Transient modelling of doubly-fed induction generator based wind turbine on full operation condition and rapid starting period based on low voltage ride-through testing

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Abstract

Transient simulation model of doubly-fed induction generator-based wind turbine has a complex model structure and considerable control parameters. An accurate simulation model is especially important for studying the static and transient characteristics of doubly-fed induction generator-based wind turbine and the grid-connected system. Based on the measured data of low voltage ride-through testing, the integrated parameter identification method is proposed here. Combined with the time-domain simulation analysis, curve fitting is used to determine the control strategy of doubly-fed induction generator-based wind turbine. The improved genetic algorithm is used to identify the generator parameters, power control parameters, and resistance of Crowbar of doubly-fed induction generator-based wind turbine. Combined with the electrical parameters provided by the wind turbine manufacturer, electromagnetic transient model on full operation condition and rapid starting period, corresponding to a measured doubly-fed induction generator-based wind turbine. In West Inner Mongolia Power Grid, is then established, which can operate in the full wind speed range and quickly enter the stable state within 1 s after start-up. Comparison of simulation results and measured data shows that the established electromagnetic transient simulation model using parameters identified by the proposed method can accurately reflect the key characteristics of doubly-fed induction generator-based wind turbine.

1 | INTRODUCTION

With the rapid development of the world economy, the contradiction between environmental pollution caused by the use of fossil energy and a tight supply of energy is gradually emerging. In view of the typical high carbon characteristics of the global economy [1], renewable energy power generation has become one of the effective ways to solve the contradiction. In the background, the installed capacity of renewable energy power generation has increased year by year. Especially after the promulgation of the Renewable Energy Law in 2006, the development speed of photovoltaic power generation and wind power generation continues to accelerate under the support of policies [2, 3]. As the increase of installed capacity of new energy sources, its impact on grid characteristics is also raising [4–6]. And the high proportion of new energy units connected to the power system has an essential effect on the safe and stable operation of the power grid. For wind power generation, its simulation model is the important basis for studying the safety operation of the large power grid. Therefore, it is especially important to establish an accurate electromagnetic transient simulation model of the DFIG-WT according to the actual operation situation.

In recent years, relevant scholars at home and abroad have carried out lots of research work gained a deep understanding of the basic principles and model structure of wind power [7–10]. With the penetration of wind power, the control technology and characteristics of wind power generation are continuously improved. To analyze the related problems of actual wind power connected in the grid network, it is necessary to establish an accurate simulation model [11]. When a low voltage fault
occurs, grid connection point of wind power will exhibit different external characteristics, because the control strategy during low voltage ride-through (LVRT) and parameters of different types of DFIG-WTs in different external environments are not the same. Therefore, it is important to have a feasible method to model the DFIG-WT to meet the demand of power grid calculation.

About the research of DFIG-WT model and control strategies, the literature [12, 13] use maximum power point tracking strategy, including the optimal tip speed ratio and optimal characteristic curve method, to achieve maximum wind energy capture below rated wind speed. While in literature [14], the situation that wind speed greater than DFIG-WT rated speed is discussed. In the situation, the output power of the generator and converter reaches the limit, and pitch angle control starts up to keep output power constant. The literature [15] combines the above two situations and simulates the situations that wind speed is above or below the rated wind, which provides a basis for the study of the full wind speed technology and the initial steady state technology of model in this paper. In terms of DFIG-WT parameter identification, traditional parameter identification algorithms are as follows. Literature [16] uses the least squares estimation method to identify the wind turbine MPPT module. Its advantages are simple and easy to operate. Since least-squares estimation algorithm does not have the filtering function, literature [17] proposes using the Kalman filter algorithm to identify the transient and sub-transient parameters of the generator online, which takes the continuous-time state space model of the generator as the research object. The accuracy of the method is more accurate than the above algorithm. With the deepening of research, artificial intelligence algorithm, which has good processing and adaptive ability, provides a new solution for better identification of nonlinear systems. Literature [18] proposes a DFIG parameter identification method based on the preferred initial value and micro-variation search algorithm. In literature [19], the difficulty of each identifiable parameter is studied, and identification algorithm-based ant colony optimization algorithm is designed to identify the stator and rotor resistance, stator and excitation reactance of the DFIG-WT. In literature [20], DFIG-WT model in αβ coordinate is selected, and a traditional genetic algorithm is utilized to identify the wind power parameters such as stator self-inductance and stator-rotor mutual inductance. However, the global search ability of the above artificial intelligence algorithm is generally low and convergence speed also needs to be improved. Literature [21] uses traditional genetic algorithm to determine the parameters of the induction motor equivalent motor circuit. By identifying the circuit parameters of the induction motor, the simulation time is reduced while laying a foundation for the improvement of the genetic algorithm in this paper.

