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Impact of the DFIG-Based Wind Farm Connection on the Fault Component-Based Directional Relay and a Mitigation Countermeasure

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Abstract: With high sensitivity and strong tolerance capability for the fault resistance, the fault component-based directional relay (FCBDR) has drawn considerable attention from industry and academia. However, the best application environment for FCBDR no longer exists when considering the large-scale connection of the doubly fed induction generator (DFIG)-based wind farms. Through a detailed analysis of the superimposed impedance of DFIG, this paper reveals that the performances of FCBDRs may be shown negatively impacted by the fault behaviors of DFIG when the crowbar protection inputs. In addition, this paper proposes a mitigation countermeasure to deal with those issues. The proposed countermeasure takes advantage of the different superimposed impedance features of DFIG compared with that of the synchronous generator (SG) to enhance the adaptability of the conventional FCBDRs. Extensive simulation results show that the proposed countermeasure can differentiate the fault direction clearly under different fault conditions.

Keywords: fault component-based directional relay (FCBDR); doubly fed induction generator (DFIG); superimposed impedance; synchronous generator (SG); mitigation countermeasure

1. Introduction

As a preferred approach to alleviating the energy shortage and environmental pollution issues, wind power has developed rapidly during the last decades [1,2]. Since wind resources are geographically distributed in regions located far away from the load center, the regional centralized construction and remote delivery have already become a typical utilization mode for wind power [3–5]. This kind of utilization mode determines that the wind power is generally sent out to the required regions through a long-distance transmission line, which significantly differs from the way of distributed integration and local absorption in the distribution network level. However, compared with the conventional synchronous generator (SG), the fault behaviors of wind generators represent significantly different features due to the employment of the nonlinear power electronic devices and the various low voltage ride through (LVRT) control strategies [6–10]. As a consequence, constantly increasing penetration of wind power will inevitably pose challenges to the existing transmission line protections that are generally designed considering SG-based systems.

The distance protection and pilot protection are the two predominantly used types of protection in a transmission line connected to the wind farm. Thus far, extensive research mainly focuses on the impact analysis of the wind farm integration on distance protection. In [11], the influence of the frequency deviation feature of the fault current contributed from a doubly fed induction generator (DFIG)-based wind farm on distance protection is exhaustively investigated and a corresponding solution is proposed in [12]. With the consideration of the mutual coupling effect, the work in [13]
points out that the trip boundaries of the conventional distance relay are more easily affected when the wind farm is connected through a single terminal transmission line compared to a double terminal transmission line. As a remedy, an adaptive distance relay setting principle is proposed in [13] and is further applied to the shunt-FACTS compensated transmission line connected with wind farms in [14]. Similarly, another adaptive distance protection scheme aiming at the wind farm connection environment is proposed in [15]. As for the pilot protection, more attention is paid to the adaptability problem of the differential pilot protection [16–18]. Theoretically, the differential protection can operate correctly with high sensitivity for the internal fault due to the apparent weak-infeed characteristics of the wind farm side by contrast to the power grid side. However, it is demonstrated in [16] that the differential protection may face the dilemma that it cannot be activated properly due to the limited fault-current feeding capabilities of the wind farms. Meanwhile, the authors of [17,18] illustrated that the frequency deviation feature will also result in the power frequency current phasor cannot be extracted correctly and the malfunction of differential relays. Given all the considerations, some advanced pilot protection schemes are proposed recently from the perspective of using the full-time transient current similarity comparison in [19,20]. Taking advantage of the obvious different fault current waveform signatures between the SG-based power grid side and the wind farm side, those schemes also exhibit inspiring performance.

Although great contributions have been made by the above-mentioned studies, it has never reached a comprehensive level. For instance, little research has been done on the impact of the wind farm connection on the directional comparison pilot protection. In practice, the operation of the directional comparison pilot protection relies on the fault direction identification results of the direction relays at two ends, whereas the performances of the direction relays are shown negatively impacted by the fault behaviors of wind generators. As reported in [21], the incorrect fault direction identification or deactivation of the directional elements may be caused by the reactive current consumption and the reduced active current generation of DFIG. To deal with this issue, a new directional element based on the impedance plane is also proposed in [21]. Although the proposed directional element aims at a microgrid environment, it has a good reference significance for a high-voltage transmission line as well. Another issue arises for the directional relays following a serve three-phase short fault condition, where the crowbar protection is activated for DFIG [22]. Because the fault current frequency of DFIG may considerably deviate from the nominal frequency in such a case, the malfunction possibility of the conventional directional relays by comparing the phase difference between voltage and current signals is also greatly increased. Moreover, for a transmission line connected to the wind farm, the fault component-based direction relays (FCBDRs) are widely used and their performances are also affected. In [23], the main reason for the performance degradation of the FCBDRs is blamed on the measured impedance at the wind farm having the characteristics of varying with time and deviating from the inductive region. To solve this problem, a time domain-algorithm-based directional element, the essence of which is that the forward and reverse fault conditions satisfy two vastly different R-L models receptively, is proposed in [24]. Based on our previous work [25], it has been found that the impedance measured by the direction relay at the wind farm side using the voltage and current fault components is not the real impedance of the wind farm, which is further named as equivalent superimposed impedance in [26]. Furthermore, since the phase angle of the equivalent superimposed impedance is determined by the LVRT control strategies and generally shows different impedance properties in the positive- and negative-sequence fault component network, the adaptability of the related FCBDRs based on phase comparison needs further investigation. On the other hand, how to improve the performance of the conventional FCBDRs in a DFIG-based wind farm connected scenario also remains an urgent problem. Unfortunately, to the best of the authors’ knowledge, those aspects are nearly missing from the majority of present literature.

The core contributions of this paper include the following:

- The expressions of positive- and negative-sequence superimposed impedance of DFIG when crowbar protection inputs are deduced and their characteristics are analyzed in detail from
three stages: the fault initial stage, the fault transient stage, and the fault steady stage. The results indicate that the positive-sequence superimposed impedance of DFIG has an obvious transient process, and its amplitude is large and fluctuates evidently after the fault. More importantly, its phase angle gradually increases or decreases from the initial phase angle and finally stabilizes at $-90^\circ$ to $-180^\circ$. As for the negative-sequence superimposed impedance of DFIG, its amplitude is relatively small, and its phase angle is between $0^\circ$ and $90^\circ$.

- Based on the working principle of FCBDR, it is pointed out that the wide range variation of the phase angle of the superimposed impedance (especially the positive-sequence superimposed impedance) may result in the sensitivity decline or misjudgment of the related FCBDRs.

- To enhance the adaptability FCBDRs in the DFIG-based wind farm connection scenario, a mitigation countermeasure based on the distinctive amplitude and phase angle features of the superimposed impedance (especially the positive-sequence superimposed impedance of DFIG) is proposed. To enhance the adaptability FCBDRs in the DFIG-based wind farm connection scenario, a mitigation countermeasure making use of the significantly different features of the superimposed impedance between DFIG and SG is proposed.

The remainder of this paper is organized as follows. Section 2 gives a brief introduction of the principles of FCBDRs. In Section 3, the definition and calculation of the superimposed impedance of DFIG are described. In Section 4, the characteristics of the superimposed impedance of DFIG and their impacts on FCBDRs are analyzed in detail. A mitigation method including three supplementary direction criteria is proposed in Section 5. The simulation results and discussions are presented in Section 6, followed by conclusions in Section 7.

2. Principle of FCBDR

To get a thorough understanding of the principle of FCBDR, the model of a conventional transmission line with two SG-based sources (include the power grid) at both ends is shown in Figure 1a, and the corresponding fault component network is shown in Figure 1b. The meanings of the symbols in the diagram are as follows:

- $\Delta u_m, \Delta u_n = $ fault component voltage at busbar $m$ and busbar $n$ respectively.
- $\Delta i_m, \Delta i_n = $ fault component current at busbar $m$ and busbar $n$ respectively.
- $\Delta u_f, \Delta i_f = $ fault component voltage and current at fault point $f_1$ respectively.
- $Z_m, Z_n = $ equivalent impedance of the SG-based sources at busbar $m$ and busbar $n$ respectively.
- $Z_{lm}, Z_{ln} = $ equivalent line impedance between busbar $m, n$ and fault point $f_1$ respectively.
- $f_1, f_2 = $ forward and reverse fault seen by the directional relay $R_n$ at busbar $n$ respectively.

![Figure 1](image.png)

Figure 1. Model of the conventional transmission line and its fault component network: (a) transmission line model; and (b) fault component network.

Take the directional relay $R_n$ at busbar $n$ as an example; for the forward fault at $f_1$, the impedance measured by $R_n$ using fault component voltage and current can be expressed as follows:

$$\frac{\Delta u_n}{\Delta i_n} = -Z_n$$  \hfill (1)

and for the reverse fault at $f_2$, the impedance measured by $R_n$ can be expressed as follows:

$$\frac{\Delta u_n}{\Delta i_n} = Z_m + Z_{lm} + Z_{ln}$$  \hfill (2)
Theoretically, the transmission line and the SG-based sources at two ends show a similar impedance property, which is generally supposed to be pure inductive. Hence, for the forward fault, the phase angle of the measured impedance equals \(-90^\circ\), while, for the reverse fault, the corresponding phase angle equals \(90^\circ\). Using the different phase angle features between the two fault conditions and considering a certain margin, the principle of the FCBDR can be given by

\[
-180^\circ < \arg\left(\frac{\Delta u}{\Delta i}\right) < 0^\circ \quad \text{Forward fault} \tag{3}
\]

\[
0^\circ < \arg\left(\frac{\Delta u}{\Delta i}\right) < 180^\circ \quad \text{Reverse fault} \tag{4}
\]

Besides, based on the different form of the used fault component, the specific FCBDR can be divided into the following categories \[27\]:

- Positive-sequence FCBDR: \(\Delta u_{+}, \Delta i_{+}\).
- Negative-sequence FCBDR: \(u_{-}, i_{-}\).
- Zero-sequence directional relay: \(u_{0}, i_{0}\).
- Phasor FCBDR: \(\Delta u_{\phi}, \Delta i_{\phi} - i_{\phi} (\phi = A, B, C)\).
- Phasor difference FCBDR: \(\Delta u_{\phi\phi}, \Delta i_{\phi\phi} (\phi\phi = AB, BC, CA)\).

