Abstract

In the dynamics of grid-connected operation of brushless doubly-fed generators, grid voltage dips can cause the extreme imbalance between the voltage and the back electromotive forces in power winding. When these imbalances are combined with the influence of the inertia link composed of converter and generator, a serious over-current and current oscillation forms in power winding and control winding. This paper gives a process analysis and proposes an improved control to the system during the low voltage ride through event. According to the mathematical model of the generators, the correlation between the power winding and control winding currents is established and then a fully equivalent simplified model is obtained accordingly. When the voltage suddenly drops to zero, the analytic expressions of power winding and control winding are calculated in the complex frequency domain and the influence factors of overshoot and oscillations are analyzed. The conventional control method relies on limited PI regulation that cannot eliminate the oscillations completely. It is found that after adjusting a proportional coefficient and eliminating the integral link of the control winding current controller, the order of the control system reduces. Therefore, the generation system can quickly recover to a steady state without oscillations. Finally, the analysis and improvement are verified by the simulation model and experimental results.

1 INTRODUCTION

Brushless doubly-fed electric generators with no-slip ring have superior characteristics, including low maintenance costs and high reliability [1–3]. Accordingly, many scholars and scientific research institutions have studied this issue in the past few years [4, 5]. More specifically, studies show that these generators outperform the conventional brush doubly fed induction generators (DFIG) in the field of wind power generation [6, 7].

The schematic configuration of a brushless doubly fed wind power generation system as depicted in Figure 1. The wind turbine is connected to the generator through a gear box. The power winding (PW) of the stator is directly connected to the power grid, and the control winding (CW) is connected to the grid through a bidirectional converter [8]. Some systems are equipped with crowbars to absorb energy during low voltage ride through (LVRT) events. Based on a generator’s characteristics, the capacity of a converter is generally less than one third of the rated power of the generator.

The present study mainly focuses on their operation under normal conditions. If the grid voltage drastically falls, it causes severe over-currents and oscillations in brushless doubly-fed generators’ (BDFGs’) windings. A variety of relevant research has been described in the literature.

Shao and Ehsan [9] performed a dynamic analysis to investigate LVRT events with symmetric drops set to 50% and zero. However, they did not propose a certain strategy in this regard. By referencing the general ideas of how doubly fed generation systems should work, crowbars or Series Dynamic Resistors are installed between a CW and a generator to absorb the excess power [10], the disadvantage is the system cost will increase.

Reviewing the literature indicates that typical methods normally adopt different control strategies before and after fault [11–13]. For example, the real current in the PW is at its...
nominal value and the reactive current is set to zero. In other words, the PW operates at the nominal rating with a unity power factor. When the LVRT event occurs, the commanded values for the active and reactive current are set to zero and the rated value, respectively. But there are some large overshoot and oscillations in these strategies.

In [14], the command voltage value for the CW is added with a compensation term of the reaction rate of the PW, CW, and RW, to reduce the current oscillations. The simulation results show that this method can effectively reduce the amplitude of oscillations when the grid voltage dips, but more experimental verifications are required in this regard. A comparative analysis of BDFGs and synchronous generators is put in [15], it introduces a virtual synchronous machine approach to compensating for the current signal. This gives a virtual increase in the rotating inertia, making the system respond more slowly to the impact of faults. However, the main drawback of this scheme is that the voltage drops to 70% rather than approaching to zero.

In [16], a new reduced dynamic T-model was proposed, and a detailed mathematical analysis was derived for PW’s and CW’s variables (flux, current, and voltage) subject to voltage-dip conditions including open-and short-circuited CW, and converter-fed CW conditions. It depends on the generator design to reduce the overvoltage and overcurrent rather than improvement of the control strategy.

