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Fault-tolerant control strategy of open-winding brushless doubly fed wind power generator based on direct power control

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1 | INTRODUCTION

Nowadays, the brushless doubly fed reluctance generator (BDFRG) has been proposed as a potential alternative to the existing solutions for wind power applications. The main reasons of this increasing interest could be found in reasonable cost, brushless structure, flexibly controllable active and reactive power, low converter capacity, and so on [1–5]. The reliable and stable operation of the practical wind power generation system relies highly on its capability of continuous fault-free operation. However, power switches in the converter are one of the most vulnerable components and thus play a key role in the robustness and reliability of the entire system [6]. Therefore, scholars have made great efforts to provide reliable post-fault operation for various motor/generator systems that attach absolute importance to safety.

There are two general approaches to endow a typical three-phase converter fault-tolerant to switch fault, either without or with converter topology reconfiguration. The former is achieved through hardware redundancy. A redundant leg can be connected to all the converter phases through TRIACs, permitting the replacement of the faulty leg and keeping the same converter topology [7–9]. The latter changes the system topology by activating extra switches for post-fault operation, including split-capacitor (SC) topology, extra-leg SC (ELSC) topology, extra-leg extra-switch (ELES) topology, double switch-redundant topology, four-leg inverter topology, and four-leg inverter topology, and so on. In SC topology, the faulty phase is connected to the midpoint of the dc bus. In ELSC topology, the machine neutral point is another alternative topology (ELES topology, double switch-redundant topology, and four-leg inverter topology). It required additional stator leads to be brought out of the machine in ELES topology, ELES topology, and four-leg inverter topology. A comparative performance study of SC topology, ELSC topology, and ELES topology for VM-based DTC BLAC drives has been presented [10]. Many fault-tolerant three-phase ac motor drive topologies have been compared, including SC topology, ELSC topology, phase-redundant topology, double switch-redundant topology, four-leg inverter topology, and so
on [11]. In a back-to-back converter, the phases of both sides (grid/machine) can be connected to each other through TRIACs [12]. Then, under post-fault operation, one leg is shared, forming the five-leg converter topology, which requires switches with power rating four times higher. This topology was adopted and studied for fault-tolerant control of doubly fed induction generator (DFIG)-based wind energy conversion application [13, 14]. For the back-to-back converter, the phases of both sides can also be considered separately; only the grid side is connected to the midpoint of the dc bus through TRIACs [15]. The multi-level converter is also an effective solution for fault tolerance because of more additional switching states. An active fault-tolerant space vector pulse width modulation (PWM) strategy for single-phase faults in three-phase multi-level converters is proposed [16]. The multi-level converter is converted into a two-level converter for post-fault operation. As a special multi-level converter structure, the dual converter topology connected to an open-winding machine has been discussed [17–19] and applied in fault-tolerant control [20, 21]. The effectiveness of this structure in induction machine direct torque control based under incipient faults of the power switches in single dc-link dual inverters has been verified [20]. This structure was applied to a DC-biased vernier reluctance machine to maintain the output capability after the open-circuit fault [21]. In the dual converter topology, both ends of phases can also be connected to the midpoint of the corresponding dc bus [22]. Compared with the conventional single converter driving system, open-winding dual converter topology has merits of low-voltage stress, low switching losses, better fault tolerance, and also has the advantages of non-neutral voltage fluctuation, smaller converter capacity compared with conventional multi-level topology [17–19, 21]. This solution provides additional assistance for healthy cases, but with raised total cost.

The control strategy needs to match the system structure in post-fault operation, which is related to the converter topology and the control object. Various PWM and space vector modulation technologies have been proposed for FSTPC, for the purpose of current distortion reduction [23, 24] and dc-link imbalance compensation [25, 26]. The control methods for the topology, where an extra leg connected to the machine neutral point, have also been widely discussed [27–29]. The control strategies of five-leg converter topology based on vector control (VC) studied [12–14]. The dual converter topology has gradually aroused the interest of scholars, and various researches on it have emerged [17–21], including the control strategy of both healthy operation and post-fault operation. Regarding the control of the various fault-tolerant converters, VC strategies are widely used, while direct control technology has been less studied. Direct power control (DPC) has fast dynamic power response, which has been successfully applied to the DFIG-based wind power generation systems, but its application in BDFRG-based systems is not yet abundant and mature.

The post-fault operation strategy based on DPC of open-winding BDFRG (OW-BDFRG) is studied here. The control winding (CW) of BDFRG is designed as an open-winding structure and then connected with the dual converter. For post-fault operation, the dual converter topology is changed by closing the TRIACs, which connect the faulty phase with the midpoint of the dc bus. The output voltage of the dual converter is selected through a predetermined lookup table, which is constructed based on DPC. The active and reactive power of PW can still be effectively controlled when power switch faults. The feasibility of the proposed strategy is verified by simulation and experimental studies.