3. Definition and Calculation of the Superimposed Impedance of DFIG

3.1. Definition of the Superimposed Impedance of DFIG

The fault component network of a transmission line connected to a DFIG-based wind farm is depicted in Figure 2a. The major distinction between and Figures 1 and 2a lies is that an additional time-varying potential component \(\Delta u(t)\) is introduced into Figure 2a. The reason for this phenomenon is that, since DFIG is comprised of nonlinear power electronic devices with a fast response characteristic, its equivalent internal potential cannot maintain constant in the pre-fault and post-fault condition. In this situation, the equivalent impedance at the backside of \(Rn\) in the fault component network is not the real impedance of DFIG \(Z_{w}\), which is defined as the superimposed impedance of DFIG in this paper. Furthermore, based on the conventional fault component extraction algorithm, the positive- and negative-sequence superimposed impedance of DFIG can be represented in the corresponding fault component network by Equations (5) and (6), respectively, i.e.,

\[
Z_{w+} = \frac{\Delta u_{+}}{\Delta i_{+}} \tag{5}
\]

\[
Z_{w-} = \frac{u_{-}}{i_{-}} \tag{6}
\]

Figure 2. Fault component network and its equivalent network of the transmission line connected to a wind farm: (a) fault component network; and (b) equivalent network.

Benefited from the above definition, Figure 2a can be equivalent to Figure 2b and then has a similar structure as the fault component network of the SG-based system. As aforementioned, the FCBDR depends on the phase comparison to differentiate the forward and reverse fault.
Therefore, the fundamental premise required from the FCBDR is that the fault component network is with the unified phase angle property. However, as shown in the following contents, the superimposed impedance of DFIG cannot be regarded as pure induction during the fault period due to the influence of low voltage ride through (LVRT) control schemes. Consequently, the performances of the related FCBDRs are shown negatively impacted by the fault behaviors of DFIG.

3.2. Calculation of the Superimposed Impedance of DFIG

3.2.1. Positive- and Negative-Sequence Fault Currents of DFIG

To ride through the fault period without disconnecting from the power grid, it is required that DFIG be equipped with the LVRT capability nowadays. According to the different voltage sag extent, two typical ways to realize LVRT for DFIG are inputting the crowbar protection and changing the control strategy of the converter. In this paper, we only focus on the characteristics of the superimposed impedance of DFIG when the crowbar protection is activated due to a severe voltage sag, and its characteristics under converter control will be discussed in the next paper.

Equations (5) and (6) show that, to calculate the superimposed impedance of DFIG, the positive- and negative-sequence fault current at DFIG outlet should be calculated first. The voltage and flux vector relationships of DFIG in the positive and negative synchronous rotation reference frames are given by Equations (7) and (8), respectively [28].

\[
\begin{align*}
\psi_{s+}^p &= R_s i_{s+}^p + D \psi_{s+}^p + j\omega_s \psi_{s+}^p, \\
\psi_{r+}^p &= R_r i_{r+}^p + D \psi_{r+}^p + j\omega_s \psi_{r+}^p, \\
\psi_{s+}^n &= L_s i_{s+}^n + L_m i_{r+}^n, \\
\psi_{r+}^n &= L_m i_{s+}^n + L_r i_{r+}^n.
\end{align*}
\]

When the \(d\)-axis stator voltage vector oriented control is adopted for DFIG, its pre-fault positive-sequence stator voltage (per-unit value) can be expressed as:

\[
u_{s0} = u_{s0} + ju_{s0} = u_{s0} = 1
\]

Then, the pre-fault output active and reactive power of DFIG can be represented as follows:

\[
\begin{align*}
P_{s0} &= -u_{s0} i_{s0} - u_{s0} i_{s0} = -i_{s0} \\
Q_{s0} &= -u_{s0} i_{s0} + u_{s0} i_{s0} = i_{s0}
\end{align*}
\]

Generally, DFIG only outputs active power to achieve the maximum power point tracking (MPPT) under normal operation conditions (\(i_{s0} = 0\)). Thus, the pre-fault stator current (per-unit value) can be written as follows:

\[
i_{s0} = i_{s0} + j i_{s0} = -P_{s0}
\]

1. Positive-sequence Fault Current of DFIG

Assuming that the fault occurs at \(t=0\)s, the post-fault positive-sequence stator voltage of DFIG can be expressed as follows:

\[
u_{s+f}^p = u_{s+f}^p = ku_{s0} = k
\]
Based on Equation (9) and with consideration of the rotor voltage and resistance change caused by inputting the crowbar protection simultaneously, applying the Laplace transform on Equation (7), there is

\[
\begin{align*}
  k/p &= R_sI_s^p(p) + [p\Psi_s^p(p) - \Psi_s^0] + j\omega_s\Psi_s^p(p) \\
  0 &= R'_rI_{r+}^p(p) + [p\Psi_{r+}^p(p) - \Psi_{r+}^0] + j\omega_r\Psi_{r+}^p(p) \\
  \Psi_{s+}^p(p) &= L_{ds}I_{s+}^p(p) + L_{ms}I_{r+}^p(p) \\
  \Psi_{r+}^p(p) &= L_{mr}I_{s+}^p(p) + L_rI_{r+}^p(p)
\end{align*}
\]

(13)

where \( R'_r = R_r + R_{cb} \). Then, the expression of the DFIG positive-sequence fault current in the frequency domain when crowbar protection inputs can be obtained as follows:

\[
I_{s+}^p(p) = \frac{(k + p\Psi_{s+}^0)[R'_r + p_2L_r] - pp_1L_ml\Psi_{r+}^0}{p[R_s + p_1L_s][R'_r + p_2L_r] - pp_1p_2L_m^2}
\]

(14)

where \( p_1 = p + j\omega_s \) and \( p_1 = p + j\omega_s \).

Considering that there is \( D\Psi_{s+}^p = D\Psi_{r+}^p = 0 \) before fault, it can be derived from Equation (7) that

\[
\begin{align*}
  \Psi_{s+}^0 &= \frac{u_{\delta+}}{j\omega_s} \\
  \Psi_{r+}^0 &= \frac{u_{\delta+}}{j\omega_sL_s} - \frac{L_m}{L_m}i_{\delta+}
\end{align*}
\]

(15)

By combining Equations (14) and (15), the positive-sequence fault current of DFIG can be obtained as follows:

\[
I_{s+}^p = \frac{k}{Z_{q+}} + \frac{1 - k}{Z_{b+}} e^{-j\omega_st/e^{-t/T'_s}} + \frac{k}{Z_{a+}} + \frac{1 - k}{Z_{b+}} e^{-j\omega_st/e^{-t/T'_s}}
\]

(16)

where \( Z_{a+} \) and \( Z_{b+} \) are the constants related to the parameters of DFIG, while \( T'_s \) and \( T'_r \) are the stator and rotor time damping constants, respectively.

\[
\begin{align*}
  Z_{a+} &= \frac{j\omega_sL_s[R'_r + j\omega_sL_r]}{R'_r + j\omega_sL_r} \\
  Z_{b+} &= \frac{j\omega_sL_s[R'_r + j(1-s)\omega_sL_r]}{R'_r + j(1-s)\omega_sL_r} \\
  T'_s &= L_{ss}/R_{ss}, L_{ss} = L_s - L_m^2/L_r \\
  T'_r &= L_{rr}/R'_r, L_{rr} = L_r - L_m^2/L_r
\end{align*}
\]

(17)

2. Negative-sequence Fault Current of DFIG

Since there is no negative-sequence components before fault, \( \Psi_{\delta+}^0 \) and \( \Psi_{r+}^0 \) all equals zero. By assuming the post-fault negative-sequence stator voltage as \( u_{s-}^N \) and applying the Laplace transform on Equation (8), there is

\[
\begin{align*}
  u_{s-}^N/p &= R_sI_{s-}^N(p) + p\Psi_{s-}^N(p) - j\omega_s\Psi_{s-}^N(p) \\
  0 &= R'_rI_{r-}^N(p) + p\Psi_{r-}^N(p) - j(2-s)\omega_s\Psi_{r-}^N(p) \\
  \Psi_{s-}^N(p) &= L_{ds}I_{s-}^N(p) + L_{ms}I_{r-}^N(p) \\
  \Psi_{r-}^N(p) &= L_{mr}I_{s-}^N(p) + L_rI_{r-}^N(p)
\end{align*}
\]

(18)
Referring to the derivation process in Equations (13)–(16), the negative-sequence fault current of DFIG can be obtained as follows:

\[
\begin{align*}
\Delta i^N_{k+} &= \frac{u^N_{sf-}}{Z_{a-}} - \frac{u^N_{sf+}}{Z_{b-}} \omega_i e^{-j/s} + \frac{u^N_{sf+}}{Z_{a-}} - \frac{u^N_{sf-}}{Z_{b-}} (2s) \omega_i e^{-j/s},
\end{align*}
\]

where \(Z_{a-}\) and \(Z_{b-}\) are also the constants related to the parameters of DFIG.

