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An Enhanced SVPWM Strategy Based on Vector Space Decomposition for Dual Three-Phase Machines Fed by Two DC-Source VSIs

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Abstract— This paper presents an enhanced space vector pulse width modulation (SVPWM) strategy based on vector space decomposition (VSD) for the dual three-phase machines fed by two DC-Source voltage source inverters (VSIs). Compared with existing methods that only account for balanced DC-link voltages, the proposed method considers unbalanced DC-link voltages in both the α - β and z_1 - z_2 planes. Two categories of medium voltage vectors are first defined in this paper. An enhanced 12-sector SVPWM strategy that toggles two categories of medium voltage vectors in each fixed 30° sector is proposed. Moreover, the performance of the proposed method, including the modulation depth, the range of the DC-link voltage ratio, and the toggling point of the medium vector is analyzed. The proposed method can reduce the computational burden of the complicated sector classifications and it easily chooses suitable vectors to track the reference voltage with changes in the DC-link voltage ratio. The experimental results of the proposed SVPWM techniques are verified in a dual three-phase permanent magnet synchronous machine (PMSM) fed by two DC-Source VSIs.

Index Terms—Dual Three-phase Machines, SVPWM, Two DC-Source VSIs, Vector Space Decomposition

I. INTRODUCTION

DUAL three-phase machines [1-3] with two sets of three-phase windings that are spatially shifted by an electrical angle of 30° exhibit outstanding advantages, such as fewer torque ripples than other machines, reduced phase current ratings, and excellent fault tolerance. They have much potential for applications in wind power, electric vehicles, electric ship propulsion systems, and electric railway traction [4-5].

The vector space decomposition (VSD) approach [6] can be used to decouple the dual three-phase machine state variables into three two-dimensional orthogonal subplanes (α - β , z_1 - z_2 , o_1 - o_2), making it a classical and powerful tool for the analysis and control of dual three-phase machines [7]. Reference [8] showed

that the current loop control method based on VSD is flexible for controlling the fifth and seventh current harmonics, and it has advantages in terms of stability and robustness. Space vector pulse width modulation (SVPWM) based on the VSD approach can be used to directly suppress the harmonics of a dual three-phase machine, and this subtype is considered a classical SVPWM approach [9]. Many SVPWM techniques based on the VSD method have been investigated for dual three-phase machines [6,9-13], and these can be divided into the 12-sector SVPWM and 24-sector SVPWM methods. 12-sector SVPWM adopts four large voltage vectors in the α - β plane to synthesize the reference voltage vectors [6]. The 24-sector SVPWM methods take advantage of the medium voltage vectors to divide the sectors. Types of this approach include the (3L+1M) method [10], the (2L+1M+1ML) method [11], and the (3L+2M) method [12], where L stands for the large voltage vectors, ML stands for the medium-large voltage vectors, medium voltage vectors are denoted by M, and small voltage vectors are denoted by S. Compared to the 12-sector method, the 24-sector method involves fewer switching operations in each PWM cycle, and it is easier to implement in the digital signal processor (DSP). Reference [13] proposed new SVPWM techniques by modifying the switching sequences of carrier-based PWM techniques. The modified SVPWM approach significantly reduces harmonic distortion factor (HDF) and provides low current total harmonic distortion (THD).

Currently, the most studied SVPWM approach for dual three-phase machines is a parallel-connected DC-link system, in which two three-phase two-level VSI DC links are connected in parallel. In fact, dual three-phase machines have different DC-link topologies. In general, DC-link topologies can be divided into three types: parallel-connected [14-16], series-connected [17-18], and separated DC-links [19-22], as illustrated in Fig. 1. The parallel-connected system in Fig. 1(a) is the most widely studied. In this case, the DC-link between the two three-phase VSIs has a balanced voltage. The series-connected system is shown in Fig. 1(b) and uses two three-phase two-level VSIs connected in series to form a cascaded DC-link. The series-connected topology can achieve a double DC-link voltage of three-phase VSIs, however, it follows that any asymmetry will cause DC-link voltage drifting unless some voltage balancing mechanism is included in the control scheme [17]. In fact, asymmetry in a dual three-phase driver system is inevitable because of the asymmetry between any two sets of windings and power inverters [23-24]. Separated DC-links can increase the availability of the drive in case of a failure. Two

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batteries that supply two DC-links of a dual three-phase PMSM are introduced in [19]. If batteries with different nominal voltages are used or the states of charge of the batteries are different, it is not guaranteed that both DC-link voltage levels are always the same [19]. Furthermore, the separated DC-links can provide the system with the ability to integrate different sources of energy [20-22]. A dual three-phase PMSM drive with a battery DC-link and ultracapacitor (or fuel cell) DC-link is investigated in [20-22]. Separated DC-links may also result in an unbalanced DC-link voltage due to the different transferred powers from the battery and ultracapacitor (or fuel cell).

Fig. 1 DC-links of the dual three-phase machine. (a) Parallel-connected DC-links (b) Series-connected DC-links (c) Separated DC-links

The projections of the voltage vectors in the $\alpha\text{-}\beta$ and $z_1\text{-}z_2$ planes are directly related to the DC-link voltage. Therefore, the projections of voltage vectors under an unbalanced DC-link voltage are quite different from those under balanced projections. Furthermore, this leads to new modulation issues for conventional VSD-based SVPWM methods. The first issue is that DC-link voltage imbalances cause a non-uniform distribution of the voltage vectors in the $\alpha\text{-}\beta$ and $z_1\text{-}z_2$ planes, thereby increasing the burden of sector classification and judgment. The second issue is that the selection of vector applications is difficult, as the vector distribution varies with the DC-link voltage ratio. Dual three-phase SVPWM is used to avoid VSD problems under unbalanced DC-link voltages [25], but dual three-phase SVPWM cannot reflect the relationship between stator flux linkage and stator voltage because of the electromagnetic couplings in the two windings. In addition, the synchrony between the dual three-phase windings is needed to reduce the sub-harmonics [26]. To the best of the authors' knowledge, there are few studies on VSD-based SVPWM that take unbalanced DC-link voltage into consideration.

