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RESEARCH ARTICLE

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Study on the SVPWM algorithm of *N*-level inverter in the context of non-orthogonal coordinates

Abstract In this paper, the authors propose a new space vector pulse width modulation (SVPWM) algorithm based on non-orthogonal coordinates for *N*-level inverters. First, it is pointed out that classical $\alpha\beta$ coordinates-based SVPWM has many shortcomings because of improper coordinate choice. Then, a non-orthogonal coordinates-based SVPWM is proposed to solve these problems. The proposed algorithm can easily identify which sector the reference space vector falls in and conduct simple operations to find the duty cycle of each vector. Finally, it is verified that the proposed SVPWM is actually a pulse–width modulation (PWM) technology based on line voltages.

Keywords Power electronics, *N*-Level, SVPWM, *KL* coordinates

1 Introduction

The modulation method is a key technology in the research of *N*-level inverters. A great deal of work has been done to find a better modulation algorithm and all kinds of algorithms have been proposed before [1-2], but these algorithms cannot solve the modulation problems well. For engineering applications, sinusoidal pulse-width modulation (SPWM) is the most popular modulation algorithm. It needs fewer calculations and can be implemented easily, but its DC voltage utilization ratio and inverter transmission capability are low. Compared with SPWM, SVPWM has the advantages of high DC voltage utilization ratio, low ripples and more forms of output voltages. However, shortcomings of its complicated calculations and the difficulty of real-time control limits its application when the inverter level increases [3].

Many advanced SVPWM algorithms have been proposed in recent years. The algorithm presented in Ref. [4] does not need space vector synthesis, which chooses a vector whose distance to the reference vector is shortest. This algorithm can only be used when the number of inverter levels is large. Otherwise, if the error between the chosen vector and the reference vector is larger, it will produce more ripples. The method in Ref. [5] divides the vector diagram of multi-level inverter into several three-level vector diagrams, using phase shift to reduce ripples and simplify control. However, it sacrifices modulation index and the calculation is still complicated. The algorithm proposed in Ref. [6] can only be used in two-level inverters, which avoids ordinary extracting roots and trigonometric function computations. This algorithm cannot be applied to multi-level inverters. Other algorithms proposed previously also cannot solve the modulation problems [7].

Classical space vector theory is based on $\alpha\beta$ coordinates. This is the ultimate cause of complicated calculations. In this paper, new coordinates (called *KL* coordinates) are proposed, based on which, a new simplified SVPWM algorithm is produced. It is the universal solution of the *N*-level inverter, which can be easily implemented with simple calculations.

2 Basic theory of SVPWM

According to space vector theory, the vector $\boldsymbol{U_r}$ corresponding to the three phase voltages u_a, u_b, u_c can be expressed as:

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$$\mathrm{U}_{\boldsymbol{r}} = \sqrt{\frac{2}{3}}\left(u_a \boldsymbol{i}_1 + u_b\left(\frac{1}{2}\boldsymbol{i}_1 + \frac{\sqrt{3}}{2}\boldsymbol{j}_1\right) + u_c\left(-\frac{1}{2}\boldsymbol{i}_1 + \frac{\sqrt{3}}{2}\boldsymbol{j}_1\right)\right)$$
$$= \sqrt{\frac{2}{3}}\left(\left(u_a - \frac{u_b + u_c}{2}\right)\boldsymbol{i}_1 + \frac{\sqrt{3}(u_b - u_c)}{2}\boldsymbol{j}_1\right) \quad (1)$$

where $\boldsymbol{i}_1$ and $\boldsymbol{j}_1$ are the unit vectors of α -axis and β -axis. If DC side voltage is kept constant (U_d) and is distributed averagely, every arm can output N levels, which can be expressed as δ_x $x \in \{a,b,c\}$, $\delta_x = n$ stands for the output level of arm nU_d . Each output state of N-level inverter can be expressed as: $\delta = [\delta_a, \delta_b, \delta_c]$. The space vector corresponding to $\boldsymbol{V}$ is:

$$\mathrm{V} = \sqrt{\frac{2}{3}}U_d\left(\left(\delta_a - \frac{\delta_b + \delta_c}{2}\right)\boldsymbol{i}_1 + \frac{\sqrt{3}(\delta_b - \delta_c)}{2}\boldsymbol{j}_1\right) \quad (2)$$