\[
\begin{align*}
\Delta i^N_{k+} &= \frac{-j\omega_i L_s [R_{a-} - j(2s) \omega_i L_s]}{R_{a-} - j(2s) \omega_i L_s} \\
\Delta i^N_{k+} &= \frac{-j\omega_i L_s [R_{b-} - j(1s) \omega_i L_s]}{R_{b-} - j(1s) \omega_i L_s}
\end{align*}
\]

### 3.2.2. Positive- and Negative-Sequence Superimposed Impedance of DFIG

1. **Positive-Sequence Superimposed Impedance of DFIG**

Equation (16) shows that \(i^N_{k+}\) is composed of three parts. After transforming into the stationary synchronous reference frame, Part I is the fundamental frequency component, Part II is the decaying DC component, and Part III is the slip-related frequency component. Among them, the DC component can be filtered by the Fourier algorithm. The DFIG accommodates different wind speeds by allowing significant rotor speed deviations around the synchronous speed, resulting in a ±30% b and for the slip [22], which also means the slip-related frequency (\(\omega_s\)) component belongs to the inter-harmonics. Since the inter-harmonics cannot be filtered by the Fourier algorithm, the influence of the slip-related frequency component on the superimposed impedance calculation deserves special consideration. Based on Equation (16) and with the consideration of the influence of the slip-related frequency component simultaneously (see Appendix A), after extracting by the Fourier algorithm, Equation (16) can be rewritten as:

\[
\begin{align*}
i^N_{k+} &= \frac{k}{Z_{a+} + \Delta A (\frac{1}{Z_{a+}} + \frac{1 - k}{Z_{b+}} + P_{sh}(t)) e^{-j\omega_s t + \Delta \varphi} e^{-j/s}},
\end{align*}
\]

where the expressions of \(\Delta A\) and \(\Delta \varphi\) are given in Appendix A.

Then, according to Equation (5), the positive-sequence superimposed impedance of DFIG is calculated as

\[
\begin{align*}
Z^N_{aw+} &= \frac{\Delta u_{aw+}}{\Delta i_{aw+}} = \frac{u^N_{sf+} - u^N_{00\hat{\varphi}}}{i^N_{00\hat{\varphi} + } - i^N_{00\hat{\varphi} - } = \frac{k - 1}{Z_{a+} + P_{sh}(t) - \Delta A (\frac{1}{Z_{a+}} + \frac{1 - k}{Z_{b+}} + P_{sh}(t)) e^{-j\omega_s t + \Delta \varphi} e^{-j/s}},
\end{align*}
\]

2. **Negative-Sequence Superimposed Impedance of DFIG**

Equation (19) shows that \(i^N_{k-}\) is also composed of three parts. After transforming into the stationary synchronous reference frame, Part I is the fundamental frequency component, Part II is the decaying DC component, and Part III is the slip-related frequency (\((2 - s) \omega_i\)) component. However, there is a major distinction between \(i^N_{k+}\) and \(i^N_{k-}\). Based on the parameters of a typical DFIG given in Table A1 in Appendix B, the amplitude relationship between \(1/Z_{a-}\) and \((1/Z_{a-} - 1/Z_{b-})\) is depicted in Figure 3. To prevent the rotor from an overcurrent, \(R_{cb}\) is generally set as dozens of times \(R_r\); then, it can be seen that the amplitude of \((1/Z_{a-} - 1/Z_{b-})\) is significantly smaller than that of \(1/Z_{a-}\), which indicates that the slip-related frequency component in Equation (19) can be ignored. In this situation, after extracting by the Fourier algorithm, \(i^N_{k-}\) in Equation (19) can be simplified as follows:

\[
i^N_{k-} = \frac{u^N_{sf-}}{Z_{a-}}
\]
Then, according to Equation (6), the negative-sequence superimposed impedance of DFIG is provided by

\[ Z_{w-}^N = \frac{u_{w-}}{i_{w-}} = \frac{u_{y-}^N}{i_{s-}^N} = Z_{a-} \]  

(24)

It is worth emphasizing here that \( Z_{w-}^N \) in Equation (24) is represented in the negative \( dq \) synchronous rotation reference frame. By replacing \( -\omega_s \) in Equation (24) with \( \omega_s \), the negative-sequence superimposed impedance of DFIG in the positive \( dq \) synchronous rotation reference frame can be rewritten as

\[ Z_{w-} = \frac{j\omega_s L_s [R'_r + j(2 - s)\omega_s L_{rr}]}{R'_r + j(2 - s)\omega_s L_{rr}} \]  

(25)

4. Characteristic Analysis of the Superimposed Impedance of DFIG and Its Impact on FCBDR

4.1. Characteristic Analysis of the Superimposed Impedance of DFIG

4.1.1. Positive-sequence Superimposed Impedance of DFIG

As it can be observed in Equation (22), the change process of \( Z_{w+}^s \) during the fault period is determined by four factors: \( k, R'_r, P_{s(0)} \), and \( s \). In addition, \( k \) is the voltage sag extent, which is determined by the fault location, fault type, and fault resistance. \( R'_r \) is determined by the value of the used crowbar resistance. \( P_{s(0)} \) and \( s \) depend on the operation status of DFIG before the fault, and there is a one-to-one mapping relationship between them when the MPPT control mode is adopted for DFIG [29]. Hence, the characteristic of \( Z_{w+}^s \) is actually determined by three factors.

Considering the complexity of Equation (22), it is not easy to study the characteristics of \( Z_{w+}^s \) directly, and, therefore, the following analysis is with the assistance of the vector diagram. To simplify the analysis, we set

\[ \left\{ \begin{array}{l} \Delta u_{s+} = k - 1 \\ \Delta i_{s+} = \Delta i_{s(0)+} + i_D \end{array} \right. \]  

(26)

where \( \Delta i_{s(0)+} \) and \( i_D \) are the steady-state component and the decaying slip-related frequency component of \( \Delta i_{s+} \), respectively,

\[ \left\{ \begin{array}{l} \Delta i_{s(0)+} = \frac{k}{Z_{s+}^r} + P_{s(0)} \\ i_D = \Delta A/L_{rr} \end{array} \right. \]  

(27)

Based on the above simplification, \( Z_{w+}^s \) can be denoted by the ratio of \( \Delta u_{s+} \) and \( \Delta i_{s+} \). Moreover, when the voltage sag extent is determined, \( \Delta u_{s+} = k - 1 \) is a fixed value, and then the characteristics of \( Z_{w+}^s \) are completely determined by \( \Delta i_{s+} \). To plot the vector diagram of \( \Delta i_{s+} \), the characteristics of \( Z_{a+}, Z_{b+}, \Delta A, \) and \( \Delta \varphi \) need to be known first. Based on Equation (17) and Table A1, the amplitude and phase angle curves of \( Z_{a+} \) and \( Z_{b+} \) are depicted in Figure 4. As shown in Figure 4a, the phase angle of \( Z_{a+} \) is greater than 90° when \( s < 0 \), while smaller than 90° when \( s > 0 \); and, as shown in Figure 4b, the phase angle of \( Z_{b+} \) is always greater than 90°. As for \( \Delta A \) and \( \Delta \varphi \), it can be observed in Figure A1 in Appendix A that, when \( s < 0, \Delta A < 1 \) and \( \Delta \varphi > 0 \); and, when \( s > 0, \Delta A < 1 \)
and $\Delta \varphi < 0$. Particularly, when $s = 0$, there is $\Delta A \approx 1$ and $\Delta \varphi \approx 0$. Another point deserves noting in Figure A1 is that a large value of $T'$, (i.e., a large crowbar resistance is used for DFIG) will result in a small value of $\Delta A$ and $\Delta \varphi$.

![Amplitude and phase curve](image)

Figure 4. Amplitude and phase angle curves of: (a) $Z_{d+}$; and (b) $Z_{b+}$.

Given all the above considerations, the vector diagrams of $Z_{w+}$ with different $s$ can be plotted as Figures 5–7 for $s < 0$, $s > 0$, and $s = 0$, respectively, and the characteristics of $Z_{w+}$ can be analyzed in three stages: the fault initial stage, the fault transient stage, and the fault steady stage.

![Vector diagram](image)

Figure 5. Vector diagram of $Z_{w+}$ when $s < 0$: (a) small $R_{cb}$; and (b) large $R_{cb}$.

![Vector diagram](image)

Figure 6. Vector diagram of $Z_{w+}$ when $s > 0$: (a) small $R_{cb}$; and (b) large $R_{cb}$.
Figure 7. Vector diagram of $Z'_{w+}$ when $s = 0$: (a) small $R_{cb}$; and (b) large $R_{cb}$.

(1) $s < 0$.

Fault initial stage: In Figure 5, it is assumed that $i'_D = (k-1)/Z_{b+} - \Delta i_{\infty+}$. If the influence of $\Delta A$ and $\Delta \phi$ is ignored, there are $\Delta i_{\infty+} = \Delta i_{\infty+} + i'_D = (k-1)/Z_{b+}$ and $Z_{w+} = \Delta u_{\infty+}/\Delta i_{\infty+} = Z_{b+}$, and then the characteristics of $Z'_{w+}$ is similar to $Z_{b+}$ (see Figure 4b). When $\Delta A$ and $\Delta \phi$ are considered, since $\Delta A < 1$ and $\Delta \phi > 0$ in this case, $i'_D$ will approach $i_{D0}(\Delta A i'_{D0}e^{\Delta \phi})$, and the position of $\Delta i_{\infty+}$ is different with the crowbar resistance. If a small crowbar resistance is used (large $\Delta A$ and $\Delta \phi$), the position of $\Delta i_{\infty+}$ will lead that of $(k-1)/Z_{b+}$ (see Figure 5a) and then the initial phase angle of $Z'_{w+}$ will be smaller than that of $Z_{b+}$. On the contrary, if a large crowbar resistance is used (small $\Delta A$ and $\Delta \phi$), the position of $\Delta i_{\infty+}$ will lag that of $(k-1)/Z_{b+}$ (see Figure 5b) and the initial phase of $Z'_{w+}$ will be larger than that of $Z_{b+}$. Moreover, since the amplitude of $\Delta i_{\infty+}$ is smaller than that of $(k-1)/Z_{b+}$ in both cases, the initial amplitude of $Z'_{w+}$ is greater than $Z_{b+}$.

