DC Voltage Balancing Strategy of a Bipolar-Output Active Rectifier for More Electric Aircraft Based on Zero Vector Redistribution

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ABSTRACT The ±270 V bipolar dc distribution has become an attractive power supply scheme in more electric aircraft (MEA). In this paper, a dc voltage balancing strategy based on zero vector redistribution (ZVR) is proposed for a three-phase coupled inductor-based bipolar-output active rectifier (TCIBAR) to achieve balanced ±270 V power supply for MEAs. First, the mathematical model of the TCIBAR is developed in the rotating reference frame and the zero-sequence equivalent circuit of the three-phase coupled inductor (TCI) branch is derived. On this basis, the effect mechanism of the zero-sequence voltage is analyzed in balancing the output dc voltages of the TCIBAR. Second, a voltage balancing control scheme is designed to control the zero-sequence voltage and maintain the dc voltage balance of the TCIBAR under unbalanced load condition. Finally, a ZVR-space vector pulse width modulation (ZVR-SVPWM) method is proposed. With the ZVR-SVPWM method, the duration time of zero vectors can be redistributed to modulate the desired zero-sequence voltage for the TCIBAR. The proposed dc voltage balancing strategy for the TCIBAR is implemented on an experimental platform, and the experimental results verify the feasibility and effectiveness of the proposed control scheme and ZVR-SVPWM method.

INDEX TERMS DC voltage balancing control, zero vector redistribution, bipolar-output active rectifier, more electric aircraft.

NOMENCLATURE

ABBREVIATIONS

- ATRU: Auto Transformer Rectifier Unit
- DSP: Digital Signal Processor
- EPS: Electric Power System
- MEA: More Electric Aircraft
- PWM: Pulse Width Modulation
- SVPWM: Space Vector Pulse Width Modulation
- TCI: Three-phase Coupled Inductor
- TCIBAR: Three-phase Coupled Inductor-based Bipolar-output Active Rectifier
- VSC: Voltage Source Converter
- ZVR: Zero Vector Redistribution

VARIABLES

- \( e_a, e_b, e_c \): three-phase voltages of ac source
- \( u_{an}, u_{bn}, u_{cn} \): neutral point voltages of three-phase bridges
- \( u_{al}, u_{bl}, u_{cl} \): three-phase voltages across the TCI
- \( i_{al}, i_{bl}, i_{cl} \): three-phase currents of ac source
- \( i_{al}, i_{bl}, i_{cl} \): three-phase currents of the TCI
- \( e_{d}, e_{q}, e_{0} \): ac source voltages in dq0 frame
- \( u_{d0}, u_{q0}, u_{00} \): neutral point voltages of three-phase bridges in dq0 frame
- \( u_{d0}, u_{q0}, u_{00} \): voltages of the TCI in dq0 frame
- \( i_{d0}, i_{q0}, i_{00} \): voltages of the TCI in dq0 frame
- \( l_{d0}, l_{q0}, l_{00} \): ac source currents in dq0 frame
- \( l_{d0}, l_{q0}, l_{00} \): currents of the TCI in dq0 frame
- \( l_{d0}, l_{q0}, l_{00} \): total zero-sequence current of the TCI
- \( U_{dc} \): dc bus voltage
In order to establish the ±270 V bipolar dc distribution system in MEA, a bipolar-output rectifier unit is essential and important. In Boeing 787, an auto transformer rectifier unit (ATRU) is used to convert 230 V ac power to ±270 V dc power [9], [10]. Nowadays, ATRU has become one of the most attractive solutions for its high reliability, simple structure and low harmonic current [16]–[18]. As is well known, ATRU is an uncontrolled rectifier, which does not have the ability to regulate the output voltage actively, and a large voltage deviation will occur if high-power loads are connected to the ±270 V dc ports. Moreover, ATRU cannot feed unbalanced dc loads at the two dc ports for the reason that it cannot eliminate the dc voltage imbalance, which is caused by the unbalanced loads. However, with the development of aircraft electrification, the type and quantity of the electrical loads in future MEAs will continue to grow. Therefore, in order to improve the adaptability of the ±270 V dc distribution system to various loads, it is necessary and meaningful to explore an active bipolar-output rectifier, which has the ability to actively regulate the output dc voltages and maintain the voltage balance between the ±270 V dc poles.

A general topology for an active bipolar-output rectifier is to use two pulse width modulation (PWM) rectifiers in series at dc port [19], [20]. However, in order to withstand the dc offset voltage caused by the series connection, a transformer with two secondary windings is required in this topology. This system structure has the disadvantage of high complexity and heavy weight, and thus it is not suitable for MEAs. An improved solution is to employ a PWM rectifier along with a voltage balancer [21]–[23]. The voltage balancer consists of a half bridge and a filter inductor connected to the neutral point of the output dc poles. By controlling the current flowing into the neutral point, the voltage balancer can maintain the voltage balance between the dc poles. However, the voltage balancer requires additional power switches and auxiliary device but does not improve the power rating of the converter. In addition, the voltage balancer also increases the cost, power loss and complexity of the converter. In recent years, a three-phase coupled inductor-based bipolar-output active rectifier (TCIBAR) has been proposed to establish the bipolar dc distribution system in decentralized power grids [24], [25]. In the topology of TCIBAR, a three-phase coupled inductor (TCI) is connected between the ac and dc sides of a two-level voltage source converter (VSC). The TCI is used to generate the zero-sequence current injected to the neutral point of the dc bus and the voltage balance between the positive and negative dc poles can be achieved by regulating the zero-sequence current. Compared with the two active bipolar-output rectifier topologies mentioned above, the TCIBAR has the advantages of simpler structure, fewer power devices and less complexity. Meanwhile, the small zero-sequence impedance of the TCI leads to a fast