The space vectors of a five-level inverter are shown in Fig. 1. We can see that oblique lines $\cdots A_{-1}A_{-1}^*, A_{-2}A_{-2}^*$, $A_1A_1^*, A_2A_2^* \cdots$, $\cdots B_{-1}B_{-1}^*, B_{-2}B_{-2}^*, B_1B_1^*, B_2B_2^* \cdots$, $\cdots A_2B_{-2}, A_3B_{-3}, A_4B_{-4}, A_{-3}^*B_3^*, A_{-2}^*B_2^* \cdots$ divide the whole area into $6(N-1)^2 = 96$ same triangles, which are called characteristic triangles. All vectors corresponding to every output state of inverter locate on the tops of these triangles. If space vector $\boldsymbol{U_r}$ falls in the triangle whose tops are $\boldsymbol{V_x}$, $\boldsymbol{V_y}$ and $\boldsymbol{V_z}$, it can be synthesized by these three vectors, whose duty cycles are t_1, t_2, t_3, we can get:

$$\begin{cases} t_1 \boldsymbol{V}_x + t_2 \boldsymbol{V}_y + t_3 \boldsymbol{V}_z = T\boldsymbol{U}_r \\ t_1 + t_2 + t_3 = T \end{cases} \quad (3)$$

The method described above is the basic theory of SVPWM. Obviously, this algorithm is very complicated. Two main problems are as follows:

1) It is hard to determine the characteristic triangle that $\boldsymbol{U_r}$ falls in and to determine $\boldsymbol{V_x}, \boldsymbol{V_y}, \boldsymbol{V_z}$.

2) To achieve the solutions, it needs a lot of trigonometric function operations making it difficult to solve Eq. (3).

3 Coordinates and transformation

Normal SVPWM is based on $\alpha\beta$ coordinates (Fig. 1), where the α -axis coincides with the A-phase axis direction. Rotating the A-axis 90 degrees counter-clockwise, we get the β -axis. This kind of coordinates is the basic cause of complicated calculations. So, we set up KL coordinates to avoid this problem, where the L-axis is along the A-phase direction and K-axis is along the B-phase direction (Fig. 2).

Assuming $\boldsymbol{i}_2$ and $\boldsymbol{j}_2$ are the unit vectors along K and L axis directions, their relation to $\boldsymbol{i}_1$ and $\boldsymbol{j}_1$ is:

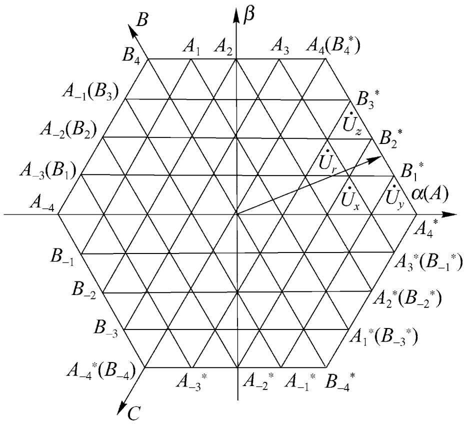

Fig. 1 Space vectors of five-level inverter

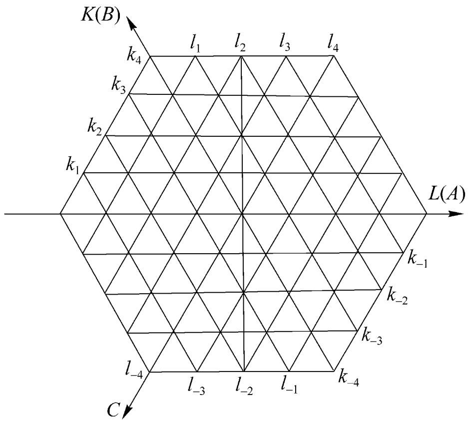

Fig. 2 Space vectors of inverter in the context of KL coordinates

$$\begin{cases} \boldsymbol{i}_1 = \boldsymbol{i}_2 \\ \boldsymbol{j}_1 = \frac{1}{\sqrt{3}}\boldsymbol{i}_2 + \frac{2}{\sqrt{3}}\boldsymbol{j}_2 \end{cases} \quad (4)$$