Fault transient stage: The transient process of $Z'_{w+}$ is determined by the change of $i_D$. As $s < 0$, $i_D$ rotates anticlockwise from the position of $i_{D0}$ and decays with $T'$, simultaneously. Moreover, if a small crowbar resistance is used, as shown in Figure 5a, $i_D$ will decay at a relatively slow rate along the dash-dotted Line 1, and then $\Delta i_{\infty+}$ will also change along Line 1 and enter the fourth quadrant after passing through the second and the third quadrant (see the dotted arrow). As a result, the phase of $Z'_{w+}$ decreases continuously from the initial phase. In addition, the sharp amplitude change of $\Delta i_{\infty+}$ during the transient process causes an evident fluctuation for the amplitude of $Z'_{w+}$; if a large crowbar resistance is used, as shown in Figure 5b, $i_D$ will decay at a relatively slow rate along the dash-dotted Line 2 and then $\Delta i_{\infty+}$ will enter the fourth quadrant from the first quadrant straightly (see the dotted arrow). Consequently, the phase angle of $Z'_{w+}$ increases gradually from the initial phase angle. Unlike the small crowbar resistance used condition, the amplitude fluctuation of $Z'_{w+}$ is gentler.

(2) $s > 0$.

Fault initial stage: Since $\Delta A > 1$ and $\Delta \phi < 0$, it can be observed in Figure 6 that $i_{D0}$ rotates clockwise from the position of $i'_D$ with a phase angle $|\Delta \phi|$. Then, the phase angle of $\Delta i_{\infty+}$ always lags that of $(k-1)/Z_{b+}$ irrespective of the crowbar resistance value and the initial phase angle of $Z'_{w+}$ is larger than that of $Z_{b+}$.

Fault transient stage: Because $s > 0$, $i_D$ rotates clockwise and $\Delta i_{\infty+}$ enters the fourth quadrant from the first quadrant straightly. Thus, the phase angle of $Z'_{w+}$ increases gradually from the initial phase angle. The trend is also not influenced by crowbar resistance. Moreover, since the amplitude change of $\Delta i_{\infty+}$ is very gentle, the amplitude of $Z'_{w+}$ does not have obvious fluctuation.

(3) $s = 0$.

When $s = 0$, $i_D$ dose not rotates by only decays in the vector diagram. In this situation, as shown in Figure 7, $\Delta i_{\infty+}$ will move to $\Delta i_{\infty+}$ along with the changing trajectory of $i'_D$, and then the phase angle characteristics of $Z'_{w+}$ is basically consistent with those when $s > 0$. On the other hand, the amplitude fluctuation level of $Z'_{w+}$ is between those of $s > 0$ and $s < 0$.oplex.
When it comes to the fault steady stage, \(i_d\) decays to zero and \(\Delta i_{q+} = \Delta i_{\text{ goofy+}}\), then the unified steady-state expression of \(Z_{w+}^*\) \((s < 0, s > 0, \text{and } s = 0)\) can be obtained as follows:

\[
Z_{\text{woof+}}^* = \frac{\left( k - 1 \right) Z_{\theta+}}{k + Z_{\text{sp+}}^{\text{sp+}}}
\]

(28)

Referring to the mapping relationship between \(s\) and \(P_{\text{sp+}}\) in [29] and Equation (28), the characteristics of \(Z_{\text{woof+}}^*\) are shown in Figure 8. As observed, both the amplitude and phase angle of \(Z_{\text{woof+}}^*\) vary greatly under different conditions. Particularly, the phase angle of \(Z_{\text{woof+}}^*\) is between \(-90^\circ\) and \(-180^\circ\), which significantly differs from the phase angle of the equivalent impedance of SG (generally regarded as \(90^\circ\)).

![Figure 8](image)

Figure 8. Characteristic of \(Z_{\text{woof+}}^*\): (a) amplitude; and (b) phase angle.

4.1.2. Negative-Sequence Superimposed Impedance of DFIG

From Equation (25), it can be learned that the characteristics of \(Z_{w-}^*\) is only determined by two factors: \(s\) and \(R_{w+}'\). Accordingly, the amplitude and phase angle characteristics of \(Z_{w-}^*\) are shown in Figure 9. As can be seen, since the frequency of the slip-related component is \((2 - s)\alpha_{\text{sp}}\), the change of \(s\) has a tiny effect on \(Z_{w-}^*\) and the characteristic of \(Z_{w-}^*\) is mainly affected by \(R_{w+}'\). Moreover, with the increase of \(R_{w+}'\), the amplitude and phase angle of \(Z_{w-}^*\) increase and decrease, respectively. However, the phase angle of \(Z_{w-}^*\) is always between \(0^\circ\) and \(90^\circ\).

![Figure 9](image)

Figure 9. Characteristic of \(Z_{w-}^*\): (a) amplitude; and (b) phase angle.

4.1.3. Summary

By comparing the characteristics of \(Z_{w+}^*\) and \(Z_{w-}^*\), the following conclusions can be drawn:

- **Amplitude**: The amplitude of \(Z_{w+}^*\) is much larger than that of \(Z_{w-}^*\). During the fault transient stage, the amplitude of \(Z_{w+}^*\) fluctuates evidently, while the amplitude of \(Z_{w-}^*\) is basically stable.
- **Phase angle**: The phase angle of \(Z_{w+}^*\) has an evident change process during the fault transient stage and finally reaches the steady value between \(-90^\circ\) and \(-180^\circ\), while the phase angle of \(Z_{w-}^*\) is always between \(0^\circ\) and \(90^\circ\).
4.2. Impact of the DFIG-Based Wind Farm Connection on the FCBDR

A model of a transmission line connected to a DFIG-based wind farm is shown as Figure 10a, and the corresponding fault component network is shown as Figure 10b, where $Z_n$, $Z_i$, and $Z_T$ are the equivalent impedance of the SG-based power grid, the transmission line, and the main transformer, respectively. Taking the forward fault at $f_1$ as an example, the impact of the wind farm connection on the performance of the FCBDR $R_n$ (at wind farm side) are analyzed as follows.

**Figure 10.** Model of the transmission line connected to a DFIG-based wind farm and its fault component network: (a) transmission line model; and (b) fault component network.

1. Positive-sequence FCBDR

Using positive-sequence fault component voltage and current, the phase angle of the impedance measured by $R_n$ can be expressed as:

$$\text{arg}\left(\frac{\Delta u_{n+}}{\Delta i_{n+}}\right) \approx \text{arg}\left(-Z_{w+}\right) = -180^\circ + \text{arg}(Z_{w+})$$

Based on Equation (3), it is required that the phase angle of $Z_{w+}$ is between $0^\circ$ and $180^\circ$ to identify the forward fault direction. Figures 5–7 show that the phase angle of $Z_{w+}$ meets the requirement at the fault initial stage. However, with the decay of $i_0$, when the phase angle of $Z_{w+}$ changes to $0^\circ$ or $180^\circ$, the positive-sequence FCBDR will not be able to correctly judge the fault direction.

2. Negative-sequence FCBDR

Using negative-sequence fault component voltage and current, the phase angle of the impedance measured by $R_n$ can be expressed as:

$$\text{arg}\left(\frac{u_{n-}}{i_{n-}}\right) \approx \text{arg}\left(-Z_{w-}\right) = -180^\circ + \text{arg}(Z_{w-})$$

As analyzed previously, the phase angle of $Z_{w-}$ is always between $0^\circ$ and $90^\circ$. Thus, the negative-sequence FCBDR can work correctly, whereas, if a large crowbar resistance is used for DFIG, the phase angle of $Z_{w-}$ will be comparatively small (see Figure 9b) and the sensitivity of the negative-sequence FCBDR needs to be further tested.