A crowbarless LVRT control strategy based on flux linkage tracking for a BDFG under symmetrical voltage dips is proposed in [17]. A simple controller in a static reference frame rather than a rotating coordinate system is presented to implement flux linkage tracking. Based on the conventional control method, the amplitude compensation and phase compensation of the CW flux are added into the control strategy. Meanwhile, a tracking coefficient, which is defined as the ratio of the CW flux to the PW flux, is proposed and then the experiments are carried out with different coefficients. In order to both suppress CW current and increase PW reactive current, a time-sharing control and CW current-first control solution is proposed. In the most severe case, where the BDFG rotor speed is 100% of the maximum speed and under 100% symmetrical voltage dips, the experimental results show that the CW current peak can be limited to twice as the CW current rating and the torque ripple is small during the fault.

This paper focuses on the dynamics of LVRT events. First, the mathematical model of the BDFG is listed. After determining the voltage orientation and initial excitation, the correlation between the four dq axis components of the PW and the CW current is analyzed in the rotating coordinate system. Furthermore, the full equivalent model that similar to the DFIG is obtained, which is easy to analyze and control for the system. When the grid voltage dips to 0 V, according to the simplified model, the expressions of PW and CW current are calculated in the complex frequency domain, and the factors related to the overshoot and oscillations are analyzed. Then, the PI parameters are adjusted and the integral link is removed in CW current loop, so that the order of the control system is reduced, and its anti-disturbance capability is enhanced. The overshoot is reduced and the oscillations are cleared. Finally, by comparing the simulation and experimental waveforms with results from the conventional strategy, the feasibility and effectiveness of the improved strategy are validated.

The main innovation of the paper is to analyze the correlation among four current dq components. According to the expression of the CW current in the complex frequency-domain, the proportionality coefficient is set and the integral link is removed in the CW current controller to reduce the overshoot and eliminate the oscillations.

2 | STRUCTURE AND PRINCIPLE OF BDFG

2.1 | The basic characteristics of a BDFG

There are two stator windings in wound-rotor brushless doubly fed machines, the PW and the CW, but two sets of windings have different pole counts. The rotor has only one set of windings, rotor winding (RW). In terms of its characteristics, this is equivalent to two sets of windings with reverse phase sequence connections. Figure 2 shows the schematic diagram for windings in a BDFG [18, 19].

For operating generator, the mechanical angular speed \( \omega_p \) and electrical angular frequency of the RW current \( \omega_{rp} \) can be written as follows:

\[
\omega_p = \frac{\omega_p + \omega_c}{p_p + p_c}
\]

\[
\omega_{rp} = \frac{\omega_p p_c - \omega_c p_p}{p_p + p_c}
\]

where \( p_p \) and \( \omega_p \) are the pole pairs and electrical angular frequency of PW. Similarly, \( p_c \) and \( \omega_c \) represent the corresponding parameters of the CW.
2.2 Mathematical model in dq coordinate system

According to electric machine theory, the dynamic model of the generator can be obtained in the dq reference frame, synchronous with the PW. The voltage equations for the model are listed below. The generator convention is used for both the PW and CW sides. It should be noted that the initial excitation of the system is oriented with the d-axis [20, 21]

\[
\begin{align*}
    u_{pd} &= -R_p i_{pd} + \rho \psi_{pd} - \omega_p \psi_{pq} \quad (3) \\
    u_{pq} &= -R_p i_{pq} + \rho \psi_{pq} + \omega_p \psi_{pd} \quad (4) \\
    \psi_{cd} &= -R_c \psi_{cd} + \rho \psi_{cd} - \omega_c \psi_{cq} \quad (5) \\
    \psi_{eq} &= -R_c \psi_{eq} + \rho \psi_{eq} + \omega_c \psi_{cd} \quad (6) \\
    n_{rd} &= R_i \psi_{rd} + \rho \psi_{rd} - \omega_p \psi_{rq} = 0 \quad (7) \\
    n_{eq} &= R_i \psi_{eq} + \rho \psi_{eq} + \omega_p \psi_{rd} = 0. \quad (8)
\end{align*}
\]