In the context of KL coordinates, space vector $\boldsymbol{U_r}$ corresponding to the three phase voltage u_a, u_b, u_c is:

$$\mathrm{U}_{\boldsymbol{r}} = \sqrt{\frac{2}{3}}\left(\left(u_a - \frac{u_b + u_c}{2}\right)\boldsymbol{i}_2 + \frac{\sqrt{3}(u_b - u_c)}{2}\left(\frac{2}{\sqrt{3}}\boldsymbol{j}_2 + \frac{1}{\sqrt{3}}\boldsymbol{i}_2\right)\right)$$
$$= \sqrt{\frac{2}{3}}((u_a - u_c)\boldsymbol{i}_2 + (u_b - u_c)\boldsymbol{j}_2) \quad (5)$$

From Eq. (5), we find that the projections of $\boldsymbol{U_r}$ on the K and L axes are

$$\mathrm{Prj}_L \boldsymbol{U_r} = \sqrt{\frac{2}{3}}(u_a - u_c) = -\sqrt{\frac{2}{3}}u_{ca}$$

$$\mathrm{Prj}_L \boldsymbol{U_r} = \sqrt{\frac{2}{3}}(u_b - u_c) = -\sqrt{\frac{2}{3}}u_{bc}$$

as shown in Fig. 3. In the context of KL coordinates, space vector $\boldsymbol{V}$ corresponding to the inverter output states δ

is $\boldsymbol{V}=\sqrt{\frac{2}{3}}U_d((\delta_a-\delta_b)\boldsymbol{i}_2+(\delta_b-\delta_c)\boldsymbol{j}_2)$. And naturally, projections of space vector $\boldsymbol{V}$ are: $\mathrm{Prj}_{\boldsymbol{L}}\,\boldsymbol{V_r}=\sqrt{\frac{2}{3}}U_d(\delta_a-\delta_c)$

$\mathrm{Prj}_{\boldsymbol{K}}\,\boldsymbol{V_r}=\sqrt{\frac{2}{3}}U_d(\delta_b-\delta_c)$

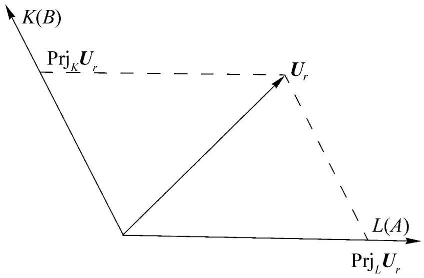

Fig. 3 Space vectors in the context of *KL* coordinates

By looking at Fig.1, we can find that oblique lines $\cdots, A_{-1}A_{-1}^{\ *},\ A_{-2}A_{-2}^{\ *}, A_1A_1^{\ *}, A_2A_2^{\ *},\cdots,$ are parallel with the *K*-axis. Projections of every point on the oblique lines are the same with the others, which can be expressed in a simple way: $\cdots, l_{-1}=-\sqrt{\frac{2}{3}}U_d,$ $l_{-2}=-2\sqrt{\frac{2}{3}}U_d, l_1=\sqrt{\frac{2}{3}}U_d, l_2=2\sqrt{\frac{2}{3}}U_d,\cdots$. In the same way we can obtain that the projections of the points on the oblique lines $\cdots, B_{-1}B_{-1}^{\ *}, B_{-2}B_{-2}^{\ *}, B_1B_1^{\ *}, B_2B_2^{\ *},\cdots,$ are $\cdots, k_{-1}=-\sqrt{\frac{2}{3}}U_d,\ k_{-2}=-2\sqrt{\frac{2}{3}}U_d, k_1=\sqrt{\frac{2}{3}}U_d, k_2=2\sqrt{\frac{2}{3}}U_d,\cdots$

As shown in Fig. 4, if a space vector corresponding to an output state δ is the intersection point of l_m, k_n, it can be indicated as $\boldsymbol{V}_{m,n}$.