### PARAMETERS

\[
\begin{align*}
\mu_p & \quad \text{voltage of positive dc pole} \\
\mu_n & \quad \text{voltage of negative dc pole} \\
\Delta u & \quad \text{voltage difference between dc poles} \\
i_{dc+} & \quad \text{positive bus current} \\
i_{dc-} & \quad \text{negative bus current} \\
i_p & \quad \text{load current of positive dc pole} \\
i_n & \quad \text{load current of negative dc pole} \\
d_{p}, d_{n}, d_{c} & \quad \text{duty cycle of upper switch in three-phase bridges} \\
d_0 & \quad \text{zero-sequence duty cycle of upper switches} \\
\varepsilon & \quad \text{voltage coefficient for the negative dc pole voltage} \\
S_a, S_b, S_c & \quad \text{switching state of three-phase bridges} \\
t_0 \sim t_7 & \quad \text{duration time of voltage space vectors} (\bar{V}_0 \sim \bar{V}_7) \text{ in one switching period} \\
\Delta t & \quad \text{difference between } t_7 \text{ and } t_0 \\
\end{align*}
\]

**I. INTRODUCTION**

With the rapid development of power electronics in recent years, significant progress has been made in the research of electric power system (EPS) for more electric aircraft (MEA) [1]–[3]. In order to reduce the weight of the aircraft and improve the power capacity of the EPS, the ±270 V bipolar dc distribution system is considered to be an optimized system solution for MEA and has attracted the attention of many researchers [4]–[9]. On the one hand, the higher voltage level in ±270 V bipolar dc distribution system can obtain lower system weight and larger power supply capacity [6]–[9]. On the other hand, the ±270 V bipolar dc distribution system can not only provide different voltage levels to the loads, but also has the advantages of high reliability and simple fault detection [11]–[15]. At present, the ±270 V bipolar dc distribution has been successfully applied to the high-voltage dc buses of the EPS in Boeing 787 [8]–[10].
response of the zero-sequence current, which enables the fast dynamic voltage balancing control of the TCIBAR.

However, the existing research on TCIBAR mainly contributes to the modelling of TCIBAR [24] and does not delve into the dc voltage balancing control of the TCIBAR under unbalanced load condition. Furthermore, the modulation method applicable to TCIBAR and its key role in dc voltage balancing control have not been paid much attention to.

Therefore, in order to maintain the dc voltage balance of TCIBAR under unbalanced load condition, this paper derives the mathematical model with zero-sequence components for the TCIBAR and analyzes the close relationship between the zero-sequence voltage and the dc voltage balancing control of the TCIBAR. Then, a voltage balancing control scheme based on zero vector redistribution (ZVR) is proposed to achieve balanced ±270 V output voltages of the TCIBAR. Moreover, in order to realize the redistribution of zero vectors, a ZVR-space vector pulse width modulation (ZVR-SVPWM) method is proposed based on the analysis of the effect mechanism of voltage space vectors, and the implementation steps of the ZVR-SVPWM method are presented.

The rest of this paper is organized as follows. The mathematical model of TCIBAR containing the zero-sequence component is deduced in Section II and the proposed dc voltage balancing control scheme based on ZVR is introduced in Section III. Section IV presents the basic principle and the implementation steps of the proposed ZVR-SVPWM method. In Section V, the experimental results are illustrated to validate the feasibility and effectiveness of the proposed dc voltage balancing control scheme as well as the ZVR-SVPWM method. Finally, the conclusions are presented in Section VI.

II. MATHEMATICAL MODEL OF TCIBAR

The topology of the TCIBAR is shown in Fig. 1. As can be seen, the TCIBAR is constructed with an additional TCI on the basis of a traditional three-phase PWM rectifier. In the model of a traditional three-phase PWM rectifier, the zero-sequence components are usually ignored since no zero-sequence current exists in the circuit. However, the TCIBAR provides a path for the zero-sequence current through the TCI, which makes the model of the traditional three-phase PWM rectifier unsuitable for the TCIBAR. Therefore, in order to analyze and utilize the zero-sequence current to control the output voltages at positive and negative dc poles (\(u_a\) and \(u_c\)), the mathematical model of the TCIBAR containing zero-sequence components is developed in this section.

In this paper, a three-phase ac voltage source is adopted as the power supply instead of a generator. Meanwhile, the variables in the ac source branch and the TCI branch are marked by subscripts “s” and “t” respectively, and the projection components of the variables on dq0 axes are represented by subscripts “d”, “q” and “0”.

As shown in Fig. 1, the phase voltage equations for the ac source branch can be expressed as

\[
\begin{bmatrix}
e_d \\
e_q \\
e_0
\end{bmatrix} = L_s \begin{bmatrix}
\frac{d}{dt} i_{sa} \\
\frac{d}{dt} i_{sq} \\
\frac{d}{dt} i_{so}
\end{bmatrix} + R_s \begin{bmatrix}
i_{sa} \\
i_{sq} \\
i_{so}
\end{bmatrix} + \begin{bmatrix}
u_a \\
u_b \\
u_c
\end{bmatrix}
\]

(1)

where \(u_{aN}, u_{bN}, u_{cN}\) are the voltages between the neutral points of the three-phase bridges and the neutral point of the ac source, and \(L_s\) and \(R_s\) are the inductance and winding resistance of the filter inductors.

