New Current and Neutral Point Voltage Control Schemes for a Boost Type Three-level Rectifier

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Abstract- Two space vector control schemes are presented to improve current and neutral point voltage performance for a boost type three-level rectifier. While the exact vector scheme can make the AC line current follow the command current better, the average vector scheme can balance the DC neutral point voltage better. Both methods show much improved line current and neutral point voltage performance. Limitations and trade-offs of each scheme are also discussed in the paper. Simulation results are obtained with the proposed schemes.

I. Introduction

Conventional rectifiers have the disadvantage that the rectifiers draw current from utility with high harmonics, greatly polluting the utility source. Multilevel circuits with current control provide an approach to improve the waveform of the line current. An effective topology was proposed in [1] for a boost type three level rectifier, which draws nearly sinusoidal current from the utility line and also can provide or absorb reactive power from the utility. It is usually difficult to prevent the neutral point voltage from drifting and meanwhile to secure a satisfactory line current waveform. Furthermore, it seems that the switching complexity could affect the practical implementation.

Two space vector control strategies, using average vectors and exact vectors respectively, are proposed in this paper. Based on a boost type rectifier circuit, these two methods show excellent AC line current and DC neutral point voltage performance. The new methods also provide the simplicity in implementation, and promising values in applying to other multilevel circuits.

II. Principle of Current and Neutral Point Voltage Control

A. Current Deviation Control

The three level boost type rectifier circuit proposed in [1] is shown in Fig. 1, and switching vectors are shown in Fig. 2, with 19 distinct vectors representing 27 switching states. It should be noted that only a portion of the vectors are realizable with certain current command. As shown in Fig. 2, when the current vector is within the two dotted lines, the realizable vectors are limited to the hexagon region composed of {0 1 2 3 4 5} [1].

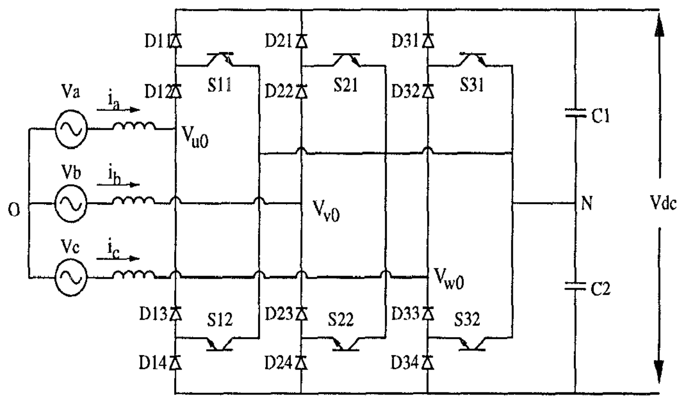

Figure 1: Three Level Rectifier Configuration

Defining $\Delta I = I^* - I$ as current deviation vector, the following relationship holds[1][4]:

$$L\frac{d(\Delta I)}{dt} = V_r - E \tag{1}$$

where E is a voltage vector defined by

$$E = V_s - (L\frac{dI^*}{dt} + RI^*) \tag{2}$$

and

$$V_s = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$ is the AC line voltage vector;

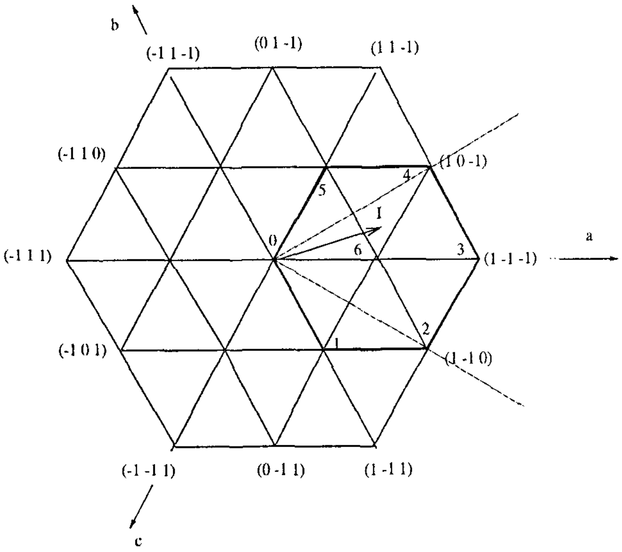

Figure 2: Switching Modes

$I = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$ is the AC line actual current vector;