In this paper, an SVPWM strategy considering unbalanced DC-link voltages is studied. Two categories of medium voltage vectors are first defined in this paper. An enhanced 12-sector SVPWM strategy is proposed that toggles two categories of medium voltage vectors in the $\alpha\text{-}\beta$ plane with a fixed 30° sector. The proposed method avoids complicated sector classification and judgment algorithms under non-uniform voltage vector distributions, and easily chooses the correct vector (positive application time) to track the reference voltage with changes in DC-link voltage ratio. Moreover, the performance of the proposed method, i.e., the modulation depth, the range of the DC-link voltage ratio, and the toggling point of the medium

vector, are analyzed in detail. The effectiveness of the proposed method is verified by the dual three-phase PMSM.

II. VOLTAGE VECTOR ANALYSES

The relationship between the dual three-phase motor stator voltage and switch states of the VSI can be presented as:

$$\begin{bmatrix} u_{A1} \\ u_{B1} \\ u_{C1} \end{bmatrix} = u_{dc1} \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ -\frac{1}{3} & \frac{2}{3} & -\frac{1}{3} \\ -\frac{1}{3} & -\frac{1}{3} & \frac{2}{3} \end{bmatrix} \begin{bmatrix} S_{A1} \\ S_{B1} \\ S_{C1} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} u_{A2} \\ u_{B2} \\ u_{C2} \end{bmatrix} = u_{dc2} \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ -\frac{1}{3} & \frac{2}{3} & -\frac{1}{3} \\ -\frac{1}{3} & -\frac{1}{3} & \frac{2}{3} \end{bmatrix} \begin{bmatrix} S_{A2} \\ S_{B2} \\ S_{C2} \end{bmatrix} \quad (2)$$

where u_{dc1} and u_{dc2} represent the voltages of the two DC-links; u_{A1} , u_{B1} , u_{C1} , u_{A2} , u_{B2} and u_{C2} represent the stator phase voltages; and S_{A1} , S_{B1} , S_{C1} , S_{A2} , S_{B2} and S_{C2} represent the upper switch states of the inverters (i.e., "1": ON and "0": OFF). By applying the VSD transformation matrix in (3), the voltage vectors $V = S_{A1} * 2^5 + S_{B1} * 2^4 + S_{C1} * 2^3 + S_{A2} * 2^2 + S_{B2} * 2^1 + S_{C2} * 2^0$ can be projected into three orthogonal planes, which are identified as $\alpha\text{-}\beta$, $z_1\text{-}z_2$, and $o_1\text{-}o_2$, respectively. The third subplane $o_1\text{-}o_2$ is excluded due to isolated neutral point.

$$\begin{bmatrix} u_\alpha \\ u_\beta \\ u_{z1} \\ u_{z2} \\ u_{o1} \\ u_{o2} \end{bmatrix} = \sqrt{\frac{1}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} & 0 \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} & \frac{1}{2} & \frac{1}{2} & -1 \\ 1 & -\frac{1}{2} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} & 0 \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} & \frac{1}{2} & \frac{1}{2} & -1 \\ 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} u_{A1} \\ u_{B1} \\ u_{C1} \\ u_{A2} \\ u_{B2} \\ u_{C2} \end{bmatrix} \quad (3)$$

The voltage vector projections into the $\alpha\text{-}\beta$ and $z_1\text{-}z_2$ planes are directly related to the two DC-link voltages. Therefore, it is necessary to further analyze the voltage vector projections under two DC-link voltages.

(1) **Large Vectors** (i.e., vectors **36** and **37**). As an example, the projection coordinates of vector **36** in the $\alpha\text{-}\beta$ and $z_1\text{-}z_2$ planes are $(\frac{1}{\sqrt{3}}u_{dc1} + \frac{1}{2}u_{dc2}, \frac{1}{2\sqrt{3}}u_{dc2})$ and $(\frac{1}{\sqrt{3}}u_{dc1} - \frac{1}{2}u_{dc2}, \frac{1}{2\sqrt{3}}u_{dc2})$, respectively. An illustration of how the symmetric vectors **36** and **37** change with the unbalanced DC-link voltage is shown in Fig. 2(a). It can be seen that both the magnitude and phase of the large vector change with the variation in the DC-link voltage ratio. The angle between vectors **36** and **37** in the $\alpha\text{-}\beta$ plane changes from 30° to 60° when $k \rightarrow 0$ and to 0° when $k \rightarrow \infty$. k is the DC-link voltage ratio which can be defined as

$$k = \frac{u_{dc1}}{u_{dc2}} \quad \begin{cases} \max(u_{dc1}, u_{dc2}) = u_{dc} \end{cases} \quad (4)$$

where u_{dc} is the nominal DC-link voltage.

(2) **Medium Vectors** (i.e., **39** and **4**). The coordinates of vector **39** in the $\alpha\text{-}\beta$ and $z_1\text{-}z_2$ planes are $(\frac{u_{dc}}{\sqrt{3}}, 0)$ and $(\frac{u_{dc1}}{\sqrt{3}}, 0)$, and those of vector **4** are $(\frac{u_{dc2}}{2}, \frac{u_{dc}}{2\sqrt{3}})$ and $(-\frac{u_{dc2}}{2}, \frac{u_{dc2}}{2\sqrt{3}})$,

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respectively, From Fig.2(b), it can be seen that the phase of the medium vector is held constant even though the DC voltage ratio changes. The magnitude of vector 4 remains constant when k changes from 1 to 0, while the magnitude of vector 39 becomes zero.

(3) Medium-Large Vectors (i.e., 53 and 44) and Small Vectors (i.e., 46 and 49). The distribution patterns of these vectors can be obtained by using the same principle, and they are illustrated in Fig. 2(c) and 2(d).

Fig. 2 Four types of vector distributions with DC-link voltage changes. (a) Large vector variation (b) Medium vector variation (c) Medium-large vector variation (d) Small vector variation

The projections of the 64 voltage vectors (except zero vectors) into the α - β and z_1 - z_2 planes with an unbalanced DC-link voltage ($k < 1$, $k = 1$, $k > 1$) are shown in Fig. 3. The above analysis shows that the magnitudes and phases of the large vectors, medium-large vectors and small vectors change when the DC-link voltage ratio varies. Therefore, the borders of each sector vary with the unbalanced DC-link voltage. The conventional VSD-based SVPWM methods may no longer be suitable for series-connected or separated DC link-based VSI. This paper proposes an SVPWM method for toggling the medium vector with fixed 30° sector angle to improve the control performance of the two DC-source VSIs fed dual three-phase machine.