The flux linkage equations, torque equation and motion equation are as follows:

\[
\begin{align*}
    \psi_{pd} &= -L_p i_{pd} + M_{pr} i_{rd} \quad (9) \\
    \psi_{pq} &= -L_p i_{pq} + M_{pr} i_{eq} \quad (10) \\
    \psi_{cd} &= -L_c \psi_{cd} - M_{cr} i_{rq} \quad (11) \\
    \psi_{eq} &= -L_c \psi_{eq} + M_{cr} i_{rd} \quad (12) \\
    \psi_{rd} &= L_c \psi_{rd} - M_{pr} i_{pd} - M_{cr} \psi_{cq} \quad (13) \\
    \psi_{rq} &= L_c \psi_{rq} - M_{pr} i_{pq} + M_{cr} \psi_{cd} \quad (14)
\end{align*}
\]

\[
T_c = -p_c M_{pr}(i_{pq} \psi_{rq} + i_{pd} \psi_{rd}) - p_c M_{cr}(i_{eq} \psi_{rq} - i_{cd} \psi_{rd}) \quad (15)
\]

\[
T_m - T_e = \frac{\partial \omega_e}{\partial t} \quad (16)
\]

where \( u_{pd}, u_{pq}, \) and \( u_{cd} \) are the d-axis components of the PW voltage, the CW voltage, and the RW voltage, \( u_{pq}, u_{eq}, \) and \( u_{eq} \) are the q-axis components of the corresponding winding, \( \psi_{pd}, \psi_{eq}, \) and \( \psi_{eq} \) are the d-axis components of the flux linkage of PW, CW, and RW. The winding currents \( i_{pd}, i_{pq}, \) and so on are named similarly. The parameters \( R_e, R_p, \) and \( R_c \) represent the resistances of the PW, RW, and CW for each phase, \( \omega_p, \omega_c, \omega_r, \) and \( \omega_p \) are the same as the variables in the BDFG structure above, and \( \rho \) represents the differential operators in the equation. The parameters \( I_{pr}, \psi_{eq}, \) and \( I_{cr} \) are then the self-inductance values for the equivalent two-phase windings of PW, CW, and RW, \( M_{pr} \) is the mutual inductance between the coaxial equivalent windings of PW and RW, and \( M_{cr} \) is mutual inductance between the coaxial equivalent windings of CW and RW. Finally, \( T_m, T_e, \) and \( f \) are mechanical torque, electromagnetic torque, and rotational inertia of a brushless doubly fed generator.

3 DYNAMIC ANALYSIS PROCESS FOR AN LVRT EVENT

3.1 Operation analysis of internal variables of generator with a general control strategy

Through a grid voltage orientation strategy, the PW voltage vector is oriented with the d-axis. So that: \( u_{pd} = u_{pm}, u_{pq} = 0, \) and \( u_{pq} \) is the amplitude of the three phase synthetic vector of PW voltage. Here, \( i_{pd} \) and \( i_{pq} \) represent active and reactive components of PW current, respectively. Due to PW d-axis initial excitation, it means \( u_{eq} = -u_{pq}, \) \( u_{cd} = 0. \) In steady state, the differential and resistance terms can be removed, from (4) and (5), \( \psi_{pd} \approx 0, \psi_{eq} \approx 0. \) Then according to (3)–(14), the generator's vector diagram in the rotating coordinate system can be depicted as follows:

Further from (3), (9), and (12), combined with the above description, and according to the generator parameters in Table 1: \( I_{cr} \approx M_{pr} + M_{cr}, I_{cr} \approx M_{cr}, I_{cr} \approx M_{cr}. \) It is specially stated

| Parameter          | Value  | Parameter          | Value  |
|--------------------|--------|--------------------|--------|
| Machine rating     | 4 kW   | \( I_{eq} \)       | 0.6659 H |
| PW/CW pole-pairs  | 1/3    | \( I_{eq} \)       | 0.1898 H |
| PW rated voltage   | 380 V(50 Hz) | \( I_{eq} \)     | 0.8442 H |
| CW rated voltage   | 230 V(30 Hz) | \( M_{pr} \)     | 0.6547 H |
| PW rated current   | 6 A    | \( M_{cr} \)       | 0.1841 H |
| CW rated current   | 10 A   | \( R_c \)          | 2.5 Ω  |
| Operating speed    | 600–1200 r/m | \( R_c \)       | 2.9 Ω  |
| Rated torque       | 80 N·m | \( R_c \)          | 2.3 Ω  |
here that not all generators’ parameters satisfy this relationship, which is related to the design of the generator body. The following equation can be easily obtained:

\[ i_{pd} = \frac{M_{pr}L_{c}}{L_{p}M_{cr}} i_{eq} \approx i_{eq} \tag{17} \]

Equation (14) is expanded to form:

\[
\psi_{pq} = L_r i_{pq} - M_{pr} i_{pq} + M_{cr} i_{cd} \approx (M_{pr} + M_{cr}) i_{pq} - M_{pr} i_{pq} + M_{cr} i_{cd} \\
= -M_{pr} i_{pq} + M_{pr} i_{pq} + (M_{cr} i_{cd} - M_{cr} i_{cd}) \tag{18}
\]

From (7), the RW resistance \( R_r \) and the differential term can be neglected

\[ \psi_{pq} \approx 0. \tag{19} \]

So the following equation is true:

\[ \psi_{pq} = \psi_{cd}. \tag{20} \]

According to (10), (11), and (20), the following equation can be obtained:

\[ i_{pq} = - \frac{(M_{cr} + M_{pr})}{L_{p}M_{cr}} i_{pq} - \frac{M_{pr}L_{c}}{L_{p}M_{cr}} i_{cd}. \tag{21} \]

Therefore, it can be considered that the active power of the PW is related to \( i_{eq} \), the reactive power is related to \( i_{eq} \), and the reactive power loop corresponds to \( i_{cd} \). The conventional control block diagram is shown in Figure 4, which is a double closed-loop vector control strategy is adopted with a power outer loop and a current inner loop [22].

It should be noted that: \( \theta_{r0} \) is an initial phase compensation. It can make the PW voltage fully track the power grid voltage. According to the strategy of maximum power point tracking, the given active power value can be obtained. The commanded reactive power value is based on the needs of the grid or control targeting the system minimum loss state [23, 24].

3.2 Analysis of oscillations and overcurrent

According to (17) and (21), it can be seen that \( i_{eq} \) synchronously changes with \( i_{pd} \), and \( i_{cd} \) changes in reverse with respect to \( i_{pq} \). If the grid voltage suddenly drops to 0 V, this is equivalent to a PW short circuit fault occurrence. The flux linkage of PW cannot change instantaneously. From (3) and (4), it is not difficult to find that when \( i_{cd} \) is suddenly increases and oscillates, \( i_{eq} \) and \( i_{pq} \) vary at the same frequency, the variable \( i_{eq} \) has a very large amplitude, and the change of \( i_{cd} \) can be analyzed using the same method. A specific analysis follows.

From (17) and (21), it can be seen that the PW and CW currents are directly related. So that the two sets of windings can be considered coupled. According to (3)–(16), a fully equivalent reduced order model after simplification is obtained, as shown below:

\[ M_{pc} = \frac{M_{pr}M_{cr}}{M_{pr} + M_{cr}} \tag{24} \]
\[ L_{np} = L_p - M_p + \frac{(I_n - M_p - M_c)M_p}{M_p + M_c} + \frac{M_p M_c}{M_p + M_c} \approx M_{pc} \]  
\[ (25) \]

\[ L_{nc} = L_c - M_c + \frac{(I_n - M_p - M_c)M_c}{M_p + M_c} + \frac{M_p M_c}{M_p + M_c} \approx M_{pc}. \]  
\[ (26) \]

According to the model, the voltage equation in the complex frequency domain is
\[ U_{pdq}(s) = (R_p + sL_{np})I_{pdq}(s) + sM_{pc}I_{cdq}(s) = 0 \]  
\[ (27) \]
\[ U_{cdq}(s) = (R_c + sL_{nc})I_{cdq}(s) + sM_{pc}I_{pdq}(s). \]  
\[ (28) \]