3. Zero-sequence directional relay

Since the neutral earthling mode is employed for the high voltage side of the main transformer at the wind farm side, DFIG is not included in the zero-sequence network and thus the zero-sequence directional relay can work correctly.
4. Phasor FCBDR

Phasor FCBDR is mainly used under a single-phase grounding fault condition. Taking the A-phase grounding fault at \( f_1 \) as an example, the phase angle of the impedance measured by \( R_n \) can be expressed as follows:

\[
\arg\left( \frac{\Delta u_{nA} - u_{n0}}{\Delta i_{nA} - i_{n0}} \right) \approx -180^\circ + \arg\left( \frac{Z_{w+}^n \Delta i_{nA+} + Z_{w-}^n i_{nA-}}{\Delta i_{nA+} + i_{nA-}} \right)
\]  

(31)

As the positive- and negative-sequence currents supplied by the fault point are equal in case of an A-phase grounding fault (i.e., \( i_{fA+} = i_{fA-} \)), the fault component current relationship in Figure 8 can be obtained as follows:

\[
\begin{align*}
\Delta i_{nA+} & \approx Z_{w+}^n i_{nA+} + Z_{w-}^n i_{nA-} \\
\Delta i_{nA-} & \approx Z_{w+}^n i_{nA+} + Z_{w-}^n i_{nA-}
\end{align*}
\]

(32)

Theoretically, the positive- and negative-sequence impedances of the SG-based \( m \) side and the transmission line can be regarded as equal, thus:

\[
\frac{\Delta i_{nA+}}{i_{nA-}} = \frac{Z_{w+}^n + Z_{lm+}^n + Z_{ln+}^n + Z_{f+}^n + Z_{w-}^n}{Z_{w+}^n + Z_{lm+}^n + Z_{ln+}^n + Z_{f+}^n + Z_{w-}^n}
\]

(33)

Considering the apparent weak-infeed characteristic of DFIG, Equation (33) can be simplified as:

\[
\Delta i_{nA+} / i_{nA-} = Z_{w-}^n / Z_{w+}^n
\]

(34)

Then, based on Equations (34) and (31), it can be rewritten as:

\[
\arg\left( \frac{\Delta u_{nA} - u_{n0}}{\Delta i_{nA} - i_{n0}} \right) \approx -180^\circ + \arg\left( \frac{2Z_{w-}^n}{Z_{w+}^n + Z_{w-}^n} \right)
\]

(35)

Equation (35) shows that the phase angle of the measured impedance is influenced by \( Z_{w+}^n \) and \( Z_{w-}^n \) simultaneously and is determined by the one with the smaller amplitude. Therefore, if \( |Z_{w+}^n| \ll |Z_{w-}^n| \), the performance of the phasor FCBDR will be affected, while, if \( |Z_{w+}^n| >> |Z_{w-}^n| \), the phasor FCBDR can work correctly.

5. Phasor difference FCBDR

Phasor difference FCBDR is mainly used under a two-phase fault condition. Taking the B-phase to C-phase fault at \( f_1 \) as an example, the phase angle of the impedance measured by \( R_n \) can be expressed as follows:

\[
\arg\left( \frac{\Delta u_{nBC}}{\Delta i_{nBC}} \right) \approx -180^\circ + \arg\left( \frac{2Z_{w-}^n}{Z_{w+}^n + Z_{w-}^n} \right)
\]

(36)

5.1. Supplementary Direction Criteria

The main reason for the performance degradation of FCBDRs is that the superimposed impedance of DFIG no longer has a similar reactance property as that of SG which jeopardizes the best application environment of Equations (3) and (4). However, this point can also be used to improve the performance
of FCBDR. Taking the FCBDR $R_m$ in Figure 10 as an example, for the forward fault at $f_1$, the measured impedance is $Z_m = -(Z_f + Z_{w})$, and, for the reverse fault at $f_2$, the measured impedance is $Z_m = (Z_f + Z_i)$. Obviously, the features of the measured impedance are different in these two cases (The former one is determined by $Z_{w}$). Taking advantage of this point, two supplementary direction criteria are proposed here to enhance the adaptability of the conventional FCBDRs in a DFIG-based wind farm connected scenario.

1. Criteria reflecting the difference between positive- and negative-sequence measured impedance

As aforementioned, there are significant differences between the features of positive- and negative-sequence superimposed impedance of DFIG (including the amplitude and phase angle features). On the other hand, since the FCBDR merely uses the fault information within a short time (one or two cycles after fault) to identify the fault direction, the positive- and negative-sequence impedance of the SG-based power grid side can be regarded as the same during this period. To illustrate this difference, the simulation diagrams of the sequence impedances of DFIG and SG under the same fault condition are compared in Figure 11.

![Figure 11. Difference features of the positive- and negative sequence-impedance: (a) DFIG; and (b) SG.](image)

Therefore, the fault direction can be differentiated by using the difference index between the positive- and negative-sequence measured impedance which can be expressed as

$$\frac{\max(|Z_{m+}|, |Z_{m-}|)}{\min(|Z_{m+}|, |Z_{m-}|)} > \lambda_{set1}$$  \hspace{1cm} (37)

$$|\arg(Z_{m+}) - \arg(Z_{m-})| > \theta_{set1}$$  \hspace{1cm} (38)

where $\lambda_{set1}$ and $\theta_{set1}$ are the thresholds of the amplitude and phase angle difference index, which can be set to 2–3 and 30°–60° respectively.

2. Criteria reflecting the amplitude difference of the positive-sequence measured impedance

Equations (37) and (38) can only be used in case of an asymmetric fault. When an asymmetrical fault occurs, there is only a positive-sequence component in the fault component network. Hence, it is necessary to use the characteristics of positive-sequence impedance to identify the fault direction.

There are two major distinctions between the features of the positive-sequence impedance of the DFIG-based wind farm side and the SG-based power grid side. (1) Large amplitude: Compared with the power grid side, the capacity of the wind farm is relatively small and the outlet voltage level of
the wind farm is very low (generally 690 V). As the voltage level of the transmission line is 110 kV or above; thus, after being transformed to the high voltage level, the positive-sequence impedance of wind farm is much larger than that of the power grid side. (2) Fluctuation extent: Due to the decay of the slip-related component, the amplitude of the positive-sequence impedance of the DFIG-based wind farm fluctuate over a larger range during the fault transient stage which is also different from the features of the power grid side.

Therefore, the fault direction can be differentiated by using the amplitude difference index, that is

$$|Z_{m+}| > K_{rel}|Z_{sys+}|_{max}$$

where $K_{rel}$ is the reliability coefficient which can be set to 1.5~2 and $|Z_{sys+}|_{max}$ is the maximum value of the positive-sequence impedance at the power grid side. For $R_m$ in Figure 10, $|Z_{sys+}|_{max}$ can be set as $|Z_{s+}|_{max}$ (the equivalent impedance of the power grid in the minimal operation mode), and, for $R_n$ in Figure 10, $|Z_{sys+}|_{max} = |Z_{s+} + Z_l|_{max}$.

In addition, the fault direction can be differentiated using the amplitude fluctuation index, that is

$$\frac{\sigma(|Z_{m+}|)}{\mu(|Z_{m+}|)} > \lambda_{set2}$$

where $\lambda_{set2}$ is the operation threshold whose value should escape the maximum amplitude fluctuation extent of the positive-sequence impedance at the SG-based power grid side and can be further given based on the practical engineering application environment. $\sigma$ and $\mu$ represent the standard deviation and the mean value of $|Z_{m+}|$, respectively, and they can be calculated as follows:

$$\mu(|Z_{m+}|) = \frac{1}{N} \sum_{i=1}^{N} |Z_{mi+}|$$

$$\sigma(|Z_{m+}|) = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (|Z_{mi+}| - \mu)^2}$$

where $N$ is the number of the sampling points in a data window.

5.2. Mitigation Countermeasure

Based on Equations (3) and (4), for the FCBDRs equipped at the wind farm side, they can identify the reverse fault correctly but may spuriously identify the forward fault as the reverse fault. To deal with this issue, the proposed supplementary direction criteria are introduced to assist the FCBDRs to identify the fault direction. The operation logic of the mitigation countermeasure at the wind farm side is depicted as Figure 12a. By paralleling the outputs of and the supplementary direction criteria and the conventional FCBDRs, the forward fault can be reliably identified. On the other hand, using the output of the supplementary direction criteria to block FCBDRs in case of a reverse fault, the reverse fault direction can be also reliably identified even the failure of FCBDRs. Besides, since the supplementary direction criteria Equation (40) can only work within a short time after fault, a self-hold circuit is added in the operation logic of Figure 12a.

On the contrary, for FCBDRs equipped at the SG-based power grid side, it can work correctly for the forward fault rather than the reverse fault. Accordingly, the operation logic of the mitigation countermeasure at the power grid side is depicted as Figure 12b. Using the parallel output results of the conventional FCBDRs and the supplementary direction criteria to identify the reverse fault, the sensitivity can be improved. In addition, using the output of the supplementary direction criteria to block FCBDRs in case of a forward fault, the fault direction can be identified even the failure of FCBDRs.

Moreover, when it comes to the practical engineering application, the operation speed of the proposed countermeasure is a very important point. Since the common Fourier algorithm is adopted
and only the fault information of one or two cycles after the fault is needed (about 20–40 ms) for the proposed countermeasure, after assuming that the sampling frequency of the directional relay is 5 kHz (general sampling level of the existing protection device), the number of sampling points in a cycle is 100 and then the calculation complexity of Fourier algorithm is 10,000 [30]. For the existing directional relay based on the DSP or FPGA processor, the calculation speed can reach 1 GHz, and thus computing time of the proposed scheme can be limited to 10–20 μs, which is completely acceptable. Hence, the proposed scheme is easy to implement under the present hardware conditions.

Figure 12. Operation logics of the mitigation countermeasures: (a) wind farm side; and (b) grid side.

6. Simulation and Discussion

A simulation model of a 220 kV transmission line connected to a DFIG-based wind farm, as shown in Figure 10, is established on MATLAB/Simulink platform. The parameters of DFIG are the same as those in Table A1 and other parameters of the simulation model are given in Table A2 in Appendix B.

6.1. Simulation Analysis of the Superimposed Impedance of DFIG

1. Expression verification

To verify the correctness of the derived expression of $Z_{w+}$ and $Z_{w-}$ (Equations (22) and (25)), Figure 13 shows the calculated and simulation values under different fault conditions. The fault is set at the outlet of DFIG and the fault time is set as 0.1 s. As the full-cycle Fourier algorithm is used for the impedance calculation, the comparison of the simulation and calculated values starts from 0.12 s. It can be observed in Figure 13 that the calculated values are consistent with the simulation values during the fault period, and the slight deviation between the simulation and calculated values of $Z_{w-}$ during the fault initial stage is caused by the neglected transient harmonics. Nevertheless, the changing trends of the simulation and calculated values during this transient period are nearly the same, which does not affect the analysis of the characteristics of $Z_{w+}$.