Fig. 3 Projections of phase voltage space vectors in the α - β and z_1 - z_2 planes considering an unbalanced DC-link voltage.

III. PROPOSED SVPWM ALGORITHM

A. 12-Sector Division

Based on the analysis in Section II, the phases of all vectors except the medium voltage vectors vary with the DC-link voltage ratio, leading to a non-uniform vector distribution in the α - β and z_1 - z_2 planes. To reduce the complexity of sector selection, the proposed SVPWM method chooses the medium vectors as the borders of each sector. Hence, only 12 sectors with fixed 30° angles are required in the α - β plane, thereby optimizing the sector selection process under DC-link voltage imbalances.

Fig. 4 Presentation of the large and medium vectors at different DC-link voltage ratios.

B. Definition of the Two Categories of Medium Vectors

During each PWM cycle, a set of four nonzero voltage vectors must be chosen to synthesize the reference voltage vectors in VSD-based SVPWM. Since the large vectors in the α - β plane have the smallest magnitudes in the z_1 - z_2 plane, this

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paper chooses three large vectors to increase the modulation ratio in the α - β plane. For example, when a reference voltage vector of the α - β plane is located in sector-1, large vector **36** is always in this sector even though the DC-link voltage ratio changes. Vectors **52** and **37** can also be chosen because they are adjacent to **36**. As indicated by Fig. 4, large vectors **36,37** and **52** in the z_1 - z_2 plane converge towards the half-plane as the DC-link voltage imbalance increases. In other words, it is necessary to use other voltage vectors to make the average volt-second on this plane be zeroed. Therefore, this paper selects the medium vectors whose phases remain constant to compensate for the volt-second produced by large vectors in the z_1 - z_2 plane. In fact, one or multiple medium vectors with fixed time proportions could be selected. To simplify the calculations, an equal time distribution is adopted when two medium voltage vectors are selected, as this reduces the amplitude fluctuations of the stator flux caused by the long-time operation of one vector [25]. As shown in Fig. 4, the possible medium voltage vectors are **32, 39** and **48,55** when $k < 1$, and these are highlighted in light blue. In contrast, the possible medium vectors change to **60, 4** and **5,61** when $k > 1$.

If the validity of time is not considered first, the application times in sector-1 with medium vectors (**39,60,39** and **48,60** and **5**) can be calculated by:

$$\begin{bmatrix} T_{37_calc} \\ T_{36_calc} \\ T_{52_calc} \\ T_{39_calc} \end{bmatrix} = \frac{T_s}{2u_{dc1}} \begin{bmatrix} k & -\sqrt{3}k & -k & -\sqrt{3}k \\ k & \sqrt{3}k-2 & -k & \sqrt{3}k+2 \\ 0 & 2 & 0 & -2 \\ -2k+\sqrt{3} & 1 & 2k+\sqrt{3} & -1 \end{bmatrix} \begin{bmatrix} u_\alpha \\ u_\beta \\ u_{z1} \\ u_{z2} \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} T_{37_calc} \\ T_{36_calc} \\ T_{52_calc} \\ T_{60_calc} \end{bmatrix} = \frac{T_s}{2u_{dc1}} \begin{bmatrix} k & -\sqrt{3}k & -k & -\sqrt{3}k \\ -k+\sqrt{3} & \sqrt{3}k-1 & k+\sqrt{3} & \sqrt{3}k+1 \\ 0 & 2 & 0 & -2 \\ 2k-\sqrt{3} & -1 & -2k-\sqrt{3} & 1 \end{bmatrix} \begin{bmatrix} u_\alpha \\ u_\beta \\ u_{z1} \\ u_{z2} \end{bmatrix} \quad (6)$$

$$\begin{bmatrix} T_{37_calc} \\ T_{36_calc} \\ T_{52_calc} \\ T_{39_and48_calc} \end{bmatrix} = \frac{T_s}{2u_{dc1}} \begin{bmatrix} k & -\sqrt{3}k & -k & -\sqrt{3}k \\ \frac{\sqrt{3}}{2} & \sqrt{3}k-\frac{3}{2} & \frac{\sqrt{3}}{2} & \sqrt{3}k+\frac{3}{2} \\ k-\frac{\sqrt{3}}{2} & \frac{3}{2} & -k-\frac{\sqrt{3}}{2} & -\frac{3}{2} \\ -2k+\sqrt{3} & 1 & 2k+\sqrt{3} & -1 \end{bmatrix} \begin{bmatrix} u_\alpha \\ u_\beta \\ u_{z1} \\ u_{z2} \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} T_{37_calc} \\ T_{36_calc} \\ T_{52_calc} \\ T_{60_and5_calc} \end{bmatrix} = \frac{T_s}{2u_{dc1}} \begin{bmatrix} \frac{\sqrt{3}}{2} & -\sqrt{3}k+\frac{1}{2} & \frac{\sqrt{3}}{2} & -\sqrt{3}k-\frac{1}{2} \\ \frac{\sqrt{3}}{2} & \sqrt{3}k-\frac{3}{2} & \frac{\sqrt{3}}{2} & \sqrt{3}k+\frac{3}{2} \\ 0 & 2 & 0 & -2 \\ 2k-\sqrt{3} & -1 & -2k-\sqrt{3} & 1 \end{bmatrix} \begin{bmatrix} u_\alpha \\ u_\beta \\ u_{z1} \\ u_{z2} \end{bmatrix} \quad (8)$$

where T represents the calculated vector application time and subscripts indicate the vectors involved. T_s represents the PWM period, and u_α , u_β , u_{z1} , and u_{z2} represent the reference voltages. It should be noted that the calculated application times of the four categories medium voltage vectors have equal absolute values. The interesting relationships among the application times of the medium vectors are indicated in (9):

$$\begin{cases} T_{39_calc} = T_{39_and48_calc} \\ T_{60_calc} = T_{60_and5_calc} \\ T_{39_calc} = -T_{60_calc} \end{cases} \quad (9)$$

Based on the application times of the medium vectors, this paper classifies the medium vectors **39, 39** and **48** as type-1 medium vectors in sector-1, while vectors **60, 60** and **5** are

classified as type-2 medium vectors. The classifications of the medium vectors in the whole sector are shown in Table I.