The commanded voltage value of the CW is obtained from the current loop in Figure 4:
\[ U_{cdq}(s)^* = \left[ I_{cdq}(s)^* - I_{cdq}(s) \right] \frac{1}{1 + T_{c,f}} \left(k_p + \frac{k_i}{s}\right). \]  
\[ (29) \]

Generally speaking, the \(dq\) components of the current inner loop need a direct-current (DC) filtering in software, which is a first-order lag filtering, with \(T_c\) as the delay coefficient. The delay of the PWM converter and rotational inertia of the generator can be synthesized into a first-order integral link, (an inertia link). \(T_g\) is the mechanical delay time constant. The actual voltage expression for the CW is
\[ U_{cdq}(s) = U_{cdq}^* \frac{1}{1 + T_{c,f}} \]  
\[ = \left[ I_{cdq}(s)^* - I_{cdq}(s) \right] \frac{1}{1 + T_{c,f}} \left(k_p + \frac{k_i}{s}\right) \frac{1}{1 + T_{c,f}}. \]  
\[ (30) \]

Neglecting the resistance \(R_p\), from (27)
\[ I_{pdq}(s) = -\frac{M_{pc}}{L_{np}} I_{cdq}(s) \approx I_{cdq}(s) \]  
\[ (31) \]

So that (30) can be manipulated to yield
\[ \left[ R_c + s \left( L_{nc} - \frac{M_{pc}}{T_{c,p}} \right) \right] I_{dq}(s) \]  
\[ = \left[ I_{dq}(s)^* - I_{dq}(s) \right] \frac{1}{1 + T_{c,f}} \left(k_p + \frac{k_i}{s}\right) \frac{1}{1 + T_{c,f}}. \]  
\[ (32) \]

Because the PI coefficient of the power loop is small, its output remains basically unchanged during the voltage sag. The current loop commanded value is the output value of the power loop at the time of a voltage sag.

In all following equations, the subscript 0 represents the initial state when the grid voltage sags. Because the coefficient \(L_{nc} - M_{pc}^2 / L_{np}\) is very small and can be ignored, the above equation can be expressed as
\[ R_c I_{cdq}(s) = \left[ \frac{I_{cdq}^0}{s} - I_{cdq}(s) \right] \frac{1}{1 + T_{c,f}} \left(k_p + \frac{k_i}{s}\right) \frac{1}{1 + T_{c,f}}. \]  
\[ (33) \]

Equation (33) can be sorted out
\[ \left[ R_c + \frac{k_p}{s(1 + T_{c,f})} \right] I_{cdq}(s) = \frac{k_p}{s^2(1 + T_{c,f})} I_{cdq}^0. \]  
\[ (34) \]

It is worth noting that the rotational inertia of the generator is unknown. Consequently, the mechanical delay time constant, \(T_g\) can not be measured. To simplify the calculation, the PI parameters of CW current controller are set as the following:
\[ k_p = T_c k_i. \]  
\[ (35) \]

The expression of DC filter can be removed, but the filtering effect could still be retained
\[ \left[ R_c + \frac{k_i}{s(1 + T_{c,f})} \right] I_{cdq}(s) = \frac{k_p s + k_i}{s^2(1 + T_{c,f})} I_{cdq}^0. \]  
\[ (36) \]

Equation (36) can be rearranged to give
\[ I_{cdq}(s) = \frac{i_{cdq}(k_p s + k_i)}{s(R_c T_g^2 + R_c s + k_i)} \]  
\[ = \frac{i_{cdq}(1)}{s} \left[ \frac{1}{(s + a)^2 + \omega^2} + \frac{k_i \omega}{(s + a)^2 + \omega^2} \right]. \]  
\[ (37) \]

The expression of the variables of \(a, \omega, \) and \(k_c\) in (36) can be described as
\[ \begin{align*} 
& a = \frac{1}{2T_g} \\
& \omega = \sqrt{\frac{k_i}{R_c T_g^2} - \frac{1}{4 T_g^2}} \\
& k_c = \frac{2k_p - R_c}{2\omega R_c T_g} 
\end{align*} \]  
\[ (38) \]

In (38), these coefficients related to generator parameters, PI coefficients.