Figure 13. Simulation and calculation values of the superimposed impedance: (a) A-phase grounding fault, $s = -0.2$, $R_{cb} = 20R_r$; and (b) B-phase to C-phase fault, $s = 0.2$, $R_{cb} = 60R_r$. 

| Supplementary Direction Criteria | Forward fault | Reverse fault |
|----------------------------------|--------------|--------------|
| (1)                              |              |              |
| (2)                              |              |              |
| (3)                              |              |              |
| (4)                              |              |              |

Oil-impedance calculation, the comparison of the simulation and calculated values starts from 0.12 s. It can be observed in Figure 13 that the calculated values are consistent with the simulation values during the fault period, and the slight deviation between the simulation and calculated values of $Z_{w-}$ during the fault initial stage is caused by the neglected transient harmonics. Nevertheless, the changing trends of the simulation and calculated values during this transient period are nearly the same, which does not affect the analysis of the characteristics of $Z_{w+}$.

Figure 13. Simulation and calculation values of the superimposed impedance: (a) A-phase grounding fault, $s = -0.2$, $R_{cb} = 20R_r$; and (b) B-phase to C-phase fault, $s = 0.2$, $R_{cb} = 60R_r$. 

| Supplementary Direction Criteria | Forward fault | Reverse fault |
|----------------------------------|--------------|--------------|
| (1)                              |              |              |
| (2)                              |              |              |
| (3)                              |              |              |
| (4)                              |              |              |

Oil-impedance calculation, the comparison of the simulation and calculated values starts from 0.12 s. It can be observed in Figure 13 that the calculated values are consistent with the simulation values during the fault period, and the slight deviation between the simulation and calculated values of $Z_{w-}$ during the fault initial stage is caused by the neglected transient harmonics. Nevertheless, the changing trends of the simulation and calculated values during this transient period are nearly the same, which does not affect the analysis of the characteristics of $Z_{w+}$.

Figure 13. Simulation and calculation values of the superimposed impedance: (a) A-phase grounding fault, $s = -0.2$, $R_{cb} = 20R_r$; and (b) B-phase to C-phase fault, $s = 0.2$, $R_{cb} = 60R_r$. 

| Supplementary Direction Criteria | Forward fault | Reverse fault |
|----------------------------------|--------------|--------------|
| (1)                              |              |              |
| (2)                              |              |              |
| (3)                              |              |              |
| (4)                              |              |              |
2. Characteristics verification

According to the analysis in Section 3, the characteristics of $Z_{w+}^*$ is determined by three factors ($k$, $R'_r$, and $s$) and the characteristics of $Z_{w-}^*$ is determined by two factors ($R'_r$ and $s$). Hence, three cases are presented here to verify the characteristics of $Z_{w+}^*$ and $Z_{w-}^*$, i.e.,

Case 1: $s = 0.1$, $R_{cb} = 60R_r$, and $k = 0$, 0.2, and 0.4, respectively.
Case 2: $k = 0.5$, $R_{cb} = 20R_r$, and $s = -0.2$, -0.1, 0, 0.1, and 0.2, respectively.
Case 3: $k = 0.2$, $s = -0.2$, and $R_{cb} = 20R_r$, 40$R_r$, and 60$R_r$, respectively.

Case 1: In this case, the fault condition corresponds to the theoretical analysis of Figure 6b ($s > 0$ and large $R_{cb}$). Since $i_d$ decays fast in the case, the amplitude of $Z_{w+}^*$ increases with the decrease of $\Delta i_{k+}$. Meanwhile, the phase angle of $Z_{w+}^*$ gradually increases with the rotation of $\Delta i_{k+}$ and finally passes through 180° to approach a negative angle. After reaching the fault steady stage, the amplitude and phase angle of $Z_{w+}^*$ maintain constant, and a smaller $k$ corresponds to a larger amplitude and the smaller phase angle. By comparing Figures 14 and 6b, the characteristic simulation results are consistent with the theoretical analysis.

![Figure 14. Characteristic simulation results of $Z_{w+}^*$ in Case 1.](image_url)

Case 2: The characteristic simulation results of $Z_{w+}^*$ and $Z_{w-}^*$ in Case 2 are shown in Figures 15 and 16, respectively. As can be observed in Figure 15, the amplitude of $Z_{w+}^*$ fluctuates obviously during the fault transient stage, especially when $s \leq 0$. The main reason is that when $\Delta i_{k+}$ reaches near the real-axis (see Figure 5a and the phase angle of $Z_{w+}^*$ is close to 0° or 180°), the amplitude of $\Delta i_{k+}$ is relatively small which results in a peak amplitude of $Z_{w+}^*$. Since a small crowbar resistance is used in this case, the phase angle of $Z_{w+}^*$ decreases when $s < 0$ and increases when $s > 0$. In conclusion, the simulation results of $Z_{w+}^*$ during the fault transient stage perfectly match the analysis results of Figures 5–7. In addition, after reaching the fault steady stage, the amplitude and phase angle of $Z_{w+}^*$ maintain constant, which is also consistent with Figure 8. As for $Z_{w-}^*$, it can be seen in Figure 17 that the amplitude and phase angle of $Z_{w-}^*$ remain basically constant when $s$ varies over a wide range, which is consistent with the theoretical analysis of Figure 9.

![Figure 15. Characteristic simulation results of $Z_{w+}^*$ in Case 2.](image_url)
Case 3: The characteristic simulation results of $Z_{w+}$ and $Z_{w-}$ in Case 3 are shown in Figure 17a,b, respectively. As shown in Figure 17a, since $s < 0$ in this case, the amplitude of $Z_{w+}$ fluctuates obviously during the fault transient stage. Moreover, when $R_{cb} = 20R_r$, the phase angle of $Z_{w+}$ decreases gradually from the initial phase angle and then passes through $0^\circ$ to become a negative angle; while when $R_{cb} = 20R_r$ or $40R_r$, the phase angle of $Z_{w-}$ increases gradually from the initial phase angle and then passes through $180^\circ$ to become a negative angle, which matches the analysis results of Figure 5a,b. As shown in Figure 17b, with the increase of $R_{cb}$, the amplitude and phase angle of $Z_{w-}$ increases and decreases, respectively, which also match the theoretical analysis.

![Figure 16](image1)

**Figure 16.** Characteristic simulation results of $Z_{w-}$ in Case 2.

![Figure 17](image2)

**Figure 17.** Characteristic simulation results of $Z_{w+}$ and $Z_{w-}$ in Case 3: (a) $Z_{w+}$; and (b) $Z_{w-}$.

6.2. Simulation Analysis of FCBDRs and the Proposed Mitigation Countermeasure

Three cases are presented to verify the performance of the mitigation countermeasure. Meanwhile, the performances of the conventional FCBDRs are also given for comparison.

Case 4: The A-phase grounding fault occurs at $f_1$. ($R_{cb} = 20R_r$).
Case 5: The A-phase to B-phase grounding fault occurs at $f_2$. ($R_{cb} = 40R_r$).
Case 6: The A-phase grounding fault occurs at $f_3$. ($R_{cb} = 60R_r$).

(1) Performances of the Conventional FCBDRs

The performances of each conventional FCBDRs equipped at busbar $n$ and busbar $m$ are shown in Figure 18. In Figure 18, the forward and reverse identification regions for the FCBDRs are marked with the shadow regions according to Equations (3) and (4).
Case 4: Figure 18a shows that the positive-sequence and phasor (difference) FCBDR at busbar $n$ reaches the reverse identification region about half-cycle and one cycle after the fault, respectively, which causes the misjudgment of fault direction. In this situation, for the directional blocking pilot protection, the protection scheme cannot trip the internal fault correctly. Besides, the negative-sequence FCBDR and zero-sequence directional relay at two ends are not affected by the fault behavior of DFIG, the different types of FCBDRs at busbar $m$ can identify the forward direction fault sensitively.

Case 5: For the fault at $f_2$, since both the FCBDRs at busbar $m$ and busbar $n$ are not affected by the fault behavior of DFIG, the different types of FCBDRs can correctly identify the fault direction, as shown in Figure 18b.

Case 6: For the fault at $f_3$, both the FCBDRs at busbar $m$ and $n$ are affected by the fault behavior of DFIG. As can be observed in Figure 18c, the positive-sequence FCBDRs at busbar $n$ and busbar $m$ will misjudge the fault direction about half-cycle after the fault. Besides, the phasor (difference) FCBDR at busbar $n$ will also identify the fault direction incorrectly after about one cycle. Although the phasor (difference) FCBDR at busbar $m$ can work correctly, its sensitivity significantly declines since it nearly reaches the boundary of the identification region. Similarly, the performances of the negative-sequence FCBDR and zero-sequence directional relay at two ends are not affected.