TABLE I
CLASSIFICATIONS OF MEDIUM VECTORS

Sector	Type-1 medium vectors	Type-2 medium vectors
1	39, 32, 39 and 48, 32 and 55	4, 60, 5 and 60, 4 and 61
2	48, 55, 39 and 48, 32 and 55	4, 60, 6 and 60, 4 and 62
3	48, 55, 23 and 48, 16 and 55	6, 62, 6 and 60, 4 and 62
4	16, 23, 23 and 48, 16 and 55	6, 62, 6 and 58, 2 and 62
5	16, 23, 16 and 31, 23 and 24	2, 58, 6 and 58, 2 and 62
6	24, 31, 16 and 31, 23 and 24	2, 58, 3 and 58, 2 and 59
7	24, 31, 8 and 31, 15 and 24	3, 59, 3 and 58, 2 and 59
8	8, 15, 8 and 31, 15 and 24	3, 59, 3 and 57, 1 and 59
9	8, 15, 8 and 47, 15 and 40	1, 57, 3 and 57, 1 and 59
10	40, 47, 8 and 47, 15 and 40	1, 57, 5 and 57, 1 and 61
11	40, 47, 32 and 47, 39 and 40	5, 61, 5 and 57, 1 and 61
12	39, 32, 32 and 47, 39 and 40	5, 61, 5 and 60, 4 and 61

C. Proposed SVPWM for Toggling the Medium Voltage Vectors

Because the type-1 and type-2 medium vectors have the opposite calculated application times, it is possible to toggle two types of medium vectors if the calculated application time of medium vector is less than zero. This paper defines the proposed medium vector toggling method with only one medium vector in a PWM period as C6ΦSVPWM12-A, and with two medium vectors as C6ΦSVPWM12-B. The vector sequences and application times are shown in Table II, where T_n ($n=1...30$) represents the nonzero vector application times, as shown in Appendix A. T_0 is the remaining times which the zero vectors (**0, 7, 56** or **63**) are applied.

TABLE II
C6ΦSVPWM12-A VECTOR SEQUENCES AND APPLICATION TIMES

Sector	Vector sequences	Vector applying times
1	7,37,36,52,60,56 7,39,37,36,52,56 63,54,52,36,4,0	$T_0/2, T_1, T_2, T_3, T_4, T_0/2$ $T_0/2, -T_4, T_1, T_9, T_3, T_0/2$ $T_0/2, -T_1, T_6, T_5, T_7, T_0/2$
2	63,55,54,52,36,0 56,52,54,22,6,7 56,48,52,54,22,7 0,18,22,54,62,63	$T_0/2, -T_7, -T_1, T_{11}, T_5, T_0/2$ $T_0/2, T_8, -T_4, -T_5, T_9, T_0/2$ $T_0/2, -T_9, T_8, T_2, -T_5, T_0/2$ $T_0/2, -T_8, T_{11}, T_{10}, -T_6, T_0/2$
3	0,16,18,22,54,63 7,22,18,26,58,56 7,23,22,18,26,56 63,27,26,18,2,0	$T_0/2, T_6, -T_8, T_7, T_{10}, T_0/2$ $T_0/2, T_{12}, -T_9, -T_{10}, T_2, T_0/2$ $T_0/2, -T_2, T_{12}, -T_3, -T_{10}, T_0/2$ $T_0/2, -T_{12}, T_7, T_3, -T_{11}, T_0/2$
4	63,31,27,26,18,0 56,26,27,11,3,7 56,24,26,27,11,7 0,9,11,27,59,63	$T_0/2, T_{11}, -T_{12}, -T_6, T_3, T_0/2$ $T_0/2, -T_{11}, -T_2, -T_3, -T_4, T_0/2$ $T_0/2, T_4, -T_1, -T_9, -T_3, T_0/2$ $T_0/2, T_{11}, -T_6, -T_5, -T_7, T_0/2$
5	0,8,9,11,27,63 7,11,9,41,57,56 7,15,11,9,41,56 63,45,41,9,1,0	$T_0/2, T_7, T_1, -T_{11}, -T_5, T_0/2$ $T_0/2, -T_8, T_3, T_5, -T_9, T_0/2$ $T_0/2, T_9, -T_8, -T_2, T_5, T_0/2$ $T_0/2, T_8, -T_{11}, -T_{10}, T_6, T_0/2$
6	63,47,45,41,9,0 56,41,45,37,5,7 56,40,41,45,37,7 0,36,37,45,61,63	$T_0/2, -T_6, T_8, -T_7, -T_{10}, T_0/2$ $T_0/2, -T_{12}, T_9, T_{10}, -T_2, T_0/2$ $T_0/2, T_2, -T_{12}, T_3, T_{10}, T_0/2$ $T_0/2, T_{12}, -T_7, -T_3, T_{11}, T_0/2$
7	0,32,36,37,45,63	$T_0/2, -T_{11}, T_{12}, T_6, -T_3, T_0/2$

The voltage vector application sequences in sector-1 with medium vectors (**39, 60, 39** and **48, 60** and **5**) are illustrated in Fig. 5. It can be observed that there are only two switching actions in each phase. Hence, the switching frequencies can be regarded as equivalent. According to the above analysis, the 12-sector medium vector toggling modulation scheme can be obtained, and it is illustrated in Fig. 6.