Based on the Park transformation, the voltage equations in (1) can be rewritten in dq0 frame as (2).

\[
\begin{bmatrix}
e_d \\
e_q
\end{bmatrix} = L_s \begin{bmatrix}
\frac{d}{dt} i_{sd} \\
\frac{d}{dt} i_{sq}
\end{bmatrix} + L_s \begin{bmatrix}
-\omega i_{sd} \\
0
\end{bmatrix} + R_s \begin{bmatrix}
i_{sd} \\
i_{sq}
\end{bmatrix} + \begin{bmatrix}
u_a \\
u_b
\end{bmatrix}
\]

(2)

where \(\omega\) is the angular frequency of the ac source voltage.

Because the ac source branch does not contain zero-sequence current (\(i_{so} = 0\)), the zero-sequence component in (2) can be ignored and (2) can be simplified as

\[
\begin{bmatrix}
e_d \\
e_q
\end{bmatrix} = L_s \begin{bmatrix}
\frac{d}{dt} i_{sd} \\
\frac{d}{dt} i_{sq}
\end{bmatrix} + L_s \begin{bmatrix}
-\omega i_{sd}
\end{bmatrix} + R_s \begin{bmatrix}
i_{sd} \\
i_{sq}
\end{bmatrix} + \begin{bmatrix}
u_a \\
u_b
\end{bmatrix}
\]

(3)

Equation (3) is the same as the mathematical model of a traditional three-phase PWM rectifier, which can only be used to regulate the total dc bus voltage \(U_{dc}\). Therefore, in order to realize balanced dc voltages for the two dc poles in TCIBAR, the voltage equations for the TCI branch are derived as follows:

\[
L_{TCI} \frac{d}{dt} \begin{bmatrix}
i_{ta} \\
i_{tb}
\end{bmatrix} + R_{TCI} \begin{bmatrix}
i_{ta} \\
i_{tb}
\end{bmatrix} = \begin{bmatrix}
u_{aN} \\
u_{bN}
\end{bmatrix}
\]

(4)

where \(u_{aN}, u_{bN}, u_{cN}\) are the voltages across the TCI, and \(L_{TCI}\) and \(R_{TCI}\) are the inductance matrix and winding resistance matrix of the TCI.

Considering that there may be a large zero-sequence current flowing through the TCI when the loads at the two dc poles are unbalanced, the TCI can adopt a balanced three-
phase magnetic core to avoid core saturation [26]. The inductance matrix and winding resistance matrix of the TCI with a three-phase balanced magnetic core are shown in (5).

\[
\begin{align*}
L_{TCI} &= \begin{bmatrix} L & -M & -M \\ -M & L & -M \\ -M & -M & L \end{bmatrix} \\
R_{TCI} &= \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix}
\end{align*}
\]

(5)

where \( L, M \) and \( R \) are the self-inductance, mutual inductance, and winding resistance of the TCI.

By applying the Park transformation, the impedance matrices as well as the voltage equations for the TCI in dq0 frame are obtained as follows:

\[
\begin{align*}
L_{TCI,dq0} &= \begin{bmatrix} L_d & 0 & 0 \\ 0 & L_q & 0 \\ 0 & 0 & L_0 \end{bmatrix} \\
0 & L_0 & 0 \\
R_{TCI,dq0} &= \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix}
\end{align*}
\]

(6)

It can be seen from (6) that the zero-sequence inductance \( L_0 \) is much lower than the inductances \( L_d \) and \( L_q \) on dq axes. The large dq-axes inductances can limit the dq-axes current of the TCI to reduce the loss, and the small zero-sequence inductance leads to the fast response of zero-sequence current, which facilitates the voltage balancing control of the two dc poles.

In order to analyze the relationship between the voltage balancing control and the zero-sequence current of the TCIBAR under unbalanced load condition, the average current equations for the positive and negative capacitors are deduced as (8).

\[
\begin{align*}
\frac{du_i}{dt} &= \frac{i_{dc+} - i_p}{C_{+}} \\
\frac{d(-u_i)}{dt} &= \frac{i_{dc-} - i_n}{C_{-}}
\end{align*}
\]

(8)

To keep the voltage balance between the positive and negative capacitors, the currents flowing into the capacitors should be the same and thus (9) can be obtained according to (8).

\[
\begin{align*}
i_{dc+} - i_{dc-} &= i_p - i_n
\end{align*}
\]

(9)

Defining the duty cycle of the upper switch in phase \( x \) (\( x=a, b, c \) as \( d \)), the positive bus current \( i_{dc+} \) can be expressed as follows:

\[
i_{dc+} = d_x(i_{a_x} - i_{a_x}) + d_y(i_{b_y} - i_{b_y}) + d_z(i_{c_z} - i_{c_z})
\]

(10)

Since the upper and lower switches in a bridge are complementary, the negative bus current \( i_{dc-} \) can be derived as (11).

\[
i_{dc-} = (d_x - 1)(i_{a_x} - i_{a_x}) + (d_y - 1)(i_{b_y} - i_{b_y}) + (d_z - 1)(i_{c_z} - i_{c_z})
\]

(11)

Substituting (10) and (11) into (9), the constraint equation for keeping the capacitors voltage balanced can be further deduced as follows:

\[
i_p - i_n = i_{dc+} + i_{dc-} - i_{dc-} - i_{dc+} = -3i_{10}
\]

(12)

Therefore, by actively controlling the zero-sequence current \( i_{10} \) of the TCI, the voltage balance between the dc poles can be maintained even under unbalanced load condition.