2 | MATHEMATICAL MODEL AND DPC THEORY

The space vector equations of BDFRM are expressed as [1–4]:

\[
u_p = R_p i_p + \frac{d\lambda_p}{dt} + j\omega \lambda_p,
\]

where \( R \) and \( L \) represent resistance and inductance, respectively. \( u, i \) and \( \lambda \) represent voltage, current and flux vector, respectively. \( L_{pc} \) is the mutual inductance between PW and CW. \( \omega_r = p_\omega \omega_m \) is rotor mechanical electrical angular velocity, and \( p \) is rotor poles. Subscript \( p \) and \( c \) indicate PW and CW, respectively. Sub-subscript \( r \) indicates that the vector is in a rotating reference frame. Note that PW and CW variables are with reference to different reference frames: the \( \omega \) frame for PW and \( \omega_r \) frame for CW. Superscript * indicates conjugate. Define the reference frame for CW to be rotating at zero, that is, \( \omega = \omega_r \). Therefore, PW reference frame is now \( \omega_r \).

Therefore, the equations for the system become:

\[
u_p = R_p i_p + \frac{d\lambda_p}{dt} + j\omega \lambda_p,
\]

where the sub-subscript \( s \) on the CW expression is to emphasise that the frame is stationary, and similarly the \( r \) subscript on the PW equation is to signify that the frame is still rotating.

The active and reactive power of PW can be calculated from the PW voltage and current vectors as:

\[
P = \frac{3}{2} \text{Re} \left( u_p \cdot i_p^* \right) = \frac{3}{2} R_p |i_p|^2 + \frac{3}{2} \frac{\omega_r L_{pc}}{\sigma L_p L_c} \text{Im}(\lambda_c \cdot \lambda_p^*) + \frac{3}{2} \frac{\omega_r L_{pc}}{\sigma L_p L_c} |\lambda_p|^2 |\lambda_c| \sin \delta
\]
where \( \sigma = 1 - L_{pc}^2/(L_pL_c) \), \( \omega_p \) is the frequency applied to the PW. \( \delta \) is the angle between \( \lambda_c \) and \( \lambda_p^* \), which is equal to the position angle of the former minus the position angle of the latter. It is worth highlighting that \( \lambda_c \) is ahead of \( \lambda_p^* \) for motoring operation, and that it lags the latter in the generating mode. Equations (9) and (10) reveal the relationship between the power of PW and the flux vectors. The active and reactive power of the PW can be controlled directly by controlling the angle between the flux vectors and their amplitude. Assuming constant PW voltage and ignoring PW resistance, Equations (9) and (10) can be simplified as:

\[
P_p = K_1 |\lambda_c| \sin \delta \quad (11)
\]

\[
Q_p = K_1 (K_2 - |\lambda_c| \cos \delta) \quad (12)
\]

where \( K_1 \) and \( K_2 \) are constants. \( P_p \) and \( Q_p \) can be controlled by adjusting the size of \( |\lambda_c| \sin \delta \) and \( |\lambda_c| \cos \delta \), as shown in Figure 1(a). Assuming that CW is connected to a two-level converter and the CW flux vector is in Sector I (the plane is divided into six sectors on average), the effect of the voltage vector output by the converter on power is shown in Figure 1(b). Appropriate vectors \( (U_5, U_6, U_4, \text{ and } U_0) \) are selected to increase/decrease active/reactive power. Under the same voltage conditions but for the generating mode, \( \delta < 0 \) and \( P_p < 0 \), the effect of the voltage vectors does not change. In summary, if the CW flux vector lies in the kth sector, then application of voltage vectors \( U_{k+1} \) or \( U_{k+2} \) would increase \( P_p \), whereas \( U_{k-1} \) or \( U_{k-2} \) would decrease it. Meanwhile, application of voltage vectors \( U_{k+2} \) or \( U_{k-2} \) would increase \( Q_p \), whereas \( U_{k+1} \) or \( U_{k-1} \) would decrease it. It should be noted that the effect of zero vector on power is different between sub-synchronous and super-synchronous operation. The zero vector makes the CW flux vector almost unchanged, which can cause a small change in power. In sub-synchronous operation, \( \lambda_c \) and \( \lambda_p^* \) rotate counter-clockwise, application of zero vector would decrease \( |\lambda_c| \sin \delta \) (\( P_p \) decreases) and increase \( |\lambda_c| \cos \delta \) (\( Q_p \) increases). In super-synchronous operation, \( \lambda_c \) and \( \lambda_p^* \) rotate clockwise, application of zero vector would increase \( |\lambda_c| \sin \delta \) (\( P_p \) increases) and decrease \( |\lambda_c| \cos \delta \) (\( Q_p \) increases).