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TABLE III

C6ΦSVPWM12-B VECTOR SEQUENCES AND APPLICATION TIMES

Sector	Vector sequences	Vector applying times
1	7,5,37,36,52,60,56	$T_0/2, T_4/2, T_{13}, T_{14}, T_3, T_4/2, T_0/2$
2	7,39,37,36,52,48,56	$T_0/2, -T_4/2, T_1, T_{14}, T_{17}, -T_4/2, T_0/2$
3	0,32,36,52,54,55,63	$T_0/2, -T_7/2, T_{18}, T_{15}, -T_1, -T_7/2, T_0/2$
4	0,4,36,52,54,62,63	$T_0/2, T_7/2, T_5, T_{15}, T_{16}, T_7/2, T_0/2$
5	56,60,52,54,22,6,7	$T_0/2, T_9/2, T_{19}, T_{20}, -T_5, T_9/2, T_0/2$
6	56,48,52,54,22,23,7	$T_0/2, -T_9/2, T_8, T_{20}, T_{23}, -T_9/2, T_0/2$
7	63,55,54,22,18,16,0	$T_0/2, T_6/2, T_{24}, T_{21}, -T_8, T_6/2, T_0/2$
8	63,62,54,22,18,2,0	$T_0/2, -T_6/2, T_{10}, T_{21}, T_{22}, -T_6/2, T_0/2$
9	7,6,22,18,26,58,56	$T_0/2, T_2/2, T_{25}, T_{26}, -T_{10}, T_2/2, T_0/2$
10	7,23,22,18,26,24,56	$T_0/2, -T_2/2, T_{12}, T_{26}, T_{29}, -T_2/2, T_0/2$
11	0,16,18,26,27,31,63	$T_0/2, T_{11}/2, T_{30}, T_{27}, -T_{12}, T_{11}/2, T_0/2$
12	0,2,18,26,27,59,63	$T_0/2, -T_{11}/2, T_3, T_{27}, T_{28}, -T_{11}/2, T_0/2$
1	56,58,26,27,11,3,7	$T_0/2, -T_4/2, -T_{13}, -T_{14}, -T_3, -T_4/2, T_0/2$
2	56,24,26,27,11,15,7	$T_0/2, T_4/2, -T_1, -T_{14}, -T_{17}, T_4/2, T_0/2$
3	63,31,27,11,9,8,0	$T_0/2, T_7/2, -T_{18}, -T_{15}, T_1, T_7/2, T_0/2$
4	63,59,27,11,9,1,0	$T_0/2, -T_7/2, -T_5, -T_{15}, -T_{16}, -T_7/2, T_0/2$
5	7,3,11,9,41,57,56	$T_0/2, -T_9/2, -T_{19}, -T_{20}, T_5, -T_9/2, T_0/2$
6	7,15,11,9,41,40,56	$T_0/2, T_9/2, -T_8, -T_{20}, -T_{23}, T_9/2, T_0/2$
7	0,8,9,41,45,47,63	$T_0/2, -T_6/2, -T_{24}, -T_{21}, T_8, -T_6/2, T_0/2$
8	0,1,9,41,45,61,63	$T_0/2, T_6/2, -T_{10}, -T_{21}, -T_{22}, T_6/2, T_0/2$
9	56,57,41,45,37,5,7	$T_0/2, -T_2/2, -T_{25}, -T_{26}, T_{10}, -T_2/2, T_0/2$
10	56,40,41,45,37,39,7	$T_0/2, T_2/2, -T_{12}, -T_{26}, -T_{29}, T_2/2, T_0/2$
11	63,47,45,37,36,32,0	$T_0/2, -T_{11}/2, -T_{30}, -T_{27}, T_{12}, -T_{11}/2, T_0/2$
12	63,61,45,37,36,4,0	$T_0/2, T_{11}/2, -T_3, -T_{27}, -T_{28}, T_{11}/2, T_0/2$

Fig. 5 The voltage vector application sequences in sector-1. (a) Sequences for vectors 37, 36, 52, 60 (b) Sequences for vectors 37, 36, 52, 39 (c) Sequences for vectors 37, 36, 52, 60 and 5 (d) Sequences for vectors 37, 36, 52, 39 and 48

Fig. 6 Flowchart of 12-sector medium vector toggling modulation

D. Analysis of the medium vector toggling modulation method

This section analyzes the proposed modulation method in terms of three aspects: the range of the DC-link voltage ratio, modulation depth, and toggling points of two types of medium vectors.

(1) Effective range of the DC-link voltage ratio

There are two factors affecting the application times of the vectors: the DC-link voltages u_{dc1} and u_{dc2} , and the reference voltage. The magnitude and phase of the reference voltage in the α - β plane are denoted by u_{ref} and θ , respectively, and θ is $0 < \theta < 30^\circ$ in sector-1. Since the voltage reference in the z_1 - z_2 plane is much lower than that in the α - β plane [13], it can be

assumed to be zero during the analysis. Based on the monotonicity of the large vector's application times, the large vectors with the shortest application times in (5)-(8) can be derived and illustrated in (10)-(13).

$$\min(T_{36_calc}) = \frac{\sqrt{3}T_s u_{ref}}{4u_{dc2}} + \frac{T_s(\sqrt{3}u_{dc1} - 2u_{dc2})}{4u_{dc1}u_{dc2}} u_{ref} \quad (37, 36, 52, 60) \quad (10)$$

$$\min(T_{36_calc}) = \frac{T_s(-u_{dc1} + \sqrt{3}u_{dc2})}{2u_{dc1}u_{dc2}} u_{ref} \quad (37, 36, 52, 39) \quad (11)$$

$$\min(T_{52_calc}) = \frac{T_s(2u_{dc1} - \sqrt{3}u_{dc2})}{4u_{dc1}u_{dc2}} u_{ref} \quad (37, 36, 52, 60 \text{ and } 5) \quad (12)$$

$$\min(T_{37_calc}) = \frac{3T_s u_{ref}}{8u_{dc1}} - \frac{T_s(2\sqrt{3}u_{dc1} + u_{dc2})}{8u_{dc1}u_{dc2}} u_{ref} \quad (37, 36, 52, 39 \text{ and } 48) \quad (13)$$

Because the application time of an active vector cannot be less than zero, the DC-link voltage ratio in the proposed method must satisfy the following relationship:

$$\begin{cases} \frac{1}{\sqrt{3}} \leq k \leq \sqrt{3} & (37, 36, 52, 60) \text{ or } (37, 36, 52, 39) \\ \frac{\sqrt{3}}{2} \leq k \leq \frac{2}{\sqrt{3}} & (37, 36, 52, 60 \text{ and } 5) \text{ or } (37, 36, 52, 39 \text{ and } 48) \end{cases} \quad (14)$$

(2) Modulation depth analysis

According to the application times of the zero vectors, the modulation depth of the linear modulation area can be obtained. Taking sector-1 as an example, the application times of the zero vectors are given by (15). Since the modulation depth can be calculated by the application times of the zero vectors, the maximal reference voltage in the α - β plane is equal to the smaller DC-link voltage, which is either u_{dc1} or u_{dc2} .