### III. VOLTAGE BALANCING CONTROL SCHEME OF TCIBAR

In order to generate balanced ±270 V dc voltages for MEA, a well-designed voltage balancing control scheme of TCIBAR is very essential. Generally, the voltage imbalance between the positive and negative dc poles is caused by the unbalanced loads on the two dc poles, and the voltage difference increases with the growing of the load power imbalance. Based on the aforementioned derivation and analysis, the zero-sequence current of the TCI can be used to eliminate the voltage difference and maintain the voltage balance of the two dc poles under unbalanced load condition. According to (7), the zero-sequence circuit equation of the TCI can be derived as

\[
(L - 2M) \frac{d i_{10}}{dt} + R i_{10} = u_{d0}
\]

(13)

As can be seen, the zero-sequence current of the TCI depends on the zero-sequence voltage \( u_{d0} \) applied to the TCI and thus the accurate control of the zero-sequence voltage is the key to realizing voltage balance between the positive and negative poles in TCIBAR.

Since the voltage across the TCI can be expressed as (14), the zero-sequence voltage applied to the TCI can be derived by the Park transformation, as shown in (15), and the zero-sequence equivalent circuit of the TCI branch can be obtained as Fig. 2.

\[
\begin{align*}
u_{aN} &= d_x U_{d+} - \varepsilon U_{a+} \\
u_{bN} &= d_y U_{d+} - \varepsilon U_{b+} \\
u_{cN} &= d_z U_{d+} - \varepsilon U_{c+}
\end{align*}
\]

(14)
where \( \varepsilon \) (0 \( \leq \varepsilon \leq 1 \)) is the voltage coefficient for the negative dc pole voltage \( u_{dc} = -\varepsilon U_{dc} \) and \( d_0 \) is the zero-sequence duty cycle for each upper switch.

It can be seen that the zero-sequence voltage across the TCI is the voltage difference between the zero-sequence voltage modulated by the VSC and the neutral-point voltage of the dc side. Therefore, in order to synthesize the desired zero-sequence voltage applied to the TCI, the effect mechanism of the voltage space vectors on the zero-sequence voltage will be analyzed.

According to the switching state of the three-phase bridges, the instantaneous voltage across the TCI can be expressed as follows:

\[
\begin{align*}
    u_{aN} &= S_a U_{dc} - \varepsilon U_{dc} \\
    u_{bN} &= S_b U_{dc} - \varepsilon U_{dc} \\
    u_{cN} &= S_c U_{dc} - \varepsilon U_{dc}
\end{align*}
\]

(16)

where \( S_x \) (\( x=a, b, c \)) is the switching state of the bridge in phase \( x \) and the upper and lower switches in a bridge are turned on in a complementary way while \( S_x = 1 \) means that the upper switch is on and \( S_x = 0 \) means that the lower switch is on.

Based on the Clarke transformation, the phase voltage across the TCI can be represented in the \( \alpha \beta 0 \) stationary reference frame, as shown in (17).

\[
\begin{bmatrix}
    u_{\alpha} \\
    u_{\beta} \\
    u_{0}
\end{bmatrix} =
\begin{bmatrix}
    \frac{2}{3} S_a - \frac{1}{3} S_b - \frac{1}{3} S_c \\
    \frac{\sqrt{3}}{3}(S_b - S_c) \\
    \frac{1}{3}(S_a + S_b + S_c)
\end{bmatrix}
\begin{bmatrix}
    U_{dc} \\
    -\varepsilon U_{dc}
\end{bmatrix}
\]

(17)

With different switching states, there are eight cases of voltage space vectors that can be applied to the TCI. Based on (16) and (17), the eight basic voltage space vectors for the TCI are shown in Table 1, where the voltages are all normalized with reference to the dc bus voltage \( U_{dc} \).

According to the voltage amplitude of the \( \alpha \beta 0 \) axes components, \( V_0 \) and \( V_f \) are defined as zero vectors, and \( V_{1f} \) and \( V_{2f} \) are defined as non-zero vectors. As shown in Table 1, both the non-zero and zero vectors contain zero-sequence components, and the zero-sequence components depend not only on the switching states of the VSC but also on the voltage of the dc-side neutral point. It can be seen that there are four cases of the zero-sequence components: 1) \( -\varepsilon U_{dc} \) in \( V_0 \); 2) \( (1-\varepsilon)U_{dc} \) in \( V_f \); 3) \( (1/3-\varepsilon)U_{dc} \) in \( V_1 \), \( V_2 \), \( V_3 \), and \( V_4 \); and 4) \( (2/3-\varepsilon)U_{dc} \) in \( V_5 \), \( V_6 \), and \( V_7 \).

Therefore, it can be concluded that the desired zero-sequence voltage can be modulated by a special modulation method and the proposed ZVR-SVPWM method will be introduced in Section VI.

Meanwhile, in order to obtain the voltage references for modulation, a voltage balancing control scheme of the TCIBAR is proposed and shown in Fig. 3. The proposed control scheme mainly consists of bus voltage control, voltage balancing control and the ZVR-SVPWM method, among which the voltage balancing control and the ZVR-SVPWM method are the focus and main contribution of this paper.