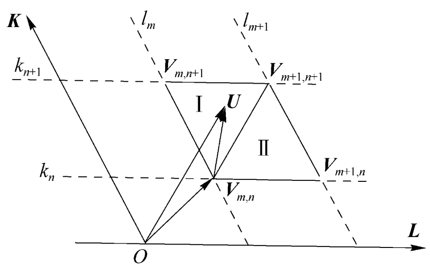

Fig. 4 Composition of space vectors in the context of *KL* coordinates

As shown in Fig.4, lines $l_m=mU_d, l_{m+1}=(m+1)\ U_d$ parallel with *K*-axis and lines $k_n=nU_d, k_{n+1}=(n+1)\ U_d$ parallel with *L*-axis constitute a rhombus, which contains two regular triangles. We call the upper triangle type I, and the other type II.

4 Synthesis of space vectors in *KL* coordinates

If $\boldsymbol{U_r}$ is located in the rhombus area shown in Fig.4, several conditions must be satisfied under *KL* coordinates:

$$\begin{cases}\mathrm{Prj}_{\boldsymbol{L}}\,\boldsymbol{U_r}\le\sqrt{\frac{2}{3}}(m+1)\ U_d\\ \mathrm{Prj}_{\boldsymbol{L}}\,\boldsymbol{U_r}\ge\sqrt{\frac{2}{3}}mU_d\\ \mathrm{Prj}_{\boldsymbol{K}}\,\boldsymbol{U_r}\le\sqrt{\frac{2}{3}}(n+1)\ U_d\\ \mathrm{Prj}_{\boldsymbol{K}}\,\boldsymbol{U_r}\ge\sqrt{\frac{2}{3}}nU_d\end{cases}\tag{6}$$

Namely,

$$\begin{cases}-\sqrt{\frac{2}{3}}u_{ca}\le\sqrt{\frac{2}{3}}(m+1)\ U_d\\ -\sqrt{\frac{2}{3}}u_{ca}\ge\sqrt{\frac{2}{3}}mU_d\\ \sqrt{\frac{2}{3}}u_{bc}\le\sqrt{\frac{2}{3}}(n+1)\ U_d\\ \sqrt{\frac{2}{3}}u_{bc}\ge\sqrt{\frac{2}{3}}nU_d\end{cases}$$

Simplified as:

$$\begin{cases}-(m+1)\ U_d\le u_{ca}\le -mU_d\\ nU_d\le u_{bc}\le(n+1)\ U_d\end{cases}\tag{7}$$

If $\boldsymbol{U_r}$ is located in the characteristic triangle of type I, an additional condition must be satisfied:

$$\mathrm{Prj}_{\boldsymbol{L}}\left(\boldsymbol{U_r}-\boldsymbol{V_{m,n}}\right)\le\mathrm{Prj}_{\boldsymbol{K}}\left(\boldsymbol{U_r}-\boldsymbol{V_{m,n}}\right)$$

Namely,

$$-\sqrt{\frac{2}{3}}u_{ca}-\sqrt{\frac{2}{3}}mU_d\le\sqrt{\frac{2}{3}}u_{bc}-\sqrt{\frac{2}{3}}nU_d$$

It can be deduced that:

$$u_{bc}+u_{ca}\ge(n-m)U_d,\quad u_{ab}\le(m-n)U_d\tag{8}$$

By the same token, if $\boldsymbol{U_r}$ is in the triangle of type II, addition condition is:

$$u_{ab}\ge(m-n)U_d\tag{9}$$

It can be seen that it's easy to judge which characteristic triangle $\boldsymbol{U_r}$ is located in according to Eqs. (6)–(8). Then we can determine vectors to synthesize $\boldsymbol{U_r}$. Next, we'll discuss the calculations of duty cycles.

If $\boldsymbol{U_r}$ locates in characteristic triangle of type I, it'll be synthesized by $\boldsymbol{V}_{m,n}$, $\boldsymbol{V}_{m,n+1}$, $\boldsymbol{V}_{m+1,n+1}$, according to the principles of vector synthesis:

$$\begin{cases}t_{m,n}\boldsymbol{V}_{m,n}+t_{m,n+1}\boldsymbol{V}_{m,n+1}+t_{m+1,n+1}\boldsymbol{V}_{m+1,n+1}=T\,\boldsymbol{U_r}\\ t_{m,n}+t_{m,n+1}+t_{m+1,n+1}=T\end{cases}$$

