltage space vector V_{70} [42] is selected. That is, interval one in time domain corresponds to the sector in the complex plane located within $-\frac{\pi}{3}$ to $\frac{\pi}{3}$ of Fig. 2.2.

Now, the following normalized three phase current errors are defined as follows [42]:

$$i_{k,error} = \frac{i_k - i_k^*}{V_{p,trig}} \quad , \quad k \in \{a, b, c\} \tag{2.5}$$

$$e_{rk} = Trig(t) - i_{k,error}(t), k \in \{a, b, c\} \tag{2.6}$$

where $V_{p,trig}$ is the peak value of the triangular wave $Trig(t)$. Thus, by comparing $i_{k,error}$ with a triangular wave, one has the following five modes corresponding to eight states of $e_{ra}(t)$, $e_{rb}(t)$ and $e_{rc}(t)$ [42].

Mode 1: $e_{ra} > 0$, $e_{rb} < 0$, $e_{rc} < 0$

This means i_a should be decreased and both currents i_b and i_c should be increased. In this mode, the voltage vector V_{43} should be selected [42].

Mode 2: $e_{ra} > 0$, $e_{rb} < 0$, $e_{rc} > 0$

This means currents both currents i_a and i_c should be decreased and i_b should be increased. In this mode, the voltage vector V_{52} should be selected [42].

Mode 3: $e_{ra} > 0$, $e_{rb} > 0$, $e_{rc} < 0$

This means both currents i_a and i_b should be decreased and i_c should be increased. Hence, the voltage vector V_{61} should be selected [42].

Mode 4: $e_{ra} > 0$, $e_{rb} > 0$, $e_{rc} > 0$

This means currents i_a , i_b and i_c should be decreased. Hence, the voltage V_{70} should be chosen to reduce the current error [42].

Mode 5: $e_{ra} < 0$, $e_{rb} > 0$ (or $e_{rb} < 0$), or $e_{rc} > 0$ ($e_{rc} < 0$)

In this mode, to maintain the normal operation principle of the traditional boostbuck DC/DC converter for the DC part of the proposed converter i_a should not be allowed to flow through C in the opposite direction. Hence, any generalized zero voltage space vectors of class B, C, D or E can be applied. For example, from the viewpoint of reducing conduction losses, the generalized zero voltage space vector of class E, namely V_{77} is preferred

[42].

Similarly, the procedure can be repeated for the other intervals of Fig. 2.4 to select the voltage space vectors. For reference, the selected voltage space vectors for different intervals of Fig. 2.4 are shown in Table 2.3. From the above, one can see that the output DC voltage is boosted only when the maximum current is larger than the corresponding command current.

Practically, due to the finite turn on/off time of semiconductor devices, it is possible to have a very short time period of short circuit of the arms during mode transitions.

Now, define the duty ratio function $d_k \quad (k = 1, 2, 3)$

$$d_k \equiv \frac{1+m_k}{2}, \quad -1 \le m_k \le 1 \tag{2.7}$$

$$\frac{m_k}{2} = d_m \cos[wt - j - \frac{2p(k-1)}{3}]. \tag{2.8}$$

where $\frac{m_k}{2}$ are called as the modulation functions.

From [42], the equivalent averaged duty cycle of the generalized zero voltage space vectors

$$d_z^1 = \begin{cases} Min\{d_k\} & \text{for interval } (2), (4) \text{ and } (6) \text{ of Fig. 2.4} \\ 1 - Max\{d_k\} & \text{for interval } (1), (3) \text{ and } (5) \text{ of Fig. 2.4} \end{cases}$$

The above control strategy was detailed in [42] and will not be repeated. However, it is also possible to have other different control strategies. For example, from the previous section, one can see that a traditional zero voltage vector V_{70} is applied in mode 4. Although the AC current errors can be reduced, however, there is no contribution to the output DC voltage. In fact, one can apply any generalized zero voltage space vectors of class B, C, D or E as well. However for reducing conduction losses, V_{77} is preferred. The procedure can be repeated for the other intervals of Fig. 2.4 to select the voltage space vectors. For reference, Table 2.4 shows the selected voltage space vectors for different intervals of Fig. 2.4 for this control strategy [42]. It is seen that in this new control strategy, the output DC voltage can be boosted during two modes. Hence, this control strategy can achieve higher V_o than that of the previous one boost-mode control strategy [42]. From [42], the equivalent averaged duty cycle of the generalized zero voltage vectors is repeated below for reference,

$$d_z^2 = \begin{cases} Min\{d_k\} + d_{Z0} & \text{for interval } (2),(4) \text{ and } (6) \text{ of Fig. 2.4} \\ 1 - Max\{d_k\} + d_{Z7} & \text{for interval } (1),(3) \text{ and } (5) \text{ of Fig. 2.4} \end{cases}$$

where d_{Z0} and d_{Z7} denote the equivalent averaged duty cycle of V_{07} and V_{70} respectively. From the above rough review, one can see that the high performance converter has only unidirectional power flow control capability. In some applications, it is desired to have regeneration capability, namely with bidirectional power flow capability. Also, the Ćuk capacitor voltage, V_C, may be excessively high rendering the application unattractive.

Finally, as far as the implementation of the converter is concerned, control the equivalent time varying duty ratio ($d_z(t)$) will be much more involved and may also contribute more ripples to the output voltage. In view of the above drawbacks, new control strategies will be proposed in later chapters to overcome the dilemma.

Table 2.3 The one-boost-mode control strategy of [42]

Space Vector / Interval	Nonzero voltage space vectors	Generalized zero voltage space vectors
Interval (1)	V_{52}, V_{43}, V_{61}	V_{70}, V_{77}
Interval (2)	V_{43}, V_{61}, V_{25}	V_{07}, V_{77}
Interval (3)	V_{61}, V_{25}, V_{34}	V_{70}, V_{77}
Interval (4)	V_{25}, V_{34}, V_{16}	V_{07}, V_{77}
Interval (5)	V_{34}, V_{16}, V_{52}	V_{70}, V_{77}
Interval (6)	V_{16}, V_{52}, V_{43}	V_{07}, V_{77}

Table 2.4 The two-boost-mode control strategy of [42]

Space Vector / Interval	Nonzero voltage space vectors	Generalized zero voltage space vectors
Interval (1)	V_{52}, V_{43}, V_{61}	V_{77}
Interval (2)	V_{43}, V_{61}, V_{25}	V_{77}
Interval (3)	V_{61}, V_{25}, V_{34}	V_{77}
Interval (4)	V_{25}, V_{34}, V_{16}	V_{77}
Interval (5)	V_{34}, V_{16}, V_{52}	V_{77}

Interval (6)	V_{16}, V_{52}, V_{43}	V_{77}