$$T_0 = \begin{cases} T_s - \frac{T_s u_{\alpha}}{u_{dc2}} + \frac{T_s u_{\beta}}{u_{dc1}} & (37, 36, 52, 60) \\ T_s - \frac{\sqrt{3}u_{\alpha}T_s}{2u_{dc1}} - \frac{u_{\beta}T_s}{2u_{dc1}} - \frac{\sqrt{3}u_{\beta}T_s}{2u_{dc1}} + \frac{u_{\alpha}T_s}{2u_{dc1}} & (37, 36, 52, 39) \\ T_s - \frac{T_s u_{\alpha}}{u_{dc2}} + \frac{T_s u_{\beta}}{u_{dc1}} & (37, 36, 52, 60 \text{ and } 5) \\ T_s - \frac{\sqrt{3}u_{\alpha}T_s}{2u_{dc1}} - \frac{u_{\beta}T_s}{2u_{dc1}} - \frac{\sqrt{3}u_{\beta}T_s}{2u_{dc1}} + \frac{u_{\alpha}T_s}{2u_{dc1}} & (37, 36, 52, 39 \text{ and } 48) \end{cases} \quad (15)$$

(3) Toggling points of two types medium vectors

If the application times of the medium vectors in sector-1 are zero, the toggling points of the medium vectors can be calculated as:

$$\left(\frac{\sqrt{3}}{2} - k\right)\cos\theta + \frac{1}{2}\sin\theta = 0 \quad (16)$$

Thus, when the reference voltage vector in the z_1 - z_2 plane is zero, the toggling point of the medium vectors in the sector-1 is:

$$\theta = \arctan(2k - \sqrt{3}) \quad (17)$$

Fig. 7 Medium voltage vector toggling point

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It can be observed that the medium vector toggling point is determined only by the DC-link voltage ratio, and u_{ref} does not affect the toggling point. The medium vector switching moments under different DC-link voltage ratios are obtained as shown in Fig. 7. 1 indicates the usage of type-1 medium vectors, and 0 indicates the usage of type-2 medium vectors. The following conclusions can be obtained.

- (1) The application times of type-2 medium vectors are shorter than those of type-1 vectors if $k < 1$.
 - (2) The application times of type-1 vectors are shorter than those of type-2 vectors if $k > 1$.
 - (3) When the DC-link voltage ratio is less than $\frac{\sqrt{3}}{2}$, type-1 medium vectors are always applied in sector-1.
 - (4) When the DC-link voltage ratio exceeds $\frac{2}{\sqrt{3}}$, type-2 medium vectors are always applied in sector-1.
 - (5) The toggling point is at the center of the sector when the DC-link voltage is balanced. Therefore, the C6ΦSVPWM12-A can be transformed to the modulation scheme proposed in [10].
- E. Comparison of the proposed method with other SVPWM approaches under unbalanced voltages*

Two typical six-phase SVPWM methods based on VSD are used for comparison purposes in this section. The first is the C6ΦSVPWM approach proposed in [27] using four large voltage vectors, and the second is the C6ΦSVPWM24 approach proposed in [10] using three large voltage vectors and one medium vector.

As an example, the DC-link voltage ratio is set to 0.9. The borders of sector-1 and sector-2 under C6ΦSVPWM and C6ΦSVPWM24 are shown in Fig. 8(a), with the nonzero vector as the sector border. It can be observed that the sectors of conventional SVPWM are non-uniform under the unbalanced DC-link voltage, while the proposed method has fixed sectors. Therefore, the proposed method can reduce the calculation burden of the complicated sector classification.

If the voltage reference in z_1 - z_2 plane is neglected, the vectors application times of three methods in sector-1 are shown in Fig. 8(b). It can be observed that the large vectors 45 and 52 in C6ΦSVPWM have negative application times, and the application time of medium vector 60 in C6ΦSVPWM24 becomes negative as the reference voltage phase increases. The proposed method avoids this negative application time by toggling the medium vector from 60 to 39. Therefore, the proposed method can easily choose the suitable vectors to track the reference voltage even though the DC-link voltage is unbalanced.

Fig. 8 Comparison of C6ΦSVPWM, C6ΦSVPWM24 and C6ΦSVPWM12-A under $k=0.9$. (a) Sector border and vector selection. (b) Calculated voltage vector application times.

IV. EXPERIMENT RESULTS

The experimental platform is constructed based on two DC-links, as shown in Fig. 9(a). The dual three-phase PMSM is coupled with an asynchronous motor as the load. The dual three-phase driver is constructed by two single three-phase drives, which have the same power inverter topology as that in Fig. 1(c). The DC-link voltages are regulated by two diode-rectifiers and transformers. The parameters of the dual three-phase PMSM used in the experiment are given in Table IV. Field-oriented control (FOC), developed in [24] based on VSD, is adopted to control the speed of the dual three-phase PMSM (shown in Fig. 9(b)). The z_1 - z_2 plane control scheme is based on synchronous frame current control using PI controllers to suppress the fifth and seventh current harmonics. The control parameters are shown in Table IV. The FOC and SVPWM algorithms are implemented by using a TMS320F28335 Texas Instruments digital signal processor, and the PWM pulse is generated by a EP2CQ208C8 field-programmable gate array (FPGA).

Fig.9 Experimental setup for dual three-phase PMSM driver. (a) Experimental platform. (b) Control method used in the experiment

TABLE IV

Dual three-phase PMSM system parameters	
Parameter	Value
Stator resistance (Ω)	1.8856
d -axis inductance (H)	0.0475
q -axis inductance (H)	0.0783
Rotor flux linkage (Wb)	0.942
Pole pairs	5
Nominal DC-link voltage(V)	570
PWM period (us)	250
Dead-band time (us)	6
Current loop proportional gain in dq	1.5
Current loop integral gain in dq	0.001
Current loop proportional gain in $z1z2$	0.2
Current loop integral gain in $z1z2$	0.001
Speed loop proportional gain	6.4
Speed loop integral gain	0.001

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A. Comparative experiment for steady-state operation

In this experiment, two conventional six-phase SVPWM methods, C6ΦSVPWM and C6ΦSVPWM24, are compared with the proposed method. Experimental results for the SVPWM strategy under $u_{dc1}=495V$ and $u_{dc2}=570V$ are presented in Fig. 10. The motor speed is controlled at 300rpm under the torque of 210Nm. The steady-state stator line voltages and current waveforms under the conventional C6ΦSVPWM and C6ΦSVPWM24 methods and the proposed C6ΦSVPWM12-A and C6ΦSVPWM12-B techniques are shown in Fig. 10(a), (b), (c), and (d). It can be observed that the proposed C6ΦSVPWM12-A and C6ΦSVPWM12-B techniques lead to higher quality stator current waveform than the conventional C6ΦSVPWM and C6 ΦSVPWM24 methods. This is because the proposed SVPWM methods have the ability to control the current in the α - β and z_1 - z_2 planes under an unbalanced DC-link voltage.

