The Application of 3D SVM Algorithm into Metro Auxiliary Converter Over Conventional 2D Scheme

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Abstract. This paper proposes the application of 3D SVPWM modulation scheme into metro auxiliary converter for the suppression of unbalanced voltage output with unbalanced load current. It is analysed and introduced in the paper that the novel 3D approach is revised 2D approach in essence, with the extension along axis γ. The comparison between 3D and 2D approach is given, concluding that unlike the capability of 2D approach in the control of positive and negative sequence, the 3D approach is capable of controlling zero sequence component, making itself notable in unbalanced output control. What’s more, the 3D approach proposed is different from its conventional counterpart in modulation wave and in DC voltage utilization ration. All the theories are finally proven with simulated and experimental results.

1. Introduction
It is for granted that the on-board auxiliary converter of metro vehicles supply stable and high-quality AC220 power to the outside.

However, conventional 3-phase-3-line converter is incapable of generating such single-phase power with the absence of neutral point. A mostly adopted approach to solve such problem is the structure of splited DC capacitors, generating a 3-phase-4-line converter [1], as is shown in Figure 1.

In Figure 1, a common modulation scheme of trigger pulses is the well-known Space Vector Pulse Width Modulation (SVPWM), which is noted for its clear physical concept and pleasing digital realization. However, with SVPWM, zero-sequence current on the AC side is inevitable, which explains the unbalanced 3-phase voltage output under unbalanced 3-phase load current [2]. What’s more, the existence of 3rd-ordered harmonic content is also a bi-product. 3rd-ordered harmonic does not act significantly under balanced AC load because there is no path for the 3rd-ordered AC currents through AC load, but it generates loop current through the AC and DC filtering capacitors, resulting in considerable heat dissipation on IGBTs and capacitors. For the elimination of 3rd-ordered harmonic
content, this paper proposes the application of 3d-SVPWM [4-11] scheme, which is different from the conventional 2D-SVPWM, and enjoys the absence of 3rd-ordered harmonic output.

2. 3D-SVPWM Modulation Scheme

In Figure 1, the neutral points of DC side and AC side are connected directly, forming a neutral line which is the path for unbalanced current and 3rd-ordered harmonic current. Such structure is often seen in metro system. In the case of 3-phase-3-line, 2D-SVPWM is mostly chosen, and in that of 3-phase-4-line, 3D-SVPWM is better. Both 2D and 3D approach base themselves on the combination of 8 different switching states of switching devices, such as IGBT. In 3D, the 8 states are transformed into a reference system with Clark transformation, forming 8 voltage vectors, as is shown in Figure 2 and Table 1.

| Switch vector \( \vec{v} \) | \( U_a/U_{dc} \) | \( U_b/U_{dc} \) | \( U_c/U_{dc} \) | \( U_{\alpha}/U_{dc} \) | \( U_{\beta}/U_{dc} \) | \( U_{\gamma}/U_{dc} \) |
|----------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Q4Q6Q2 \( \vec{v}_0 \) | -1/2 | -1/2 | -1/2 | 0 | 0 | -1/2 |
| Q1Q6Q2 \( \vec{v}_1 \) | 1/2 | -1/2 | -1/2 | 2/3 | 0 | -1/6 |
| Q1Q3Q2 \( \vec{v}_2 \) | 1/2 | 1/2 | -1/2 | 1/3 | -1/\( \sqrt{3} \) | 1/6 |
| Q4Q3Q2 \( \vec{v}_3 \) | -1/2 | 1/2 | -1/2 | -1/3 | -1/\( \sqrt{3} \) | -1/6 |
| Q4Q3Q5 \( \vec{v}_4 \) | -1/2 | 1/2 | 1/2 | -2/3 | 0 | 1/6 |
| Q4Q6Q5 \( \vec{v}_5 \) | -1/2 | -1/2 | 1/2 | -1/3 | 1/\( \sqrt{3} \) | -1/6 |
| Q1Q6Q5 \( \vec{v}_6 \) | 1/2 | -1/2 | 1/2 | 1/3 | 1/\( \sqrt{3} \) | 1/6 |
| Q1Q3Q5 \( \vec{v}_7 \) | 1/2 | 1/2 | 1/2 | 0 | 0 | 1/2 |