According to the aforementioned analysis, a voltage difference will occur between the positive and negative poles when the loads on the two poles are unbalanced. Defining the voltage difference \( \Delta u \) as (18),

\[
\Delta u = u_\alpha - |u_\alpha| \hat{u},
\]

(18)

an outer voltage loop with the reference value \( \Delta u^* \) of zero is constructed with a PI controller and the output of the outer voltage loop is set as the zero-sequence current reference of the TCI. Meanwhile, according to (12), the load current difference can be considered as a feedforward of the zero-sequence current and added to the control loop. A deadbeat controller is adopted in the inner current loop to improve the transient response of the zero-sequence current. For the digital implementation of the deadbeat controller, (13) is rewritten in discretized method based on backward Euler method, as shown in (19).

\[
(L - 2M)\left[ \frac{i_{\alpha}(k+1) - i_{\alpha}(k)}{T_s} \right] + Ri_{\alpha}(k) = u_{\alpha}(k)
\]

(19)
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In the dc voltage balancing control of the TCIBAR and thus zero-sequence voltage across the TCI plays an important role. However, the duration time of zero vectors is equally divided, and the effect of the zero-axis component is ignored. Therefore, to make the actual current track the reference value, the zero-sequence current reference $i_{00}^*$ is assigned to the estimated zero-sequence current $i_{00}(k+1)$ of next sampling period and the zero-sequence voltage reference $u_{00}^*$ can be obtained as

$$u_{00}^* = (L - 2M) \frac{i_{00}^* - i_{00}(k)}{T_s} + Ri_{00}(k)$$ (20)

In addition, the bus voltage control method is the same as that in a conventional PWM rectifier, where the outer loop is designed for regulating the dc bus voltage and the output of the outer loop is set as the active current reference $i_{sa}^*$. Meanwhile, the reactive current reference $i_{sq}^*$ can be set according to demand. In this paper, $i_{sq}^*$ is set to zero to realize unity power factor operation of the ac source. Then, the PI controllers are designed for the $dq$-axes currents to obtain the $d$-axis and $q$-axis voltage references.

When all the voltage references are obtained, the proposed ZVR-SVPWM method can modulate the desired zero-sequence voltage applied to the TCI by redistributing the duration time of the zero vectors, which will be detailed in next section.

**IV. PROPOSED MODULATION METHOD BASED ON ZVR**

The conventional SVPWM has been widely used in three-phase active rectifiers due to its advantages of low harmonics, high dc voltage utilization and easy digital implementation. In the conventional SVPWM, the reference voltages are synthesized and modulated on the $\alpha\beta$ plane, where the duration time of zero vectors is equally divided, and the effect of the zero-axis component is ignored. However, the zero-sequence voltage across the TCI plays an important role in the dc voltage balancing control of the TCIBAR and thus the duration time of zero vectors will be redistributed to modulate the zero-sequence voltage reference in the proposed ZVR-SVPWM method.

According to Table 1, the eight basic voltage space vectors can be represented in the $\alpha\beta0$ frame, as shown in Fig. 4(a), and the projection of the basic space vectors on the $\alpha\beta$ plane is shown in Fig. 4(b). It can be seen that as the voltage of the dc-side neutral point changes, the zero-sequence component contained in each space vector changes as well. In addition, the projection of the space vectors on the $\alpha\beta$ plane forms a hexagon with the side length of $2U_{dc}/3$, which is the same as the hexagon structure of the space vectors in conventional SVPWM and will not be affected by the voltage change of the dc-side neutral point.

In one switching period of the conventional SVPWM, the duration time of non-zero vectors is calculated according to the $\alpha\beta$-axes reference voltages $u_\alpha^*$ and $u_\beta^*$, and the rest time of the switching period is equally divided by two zero vectors. But as for the TCIBAR, in order to balance the voltage between the dc poles, the duration time of the zero vectors must be redistributed based on the volt-second equivalent principle to synthesize the desired zero-sequence voltage.

**FIGURE 3. Proposed voltage balancing control scheme of the TCIBAR.**

**FIGURE 4. Voltage space vector diagram of the TCIBAR. (a) Voltage space vectors in $\alpha\beta0$ frame. (b) Projection of voltage space vectors on $\alpha\beta$ plane.**
Based on the proposed control scheme, the reference voltage vector \( \mathbf{V}_{\text{ref}} \) for modulation is obtained and defined as
\[
\mathbf{V}_{\text{ref}} = \left[ \begin{array}{c} u_{\alpha}^* \\ u_{\beta}^* \\ u_{\text{0}}^* \end{array} \right]^T
\]  
(21)

By projecting the reference voltage vector \( \mathbf{V}_{\text{ref}} \) to the \( \alpha\beta \) plane and the zero-axis, the projection vectors can be expressed as
\[
\begin{align*}
\mathbf{V}_{\text{ref, \alpha\beta}} &= \left[ \begin{array}{c} u_{\alpha}^* \\ u_{\beta}^* \\ 0 \end{array} \right]^T \\
\mathbf{V}_{\text{ref, \theta}} &= \left[ 0 \ 0 \ u_{\text{0}}^* \right]^T
\end{align*}
\]  
(22)

where \( \mathbf{V}_{\text{ref, \alpha\beta}} \) is the projection vector of \( \mathbf{V}_{\text{ref}} \) on the \( \alpha\beta \) plane and \( \mathbf{V}_{\text{ref, \theta}} \) is the projection vector on the zero-axis.