### 3. TOPOLOGY OF OW-BDFRG FAULT-TOLERANT CONTROL

The topology of the OW-BDFRG connected to dual two-level converter is depicted in Figure 2. The CW is connected, connected with the dual converter, and PW is grid-connected. There are six TRIACs increased in this structure. Each phase of CW is connected to the midpoint of the dc bus through corresponding TRIACs. The TRIACs remain open under normal operation. The topology under this condition is the same as that with general dual two-level converter. If an IGBT on any phase is detected as an open-circuit fault, the TRIACs of the corresponding phase will be closed, and the other IGBT on the same phase will be in the trigger suppression state. At this time, the faulty phase is directly connected to the midpoint of the dc bus, and the IGBT on the faulty phase is isolated. According to Figure 2, the phase voltage of the CW can be expressed as Equation (15) regardless of normal operation or post-fault operation.

\[
\begin{bmatrix}
\mu_{a1d1} \\
\mu_{b1e1} \\
\mu_{c1f1}
\end{bmatrix} = \begin{bmatrix}
2 & -1 & -1 \\
-1 & 2 & -1 \\
-1 & -1 & 2
\end{bmatrix} \begin{bmatrix}
\mu_{a1n1} - \mu_{a1n2} \\
\mu_{b1n1} - \mu_{b1n2} \\
\mu_{c1n1} - \mu_{c1n2}
\end{bmatrix} \quad (13)
\]

\[
\begin{bmatrix}
\mu_{a1d1} \\
\mu_{b1e1} \\
\mu_{c1f1}
\end{bmatrix} = \frac{1}{3} \begin{bmatrix}
2 & -1 & -1 \\
-1 & 2 & -1 \\
-1 & -1 & 2
\end{bmatrix} \begin{bmatrix}
S_{4d} - S_{5d} \\
S_{4b} - S_{5b} \\
S_{4c} - S_{5c}
\end{bmatrix} \quad (14)
\]

For normal system, \( u_{x1} = U_{dc1}S_{ax}, u_{y1} = U_{dc2}S_{by} \) where \( S_{ax}, y \in \{0,1\}, x = a1, b1, c1, \text{ and } y = d1, e1, f1. \) If \( U_{dc1} = U_{dc2} = U_{dc} \), Equation (13) can be expressed as Equation (14). The voltage vector diagram of CW (Figure 3) can be drawn according to the \( a'p \) axis component of CW voltage vector. The corresponding relationship between voltage vector, switching state, and phase voltage is shown in Table 1. There are 64 switching states in the dual converter during normal operation, corresponding to 19 different CW voltage vectors. Among them, 10 kinds of switching states make the phase voltage of CW 0V, corresponding to zero vector, and the remaining 54 kinds of switching states make CW produce effective phase voltage, corresponding to 18 different effective vectors. The amplitude of the longest effective vector is \( 4U_{dc}/3 \), and the magnitude of the shortest effective vector is \( 2U_{dc}/3 \). In the dual converter.
scheme, $P_p$ and $Q_p$ are still contributed by three-phase currents of PW and CW (according to the current form expression of $P_p$ and $Q_p$). Therefore, the demanded current for a given power is similar to a conventional two-level converter scheme. However, the maximum value of the space voltage vector for the dual converter is two times that of a conventional two-level converter, which means that for the same output power, the dc bus voltage of the dual converter is half of the traditional two-level converter, and the required rated power is therefore reduced. On the other hand, the dual converter is capable of producing a fundamental peak phase voltage of 1.155 pu with space vector PWM without overmodulation, which is two times that of a conventional two-level converter.

According to Figure 2, one phase fault of dual converter includes: one phase fault in Converter1 / Converter2, one phase fault in both Converter1 and Converter2. Details are listed in Table 2. If two or three phases fault in Converter1 / Converter2, the CW voltage vectors for fault-tolerant operation cannot be formed by dual converter.

The control block diagram of the post-fault operation for OW-BDFRG system is shown in Figure 4. $P_p$ and $Q_p$ are controlled by adjusting the rotation and amplitude of $\lambda_c$ and $\lambda_e$ is regulated by $u_c$. $u_c$ is determined by the output of the power hysteresis comparator and the sector where $\lambda_e$ is located. $\lambda_e$ is estimated from $i_d$ and $i_q$ as shown in Figure 5. Figure 6 details the active and reactive power hysteresis. $P_p$ and $Q_p$ can be calculated from Equation (15).