$I^* = \begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix}$ is the AC line command current vector;

$V_r = \begin{bmatrix} V_{u0} \\ V_{v0} \\ V_{w0} \end{bmatrix}$ is the terminal voltage vector;

R, L are line resistance and inductance respectively.

With the current vector in certain sector, the realizable switching modes represented by the seven vectors constitute a permissible vector assembly element, a hexagon (Fig. 2). For current vectors residing in the 6 sectors, we have 6 permissible vector assembly elements or hexagons. The vector E has been specified with certain line and load conditions as in (2). As the parameters of the circuit are all known, we want to establish such a vector V_r to the circuit as to eliminate the current error. For R is usually small and can be neglected, the discrete form of (1) can be written as

$$V_r(k+1) = E(k) + L\left(\frac{\Delta I(k+1)}{\Delta t} - \frac{\Delta I(k)}{\Delta t}\right) \quad (3)$$

It can be expected that, if the circuit is fully compensated, then $\Delta I(k+1)$ is expected to be zero. Therefore (3) becomes

$$V_r(k+1) = E(k) - L\frac{\Delta I(k)}{\Delta t} \quad (4)$$

Thus with the present current error ΔI and designated voltage vector E we can command a necessary terminal vector V_r for the next step to compensate the current error. The terminal voltage vector is to be realized by the available switching modes in Fig. 2.

B. *Neutral Point Voltage Control*

In the previous discussion only the fast response to the current deviation is considered. However, taking the neutral point voltage into account, one may find that such scheme may cause the neutral point voltage to drift.

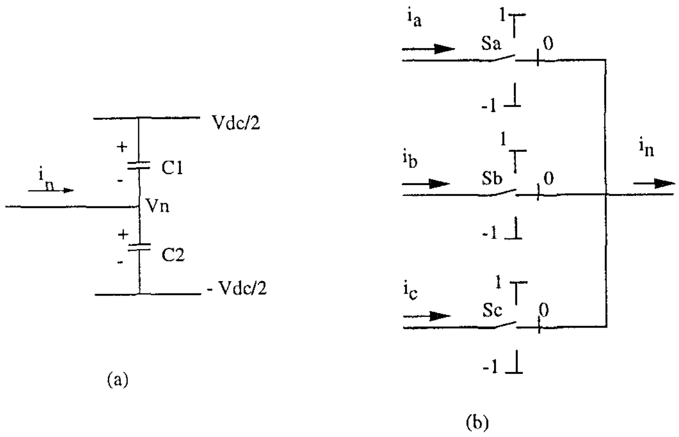

Figure 3: Neutral Point Voltage Drifting

Fig. 3(a) shows the capacitor clamped neutral point voltage. With the neutral point current i_n, the neutral point voltage V_n will be constrained by

$$C1\frac{d(V_{dc}/2 - V_n)}{dt} + i_n = C2\frac{d(V_n - (-V_{dc}/2))}{dt} \quad (5)$$

Assuming that V_{dc} keeps constant and $C1 = C2 = C$, we have

$$V_n = \frac{1}{2C}\int i_n dt \quad (6)$$

From (6) it can be seen that to control the neutral point voltage, we must control the neutral current i_n. When V_n is low, we should choose such a switching state that could provide positive i_n to boost V_n up, as well as to compensate the current deviation, and vice versa.