Namely,

$$\begin{cases} t_{m,n}\Pr j_{L}\boldsymbol{V}_{m,n}+t_{m,n+1}\Pr j_{L}\boldsymbol{V}_{m,n+1}+t_{m+1,n+1}\Pr j_{L}\boldsymbol{V}_{m+1,n+1}=T\Pr j_{L}\boldsymbol{U_r} \\ t_{m,n}\Pr j_{K}\boldsymbol{V}_{m,n}+t_{m,n+1}\Pr j_{K}\boldsymbol{V}_{m,n+1}+t_{m+1,n+1}\Pr j_{k}\boldsymbol{V}_{m+1,n+1}=T\Pr j_{K}\boldsymbol{U_r} \\ t_{m,n}+t_{m,n+1}+t_{m+1,n+1}=T \end{cases}$$

The solutions of above equations are:

$$\begin{cases} t_{m,n}=T-\dfrac{T\left(u_{bc}-nU_d\right)}{U_d} \\ t_{m,n+1}=-\dfrac{T\left(u_{ab}+(n-m)U_d\right)}{U_d} \\ t_{m+1,n+1}=-\dfrac{T\left(u_{ca}+mU_d\right)}{U_d} \end{cases} \tag{10}$$

If the location of $\boldsymbol{U_r}$ is triangle of type II, the synthesized vectors are $\boldsymbol{V}_{m+1,n+1}, \boldsymbol{V}_{m,n}, \boldsymbol{V}_{m+1,n}$. In the same way, we can get:

$$\begin{cases} t_{m,n}=T+\dfrac{T\left(u_{ca}+mU_d\right)}{U_d} \\ t_{m+1,n}=\dfrac{T\left(u_{ab}+(n-m)\ U_d\right)}{U_d} \\ t_{m+1,n+1}=\dfrac{T\left(u_{bc}-nU_d\right)}{U_d} \end{cases} \tag{11}$$

The normal SVPWM algorithm needs a large amount of extracting roots and trigonometric operations. This makes it difficult to guarantee accuracy and speed of calculation not to mention that it occupies a great deal of storage space and needs a high-level hardware system. From Eqs. (10)-(11), we can see that the proposed algorithm only contains product and add operations leading to fewer calculations and lower hardware demand, which has nothing to do with the number of levels. The theoretic error of this algorithm is zero but it is only affected by CPU word length.

Inverters are widely used in adjustable-speed drives. For decoupled control, orthogonal coordinates such as $\alpha\beta$, dq coordinates are normally used. Thus, transformation equations between KL coordinates and other coordinates must be produced. According to the basic theory of vector transformation [8], from Eq. (4), the transformation matrix from $\alpha\beta$ to KL coordinates is:

$$\boldsymbol{T}_1=\begin{bmatrix} 1 & \dfrac{1}{\sqrt{3}} \\ 0 & \dfrac{2}{\sqrt{3}} \end{bmatrix}$$

Transformation matrix from dq to KL coordinates is:

$$\boldsymbol{T_2}=\begin{bmatrix} 1 & \dfrac{1}{\sqrt{3}} \\ 0 & \dfrac{2}{\sqrt{3}} \end{bmatrix}\times\begin{bmatrix} \cos\theta & \sin\theta \\ \sin\theta & -\cos\theta \end{bmatrix} =\frac{2}{\sqrt{3}}\begin{bmatrix} \cos\left(\theta-\dfrac{\pi}{6}\right) & \sin\left(\theta-\dfrac{\pi}{6}\right) \\ \sin\theta & -\cos\theta \end{bmatrix}$$

5 Algorithm verification

It can be seen that there is great difference between the obtained results in the contexts of $\alpha\beta$ and KL coordinates. This tells us that the result in $\alpha\beta$ coordinate isn't the simplest form. Next, we'll simplify the result of a 3-level inverter in $\alpha\beta$ coordinates to verify the essential correspondence of two algorithms (Fig. 5).