![FIGURE 2 Topology of the OW-BDFRG with dual converter. OW-BDFRG, open-winding brushless doubly fed reluctance generator](image)

![FIGURE 3 Voltage vector diagram under normal operation](image)

| $u_c$ | $S_{d1}S_{d2}S_{a1}$ | $S_{a1}S_{d2}S_{a2}$ | $u_{act}^+$ | $\theta_{act}^+$ | $u_{act}^-$ |
|------|---------------------|---------------------|-------------|----------------|-------------|
| $U_0$ | 000,000; 100,100; 111,111; 111,011; 011,111; 011,011; 001,011; 101,101 | 0, 0, 0 | 100,100; 110,110; 010,010; 011,011; 000,000; 000,111; 110,000; 111,111; 011,111; 010,010; 101,110 | $U_{dc}$ $/3$, $2U_{dc}/3$, $4U_{dc}/3$ | $U_{dc}/3$, $2U_{dc}/3$, $3U_{dc}/3$ |
| $U_1$ | 100,011; 001,110; 011,110; 111,010; 101,110; 110,101; 010,101; 001,101 | $4U_{dc}/3$, $-2U_{dc}/3$, $-2U_{dc}/3$ | $U_{dc}/3$, $-U_{dc}$, $0$, $-U_{dc}$ | $2U_{dc}/3$, $2U_{dc}/3$, $-4U_{dc}/3$ | $U_{dc}/3$, $-U_{dc}$, $0$, $-U_{dc}$ |
| $U_2$ | 2U_{dc}/3, $2U_{dc}/3$, $4U_{dc}/3$ | $U_{dc}/3$, $-U_{dc}$, $0$, $-U_{dc}$ | $2U_{dc}/3$, $-2U_{dc}/3$, $0$, $-U_{dc}$ |
| $U_3$ | $-U_{dc}/3$, $2U_{dc}/3$, $3U_{dc}/3$ | $-U_{dc}/3$, $-2U_{dc}/3$, $4U_{dc}/3$ | $0$, $-U_{dc}$, $U_{dc}$ |
| $U_4$ | $U_{dc}/3$, $-U_{dc}$, $0$, $-U_{dc}$ | $0$, $-U_{dc}$, $U_{dc}$ |
| $U_5$ | $-U_{dc}/3$, $0$, $-U_{dc}$ |
| $U_6$ | $U_{dc}/3$, $-U_{dc}/3$, $2U_{dc}/3$ | $2U_{dc}/3$, $-2U_{dc}/3$, $0$, $-U_{dc}$ |
| $U_7$ | $2U_{dc}/3$, $-U_{dc}$, $0$, $-U_{dc}$ |
| $U_8$ | $U_{dc}/3$, $-U_{dc}$, $0$, $-U_{dc}$ |
| $U_9$ | $-U_{dc}/3$, $-2U_{dc}/3$, $0$, $-U_{dc}$ |
| $U_{10}$ | $0$, $-U_{dc}$, $U_{dc}$ | $2U_{dc}/3$, $-U_{dc}/3$, $-U_{dc}$ |
| $U_{11}$ | $0$, $-U_{dc}$, $U_{dc}$ |
| $U_{12}$ | $2U_{dc}/3$, $-U_{dc}/3$, $-U_{dc}$ |
| $U_{13}$ | $0$, $-U_{dc}$, $U_{dc}$ |
| $U_{14}$ | $2U_{dc}/3$, $-U_{dc}/3$, $-U_{dc}$ |
| $U_{15}$ | $0$, $-U_{dc}$, $U_{dc}$ |
| $U_{16}$ | $2U_{dc}/3$, $-U_{dc}/3$, $-U_{dc}$ |
| $U_{17}$ | $0$, $-U_{dc}$, $U_{dc}$ |
| $U_{18}$ | $2U_{dc}/3$, $-U_{dc}/3$, $-U_{dc}$ |

\[
P_p = \frac{3}{2} (u_{p,q}^1i_{p,q}^1 + u_{p,q}^2i_{p,q}^2) \quad (15)
\]

\[
Q_p = \frac{3}{2} (u_{p,q}^1i_{p,q}^1 - u_{p,q}^2i_{p,q}^2)
\]
be in the trigger suppression state. The midpoint of the dc bus is directly connected to a1, forming the topology as shown in Figure 7. From Figure 7, \( u_{\text{dcl}} = \frac{U_{\text{dc1}}}{2} \), two phases of Converter1 remain controllable. If \( U_{\text{dc1}} = U_{\text{dc2}} = U_{\text{dc3}} \), the voltage of CW can be expressed as Equation (16). According to the \( \alpha \beta \) axis component of the CW voltage vector, the voltage vector diagram can be drawn as Figure 8.