Define the switching state

$$\{S\} = \{S_a, S_b, S_c\}$$

where each of S_a, S_b, S_c could be 1, 0, or -1 as shown in Fig. 3(b). For example, if S_a is switched to the positive bus, S_b switched to the neutral point, and S_c switched to the negative bus, then $S = \{1, 0, -1\}$. For each state only when $S_i = 0$ (i=a,b,c) can the phase current influence the neutral point voltage. The neutral point current can be expressed as

$$i_n = (1 - |S_a|)i_a + (1 - |S_b|)i_b + (1 - |S_c|)i_c \quad (7)$$

There are basically two kinds of nonzero vectors, that is, outer vectors (as {2,3,4} in the hexagon {0 1 2 3 4 5} in Fig. 2), and inner vectors (as {1,5,6} in the hexagon { 0 1 2 3 4 5} in Fig. 2). To control the neutral point voltage, the inner nonzero vectors of each hexagon need to be employed. Notice that when the outer vectors are chosen, we can not control the neutral point voltage but the current deviation, while the inner nonzero vectors provide a way since all of them have switching alternatives. This can be explained as follows. The six inner vectors, represented by twelve switching states, are

{1 0 0, 0 -1 -1}, {1 1 0, 0 0 -1},{0 1 0, -1 0 -1}, {0 1 1,-1 0 0},{0 0 1, -1 -1 0},{0 -1 0, 1 0 1}

For each inner vector, the two states are complement to each other. For example, if $S1 = \{1\ 0\ 0\}$, the other must be $S1' = S1 - 1 = \{0\ -1\ -1\}$. As the three phase currents $i_a + i_b + i_c = 0$, using S1 or $S1'$ in (7) will always gives opposite values in terms of i_n, that is,

$$i_n(\text{using } S1) = -i_n(\text{using } S1')$$

Therefore, for the same vector, we can choose different switching state to either boost or reduce the neutral point voltage. Notice that this is only applicable to the inner vectors, and, for a specific permissible hexagon corresponding to a certain command current vector, of the three inner nonzero vectors, only the one residing in the center of the hexagon has alternative states to contribute to the neutral point voltage control, as {6} for the hexagon { 0 1 2 3 4 5 }. If the outer vectors or the other two inner vectors are chosen, as each of them only corresponds to one switching state, we do not have control over the neutral point voltage.

III. Vector Choosing Schemes

A. Exact Vector Scheme

The vector choosing scheme is illustrated in Fig. 4 and described as follows. Fig. 4(a) shows the locations of the current and voltage vectors in a permissible vector hexagon, and Fig. 4(b) shows the specific triangle composed of vectors $V1$, $V2$ and $V3$ which covers the required terminal vector V_r whose vertex is at P.

During one switching cycle Δt, the time durations for $V1, V2$ and $V3$ are:

$$t_1 = cb\sin\gamma, t_2 = cv\sin\varphi, t_3 = cv\sin\theta \qquad (8)$$

where

$$c = \frac{\Delta t}{v\sin\theta + v\sin\varphi + b\sin\gamma} \qquad (9)$$

and v, θ, φ and γ are as specified in Fig. 4(b).

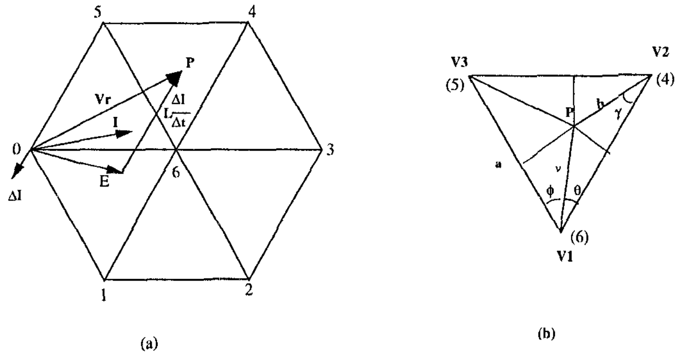

Figure 4: Required Vector and Time Duration

The vectors are chosen as follows. When the vector V_r resides in the corresponding current hexagon, using the calculations shown above, we can obtain the time duration for each vector in the switching cycle. Thus for the required vector V_r whose vertex is at P, there are 3 vectors corresponding to 3 switching states working alternatively. As an example shown in Fig. 4(b), the active operation durations for $V1, V2$ and $V3$ are t_1, t_2, and t_3 respectively in one switching cycle.