Without loss of generality, this paper takes the projection vector \( \mathbf{V}_{\text{ref, \alpha\beta}} \) in sector I as an example to analyze the implementation of the ZVR-SVPWM method, as shown in Fig. 4(b). As can be seen, the projection vector \( \mathbf{V}_{\text{ref, \alpha\beta}} \) in sector I can be synthesized by the two adjacent basic space vectors \( \mathbf{V}_4 \) and \( \mathbf{V}_6 \), which are the projection components of \( \mathbf{V}_4 \) and \( \mathbf{V}_6 \) on the \( \alpha\beta \) plane. Thus, the duration time of the non-zero vectors \( \mathbf{V}_4 \) and \( \mathbf{V}_6 \) can be obtained based on the vector synthesis of \( \mathbf{V}_{\text{ref, \alpha\beta}} \) on the \( \alpha\beta \) plane, as shown in (23).
\[
\begin{align*}
t_4 &= \frac{\sqrt{3}T_s}{U_{\text{dc}}} \left( \frac{\sqrt{3}}{2} u_{\alpha}^* - u_{\beta}^* \right) \\
t_6 &= \frac{\sqrt{3}T_s}{U_{\text{dc}}} u_{\beta}^*
\end{align*}
\]  
(23)

where \( t_4 \) and \( t_6 \) are the duration time of \( \mathbf{V}_4 \) and \( \mathbf{V}_6 \), and \( T_s \) is the switching period which equals to the sampling period.

Considering the zero-sequence component, the vector synthesis of \( \mathbf{V}_{\text{ref}} \) in a switching period can be represented as (24) and the duration time of the space vectors should satisfy (25).
\[
\mathbf{V}_{\text{ref}} = \frac{1}{T_s} \left( V_4 t_0 + V_4 t_4 + V_6 t_6 + V_7 t_7 \right)
\]  
(24)
\[
T_s = t_0 + t_4 + t_6 + t_7
\]  
(25)

where \( t_0 \) and \( t_7 \) are the duration time of \( \mathbf{V}_0 \) and \( \mathbf{V}_7 \).

As mentioned above, both the zero vectors and non-zero vectors contain zero-sequence components. Therefore, according to thevolt-second equivalent principle and the zero-sequence components contained in \( \mathbf{V}_6 \), \( \mathbf{V}_4 \), \( \mathbf{V}_7 \) and \( \mathbf{V}_\theta \), the zero-sequence reference voltage can be synthesized as
\[
u_{\text{0}}^* = \frac{1}{T_s} \left[ -\varepsilon U_{\text{dc}} t_0 + \frac{2}{3} (1-\varepsilon) U_{\text{dc}} t_4 + \frac{2}{3} (1-\varepsilon) U_{\text{dc}} t_6 + (1-\varepsilon) U_{\text{dc}} t_7 \right]
\]  
(26)

Since the duration time of the non-zero vectors (\( t_4 \) and \( t_6 \)) has been determined by (23), the desired \( \mathbf{V}_{\text{ref, \theta}} \) can be modulated by a reasonable redistribution of the duration time of the zero vectors (\( t_7 \) and \( t_0 \)). Defining the difference between \( t_7 \) and \( t_0 \) as the ZVR time \( \Delta t \), \( \Delta t \) can be deduced from (25) and (26) as
\[
\Delta t = t_7 - t_0 = \left[ 2 \left( \frac{t_7}{U_{\text{dc}}} - \varepsilon \right) \right] T_s + \frac{1}{3} (t_4 - t_6)
\]  
(27)

Therefore, the zero vector duration time can be obtained as
\[
\begin{align*}
t_4 &= \frac{T_s - t_7 - t_0}{2} + \frac{\Delta t}{2} \\
t_6 &= \frac{T_s - t_7 - t_0}{2} - \frac{\Delta t}{2}
\end{align*}
\]  
(28)

Based on (23) - (28), the redistribution process of the zero vectors in one switching period is shown in Fig. 5(a) and (b).

**FIGURE 5.** Diagram of the redistribution of zero vectors in a switching period. (a) Switching sequence of the bridges before ZVR. (b) Switching sequence of the bridges after ZVR. (c) Zero-sequence voltage applied to the TCI in one switching period.
As can be seen, the redistributed time $\Delta t$ is evenly distributed in the zero vectors while the total duration time of the zero vectors keeps unchanged and equal to $(T_s - t_4 - t_6)$. In addition, the redistribution of the zero vectors does not affect the duration time of the non-zero vectors. Fig. 5(c) shows the zero-sequence voltage applied to the TCI in one switching period. It can be seen that the real-time zero-sequence voltage applied to the TCI can be controlled by regulating the ZVR time.

When the projection vector $V_{\text{ref},\alpha\beta}$ is in other sectors (II-VI), the duration time of the corresponding voltage space vectors can be obtained in the same way. For sectors I-VI, the duration time calculation of the non-zero vectors and the calculation of the ZVR time are concluded and shown in (29) and Table 2, where $t_i$ and $t_f$ represent the duration time of the non-zero vectors that contain the zero-sequence component of $(1/3\varepsilon)U_{dc}$ and $(2/3\varepsilon)U_{dc}$ respectively.

$$
\begin{align*}
x &= \frac{\sqrt{3}T_s u_{\alpha}'}{U_{dc}} \\
y &= \frac{\sqrt{3}T_s}{U_{dc}} \left(\frac{3}{2} u_{\alpha} + \frac{1}{2} u_{\beta}'\right) \\
z &= \frac{\sqrt{3}T_s}{U_{dc}} \left(\frac{3}{2} u_{\alpha}' + \frac{1}{2} u_{\beta}\right)
\end{align*}
$$

(29)

Based on the above analysis and derivation, the diagram of the proposed ZVR-SVPWM method is shown in Fig. 6 and the implementation steps of the ZVR-SVPWM method are presented as follows.