In this case, the corresponding relationship between voltage vector, switching state, and phase voltage is shown in Table 3. There are 32 switching states in the dual converter, corresponding to 14 different CW voltage vectors. Among them, all voltage vectors are effective vectors, with no zero vector. For space vector PWM, the dual converter for post-fault operation is capable of producing a fundamental peak phase voltage of 0.866 pu without overmodulation. In DPC, to determine the sector where \( \lambda_c \) is located, the plane is evenly divided into 10 sectors according to the characteristics of vector distribution. Based on the DPC theory discussed in Section 2, the switching voltage vector selection table is constructed as Table 4. \( S_1 \) and \( S_2 \) represent the output signals of the hysteresis comparator, as shown in Figure 6.

\[
\begin{bmatrix}
    u_{\text{a1d1}} \\
    u_{\text{b1e1}} \\
    u_{\text{c1f1}}
\end{bmatrix} = \frac{U_{\text{dc}}}{3} \begin{bmatrix}
    2 & -1 & -1 \\
    -1 & 2 & -1 \\
    -1 & -1 & 2
\end{bmatrix} \begin{bmatrix}
    0.5 - S_{\text{d1}} \\
    S_{\text{b1}} - S_{\text{c1}} \\
    S_{\text{c1}} - S_{\text{f1}}
\end{bmatrix}
\] (16)

4.2 | One phase fault in both converters

4.2.1 | Same phase fault in Converter1 and Converter2

If there are IGBT faults on both a1 phase of Converter1 and d1 phase of Converter2, TR_{a1} and TR_{d1} would be closed, and the other IGBTs on the same phases would be in the trigger suppression state. a1 and d1 are directly connected to the corresponding midpoint of the dc bus, forming the topology as shown in Figure 9. From Figure 9, \( u_{\text{a1n1}} = \frac{U_{\text{dc1}}}{2} \), \( u_{\text{d1n2}} = \frac{U_{\text{dc2}}}{2} \), two phases of Converter1 and Converter2 remain controllable. If \( U_{\text{dc1}} = U_{\text{dc2}} = U_{\text{dc3}} \), the voltage of CW can be expressed as Equation (17). The voltage vector diagram of CW can be drawn as Figure 10. In this case, the corresponding relationship between voltage vector, switching state, and phase voltage is shown in Table 5. There are 16 switching states in the dual converter, corresponding to nine different CW voltage vectors. Among them, four kinds of switching states make the phase voltage of CW 0 V, corresponding to zero vector, and the remaining 12 kinds of switching states make CW produce effective phase voltage, corresponding to eight different effective vectors. For space vector PWM, the dual converter for post-fault operation is capable of producing a fundamental peak phase voltage of 0.577 pu without overmodulation. In DPC, the plane is evenly divided into six sectors. The switching voltage vector selection table is constructed as Table 6.
Abbreviations: CW, control winding.

**TABLE 3** CW voltage vector under a1 phase fault

| $U_c$ | $S_{a1}S_{c1}$ | $S_{a1}S_{c1}S_{a2}S_{c2}$ | $U_{ald1}$ | $U_{bld1}$ | $U_{cld1}$ |
|-------|----------------|---------------------------|-----------|-----------|-----------|
| $U_1$ | 00,011         |                           | $U_{dc} - U_{dc}/2, -U_{dc}/2$ |           |           |
| $U_2$ | 00,001; 10,011 |                           | $2U_{dc}/3, U_{dc}/6, -5U_{dc}/6$ |           |           |
| $U_3$ | 10,001         |                           | $U_{dc}/3, 5U_{dc}/6, -U_{dc}/6$ |           |           |
| $U_4$ | 10,101         |                           | $-U_{dc}/3, 7U_{dc}/6, -5U_{dc}/6$ |           |           |
| $U_5$ | 10,100; 11,101 |                           | $-2U_{dc}/3, 5U_{dc}/6, -U_{dc}/6$ |           |           |
| $U_6$ | 11,100         |                           | $-U_{dc}/3, U_{dc}/2, U_{dc}/2$ |           |           |
| $U_7$ | 11,110; 01,100 |                           | $-2U_{dc}/3, -U_{dc}/6, 5U_{dc}/6$ |           |           |
| $U_8$ | 01,110         |                           | $-U_{dc}/3, -5U_{dc}/6, -U_{dc}/6$ |           |           |
| $U_9$ | 01,010         |                           | $U_{dc}/3, -7U_{dc}/6, 5U_{dc}/6$ |           |           |
| $U_{10}$ | 01,011; 00,010 |                           | $2U_{dc}/3, -5U_{dc}/6, U_{dc}/6$ |           |           |
| $U_{11}$ | 00,000; 00,111; 10,010; 01,001; 11,011 | | $U_{dc}/3, -U_{dc}/6, -U_{dc}/6$ |           |           |
| $U_{12}$ | 10,000; 10,111; 00,101; 11,101; 01,001 | | $0, U_{dc}/2, -U_{dc}/2$ |           |           |
| $U_{13}$ | 11,000; 11,111; 00,100; 10,110; 01,101 | | $-U_{dc}/3, U_{dc}/6, U_{dc}/6$ |           |           |
| $U_{14}$ | 01,000; 01,111; 00,110; 11,010 | | $0, -U_{dc}/2, U_{dc}/2$ |           |           |