Figure 2. 3-D space vector

2.1 The determination of boundary conditions

In Figure 2, the hexahedron formed by 8 space vectors is the operating region of voltage vector \( \vec{v} \). Such hexahedron could be divided into six different areas, those are trihedrons P1 through P6, as are shown in Figure 3. Taking P1 as an example, it is formed by \( \vec{v}_0 \vec{v}_1 \vec{v}_2 \vec{v}_3 \), and could be further divided into two parts by the plane defined with \( \vec{v}_1 \vec{v}_2 \). Therefore, the hexahedron is divided into 12 parts in all, and a voltage vector is located with the conditions as follows: A subsubsection. The paragraph text follows on from the subsubsection heading but should not be in italic.

\[
\frac{1}{3} V_0 = 0
\]
\[ V_a - \sqrt{3}V_\beta + 4V_\gamma = 0 \]
\[ \frac{\sqrt{3}}{6} V_a - \frac{1}{6} V_\beta = 0 \]
\[ -2V_a + 2V_\gamma = 0 \]
\[ \frac{\sqrt{3}}{6} V_a + \frac{1}{6} V_\beta = 0 \]
\[ V_a + \sqrt{3}V_\beta + 4V_\gamma = 0 \]

2.2 The determination of switching intervals
With the knowledge of the location of \( \vec{V} \), the time durations of the basic vectors are determined. For example, in the upper part of area P1, the vector is reconstructed by \( \vec{V}_1 \vec{V}_2 \vec{V}_0 \vec{V}_7 \) :

\[ \vec{V}T_i = \vec{V}_1 T_1 + \vec{V}_2 T_2 + \vec{V}_c T_c \]  \( \text{(7)} \)

In equation (7), \( \vec{V}_c \) is a vector in the direction of axis y, which is formed by \( \vec{V}_0 \vec{V}_7 \). \( T_s \) is half the switching period, and \( T_1, T_2 \) and \( T_c \) are the time duration of \( \vec{V}_1, \vec{V}_2 \) and \( \vec{V}_c \), respectively.

From equation (7), it gives:

\[
\begin{bmatrix}
T_1 \\
T_2 \\
T_c
\end{bmatrix} = T_s \begin{bmatrix}
\frac{2\sqrt{3}}{3} & -\sqrt{3}/2 & 0 \\
0 & \sqrt{3} & 0 \\
\frac{1}{2} & -\sqrt{3}/2 & 2
\end{bmatrix}^{-1}
\begin{bmatrix}
V_a \\
V_\beta \\
V_\gamma
\end{bmatrix}
\]  \( \text{(8)} \)
\[ T_s = \left( T_p - T_1 - T_2 + T_c \right) / 2 \]  \hspace{1cm} (9) \\
\[ T_c = T_p - T_1 - T_2 + T_s \]  \hspace{1cm} (10)

In this paper, 7-segment scheme of SVPWM is recommended, in the consideration of less switching actions during the transition of different basic vectors, as is shown in Table 2.