Step 1: Determine the sector (I-VI) where the projection vector $V_{\text{ref},\alpha\beta}$ is located according to the voltage reference on $\alpha\beta$-axes ($u_{\alpha}$ and $u_{\beta}$).

Step 2: Calculate the duration time of the two adjacent non-zero vectors according to (29) and Table 2.

Step 3: Calculate the ZVR time $\Delta t$ according to the zero-sequence voltage reference $u_{\alpha}^*$, the dc-side neutral point voltage $u_6$ and Table 2.

Step 4: Redistribute the duration time of the two zero vectors $V_0$ and $V_7$ based on (28) and the results of Step 2 and Step 3.

Table 2. Duration time calculation of voltage space vectors.

| Sector | Vectors | $t_i$ | $t_f$ | $\Delta t$ |
|--------|---------|-------|-------|-----------|
| I      | $V_0, V_1, V_2, V_3$ | $-Z$ | $X$ | $(2[u_{\alpha}^*/U_{dc} + \varepsilon] - 1)T_s - (X + Z)/3$ |
| II     | $V_0, V_4, V_5, V_6$ | $Z$ | $Y$ | $(2[u_{\alpha}^*/U_{dc} + \varepsilon] - 1)T_s + (Z - Y)/3$ |
| III    | $V_0, V_2, V_3, V_4$ | $X$ | $-Y$ | $(2[u_{\alpha}^*/U_{dc} + \varepsilon] - 1)T_s + (X + Y)/3$ |
| IV     | $V_0, V_1, V_2, V_3$ | $-X$ | $Z$ | $(2[u_{\alpha}^*/U_{dc} + \varepsilon] - 1)T_s - (X + Z)/3$ |
| V      | $V_0, V_4, V_5, V_6$ | $-Y$ | $-Z$ | $(2[u_{\alpha}^*/U_{dc} + \varepsilon] - 1)T_s + (Z - Y)/3$ |
| VI     | $V_0, V_1, V_2, V_3$ | $Y$ | $-X$ | $(2[u_{\alpha}^*/U_{dc} + \varepsilon] - 1)T_s + (X + Y)/3$ |

V. EXPERIMENTAL VERIFICATION

A. EXPERIMENTAL PLATFORM AND PARAMETERS

An experimental platform of the TCIBAR is developed in the laboratory to validate the feasibility of the proposed voltage balancing control scheme and the ZVR-SVPWM method. As shown in Fig. 7, the experimental platform consists of a VSC, a TCI, sampling sensors, a three-phase programmable ac source, dc loads and a control unit. The parameters of the experimental platform are shown in Table 3. The control unit of the platform is constructed based on a TMS320F28335 digital signal processor (DSP) and the sampling frequency of the control system is set as 10 kHz.

Table 3. Experimental platform parameters.

| Parameter | Symbol | Value |
|-----------|--------|-------|
| Rated dc bus voltage | $U_{dc}$ | 540 V |
| Rated positive pole voltage | $u_p$ | 270 V |
| Rated negative pole voltage | $u_n$ | -270 V |
| Rated power | $P$ | 5 kW |
| Phase RMS voltage of ac source | $U_{ac}$ | 230 V |
| Frequency of ac source | $f_{ac}$ | 400 Hz |
| Filter inductance | $L_{f}$ | 0.3 mH |
| Positive pole capacitance | $C_p$ | 6600 µF |
| Negative pole capacitance | $C_n$ | 6600 µF |
| Self-inductance of TCI | $L$ | 0.526 H |
| Mutual inductance of TCI | $M$ | 0.259 H |
| Switching frequency | $f_s$ | 10 kHz |
B. STEADY-STATE EXPERIMENTAL RESEARCH

To research the steady-state performance of the proposed voltage balancing control scheme under unbalanced load condition, comparative experiments were carried out with two different methods respectively. Method I is the conventional control method of rectifiers with SVPWM and Method II is the proposed voltage balancing control scheme based on ZVR. To constitute the unbalanced load condition, a 30 Ω resistive load is connected to the negative pole of the TCIBAR and the positive pole keeps unloaded.

The steady-state experimental results of the two methods under unbalanced load condition are shown in Fig. 8 and Fig. 9 respectively. To judge whether the two dc-pole voltages ($u_p$ and $u_n$) are balanced visually and easily, $u_p - u_n$ are shown in the waveforms. Meanwhile, the total zero-sequence current ($i_{l0} = 3i_{l0}$), which is injected to the dc-side neutral point, is measured and given in the results.

![Time (5 ms/div)](a)

![Time (5 ms/div)](b)

![Time (5 ms/div)](c)

![Time (20 μs/div)](d)

**FIGURE 8.** Steady-state experimental results of Method I under unbalanced load condition. (a) Load currents and total zero-sequence current. (b) Voltages of the two dc poles and the dc bus. (c) Three-phase input currents of the TCIBAR. (d) Driving pulses generated by DSP.

As shown in Fig. 8(a), when the load currents of the positive and negative poles are severely unbalanced, the total zero-sequence current of the TCI is not equal to the load current difference, which does not satisfy the constraint equation for keeping the voltage balance in (12). Therefore, the positive and negative pole voltages cannot maintain balance with Method I and a voltage difference around 30 V exists between the poles, as shown in Fig. 8(b).