**TABLE 4** Vector selection table (a1 phase fault)

| Signal | Sector |
|--------|--------|
| $S_1$ | $S_2$ |
| I     | II     | III    | IV     | V      |
| 0     | 0     | $U_{10}$ | $U_1$ | $U_2$ | $U_3$ | $U_4$ |
| 0     | 1     | $U_7$  | $U_8$ | $U_9$ | $U_{10}$ | $U_1$ |
| 1     | 0     | $U_2$  | $U_3$ | $U_4$ | $U_5$ | $U_6$ |
| 1     | 1     | $U_5$  | $U_6$ | $U_7$ | $U_8$ | $U_9$ |

**FIGURE 7** The topology of dual converter when a1 phase fault

**FIGURE 8** Voltage vector diagram of CW when a1 phase fault. CW, control winding.

**TABLE 4** Vector selection table (a1 phase fault)

| Signal | Sector |
|--------|--------|
| $S_1$ | $S_2$ |
| VI    | VII    | VIII   | IX     | X     |
| 0     | 0     | $U_5$  | $U_6$ | $U_7$ | $U_8$ | $U_9$ |
| 0     | 1     | $U_2$  | $U_3$ | $U_4$ | $U_5$ | $U_6$ |
| 1     | 0     | $U_7$  | $U_8$ | $U_9$ | $U_{10}$ | $U_1$ |
| 1     | 1     | $U_{10}$ | $U_1$ | $U_2$ | $U_3$ | $U_4$ |

\[
\begin{align*}
\begin{bmatrix} u_{ald1} \\ u_{bld1} \\ u_{cld1} \end{bmatrix} &= \frac{U_{dc}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S_{c1} - S_{c1} \\ S_{c1} - S_{c1} \end{bmatrix}
\end{align*}
\]

4.2.2 | Different phase fault in Converter₁ and Converter₂

If there are IGBTs fault both on the a1 phase of the Converter₁ and the e₁ phase of the Converter₂, TR₁ and TR₂ would be closed, and the other IGBTs on the same phases would be in the trigger suppression state. a₁ and e₁ are directly connected to the corresponding midpoint of the dc bus, forming the topology as shown in Figure 11. From Figure 11, $u_{a1n1} = U_{dc1}/2$, $u_{c1n2} = U_{dc2}/2$. If $U_{dc1} = U_{dc2} = U_{dc}$, the voltage of CW can be expressed as Equation (18). The voltage vector diagram of CW can be drawn as Figure 12. In this case, the corresponding relationship between voltage vector, switching state, and phase voltage is shown in Table 7. There are 16 switching states in the dual converter, corresponding to 10 different CW voltage vectors. All voltage vectors are effective vectors. For space vector PWM, the dual converter for post-fault operation is capable of producing a fundamental peak phase voltage of 0.577 pu.
when both a1 phase and d1 phase fault.