Putting the above expressions back into the time domain by the Laplace inverse transform
\[ i_{cdq}(t) = i_{cdq}(1 + \sqrt{1 + k_c^2 e^{-at} (\sin \omega t + \theta_c)} \right] \]  
\[ (39) \]

where
\[ \theta_c = \arctan \frac{1}{k_c}. \]  
\[ (40) \]
It can be seen from (39), \( \omega \) is the oscillation frequency, and \( \tau \) is time constant. They can be calculated from experimental data, as in the following section. Equation (31) indicates that there are oscillations in \( I_{\text{cdq}} \). Moreover, combining the torque Equation (15) and the motion Equation (16) shows that there are oscillations in \( T_e \) and \( \omega_c \). It is concluded that overshoot and oscillations of these variables are affected by PI coefficients, generator parameters.

The expression for the CW current in the two-phase static coordinate system is in the form below:

\[
\begin{bmatrix}
    i_{cd}^{*} \\
    i_{c q}^{*}
\end{bmatrix} = \begin{bmatrix}
    \cos \omega c t - \sin \omega c t \\
    \sin \omega c t + \cos \omega c t
\end{bmatrix} \begin{bmatrix}
    i_{cd} \\
    i_{c q}
\end{bmatrix}.
\]  

(41)

It is found that after expansion, the actual current of CW and PW has three main frequency components.

### 3.3 The improvement of the control algorithm

As mentioned before, in order to cope with the adverse effects of the LVRT event, some approaches directly give two command values to \( i_{cd}^{*} \) and \( i_{c q}^{*} \) during the fault. It switches to the original control mode after voltage recovery. This strategy also causes the system to oscillate. The situation is a little better than that under the traditional control strategy.

Previously, the situation in which the grid voltage drops suddenly to zero has been analyzed. For a BDFG system, which is a higher order system, the grid voltage drop can be regarded as a very large disturbance. This is similar to a step input. Moreover, it inevitably causes a sudden increase and oscillations in PW and CW currents.

According to (37), the expression in the complex frequency domain, \( I_{\text{cdq}}(s) \), is similar to the step response of a second-order system with proportional differential control. Based on the automatic control theory, some performance parameters such as overshoot, rise time and other performance indicators can be improved under this situation, but in essence, it does not reduce the order of the system, and the oscillations cannot be completely eliminated.

Therefore, according to the structure of the control system, the current loop integral link can be removed to eliminate the influence of the inertia link and reduce the order of the control system. By selecting the appropriate proportion coefficient, the expression of \( I_{\text{cdq}}(s) \) becomes similar to the unit step response of a first-order system, then the output have no overshoot, oscillations, etc., and has a very good response speed. It can keep the CW current basically unchanged during a fault, and the system can quickly restore stability, and reduce the potential damage caused by disturbance. This is the core idea of the new algorithm. The control block diagram during fault is shown in Figure 6:

According to equation (33), after offsetting the DC filter link and removing integration links in the PI controller, the following equation is obtained:

\[
R_c I_{\text{cdq}}(t) = \left( \frac{i_{\text{cdq}}(t)}{s} - I_{\text{cdq}}(t) \right) \frac{k_p}{1 + T_e s}.
\]  

(42)

Equation (42) can be further expressed as

\[
I_{\text{cdq}}(t) = \frac{i_{\text{cdq}}(t)}{s(R_c T_e s + k_p + R_c)} = \frac{i_{\text{cdq}}(1)}{k_p + R_c} \left( 1 + \frac{k_p + R_c}{R_c} \left( 1 + \sigma \right) \right)
\]  

(43)

where

\[
\sigma = \frac{k_p + R_c}{R_c T_e}.
\]  