Table 2. Computing matrix and vector sequence

| Area | Upper transformation metrix | Lower transformation metrix | Vector sequence |
|------|-----------------------------|-----------------------------|-----------------|
| P1   | \[ \begin{bmatrix} \frac{1}{2} \sqrt{2} & 0 \\ \frac{1}{2} \sqrt{2} & 0 \\ \frac{1}{2} \sqrt{2} & 2 \end{bmatrix} \] | \[ \begin{bmatrix} \frac{1}{2} \sqrt{2} & 0 \\ \frac{1}{2} \sqrt{2} & 0 \\ -\frac{1}{2} \sqrt{2} & 2 \end{bmatrix} \] | V0V2V1V0V6V6V0V6 |
| P2   | \[ \begin{bmatrix} 0 & \frac{1}{2} \sqrt{2} & 0 \\ \frac{1}{2} \sqrt{2} & 0 & 0 \\ -1 & 0 & 2 \end{bmatrix} \] | \[ \begin{bmatrix} 0 & \frac{1}{2} \sqrt{2} & 0 \\ \frac{1}{2} \sqrt{2} & 0 & 0 \\ 1 & 0 & -2 \end{bmatrix} \] | V0V2V1V0V6V6V0V6 |
| P3   | \[ \begin{bmatrix} \frac{1}{2} \sqrt{2} & 0 \\ \frac{1}{2} \sqrt{2} & 0 \\ \frac{1}{2} \sqrt{2} & 2 \end{bmatrix} \] | \[ \begin{bmatrix} \frac{1}{2} \sqrt{2} & 0 \\ \frac{1}{2} \sqrt{2} & 0 \\ \frac{1}{2} \sqrt{2} & -2 \end{bmatrix} \] | V0V2V1V0V6V6V0V6 |
| P4   | \[ \begin{bmatrix} 0 & \frac{1}{2} \sqrt{2} & 0 \\ \frac{1}{2} \sqrt{2} & 0 & 0 \\ -\frac{1}{2} \sqrt{2} & 2 \end{bmatrix} \] | \[ \begin{bmatrix} 0 & \frac{1}{2} \sqrt{2} & 0 \\ \frac{1}{2} \sqrt{2} & 0 & 0 \\ -\frac{1}{2} \sqrt{2} & -2 \end{bmatrix} \] | V0V2V1V0V6V6V0V6 |
| P5   | \[ \begin{bmatrix} \frac{1}{2} \sqrt{2} & 0 \\ \frac{1}{2} \sqrt{2} & 0 \\ -1 & 0 & 2 \end{bmatrix} \] | \[ \begin{bmatrix} \frac{1}{2} \sqrt{2} & 0 \\ \frac{1}{2} \sqrt{2} & 0 \\ 1 & 0 & -2 \end{bmatrix} \] | V0V2V1V0V6V6V0V6 |
| P6   | \[ \begin{bmatrix} \frac{1}{2} \sqrt{2} & 0 \\ \frac{1}{2} \sqrt{2} & 0 \\ 0 & \frac{1}{2} \sqrt{2} & 2 \end{bmatrix} \] | \[ \begin{bmatrix} \frac{1}{2} \sqrt{2} & 0 \\ \frac{1}{2} \sqrt{2} & 0 \\ 0 & \frac{1}{2} \sqrt{2} & -2 \end{bmatrix} \] | V0V2V1V0V6V6V0V6 |

3. The comparison between 2D and 3D schemes

It should be noted that the 3D approach is the extension of 2D in essence, with the addition of vectors in the direction of axis γ for the elimination of zero-sequence content. What’s more the difference between them also exists in DC voltage utilization.

3.1 The comparison of modulation waves

All of the frequently used modulation wave for PWM could be given as:

\[ u_i(t) = u'_i(t) + e(t) \]  \hspace{1cm} (11)

Where \( u'_i(t) \) is the fundamental wave, and \( e(t) \) is harmonic component.

The phase voltage outputs of converter could be given as:

\[ U_{a}(t) = \frac{U_{dc}}{2} \left[ m \cos \omega t + e(t) \right] \]
\[ U_{b}(t) = \frac{U_{dc}}{2} \left[ m \cos \left( \omega t + \frac{2}{3} \pi \right) + e(t) \right] \]  \hspace{1cm} (12)
\[ U_{c}(t) = \frac{U_{dc}}{2} \left[ m \cos \left( \omega t + \frac{4}{3} \pi \right) + e(t) \right] \]

Where \( m \) is modulation ratio.