To further analyse the stator currents and voltages, the

waveform data of U_{AB1} and I_{A1} are imported into MATLAB for fast Fourier transform (FFT) analysis. The FFT results of line voltage U_{AB1} under the four VSD based SVPWM approaches are shown in Fig. 10(e), (f), (g) and (h). As seen from the harmonic spectra, the conventional SVPWM methods contain more $6k \pm 1$ order harmonics, such as 5th, 7th, 11th and 13th order harmonics than the proposed methods, and this mainly results from the error voltage vectors selection under the unbalanced DC-link voltage. Consequently, the conventional SVPWM methods produce the most harmonic current under the unbalanced DC-link voltage as shown in Fig. 10(i) and (j), while the proposed C6ΦSVPWM12-A and C6ΦSVPWM12-B methods can suppress the stator current as shown in Fig. 10(k) and (m). The C6ΦSVPWM12-B PWM technique has the lowest THD because the two medium voltage vectors are used in one PWM cycle, thereby producing a reduced ripple current.

Fig.10 Experimental results for steady-state operation ($u_{dc1}=495V$, $u_{dc2}=570V$, 25Hz, 210Nm) using the C6ΦSVPWM, C6ΦSVPWM24, C6ΦSVPWM12-A, and C6ΦSVPWM12-B methods. (a), (b), (c), and (d) Stator voltages and currents under the four SVPWM methods. (e), (f), (g), and (h) FFT results for the stator voltages under the four SVPWM methods. (i), (j), (k), and (m) FFT results for the stator currents under the four SVPWM methods.

The four SVPWM methods (C6ΦSVPWM, C6ΦSVPWM24, C6ΦSVPWM12-A, and C6ΦSVPWM12-B) under different DC-link voltage ratios are compared in terms of their stator current total harmonic distortions (THDs). The THD results of stator current I_{A1} under different DC-link voltage ratios are presented in Fig. 11. The stator current THDs of the conventional C6ΦSVPWM and C6ΦSVPWM24 techniques increase rapidly as the DC-link voltage imbalance increases, and the THDs of C6ΦSVPWM12-A and C6ΦSVPWM12-B are less affected by DC-link voltage imbalances. These results confirm that the proposed SVPWM technique provides better performance than the conventional methods under unbalanced DC-link voltages. Since the proposed C6ΦSVPWM12-A method is equivalent to C6ΦSVPWM24 under a balance DC-

link voltage, the THD of the C6ΦSVPWM12-A method is close to that of C6ΦSVPWM24 when the DC-link voltages are the same. C6ΦSVPWM12-B leads to a lower THD than that of C6ΦSVPWM12-A. This is because two medium voltage vectors are used in one PWM cycle. The current THD of C6ΦSVPWM24 under the $k=495/570$ is obviously larger than that under $k=495/570$. The reason is that the current is unbalanced and the fundamental current (12.27 A) of phase A1 is less than those of the others (approximately 15A), as shown in Fig.10(i) (j) (k) (m).

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Fig.11 Stator current THDs for different SVPWM techniques at 25 Hz and 210 Nm.

B. Experiment with regard to dynamic operation

The dynamic experiments are carried out by changing the motor speed. The rotational speed of the dual three-phase machine accelerates linearly from 100 rpm to 300 rpm and then decelerates to 100 rpm with a constant load torque of 210 Nm. The dual three-phase PMSM electromagnetic torque, rotational speed and phase current for A1 and A2 under the proposed SVPWM methods are shown in Fig.12(a) and (b). It is evident that the phase current can remain balanced during the whole transient operation. It is shown that the proposed SVPWM methods can achieve good performances under a variable-speed operation. This paper focuses on solving the VSD-based SVPWM problem under unbalanced DC-link voltages, and it is necessary to verify the effectiveness of the proposed methods with dynamic changes in the DC-link voltage. Experimental results under manual u_{dc1} changes are presented in Fig. 12(c) and (d). u_{dc2} is set to 570 V, and the motor speed and torque are set to the 300 rpm and 210Nm, respectively. It can be observed that the stator current can remain balanced in spite of DC-link voltage ratio fluctuations. The medium voltage vector toggling modulation approach proposed in this paper can control the output voltage effectively during the dynamic process.

Fig. 12 Dynamic experimental results. (a) Speed transition under C6ΦSVPWM12-A. (b) Speed transition under C6ΦSVPWM12-B. (c) DC-link voltage transition under C6ΦSVPWM12-A. (d) DC-link voltage transition under C6ΦSVPWM12-B.

V. CONCLUSION

In this paper, an enhanced SVPWM technique suitable for imbalanced DC-link voltages based on VSD is investigated.

According to the characteristics of medium voltage vectors, two modulation strategies, C6ΦSVPWM12-A and C6ΦSVPWM12-B, with medium voltage vector toggling are proposed. A detailed analysis of the proposed method in terms of the modulation depth, the range of the DC-link voltage ratio and the toggling point of the medium vector is presented. The proposed method can avoid complicated sector judgment algorithms under a non-uniform voltage vector distribution, and satisfy the voltage output requirements in the α - β and z_1 - z_2 planes with a certain range of DC-link voltage ratio changes. The effectiveness of the proposed method is verified by comparative experiments on a prototype dual three-phase PMSM system. The obtained results show that the proposed methods provide lower stator current harmonic components than those of conventional six-phase SVPWM approaches under an imbalanced DC-link voltage, and the proposed C6ΦSVPWM12-B method achieves better harmonic current performance than C6ΦSVPWM12-A. The dynamic experimental results confirm the viability of the proposed SVPWM method.