(44)

The time-domain equation is

\[
i_{\text{cdq}}(t) = \frac{\frac{i_{\text{cdq}}(1)}{k_p + R_c} \left( 1 + \frac{k_p + R_c}{R_c} \left( 1 + \sigma \right) \right)}{1 + e^{-\sigma t}}.
\]  

(45)

Equation (45) is similar to the step response of the first-order control system. If \( k_p \) is set as shown in Figure 6, the output is a unit step response, there are no oscillations in \( i_{\text{cdq}} \) and \( i_{\text{pdq}} \), which in consistency with discussed theory in front of this section. Therefore, in the three-phase static coordinate system, the winding current basically does not oscillate and quickly returns to stable values. The system can smoothly ride through the fault period.

## 4 RESULTS AND DISCUSSION

### 4.1 Analysis of simulation model

This section presents the analysis of the simulation model. The parameters of the model are as the following: the total power of the generator is 120 kW, pole pair is 1/3, grid phase voltage is 220V/50 Hz, and the rotor speed is 900 rpm. Figures 7 and 8 show the comparative simulation waveforms of the conventional method and the improved method.

The rated value of PW current is 134 A, so its amplitude is 190 A. From Figure 7(b), it is observed that the correlation among the \( dq \)-axis components is basically consistent with the previous calculation. That is when the grid voltage drops to zero without any compensation, \( i_{pd} = i_{c q}, i_{pq} = -i_{cd} \). The amplitudes...
of these four dq components are large and the oscillation duration is long. The phase current of PW and CW is also large. In contrast, for the novel algorithm, when the order of the control system is reduced, there is almost no current oscillation in the dq-axis components of PW and CW. The amplitude of PW and CW current is obviously better than which under the conventional method.

It can be concluded that if the order of control system is reduced, the anti-disturbance capability of the system is enhanced. Therefore, the performed theoretical analysis in Section 3.3 is correct and the improved method is feasible.

### 4.2 Experimental results

Figure 9 shows the power generation system platform. The prime mover is a three-phase variable frequency induction motor (VFIM), which simulates the wind turbine. The speed of the motor $\omega_r$ is controlled by a general-purpose inverter. The permanent magnet synchronous generator (PMSG) is a speed measurement motor. The three motors are coaxial, and the system is equipped with an AC Source which can generate voltages with arbitrary amplitudes and frequencies within a certain range, causing grid voltage to drop suddenly.

The fixed conditions are that the root mean square (RMS) of grid voltage phase-phase is 380 V, so the peak value is 540 V, and the frequency is 50 Hz. The rotor speed is regulated at 900 rpm.

The active power is rated power, 4 kW, the reactive power is 0, and the experimental period length is 20 s. Because of special design of the AC Source, its minimum value is 8 V.

In the conventional strategy, at $t = 2.1$ s, the grid voltage drops to almost 0 V. After an additional period of 3.5 s, when $t = 5.6$ s, it begins to recover. For the improved strategy, when $t = 2.0$ s, the voltage starts to drop. The fault period length of time is 4 s; at $t = 6.0$ s it begins to recover.

It should be indicated that this control strategy uses an equal amplitude coordinate transformation, and sets the direction that PW current flows to the power grid as the positive reference direction. The active component of PW current $i_{pd}$ is positive. The oscilloscope samples the two-phase grid line voltage, from which the grid voltage phase can be measured using a PLL, and the RW phase is measured by sampling two phase line voltage of the PMSG. Therefore, the dq-axis components of the currents in the PW and the CW can be measured.

The following are the waveforms for the power grid voltage, PW current, CW current, their dq-axis components, active and
reactive power of PW, and the rotor speed. The PW current and the CW current are single-phase currents.

Figures 10 and 11 are experimental waveforms for the whole process when runs with the conventional strategy, and improved control strategy, respectively. Figures 12 and 13 are experimental waveforms for PW and CW currents, and their dq-axis components during the fault process.