(2) Performances of the Proposed Mitigation Countermeasure

Case 4: The operation thresholds of Equations (37), (38), (39), and (40) are set as $\lambda_{set1} = 2$, $\theta_{set1} = 30^\circ$, $K_{rel} = 1.5$, and $\lambda_{set2} = 0.2$, respectively. Based on the positive- and negative-sequence impedances measured by the FCBDRs equipped at busbar $m$ and $n$, the direction identification results of the supplementary direction criteria (Equations (37), (38), (39), and (40)) are shown in Figure 19. Meanwhile, the performances of the positive-sequence FCBDR (Equations (3) and (4)) are also given in Figure 19 for comparison. As can be observed in Figure 19a, due to the phase angle variation of
the superimposed impedance of DFIG, the positive-sequence FCBDR at busbar \( n \) can only identify the forward fault correctly within a short time after the fault \( (t \leq T) \). However, Equation (39) always has a stable output during the fault, and Equations (37) and (38) identify the forward direction at \( t = T_1 \) and maintain a stable output thereafter. In addition, Equation (40) switches the output at \( t = T_2 \) and will also maintain a stable output afterward due to the use of the self-hold circuit. Since the proposed mitigation countermeasure at busbar \( n \) (see Figure 12a) uses the parallel output result of the conventional FCBDR and the supplementary direction criteria to identify the fault direction, the proposed mitigation countermeasure can ensure that the forward direction fault can be reliably identified during the whole fault period. On the other hand, since the positive-sequence FCBDR at busbar \( m \) is not affected by the fault behavior of DFIG, it can correctly identify the forward fault, as shown in Figure 19b. Simultaneously, there is no output from the supplementary direction criteria at busbar \( m \). To observe the improvement more clearly, the operation results of FCBDR with and without the proposed countermeasures are shown in Figure 20.

![Figure 19](image1.png)

**Figure 19.** Performances of the mitigation countermeasure in Case 4 (a) busbar \( n \); and (b) busbar \( m \).

![Figure 20](image2.png)

**Figure 20.** Operation results of the directional relay with and without the proposed countermeasure in Case 4 (a) busbar \( n \); and (b) busbar \( m \).

Case 5: As aforementioned, the performance of FCBDRs at two ends are not be affected by the fault behaviors of DFIG when the fault is located at \( f_2 \). Hence, the simulation result is not presented here.

Case 6: The direction identification results of the supplementary direction criteria and the positive-sequence FCBDR are shown in Figure 21. In this case, the superimposed impedance of DFIG is included in both the measured impedances of the busbar \( m \)- and \( n \)-side positive-sequence FCBDR.
As a result, it can be seen in Figure 21 that the positive-sequence FCBDR at two ends can only work correctly in a short time after the fault \((t \leq T)\). For the supplementary direction criteria at busbar \(n\), as shown in Figure 21a, Equation (39) always has a stable output during the fault and Equations (37) and (38) identify the forward fault direction at \(t = T_1\) and maintain a stable output thereafter. Moreover, Equation (40) switches the output at \(t = T_2\) and maintain a stable output due to the use of the self-hold circuit. According to the operation logic of the proposed mitigation countermeasure at busbar \(n\), the forward direction fault can be reliably identified during the whole fault period. For the supplementary direction criteria at busbar \(m\), as shown in Figure 21b, Equations (38) and (40) have a stable output after \(t = T_1\), and Equation (39) have a stable output after \(t = T_2\). According to the operation logic of the proposed mitigation countermeasure at busbar \(n\) (see Figure 12b), the reverse direction fault can be reliably identified during the whole fault period. To observe the improvement more clearly, the operation results of FCBDR with and without the proposed countermeasures are shown in Figure 22.

![Figure 21. Performances of the mitigation countermeasure in Case 6: (a) busbar \(n\); and (b) busbar \(m\).](image)

![Figure 22. Operation results of the directional relay with and without the proposed countermeasure in Case 6: (a) busbar \(n\); and (b) busbar \(m\).](image)

Those simulation findings illustrate that, due to the impact of the superimposed impedance of DFIG (especially the positive-sequence superimposed impedance) when the positions of FCBDRs are located between the fault point and the DFIG-based wind farm, the positive-sequence FCBDR and the phasor (difference) FCBDR may misjudge the fault direction. As a remedy, the proposed mitigation countermeasure can effectively avoid these issues.
7. Conclusions

This paper reveals some easily overlooked problems associated with FCBDRs when applied in a DFIG-based wind farm connected scenario. Due to the fast response characteristic of DFIG after fault, an additional potential is introduced into the fault component network apart from the one at the fault point. This phenomenon may jeopardize the unified phase angle property of the fault component network which is the fundamental premise required from FCBDRs. As a result, the performances of the related FCBDRs are shown negatively impacted by the fault behavior of DFIG. This paper also proposes a mitigation countermeasure to address those issues. Theoretical analysis and simulation results show that with the assistance of the proposed countermeasure, the improved FCBDRs can differentiate the forward and reverse fault clearly under different fault conditions. By contrast with the conventional FCBDRs, the highlights of the proposed mitigation countermeasure are summarized as follows:

- The proposed mitigation countermeasure includes two supplementary direction criteria which can remedy the limitation of the conventional FCBDRs solely depending on the phase angle comparison.
- Using the significantly different features of the superimposed impedance between DFIG and SG to identify the fault direction, the influences of the fault behavior of DFIG on the FCBDR are significantly weakened.
- The adaptive operation logic of the proposed mitigation countermeasure can ensure that the conventional FCBDRs can identify the fault direction with high sensitivity at both the wind farm side and the power grid side.

The characteristics of DFIG superimposed impedance and their impacts on FCBDRs in the case of the converter control mode were not considered in this paper, which could be considered as an extension of the current work. In addition, the effectiveness of the proposed mitigation countermeasure under the real engineering environment should be further tested and discussed.

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**Nomenclature**

- $u_s, u_r$: Stator and rotor voltage vectors.
- $i_s, i_r$: Stator and rotor current vectors.
- $\psi_s, \psi_r$: Stator and rotor flux linkage vectors.
- $R_s, R_r$: Stator and rotor resistances.
- $\omega_s$: Synchronous angular frequency.
- $p, D$: Laplace and differential operators.
- $k$: Voltage sag extent.
- $L_s, L_r$: Stator and rotor inductances.
- $L_m$: Magnetizing inductance.
- $s$: Slip.
- $R_{cb}$: Crowbar resistance.
- $j$: Imaginary unit.
- $\Delta$: Fault component.
- $+$: Positive-sequence quantity.
- $-$: Negative-sequence quantity.
- $|0|, \infty$: Pre-fault and steady-state values.
- $0$: Zero-sequence quantity.
- $P, N$: Positive and negative synchronous rotation reference frames.
Appendix A

Assume that the expression of a slip-related frequency component is as follows:

\[ i(t) = Ae^{-\frac{2\pi}{T}t} \sin((1-s)\omega_s t + \varphi) \]  

(A1)

where \( A \) is the amplitude, \( \varphi \) is the initial phase, and \( \omega_s = 100\pi \).

The real and imaginary parts of the full-wave fundamental-frequency Fourier algorithm can be expressed as:

\[
\begin{align*}
I_R(t) &= \frac{2}{T} \int_0^T i(m) \sin(\omega_s m) \, dm \\
I_I(t) &= \frac{2}{T} \int_0^T i(m) \cos(\omega_s m) \, dm
\end{align*}
\]

(A2)

where \( T \) is the fundamental-frequency cycle.

Substituting Equation (A1) into (A2), there is

\[
\begin{align*}
I_R(t) &= \frac{A T e^{-\frac{2\pi}{T}t}}{1 + T^2 \omega_s^2} \left[ X(s) + T' r s o_y Y(s) \right] + \\
&\frac{A T e^{-\frac{2\pi}{T}t}}{1 + T^2 \omega_s^2 \omega_0^2} \left[ X(s-2) + T' r (s-2) \omega_s Y(s-2) \right] \\
I_I(t) &= \frac{A T e^{-\frac{2\pi}{T}t}}{1 + T^2 \omega_s^2} \left[ Y(s) - T' r s o_y X(s) \right] - \\
&\frac{A T e^{-\frac{2\pi}{T}t}}{1 + T^2 \omega_s^2 \omega_0^2} \left[ Y(s-2) - T' r (s-2) \omega_s X(s-2) \right]
\end{align*}
\]

(A3)

In (A3), the expressions of \( X(s) \) and \( Y(s) \) are as follows:

\[
\begin{align*}
X(s) &= e^{-\frac{2\pi}{T}T'} \cos(-s \omega_s t - 2s \pi + \varphi) - \cos(-s \omega_s t + \varphi) \\
Y(s) &= e^{-\frac{2\pi}{T}T'} \sin(-s \omega_s t - 2s \pi + \varphi) - \sin(-s \omega_s t + \varphi)
\end{align*}
\]

(A4)

Since the premise that \( T' r s o_y << 1 \) and \( -0.3 \leq s \leq 0.3 \) is met, \( 1 + T^2 (s-2)^2 \omega_s^2 << 1 + T'^2 s^2 \omega_s^2 \) and the latter term in (A3) can be ignored accordingly. Furthermore, using the simplified \( I_R(t) \) and \( I_I(t) \), the amplitude and phase of \( i(t) \) after extracted by the Fourier algorithm can be obtained as (A3) and (A6):

\[
I(t) = \frac{A T e^{-\frac{2\pi}{T}t}}{T} \sqrt{1 - 2e^{-\frac{2\pi}{T}T'} \cos(2s \pi) + e^{-2\frac{2\pi}{T}T'}} \tag{A5}
\]

\[
\tan(\varphi(t)) = \frac{-Y(s) + T' r s o_y X(s)}{-X(s) - T' r s o_y Y(s)} \tag{A6}
\]

By comparing (A1) and (A5), it can be found that, after extracting by the Fourier algorithm, the amplitude of the slip-related frequency component still decays following the same exponential law (\( T' r \)) and there is only an amplitude difference coefficient \( \Delta A \) whose expression is as follows:

\[
\Delta A = \frac{T' r}{T} \sqrt{1 - 2e^{-\frac{2\pi}{T}T'} \cos(2s \pi) + e^{-2\frac{2\pi}{T}T'}} \tag{A7}
\]