APPENDIX

Applying time	value
T ₁	$\frac{T_s}{2u_{dc1}}(ku_a - \sqrt{3}ku_\beta - ku_{z1} - \sqrt{3}ku_{z2})$
T ₂	$\frac{T_s}{2u_{dc1}}[-(k-\sqrt{3})u_a + (\sqrt{3}k-1)u_\beta + (k+\sqrt{3})u_{z1} + (\sqrt{3}k+1)u_{z2}]$
T ₃	$\frac{T_s}{u_{dc1}}(u_\beta - u_{z2})$
T ₄	$\frac{T_s}{2u_{dc1}}[(2k-\sqrt{3})u_a - u_\beta - (2k+\sqrt{3})u_{z1} + u_{z2}]$
T ₅	$\frac{T_s}{2u_{dc1}}(\sqrt{3}u_a - u_\beta + \sqrt{3}u_{z1} + u_{z2})$
T ₆	$\frac{T_s}{2u_{dc1}}[ku_a - (\sqrt{3}k-2)u_\beta - ku_{z1} - (2+\sqrt{3}k)u_{z2}]$
T ₇	$\frac{T_s}{2u_{dc1}}[(k-\sqrt{3})u_a + (\sqrt{3}k-1)u_\beta - (k+\sqrt{3})u_{z1} + (\sqrt{3}k+1)u_{z2}]$
T ₈	$\frac{T_s}{u_{dc1}}(ku_a - ku_{z1})$
T ₉	$\frac{T_s}{2u_{dc1}}[ku_a + (\sqrt{3}k-2)u_\beta - ku_{z1} + (2+\sqrt{3}k)u_{z2}]$
T ₁₀	$\frac{T_s}{2u_{dc1}}(-\sqrt{3}u_a + u_\beta + \sqrt{3}u_{z1} - u_{z2})$
T ₁₁	$\frac{T_s}{2u_{dc1}}[(2k-\sqrt{3})u_a + u_\beta - (2k+\sqrt{3})u_{z1} - u_{z2}]$
T ₁₂	$\frac{T_s}{2u_{dc1}}(ku_a + \sqrt{3}ku_\beta - ku_{z1} + \sqrt{3}ku_{z2})$
T ₁₃	$\frac{T_s}{4u_{dc1}}[\sqrt{3}u_a + (1-2\sqrt{3}k)u_\beta + \sqrt{3}u_{z1} - (1+2\sqrt{3}k)u_{z2}]$
T ₁₄	$\frac{T_s}{4u_{dc1}}[\sqrt{3}u_a + (2\sqrt{3}k-3)u_\beta + \sqrt{3}u_{z1} + (3+2\sqrt{3}k)u_{z2}]$
T ₁₅	$\frac{T_s}{4u_{dc1}}[(3k-\sqrt{3})u_a + (3-\sqrt{3}k)u_\beta - (3k+\sqrt{3})u_{z1} - (3+\sqrt{3}k)u_{z2}]$
T ₁₆	$\frac{T_s}{4u_{dc1}}[(\sqrt{3}-3k)u_a + (\sqrt{3}k+1)u_\beta + (3k+\sqrt{3})u_{z1} + (\sqrt{3}k-1)u_{z2}]$
T ₁₇	$\frac{T_s}{4u_{dc1}}[(2k-\sqrt{3})u_a + 3u_\beta - (2k+\sqrt{3})u_{z1} - 3u_{z2}]$
T ₁₈	$\frac{T_s}{4u_{dc1}}[(k+\sqrt{3})u_a + (\sqrt{3}k-3)u_\beta - (k-\sqrt{3})u_{z1} + (\sqrt{3}k+3)u_{z2}]$
T ₁₉	$\frac{T_s}{4u_{dc1}}[3ku_a + (2-\sqrt{3}k)u_\beta - 3ku_{z1} - (\sqrt{3}k+2)u_{z2}]$
T ₂₀	$\frac{T_s}{4u_{dc1}}[(2\sqrt{3}-3k)u_a + \sqrt{3}ku_\beta + (3k+2\sqrt{3})ku_{z1} + \sqrt{3}ku_{z2}]$
T ₂₁	$\frac{T_s}{4u_{dc1}}[(3k-2\sqrt{3})u_a + \sqrt{3}ku_\beta - (3k+2\sqrt{3})ku_{z1} + \sqrt{3}ku_{z2}]$
T ₂₂	$\frac{T_s}{4u_{dc1}}[-3ku_a + (2-\sqrt{3}k)u_\beta + 3ku_{z1} - (\sqrt{3}k+2)u_{z2}]$
T ₂₃	$\frac{T_s}{4u_{dc1}}[(k-2\sqrt{3})u_a + \sqrt{3}ku_\beta - (k+2\sqrt{3})ku_{z1} + \sqrt{3}ku_{z2}]$

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$$\begin{aligned}
 T_{24} &= \frac{T_s}{4u_{dc1}} \left[(2\sqrt{3}-k)u_a + \sqrt{3}ku_\beta + (k+2\sqrt{3})ku_{\alpha 1} + \sqrt{3}ku_{\alpha 2} \right] \\
 T_{25} &= \frac{T_s}{4u_{dc1}} \left[(3k-\sqrt{3})u_a + (\sqrt{3}k+1)u_\beta - (3k+\sqrt{3})u_{\alpha 1} + (\sqrt{3}k-1)u_{\alpha 2} \right] \\
 T_{26} &= \frac{T_s}{4u_{dc1}} \left[(\sqrt{3}-3k)u_a + (3-\sqrt{3}k)u_\beta + (3k+\sqrt{3})u_{\alpha 1} - (\sqrt{3}k+3)u_{\alpha 2} \right] \\
 T_{27} &= \frac{T_s}{4u_{dc1}} \left[-\sqrt{3}u_a + (2\sqrt{3}k-3)u_\beta - \sqrt{3}u_{\alpha 1} + (1+2\sqrt{3}k)u_{\alpha 2} \right] \\
 T_{28} &= \frac{T_s}{4u_{dc1}} \left[-\sqrt{3}u_a + (1-2\sqrt{3}k)u_\beta - \sqrt{3}u_{\alpha 1} - (1+2\sqrt{3}k)u_{\alpha 2} \right] \\
 T_{29} &= \frac{T_s}{4u_{dc1}} \left[-(k+\sqrt{3})u_a + (\sqrt{3}k-3)u_\beta + (k-\sqrt{3})u_{\alpha 1} + (\sqrt{3}k+1)u_{\alpha 2} \right] \\
 T_{30} &= \frac{T_s}{4u_{dc1}} \left[(\sqrt{3}-2k)u_a + 3u_\beta + (2k+\sqrt{3})u_{\alpha 1} - 3u_{\alpha 2} \right]
 \end{aligned}$$

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