Since with each triangle which covers P, we always have one vector that is an inner vector capable of neutral point voltage control, as $V1$ in Fig. 4. Thus the neutral point voltage can be controlled by properly choosing the switching state for $V1$ (either { 1 0 0 } or { 0 -1 -1 }) during each switching cycle. For example, as shown in Fig. 4, if V_n is found low, then we should use { 1 0 0 } to obtain a positive i_n, and vice versa. Hence, we can expect improved neutral point voltage performance as well as the current tracking performance, since we can secure a certain time (as t_1) to control the neutral point voltage in each switching cycle.

If the vector V_r resides out of the corresponding hexagon related to a current I, simply the boundary vectors are chosen.

B. Average Vector Scheme

The above scheme has good current and neutral point voltage performance. However the algorithm involves heavy computations including multiplication, division and *sin* operations. To further simplify the implementation, the average vector method is presented. Again using the example of Fig. 4, when the required vector V_r (whose vertex is at P in Fig. 4(b)) resides in the triangle defined by $V1, V2, V3$, instead of using the exact time t_1, t_2, and t_3, we can just let $V1, V2$ and $V3$ work each for $\Delta t/3$.

With such a simplified scheme, we can expect a better neutral point voltage control since now we have guaranteed a time duration $\Delta t/3$ for neutral point voltage control in each switching cycle while in the exact vector scheme the duration for neutral point voltage control is rather random. Meanwhile the current tracking performance would be reduced since the resultant terminal voltage cannot fully compensate the current deviation.

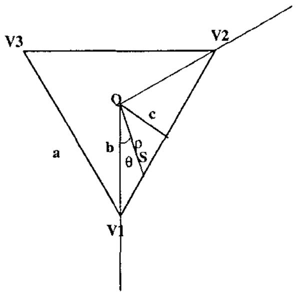

Figure 5: Error Current Estimation

The current error can be estimated as follows. As we choose the 3 vectors equally, equivalently we are using a vector residing at the center of the triangle, Q, as in Fig. 5. Assuming that the required exact vector is at S and statistically S is uniformly distributed in the triangle, we have the error vector V_{er} as:

$$V_{er} = \overline{QS} \tag{10}$$

The expected value of V_{er} can be expressed as:

$$E\{V_{er}\} = \frac{1}{\Delta}\int\int V_{er} ds \tag{11}$$

The integral can be obtained as

$$\begin{aligned} E\{V_{er}\} &= \frac{1}{\Delta}\int\int V_{er} ds & (12)\\ &= \frac{1}{\Delta}\int_0^{2\pi}\int_0^{\frac{b}{2\cos(\frac{\pi}{3}-\theta)}} \rho^2 d\rho d\psi & (13)\\ &= \frac{b^3}{8\Delta}\int_0^{\frac{2\pi}{3}} \frac{1}{\cos^3(\frac{\pi}{3}-\psi)} d\psi & (14)\\ &= 0.275a & (15) \end{aligned}$$

where a and b are shown in Fig. 4(b) and Δ is the trianglar area.

We can reasonably regard $E\{V_{er}\}$ as the statistic error vector,

$$V_{er} = L\frac{\Delta I}{\Delta t} \tag{16}$$

hence statistically the current error would be

$$\Delta I = 0.275a\frac{1}{f_z L} \tag{17}$$

where f_z is the switching frequency. Since $a = V_{dc}/3$, the statistic current error can be expressed as

$$\Delta I = 0.092V_{dc}\frac{1}{f_z L} \tag{18}$$

As an example, if the DC bus voltage V_{dc} is 400 V, L is 3.5 mH, and f_z is 7.2 kHz, the current error would be 1.4 A.