First, the system waveform under the traditional control was observed and analyzed. It is clear from Figures 8 and 10, during the process of voltage sags, the change of PW current is very obvious. Its peak value increases from 8.5 to 30 A, an increase of approximately 3.5 times. The CW current amplitude is 15.8 A before falling, and it suddenly rises to 32 A. These two currents oscillate continuously, at a frequency \( \omega \) of 6.25 Hz. The duration of the oscillation is 1.3 s. Also, \( i_{cq} \) is synchronous with \( i_{cd} \), but \( i_{cd} \) changes and its phase reversal is compared to \( i_{pq} \). At any moment, \( i_{pd} = i_{cq} \) \( i_{pq} = -i_{cd} \), there are severe oscillations in the four dq components. This verifies the conclusions in Section 3.1. The active and reactive power of the PW are close to zero during the drop period, and there are large impact and oscillation in these two variables during the recovery process. Active power is related to \( i_{pd} \), while reactive power is related to \( i_{pq} \). Meanwhile, the rotor speed \( \omega \) oscillates similarly. Therefore, (15) and (16) shows that there are significant corresponding fluctuations in \( T_m \) and \( T_e \).

In summary, there is a large and continuous oscillation that goes far outside the system normal operational range. The peak currents and torques can be quite bad for a generator. Therefore, the conventional control strategy has performance defects and needs to be improved.

Then, the system waveform under the improved control strategy is analyzed. The results are shown in Figures 9 and 11. When the power grid voltage falls to 0 V, the peak value of the PW current increases to 25.5 from 8.5 A, and is been stabilized after three cycles. Its stable value is only 17 A. The CW current oscillates less than the PW current, and its oscillation dies away after a period. Its maximum amplitude is not more than twice its rated value, which is 27 A. Moreover, the stable value is the same as the rated value. The change of the four dq components is also seen: \( i_{pd} \) increases to 19 from 8.5 A, and \( i_{cq} \) increases to 16 from 7.5 A. However, they stabilize quickly. Then \( i_{pq} \) drops to -10 from 0 A, but it can be stabilized in short order. Furthermore, \( i_{cd} \) changes very little and stays near 12.5 A. Similarly, there are impact and oscillations in active and reactive power during the recovery process, this is because the new strategy used during the low-voltage period is different from the control method after voltage recovery. The conventional control method is adopted after recovery, so there will be impact and oscillations when switching control algorithm. Finally, it is clear that the amplitude and oscillation time of shaft speed is obviously better (shorter) than with the conventional control strategy. There are slight fluctuations accordingly in electromagnetic torque \( T_e \).

Looking through the whole LVRT process, the amplitude of the oscillations and timing characteristics are superior to those of the conventional control strategy. The feasibility of the improved algorithm has been verified by the experimental data.
FIGURE 11  Experimental waveforms during the whole process under the improved strategy. (a) Grid voltage, PW current, and CW current. (b) PW and CW current dq components. (c) Active and reactive power of PW. (d) Shaft speed

FIGURE 12  Experimental waveforms during the fault process with the conventional strategy. (a) PW current. (b) CW current. (c) PW and CW current dq components

5  |  CONCLUSION

This study analyzes the shortcomings of the conventional control method and develops a novel theoretical approach considering the process of LVRT in BDFG. The improved control strategy does not require a crowbar. The correlation between the four dq-axis components of the PW and the CW current is initially analyzed and a simplified generator model is established. Further, during the fault, according to the dq-axis expression of the CW current in the complex frequency-domain, after proportional coefficient adjustment and integral link elimination in the CW current controller, the order of control system is reduced, and which can compensate the influence of the inertial link, decrease the overshoot and eliminate oscillations. Finally, the simulation data and experimental waveforms show that when the grid voltage dips to 0 V, the PW current and its dq components return to a stable state quickly. More specifically,
The CW current and its $dq$ components are almost unchanged. The system has good disturbance-rejection capabilities and stability. Therefore, the validity, practicality, and feasibility of the improved strategy are verified by the simulation model data and experimental results.

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