**TABLE 5** CW voltage vector (a1&d1 phase fault)

| $u_s$ | $S_{1b}S_{1b}$ | $S_{4b}S_{1b}$ | $u_{al1d1}$ | $u_{bl1e1}$ | $u_{cl1f1}$ |
|-------|----------------|----------------|-------------|-------------|-------------|
| $U_1$ | 0,11           | 0,11           | $2U_{dc}/3$, $-U_{dc}/3$, $-U_{dc}/3$ | 0, $U_{dc}$, $-U_{dc}$ |
| $U_2$ | 0,01; 10,11    | 0,01; 10,11    | $U_{dc}/3$, $U_{dc}/3$, $-2U_{dc}/3$ | 0, $U_{dc}$, $-U_{dc}$ |
| $U_3$ | 10,01          | 10,01          | 0, $U_{dc}$, $-U_{dc}$ | $-U_{dc}/3$, $2U_{dc}/3$, $-U_{dc}/3$ |
| $U_4$ | 10,00; 11,01   | 10,00; 11,01   | $-U_{dc}/3$, $2U_{dc}/3$, $-U_{dc}/3$ | 0, $U_{dc}$, $-U_{dc}$ |
| $U_5$ | 11,00          | 11,00          | $-2U_{dc}/3$, $U_{dc}/3$, $U_{dc}/3$ | $-U_{dc}/3$, $-U_{dc}$, $2U_{dc}/3$ |
| $U_6$ | 11,10; 01,00   | 11,10; 01,00   | $-U_{dc}/3$, $-U_{dc}/3$, $2U_{dc}/3$ | 0, $U_{dc}$, $-U_{dc}$ |
| $U_7$ | 01,10          | 01,10          | 0, $-U_{dc}$, $U_{dc}$ | $U_{dc}/3$, $-2U_{dc}/3$, $U_{dc}/3$ |
| $U_8$ | 01,11; 00,10   | 01,11; 00,10   | $U_{dc}/3$, $-2U_{dc}/3$, $U_{dc}/3$ | 0, $U_{dc}$, $-U_{dc}$ |
| $U_9$ | 00,00; 10,10; 11,11; 01,01 | 00,00; 10,10; 11,11; 01,01 | 0, 0, 0 | 0, 0, 0 |

Abbreviations: CW, control winding.

**TABLE 6** Vector selection table (a1&d1 phase fault)

| Signal | Sector | I | II | III | IV | V | VI |
|--------|--------|---|----|-----|----|---|----|
| S₁    | S₂    |   |    |     |    |   |    |
| 0 0   | U₆    | U₁ | U₂ | U₄  | U₅ | U₆|
| 0 1   | U₆    | U₈ | U₁ | U₂  | U₄ | U₅|
| 1 0   | U₂    | U₄ | U₅ | U₆  | U₈ | U₁|
| 1 1   | U₄    | U₅ | U₆ | U₈  | U₁ | U₂|

**FIGURE 9** The topology of dual converter when both a1 phase and d1 phase fault.

**FIGURE 10** Voltage vector diagram of CW when both of a1 phase of Converter₁ and d1 phase of Converter₂ are fault. CW, control winding.

without overmodulation. In DPC, the plane is evenly divided into eight sectors. The switching voltage vector selection table is constructed as Table 8.

\[
\begin{bmatrix}
  u_{al1d1} \\
  u_{bl1e1} \\
  u_{cl1f1}
\end{bmatrix} = \frac{U_{dc}}{3} \begin{bmatrix}
  2 & -1 & -1 \\
  -1 & 2 & -1 \\
  -1 & -1 & 2
\end{bmatrix} \begin{bmatrix}
  0.5 - S_{1l} \\
  S_{1l} - 0.5 \\
  S_{1l}
\end{bmatrix}
\] (18)

5 | SIMULATION RESULTS

The performance analysis of the post-fault operation control strategy is carried out in MATLAB/Simulink using the OW-BDFRG prototype data from Table 9. The post-fault operation under the three types of fault described in Section 4 is simulated. In the simulation process, different speed, $P_p$, and $Q_p$ references are set respectively to verify the variable-speed constant-frequency (VSCF) operation characteristics and power tracking. The speed range is set to 10% of the synchronous speed (500 r/min). From 0 s to 2.5 s, the OW-BDFRG runs at sub-synchronous speed (450 r/min), accelerates to the super-synchronous speed operating point at 3.5 s, from 3.5 s to 5.5 s, the motor runs at super-synchronous speed (550 r/min), and decelerates to synchronous speed at 6 s. The initial reference value of $P_p$ and $Q_p$ is −5 kW and 0 kVar, respectively. Subsequently, the reference value of $P_p$ changes to −10 kW (at 1.5 s) and −15 kW (at 4.5 s), respectively. The reference value of $Q_p$ changes to 5 kVar at 4 s. The power here is only given in the form of simulation to illustrate the effectiveness of the method. The hysteresis thresholds of $P_p$ and $Q_p$ are 0.1 kW and 0.1 kVar, respectively. The results, including the PW current, CW current, active power, and reactive power waveforms, are shown in Figures 13–15, which show satisfactory control effects and have been successfully verified by experiments. The analysis is given in the next section, along with the experimental results.

6 | EXPERIMENTAL RESULTS

A photo of the OW-BDFRG test rig is shown in Figure 16. An induction motor is taken as the prime motor to simulate the actual wind turbine. The rated capacity of one converter is 35
The power switching devices adopt Infineon high-speed IGBT power module (FF75R12RT4). The main controller core is DSP TMS320F28335. LC filter is 2.3 mH/2.5 μF.
FIGURE 14 System results (a1&d1 phase fault). (a) PW a-phase current, (b) CW current, and (c) PW active and reactive power. CW, control winding; PW, power winding.