The block diagram of the proposed schemes is shown in Fig. 6.

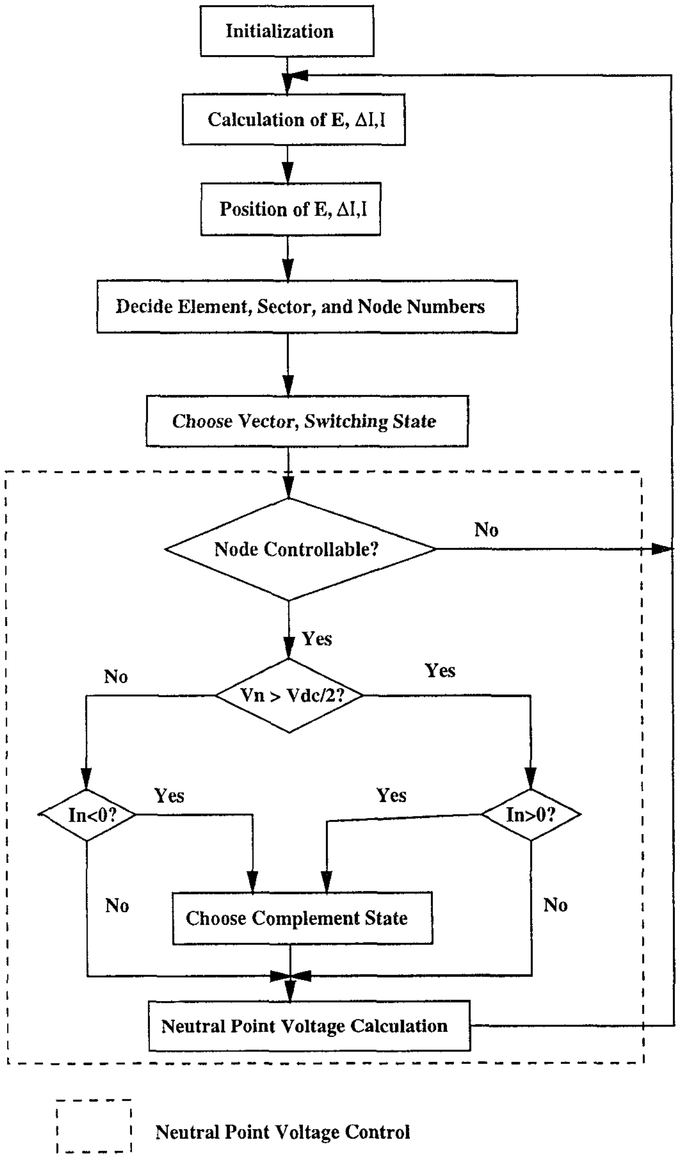

Figure 6: Block Diagram of Current and Neutral Point Voltage Control

IV. Simulation Results

A simulation program has been developed to further evaluate the two proposed space vector control algorithms. The following parameters are used:

- AC source voltage: 115V, 60Hz;

- DC bus voltage: 400V;
- DC capacitors: $2\times1000\mu$F;
- Input Inductors: 3×3.5mH;
- Switching Frequency: 7.2 kHz.

A. *Phase Current in Phase with Back EMF*

When the reference current is in phase with the back EMF voltage, the waveforms of the AC phase current and neutral point voltage are shown in Fig. 7, for the cases of no neutral point voltage control, average vector scheme, and exact vector scheme respectively.