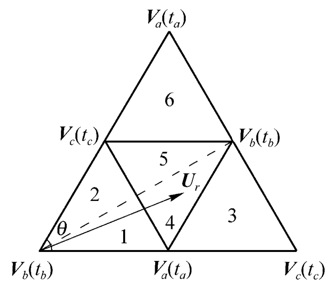

Fig. 5 Diagram of the space vectors of three-level inverter in the first sector

In Ref. [3], the solutions of vector synthesis in the case of different sectors when $0\le\theta\le\pi/3$ are given, as follows:

Table 1 Solution of SVPWM of three-level inverter in the first sector in the context of $\alpha\beta$ coordinates

	Sect.1-2	Sect.3	Sect.4-5	Sect.6
$\frac{t_a}{T}$	$\sqrt{3}m\sin\left(\frac{\pi}{3}-\theta\right)$	$2-\sqrt{3}m\sin\left(\frac{\pi}{3}+\theta\right)$	$1-\sqrt{3}m\sin\theta$	$\sqrt{3}m\sin\theta-1$
$\frac{t_b}{T}$	$1-\sqrt{3}m\sin\left(\frac{\pi}{3}+\theta\right)$	$\sqrt{3}m\sin\theta$	$\sqrt{3}m\sin\left(\frac{\pi}{3}+\theta\right)-1$	$\sqrt{3}m\sin\left(\frac{\pi}{3}-\theta\right)$
$\frac{t_c}{T}$	$\sqrt{3}m\sin\theta$	$\sqrt{3}m\sin\left(\frac{\pi}{3}-\theta\right)-1$	$1-\sqrt{3}m\sin\left(\frac{\pi}{3}-\theta\right)$	$2-\sqrt{3}m\sin\left(\frac{\pi}{3}+\theta\right)$

where $m=\lVert U_r\rVert/U_d$, θ is the angle between $\boldsymbol{U_r}$ and α coordinate axis

From Table 1, we can find that vector synthesis contains three basic calculations: $\|\boldsymbol{U}_r\|\sin(\theta)$, $\|\boldsymbol{U}_r\|\sin\left(\theta+\frac{\pi}{3}\right)$, $\|\boldsymbol{U}_r\|\sin\left(\frac{\pi}{3}-\theta\right)$.

Normally, we get modulus $\|\boldsymbol{U}_r\|$ and phase angle θ first, then get the solutions. In fact, $\|\boldsymbol{U}_r\|$ and θ aren't independent, if we consider them as a whole one, calculation will become very simple, verified as follows:

$$\|\boldsymbol{U}_r\| = \sqrt{\frac{2}{3}\left(\left(u_a-\frac{1}{2}u_b-\frac{1}{2}u_c\right)^2+\left(\frac{\sqrt{3}}{2}u_b-\frac{\sqrt{3}}{2}u_c\right)^2\right)} \quad (12)$$

$$\tan(\theta)=\frac{\frac{\sqrt{3}}{2}u_b-\frac{\sqrt{3}}{2}u_c}{u_a-\frac{1}{2}u_b-\frac{1}{2}u_c} \quad (13)$$

From Eqs. (12)-(13):

$$\|\boldsymbol{U}_r\|\sin(\theta)=\sqrt{\|\boldsymbol{U}_r\|^2\sin^2(\theta)}=\sqrt{\frac{\|\boldsymbol{U}_r\|^2}{\left(1+\tan^2(\theta)\right)}}=\frac{u_{bc}}{\sqrt{3}} \quad (14)$$

$$\|\boldsymbol{U}_r\|\sin\left(\theta+\frac{\pi}{3}\right)=\sqrt{\|\boldsymbol{U}_r\|^2\sin^2\left(\theta+\frac{\pi}{3}\right)}$$
$$=\sqrt{\|\boldsymbol{U}_r\|^2\left(\frac{1}{2}+\frac{1-\tan^2(\theta)}{4(1+\tan^2(\theta))}+\frac{2\sqrt{3}\tan\theta}{4(1+\tan^2(\theta))}\right)}=-\frac{u_{ca}}{\sqrt{3}} \quad (15)$$

$$\|\boldsymbol{U}_r\|\sin\left(\frac{\pi}{3}-\theta\right)=\sqrt{\|\boldsymbol{U}_r\|^2\sin^2\left(\frac{\pi}{3}-\theta\right)}$$
$$=\sqrt{\|\boldsymbol{U}_r\|^2\left(\frac{1}{2}+\frac{1-\tan^2(\theta)}{4(1+\tan^2(\theta))}-\frac{2\sqrt{3}\tan(\theta)}{4(1+\tan^2(\theta))}\right)}=\frac{u_{ab}}{\sqrt{3}} \quad (16)$$