FIGURE 15 System results (a1 & e1 phase fault). (a) PW a-phase current, (b) CW current, and (c) PW active and reactive power. CW, control winding; PW, power winding.

1200VAC. The experimental parameters and operating conditions are consistent with the simulation. Set the IGBT to trigger suppression state to mimic its open-circuit fault. The experimental results are shown in Figures 17–19.

The PW current waveform exhibits a good sinusoidal shape with a constant frequency of 50 Hz regardless of sub-synchronous, synchronous, or super-synchronous operation, which meets the requirements of the VSCF power generation. The phase sequence of the PW current is unchanged during operation. The frequency of CW current varies with the reference speed. The CW current frequency is 5 Hz in sub-synchronous operation and 15 Hz in super-synchronous operation, which means the change of the phase sequence and CW power flow. The CW current during synchronous operation is dc, at which point the output power of PW is only provided by the mechanical power injected from the rotor. The amplitude of PW current varies with the reference of $P_c$ and $Q_c$. The amplitude of CW current is affected by the reference of $P_m$, $Q_m$, and speed. CW current is in adjustment process from 2.5 to 3.5 s, and from 5.5 to 6 s. The reference value of $P_c$ changes from 5 to −10 kW at 1.5 s and to −15 kW at 4.5 s, respectively, which results in the increase of the amplitude of PW current at the corresponding time. The reference value of $Q_c$ affects the distribution of PW current and CW current to the excitation current. All excitation current is provided by the CW current when the reference value of $Q_c$ is set to 0 kVar, corresponding to the operation from 0 s to 4 s. The excitation current is provided by both the CW current and the PW current when the reference value of $Q_c$ is not 0 kVar (e.g., 5 kVar from 4 s to 7 s). Therefore, the reason of the amplitude of PW current increases and the amplitude of CW current decreases at 4 s which could be explained, that is, part of the excitation current is provided by PW instead of all the excitation current provided by CW when $Q_c$ changes from 0 kVar to 5 kVar.
FIGURE 17 Experimental results (a1 phase fault). (a) PW a-phase current, (b) CW a-phase current, (c) active power of PW, and (d) reactive power of PW. CW, control winding; PW, power winding.

FIGURE 18 Experimental results (a1&d1phase fault). (a) PW a-phase current, (b) CW a-phase current, (c) active power of PW, and (d) reactive power of PW. CW, control winding; PW, power winding.
For post-fault operation of a1 phase fault, the deviation of $P_p$ can be kept within $\pm 0.6$ kW when the OW-BDFRG is in sub-synchronous stable operation and within $\pm 0.4$ kW in super-synchronous stable operation. The deviation of $Q_p$ can be kept within $\pm 0.4$ kVar in both sub-synchronous and super-synchronous speed operation. For post-fault operation of a1&c1 phase fault, the deviation of $P_p$ can be kept within $\pm 0.4$ kW in both sub-synchronous and super-synchronous speed operation. The deviation of $Q_p$ can be kept within $\pm 0.4$ kVar in both sub-synchronous and super-synchronous speed operation.

For post-fault operation of a1&c1 phase fault, the deviation of $P_p$ can be kept within $\pm 0.75$ kW in sub-synchronous operation and within $\pm 0.5$ kW in super-synchronous operation. The deviation of $Q_p$ can be kept within $\pm 0.4$ kVar in both sub-synchronous and super-synchronous speed operation. $P_p$ has relatively large fluctuations in post-fault operation as compared with normal operation (the deviation of $P_p$ can be kept within $\pm 0.4$ kW for normal operation), especially for post-fault operation of a1&c1 phase fault. The deviation of $Q_p$ in post-fault operation is similar to that in normal operation (the deviation of $Q_p$ can be kept within $\pm 0.4$ kVar for normal operation).

During sub-synchronous speed operation, part of the PW output power comes from the converter connected with CW, which affects the fluctuation of $P_p$ to a certain extent. $P_p$ and $Q_p$ follow the reference value to change rapidly (the transition time occurs within 0.01 s). The results prove that the OW-BDFRG post-fault control strategy based on DPC enables the system to track the reference power stably after the power switch fault in converter and can simultaneously implement the VSCF operation.

7 | CONCLUSION

A fault-tolerant control strategy based on DPC is proposed to implement post-fault operation of the OW-BDFRG system under switch fault in converter. This control scheme has the advantages of good real time, lower converter capacity, and strong fault tolerance capability. The results verify that with the proposed fault-tolerant scheme, the OW-BDFRG system is able to maintain its stable operation as well as rapidly track the reference active and reactive power of PW and simultaneously implement the VSCF operation.

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