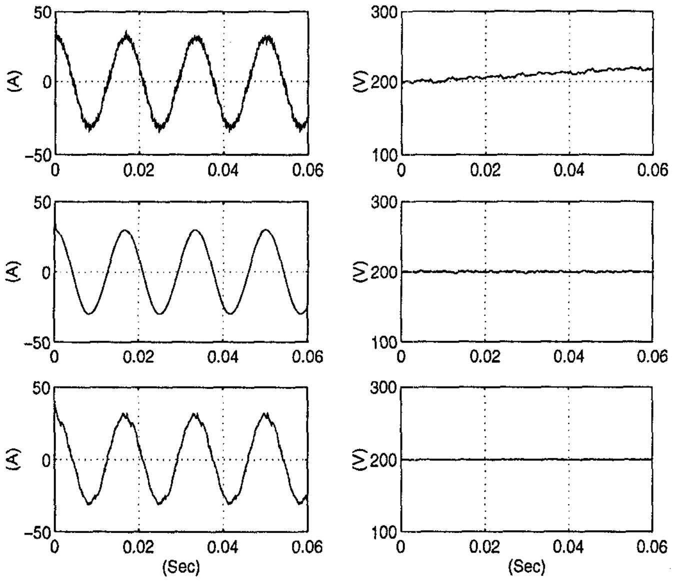

Figure 7: Phase Current and Neutral Point Voltage, In Phase, V_{dc}=400V, f_z=7.2kHz, I_m=30A, Upper: Without Neutral Point Voltage Control; Middle: Exact Vector Scheme; Lower: Average Vector Scheme

As was expected, the average vector scheme shows the best neutral point voltage control performance and the exact vector scheme shows the best current regulation performance. In both cases (average and exact vector) the combined performance of current with neutral point voltage are much improved.

B. *Phase Current Lagging to Back EMF*

Fig. 8 shows the phase current and neutral point voltage when the current is lagging to the Back EMF voltage by $\pi/6$. It is seen that the current waveform and neutral point voltage are improved, and, similar to the results in A, the exact vector scheme has better current waveform while the average vector scheme has more balanced neutral point voltage.

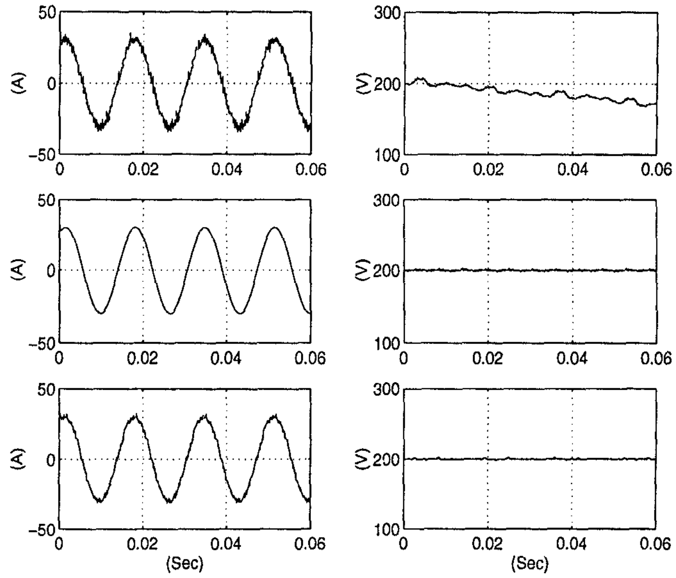

Figure 8: Phase Current and Neutral Point Voltage, Lagging, V_{dc}=400V, f_z=7.2kHz, I_m=30A, Upper: Without Neutral Point Voltage Control; Middle: Exact Vector Scheme; Lower: Average Vector Scheme

C. *Phase Current Leading to Voltage*

Fig. 8 shows the phase current and neutral point voltage when the current is leading to the voltage by $\pi/6$. We can see that the current waveforms in this situation are not as good as in the previous situations.

It needs to be noted that in the leading case, one should pay careful attention to the effective operation range of the current and neutral point voltage control. The control region is affected by the load condition as well as the voltage levels, and in the leading case this influence is more significant. With a large load current, it is possible that the required terminal voltage exceeds or is very close to the boundary of the outer vectors (see Fig. 2), hence the current regulation becomes weak and the neutral point voltage control is not sufficient.