According to Eqs. (14)-(16), Table 1 is simplified to Table 2

Table 2 Simplified solution of SVPWM of three-level inverter in the first sector in the context of $\alpha\beta$ coordinates

	Sec.1-2	Sec.3	Sec.4-5	Sec.6
$\frac{t_a}{T}$	$\frac{u_{ab}}{U_d}$	$2+\frac{u_{ca}}{U_d}$	$1-\frac{u_{bc}}{U_d}$	$\frac{u_{bc}}{U_d}-1$
$\frac{t_b}{T}$	$1+\frac{u_{ca}}{U_d}$	$\frac{u_{bc}}{U_d}$	$-1-\frac{u_{ca}}{U_d}$	$\frac{u_{ab}}{U_d}$
$\frac{t_c}{T}$	$\frac{u_{bc}}{U_d}$	$\frac{u_{ab}}{U_d}-1$	$1-\frac{u_{ab}}{U_d}$	$2+\frac{u_{ca}}{U_d}$

From Eqs. (10)-(11), we can get the same solution as Table 2 in the context of $\alpha\beta$ coordinates. In the same way, solutions of other sections can be obtained, which verify the correctness of proposed algorithm.

6 Essence of SVPWM

According to pulse area equal principle, the responses of different narrow pulses with equal impulses (pulse area) and different shapes are equivalent. They can alternate each other. SPWM is based on this theory, whose basic idea is to make the area surrounded by the output pulse of inverter equal to the one surrounded by referent voltage in a carrier wave cycle. In the normal realizing process of SPWM, referent voltages of three half bridges are u_a, u_b, u_c. This method can be called PWM based on phase voltages. Actually, any change of voltage of any half bridge will affect voltages of the other phases. So, it is better to take three phases as a whole than to consider them respectively.

Different from SPWM, SVPWM is a PWM algorithm based on line voltages. It's to make the addition of two areas surrounded by output pulses of any two half bridges equal to the addition of two areas surrounded by corresponding referent line voltages. This can be verified easily in the context of KL coordinates which is presented in this paper.

Assuming, in a carrier wave cycle T, referent vector is synthesized by V_x, V_y, V_z, whose duty cycles are t_1, t_2, t_3 respectively, in duration of t_1, area surrounded by the impulse of bridge arm c and a is $t_1(\delta_c-\delta_a)\,U_d = -\sqrt{\frac{3}{2}}\mathrm{Prj}_{\boldsymbol{L}}\,\mathrm{V_x}\,t_1$; in duration of t_2, it's $-\sqrt{\frac{3}{2}}\mathrm{Prj}_{\boldsymbol{L}}\,\mathrm{V_y}\,t_2$; in duration of t_3, it's $-\sqrt{\frac{3}{2}}\mathrm{Prj}_{\boldsymbol{L}}\,\mathrm{V_z}\,t_3$. So in the whole carrier cycle, it's as following:

$$-\sqrt{\frac{3}{2}}\left(\mathrm{Prj}_{\boldsymbol{L}}\boldsymbol{V}_x t_1+\mathrm{Prj}_{\boldsymbol{L}}\boldsymbol{V}_y t_2+\mathrm{Prj}_{\boldsymbol{L}}\boldsymbol{V}_z t_3\right)=-\sqrt{\frac{3}{2}}\mathrm{Prj}_{\boldsymbol{L}}\boldsymbol{V}_r T$$
$$=\sqrt{\frac{3}{2}}\times\sqrt{\frac{2}{3}}u_{ca}T=u_{ca}T$$

The verifications of the other two situations are the same.

7 Conclusions

This paper proposes KL coordinates, based on which, a new SVPWM simplified algorithm is also proposed. For inverter of any level, it has the advantages as following:

1) It can find the characteristic triangle where space vector $\boldsymbol{U}_r$ locates in conveniently.

2) It can synthesize vector easily.

For three phase inverter, the same essences of SVPWM and regular algorithm have been verified. Finally, it's pointed out that SVPWM is a PWM technology based on line voltages actually. Acknowledging the essence, we can use it to realize optimizing control of inverter, for example: reducing switch frequency, realizing balance of voltages. We'll describe these applications in other papers.

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