In reference 11, \( e(t) \) values.
\[-1-U^*_\min \leq e(t) \leq 1-U^*_\max \]  

(13)

If \( e(t) = k(t)(-1-U^*_\min ) + (1-k(t))(1-U^*_\max ) \), then in the 1st sector of 7-segment modulation, it gives

\[
U_a(t) = \frac{U_{dc}}{2} \frac{T_3 + T_1 + T_4 - T_0}{T_s} \\
U_b(t) = \frac{U_{dc}}{2} \frac{T_3 + T_1 - T_0 - T_4}{T_s} \\
U_c(t) = \frac{U_{dc}}{2} \frac{T_3 - T_0 - T_1 - T_2}{T_s} 
\]

(14)

With \( e(t) = [U_a(t) + U_b(t) + U_c(t)]/3 \), it gives

\[
e(t) = -\frac{T_0}{T_s} - \frac{T_2}{3T_s} + \frac{T_1}{3T_s} + \frac{T_4}{T_s}
\]

(15)

In the 1st sector, \( u^*_\min \) is \( u^*_c(t) \), and \( u^*_\max \) is \( u^*_a(t) \), therefore, with equation(14) and equation(15) it gives

\[ k(t) = 0.5 \]

(16)

Based on the analysis above, the waveform of \( e(t) \) is illustrated in Figure 4.

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Based on the analysis above, the waveform of \( e(t) \) is illustrated in Figure 4.

![Figure 4. SVPWM modulation wave](image)

In Figure 4, it is obvious that the 3D approach shows no 3rd-ordered component, due to

\[ e(t) = U_\gamma = [U_a(t) + U_b(t) + U_c(t)]/3 = 0 \]

(17)

3.2 The comparison of voltage utilization ratio

Being fully modulated, conventional 2D approach generates phase voltage of \( \sqrt{3}U_{dc}/3 \), and line voltage of \( U_{dc} \) [3]. In the case of 3D approach, a maximum voltage vector is derived on the inscribed sphere of the hexahedron, therefore, the maximum amplitude of phase voltage is \( 0.5U_{dc} \), with that of line voltage of \( \sqrt{3}U_{dc}/2 \). This is an inevitable shortcoming of the 3D approach.
4. Simulated results
A model for simulation is built with Simulink/S-Function, and the modulation scheme proposed is carried out with the control strategy in ref.12. In the model, the voltage input is DC700V, and the filtering inductor is 1mH, with filtering capacitor of 50uF. The resistance load of Phase A and B is 29ohm, and Phase C is load-free. The simulated result with unbalanced load surge is shown in Figure 6.

In Figure 6, the voltage output with 3D approach is pure sinusoidal, without 3rd-ordered harmonic component, due to the capability of respective control positive, negative and zero sequence vector. Under unbalanced load current, the phase output voltage of the converter shows no difference.

5. Experimental results
An equipment prototype for experiment is also built for validation of the effectiveness of the scheme proposed, with the same parameters and control strategy as in the simulation.
Figure 7. The experimental waveform of sudden unbalanced load

In Figure 7, the waveforms under unbalanced load surge are recorded by a virtual oscilloscope [13] (Figure 7 (a)) and actual oscilloscope (Figure 7 (a)), respectively. Figure 7 shows similar result to Figure 6, of the capability in inhibiting unbalanced voltage output under unbalanced load current.

6. Conclusions

After being extended along axis γ, the novel 3D SVPWM modulation scheme is capable of controlling zero-sequence component, making it enjoy more advantages over the conventional 2D scheme, especially in the application of 3-line-4-phase converters. In this paper, the realization of 3D approach is introduced thoroughly, together with the comparison between 3D and 2D schemes. In the last part, the simulated and experimental results show the capability of the scheme proposed, in the aspects of zero-sequence elimination and unbalanced voltage output inhibition.

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