V. Conclusions

Two new schemes of current and neutral point voltage control for a boost type three-level rectifier have been proposed. The current deviation control strategy can make the current follow the sinusoidal command current and the neutral point voltage control can balance the neutral point voltage. The employment of the multilevel voltages also alleviate the voltage ratings of the switches.

1. Simulation shows that the new schemes can secure a balanced neutral point voltage as well as very good current waveforms, hence can make the circuit

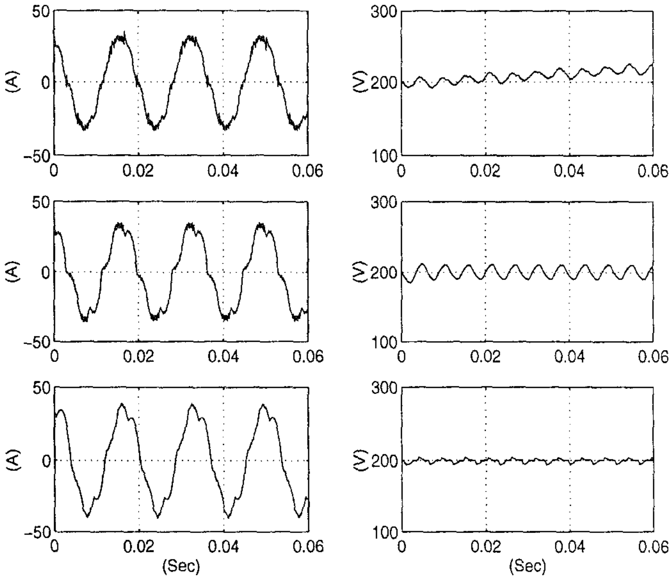

Figure 9: Phase Current and Neutral Point Voltage, Leading, V_{dc}=400V, f_z=7.2kHz, I_m=30A, Upper: Without Neutral Point Voltage Control; Middle: Exact Vector Scheme; Lower: Average Vector Scheme

work properly while solving the pollution problem to the utility source.

2. Attentions need to be paid in choosing different control strategies. The average vector scheme is recommended to obtain a more balanced neutral point voltage, while the exact vector scheme is most suitable to obtain a nearly perfect current waveform.

3. In implementation both schemes are simple and direct. The average scheme is especially convenient for implementation.

It needs to be noted that effective control regions are also affected by the load conditions. When the command current is large, especially in leading case, it is possible that the current deviation cannot be compensated sufficiently. One should be careful to properly choose the voltage and current ratings, especially in leading case.

The circuit and the schemes discussed in this paper have significant practical value and will be implemented using DSP. The proposed schemes are also applicable in other multilevel circuits. With the neutral point voltage control, the neutral point drifting problem in multilevel circuits can be solved.

VI. References

[1] Yifan Zhao, Yue Li, and Thomas A. Lipo, "Force commutated three level boost type rectifier", *IEEE Trans. on Ind. Applicat.*, vol. 31, no. 1, pp. 155-161, Jan./Feb. 1995.

[2] A. Nabae, I. Takahashi, and H. Akagi, "A new neutral-point-clamped PWM inverter", *IEEE Trans. on Ind. Applicat.*, vol. IA-17, no.5, pp. 518-523, Sept./Oct. 1981

[3] Jie Zhang, "High Performance Control of a Three-level IGBT Inverter Fed AC Drive", *Conf. Rec. of IEEE Ind. Applicat. Soc. Ann. Meeting,*, Orlando, FL., Oct. 8-12, 1995, vol. 1, pp. 22-28.

[4] A. Nabae, S. Ogasawara, and H. Akagi, "A novel control scheme for current-controlled PWM inverters," *IEEE Trans. on Ind. Applicat.*, vol. 22, no. 4, pp. 697-701, July/Aug. 1981.