Meanwhile, it can be seen from Fig. 8(a) that the ripple of the total zero-sequence current is high. The high current ripple will not only result in high loss and noise of the TCI, but also bring the disadvantages of voltage ripple on the two dc poles and reduced capacitor life, which is not conductive to the application of the TCIBAR in MEAs.

With the proposed dc voltage balancing control scheme based on ZVR, the total zero-sequence current of the TCI is controlled to be almost equal to the load current difference.

![Time (5 ms/div)](a)

![Time (5 ms/div)](b)

![Time (5 ms/div)](c)

![Time (20 μs/div)](d)

**FIGURE 9.** Steady-state experimental results of Method II under unbalanced load condition. (a) Load currents and total zero-sequence current. (b) Voltages of the two dc poles and the dc bus. (c) Three-phase input currents of the TCIBAR. (d) Driving pulses generated by DSP.
between the two dc poles, as shown in Fig. 9(a). Therefore, the voltages of the two dc poles can be balanced with Method II under unbalanced load condition, as shown in Fig. 9(b). Meanwhile, it can be seen from Fig. 9(a) that the zero-sequence current ripple can be greatly reduced with Method II. In addition, the reduction of the zero-sequence current ripple can lead to lower voltage ripple on the two dc poles, which can be found by comparing Fig. 8(b) and Fig. 9(b).

The driving pulses generated by DSP with the conventional SVPWM method in Method I are shown in Fig. 8(d), where PWM_a, PWM_b and PWM_c are the driving pulses of the upper switches in the bridges of phases a, b, and c. The zero-sequence components contained in the corresponding space vectors are also given in Fig. 8(d). As can be seen, the duration time of the zero vectors (000) and (111) is almost the same and the small error is caused by the dead time for the switches. Fig. 9(d) shows the waveforms of the driving pulses of the proposed ZVR-SVPWM method and the corresponding zero-sequence components. By comparing the zero-sequence components in Fig. 8(d) and Fig. 9(d), it can be found that the duration time of the zero vectors is redistributed with the proposed ZVR-SVPWM method to modulate the zero-sequence voltage reference and the duration time of the non-zero vectors remains unchanged.

Therefore, the steady-state experimental results verify the feasibility of the ZVR-SVPWM method and prove that the proposed dc voltage balancing strategy of the TCIBAR has good steady-state performance under unbalanced load condition.

C. DYNAMIC EXPERIMENTAL RESEARCH

To research the dynamic performance of the proposed dc voltage balancing strategy, load step experiments were done with balanced and unbalanced loads respectively.

The experimental results with balanced step loads are shown in Fig. 10. At a certain point in time, 60 Ω step resistive loads are connected to both the positive and negative poles of the TCIBAR. As shown in Fig. 10(b), the balanced step loads cause a voltage drop around 20 V on both of the two dc poles and the total dc bus drops about 40 V. Once the voltage drop is detected by the control unit, the TCIBAR immediately increases the three-phase input currents and provides the required load power, as shown in Fig. 10(c). Meanwhile, it can be seen from Fig. 10(b) that the two dc-pole voltages of the TCIBAR can be restored to ±270 V within 40 ms with the proposed control scheme. In the dynamic process, the two dc-pole voltages are balanced and the total zero-sequence current of the TCI remains almost zero with only a small ripple, as shown in Fig. 10(a).

The dynamic experimental results of unbalanced step loads are shown in Fig. 11. As shown in Fig. 11(a), a 30 Ω step resistive load is connected to the negative pole of the TCIBAR at a certain instant while the positive pole keeps unloaded. It can be seen from Fig. 11(b) that the negative-pole voltage drops about 30 V while the voltage of positive

FIGURE 10. Dynamic experimental results of the proposed voltage balancing strategy with balanced step loads. (a) Load currents and total zero-sequence current. (b) Voltages of the two dc poles and the dc bus. (c) Three-phase input currents of the TCIBAR.

FIGURE 11. Dynamic experimental results of the proposed voltage balancing strategy with unbalanced step loads. (a) Load currents and total zero-sequence current. (b) Voltages of the two dc poles and the dc bus. (c) Three-phase input currents of the TCIBAR.
pole remains almost constant, which leads to a voltage imbalance between the two dc poles. Owing to the proposed voltage balancing control scheme, the TCIBAR can respond immediately when the unbalanced step load is switched on. On the one hand, the three-phase input currents are increased quickly to provide the load power, as shown in Fig. 11(c). On the other hand, the zero-sequence current is regulated rapidly to a new steady state and restores the voltage balance between the dc poles, as shown in Fig. 11(a) and Fig. 11(b). It can be seen that the whole dynamic process of unbalanced load step is smooth and only takes about 40 ms.

VI. CONCLUSION

This paper proposes a dc voltage balancing strategy based on ZVR for the TCIBAR to generate balanced ±270 V bipolar power supply for MEAs. Based on the proposed control scheme, the zero-sequence voltage across the TCI is used to regulate the zero-sequence current injected to the dc-side neutral point and maintain the voltage balance between the ±270 V dc poles of the TCIBAR. Moreover, by redistributing the duration time of zero vectors, the desired zero-sequence voltage can be modulated accurately with the proposed ZVR-SVPWM method. The experimental results under unbalanced load condition show that the proposed control scheme has good steady-state and dynamic performance in dc voltage balancing control of TCIBAR. Therefore, the TCIBAR with the proposed dc voltage balancing strategy can be considered as a proper candidate for supplying balanced ±270 V dc power in future MEAs.

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