Based on (A6), it can be found that, after extracting by the Fourier algorithm, the phase of the slip-related frequency component will change with the frequency of \( -s \omega_s \). Moreover, the initial phase is no longer \( \varphi \) and the phase variation \( \Delta \varphi = \varphi(0) - \varphi \) can be calculated by:

\[
\tan \Delta \varphi = \frac{e^{-\frac{2\pi}{T}T'} \sin(2s \pi) + T' r s o_y e^{-\frac{2\pi}{T}T'} \cos(2s \pi) - T' r s o_y}{e^{-\frac{2\pi}{T}T'} \sin(2s \pi) + T' r s o_y e^{-\frac{2\pi}{T}T'} \cos(2s \pi) + 1} \tag{A8}
\]

It can be found from (A7) and (A8) that \( \Delta A \) and \( \Delta \varphi \) are related to \( T' r \) and \( s \). When \( T' r \to 0 \), \( \Delta A \to 0 \), and \( \Delta \varphi \to 0 \); \( T' r \to +\infty \), \( \Delta A = \sin(\pi s) / (\pi s) \), and \( \Delta \varphi = -\pi s \). Figure A1 depicts the relationship of \( \Delta A \) and \( \Delta \varphi \) with \( T' r \) and \( s \).
When the half-wave Fourier algorithm is used, by replacing $T$ with $T/2$, the above conclusions still work.

**Appendix B**

### Table A1. Parameters of DFIG.

| Parameters | $R_r$ | $R_s$ | $L_d$ | $L_f$ | $L_m$ |
|------------|-------|-------|-------|-------|-------|
| Vaule (pu) | 0.006 | 0.008 | 3.072 | 3.055 | 2.9   |

### Table A2. Parameters of the simulation model.

| Parameters | $Z_{s+,-}$ | $Z_{f+,-}$ | $Z_{T+,-}$ |
|------------|------------|------------|------------|
| Vaule (Ω)  | 0.58 + j19.36 | 3.06 + j65.97 | 3.23 + 64.53 |

**References**

1. Telukunta, V.; Pradhan, J.; Agrawal, A. Protection challenges under bulk penetration of renewable energy resources in power systems: A review. *CSEE J. Power Energy Syst.* 2017, 3, 365–379. [CrossRef]
2. Ren, G.; Liu, J.; Wan, J.; Guo, Y.; Yu, D. Overview of wind power intermittency: Impacts, measurements, and mitigation solutions. *Appl. Energy* 2017, 204, 47–65. [CrossRef]
3. Georgilakis, P.S. Technical challenges associated with the integration of wind power into power systems. *Renew. Sustain. Energy Rev.* 2008, 12, 852–863. [CrossRef]
4. Yang, J.; Song, D.; Wu, F. Regional variations of environmental co-benefits of wind power generation in China. *Appl. Energy* 2017, 206, 1267–1281. [CrossRef]
5. Jia, K.; Yang, Z.; Fang, Y.; Bi, T.; Sumner, M. Influence of inverter-interfaced renewable energy generators on directional relay and an improved scheme. *IEEE Trans. Power Electron.* 2019, 34, 11843–11855. [CrossRef]
6. Tohidi, S.; Oraee, H.; Zolghadri, M.R.; Shao, S.; Tavner, P. Analysis and enhancement of low-voltage ride-through capability of brushless doubly fed induction generator. *IEEE Trans. Ind. Electron.* 2013, 60, 1146–1155. [CrossRef]
7. Li, J.; Zheng, T.; Wang, Z.P. Short-circuit current calculation and harmonic characteristic analysis for a doubly-fed induction generator wind turbine under converter control. *Energies* 2019, 11, 2471. [CrossRef]
8. Li, X.; Lu, Y.P. Improved amplitude differential protection scheme based on the frequency spectrum index for distribution networks with DFIG-based wind DGs. *IEEE Access* 2020, 8, 64225–64237. [CrossRef]
9. Ouyang, J.X.; Xiong, X.F. Research on short-circuit current of doubly fed induction generator under non-deep voltage drop. *Electr. Power Syst. Res.* 2014, 107, 158–166. [CrossRef]
10. Huang, T.; Lu, Y.P.; Cai, C. A new simulation and analysis for low voltage ride through property of wind farm. In Proceedings of the IEEE Power and Energy Society General Meeting Conference & Exposition, San Diego, CA, USA, 22–26 July 2012.
11. Hooshyar, A.; Azzouz, M.A.; El-Saadany, E.F. Distance protection of lines connected to induction generator-based wind farms during balanced faults. *IEEE Trans. Energy Convers.* 2014, 5, 1193–1203. [CrossRef]
12. Chen, Y.; Wen, M.; Yin, X.; Cai, Y.; Zheng, J. Distance protection for transmission lines of DFIG-based wind power integration system. *Int. J. Elect. Power Energy Syst.* 2018, 100, 438–448. [CrossRef]
13. Dubey, R.; Samantaray, S.R.; Panigrahi, B.K.; Venkoparao, G.V. Adaptive distance relay setting for parallel transmission network connecting wind farms and UPFC. *Int. J. Elect. Power Energy Syst.* 2015, 65, 113–123. [CrossRef]

14. Dubey, R.; Samantaray, S.R.; Panigrahi, B.K. Adaptive distance protection scheme for shunt-FACTS compensated line connecting wind farm. *IET Gener. Transm. Distrib.* 2016, 10, 247–256. [CrossRef]

15. Pradhan, A.K.; Joos, G. Adaptive distance relay setting for lines connecting wind farms. *IEEE Trans. Energy Convers.* 2007, 22, 206–213. [CrossRef]

16. Yang, G.; Dong, M.; Zhou, Z.; Zhou, C.; Du, D.; Zhan, Z.; Yang, D. The influences and countermeasures of wind farm access to transmission line differential protection. In Proceedings of the IEEE Power Electronics and Machines in Wind Applications, Denver, CO, USA, 16–18 July 2012; pp. 1–4.

17. Yang, J.; Wang, B. Adaptability analysis of fault component differential protection in large capacity double-fed wind farm outgoing transmission line protection. In Proceedings of the International Conference on Smart Grid and Clean Energy Technologies, Chengdu, China, 19–22 October 2016; pp. 221–225.

18. Wei, W.; Zhang, L.; Gao, B.; Tang, Y.; Chen, N.; Zhu, L. Frequency inconsistency in DFIG-based wind farm during outgoing transmission line faults and its effect on longitudinal differential protection. In Proceedings of the 4th Annual IEEE International Conference on Cyber Technology in Automation, Control and Intelligent, Hong Kong, China, 4–7 June 2014; pp. 25–30.

19. Jia, K.; Li, Y.B.; Fang, Y.; Zheng, L.; Bi, T.; Yang, Q. Transient current similarity based protection for wind farm transmission lines. *Appl. Energy* 2018, 225, 42–51. [CrossRef]

20. Chen, L.; Ling, X.N.; Li, Z.T.; Wei, F.R.; Zhao, H.; Bo, Z.Q.; Huang, J.G.; Deng, K. Similarity comparison based high-speed pilot protection for transmission line. *IEEE Trans. Power Del.* 2018, 33, 938–948. [CrossRef]

21. Hooshyar, A.; Iravani, R. A new directional element for microgrid protection. *IEEE Trans. Smart Grid* 2018, 9, 6862–6876. [CrossRef]

22. Hooshyar, A.; Azzouz, M.A.; El-Saadany, E.F. Three-phase fault direction identification for distribution systems with DFIG-Based Wind DG. *IEEE Trans. Sustain. Energy* 2014, 5, 747–756. [CrossRef]

23. Tang, J.; Song, G.; Wang, C. Adaptability analysis of directional relays in power systems with wind farms. In Proceedings of the 13th International Conference on Development in Power System Protection 2016, Edinburgh, UK, 7–10 March 2016; pp. 1–6.

24. Wang, C.Q.; Song, G.B.; Zhang, J.H. A novel principle of directional relay for wind power integration based on model recognition in time-domain. In Proceedings of the 2016 IEEE PES Asia-Pacific Power and Energy Engineering Conference, Xi’an, China, 25–28 October 2016; pp. 1851–1855.

25. Huang, T.; Lu, Y.P. Improved superimposed current phase selector of wind farm with crowbar system. In Proceedings of the 2014 IEEE PES General Meeting Conference & Exposition, National Harbor, MD, USA, 27–31 July 2014; pp. 1–5.

26. Huang, T.; Lu, Y.P.; Cai, C. Analysis of phase angle characteristics of DFIG equivalent sequence superimposed impedances and its impact on fault components based direction relay. *Proc. CSEE* 2016, 14, 3929–3939.

27. Ge, Y.Z. *New Types of Protective Relaying and Fault Location: Their Theory and Techniques*; Xi’an Jiao Tong University Press: Xi’an, China, 2007; p. 93.

28. Ouyang, J.X.; Zheng, D.; Xiong, X.F.; Xiao, C.; Yu, R. Short-circuit current of doubly fed induction generator under partial and asymmetrical voltage drop. *Renew. Energy* 2016, 88, 1–11. [CrossRef]

29. LokFu, P.; Dinavahi, V. Real-time simulation of a wind energy system based on the doubly-fed induction generator. *IEEE Trans. Power Syst.* 2009, 24, 1301–1309. [CrossRef]

30. Trefethen, L.N.; Bau, D. *Numerical Linear Algebra III*; SIAM: Philadelphia, PA, USA, 1997; pp. 83–84.

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