In this paper, it starts from the characteristics and model structure of DFIG-WT, combines the practical problems focused by West Inner Mongolia Power Grid, considers the DFIG-WT active and reactive characteristics before and after grid fault to build the DFIG-WT electromagnetic transient simulation model on full operation condition and rapid starting period. Initialization technique is also researched to keep the electromagnetic transient model to enter a stable state within 1 s after start-up quickly. In addition, the integrated parameter identification method, including curve fitting, improved genetic algorithm, wind turbine manufacturer providing electrical parameters and typical controller parameters selection, is adopted according to the influence degree of different parameters on the system. Finally, compare the simulation data and the measured data to verify the correctness of the integrated parameter identification method and the accuracy of DFIG-WT simulation model.

2 | MODEL STRUCTURE OF DFIG-WT

The structure of DFIG-WT is shown in Figure 1. In the electromagnetic transient simulation, the DFIG-WT model includes the aerodynamic model, shafting model, generator model and inverter model.

The structure of the DFIG-WT is relatively complex, and the control method of the corresponding simulation model is also diverse. Figure 2 shows the basic structure of the electromagnetic transient model of DFIG-WT, which includes:

1. Electromechanical system model. It mainly comprises aerodynamic model, shafting model, generator model and inverter model (Doubly-fed induction generator, inverter) and so on.
2. Control system model. It mainly includes the rotor-side inverter control model (the control of normal operation condition and low voltage ride-through operation condition) and the grid-side inverter control model.
3. Protection system model. It mainly includes low voltage ride-through protection devices, such as Crowbar.
transformation of the mathematical model in three-phase static coordinate system. The d-axis is selected as the stator flux linkage direction. The q-axis lags behind the d-axis by 90°. Because the d-axis and q-axis are perpendicular to each other, there is no coupling between the two-phase windings. Then the DFIG mathematical model can be greatly simplified to facilitate the design of the controller. In the DFIG mathematical model, the expressions of stator and rotor voltage are as follow [22]:

$$\begin{align*}
    u_{sd} &= R_{sd}i_{sd} - \omega_s\psi_{sq} + d\psi_{sd}/dt \\
    u_{sq} &= R_{sq}i_{sq} + \omega_s\psi_{sd} + d\psi_{sq}/dt \\
    u_{rd} &= R_{rd}i_{rd} - \omega_r\psi_{rq} + d\psi_{rd}/dt \\
    u_{rq} &= R_{rq}i_{rq} + \omega_r\psi_{rd} + d\psi_{rq}/dt
\end{align*}$$

Where $u_{sd}$, $u_{sq}$, $u_{rd}$ and $u_{rq}$ are the voltage components of stator and rotor in d-axis and q-axis, $i_{sd}$, $i_{sq}$, $i_{rd}$ and $i_{rq}$ are the current components of stator and rotor in d-axis and q-axis, $\psi_{sd}$, $\psi_{sq}$, $\psi_{rd}$ and $\psi_{rq}$ are the flux components of stator and rotor in d-axis and q-axis, $\omega_{s1}$ is the slip angle velocity, $\omega_s = \omega_e - \omega_r$.

The equations of stator and rotor flux are as follows [22]:

$$\begin{align*}
    \psi_{sd} &= L_s i_{sd} + L_{m} i_{rd} \\
    \psi_{sq} &= L_s i_{sq} + L_{m} i_{rq} \\
    \psi_{rd} &= L_r i_{rd} + L_{m} i_{sd} \\
    \psi_{rq} &= L_r i_{rq} + L_{m} i_{sq}
\end{align*}$$

where, $L_{m}$ is the equivalent mutual inductance between the stator winding and the rotor winding in the synchronous coordinate system, $L_m = 3/2L_{sm}$. $L_s$ is the self-inductance of the stator winding in the synchronous coordinate system, $L_s = L_{sa} + L_{sm}$. $L_r$ is the self-inductance of the rotor winding in the synchronous coordinate system, $L_r = L_{ra} + L_{rm}$. $L_{sa}$ and $L_{ra}$ are the excitation inductance of stator and rotor winding. $L_{sa}$ and $L_{rm}$ are the leakage inductance of stator and rotor.

As the transmission system of DFIG-WT, the shafting part realizes the energy conversion between wind energy and electric energy. Since the equivalent two mass blocks can accurately reflect the characteristics of various operating conditions, including low-frequency oscillation and low voltage ride-through, the two-mass drive train model of shafting is adopted in this paper. The wind turbine is equivalent to one mass block, and the generator and gearbox are equivalent to another mass block. The shafting model of two mass blocks is shown in Figure 5, and its model expression is as follows [23]:

$$\begin{align*}
    \frac{d\omega_{wt}}{dt} &= \frac{1}{2H_{wt}} \left[ T_m - K_{sh} \omega_{sh} - D_{sh} \omega_{wt} (\omega_{wt} - \omega_t) \right] \\
    \frac{d\omega_t}{dt} &= \frac{1}{2H_{t}} \left[ K_{sh} \omega_{sh} + D_{sh} \omega_{wt} (\omega_{wt} - \omega_t) - T_e \right] \\
    \frac{d\omega_{sh}}{dt} &= \omega_h (\omega_{wt} - \omega_t)
\end{align*}$$

The rotor-side converter control is the dominant part of the converter and the core of DFIG-WT control. Control mode is divided into the normal operation condition and the low voltage ride-through operation condition. The main control functions are shown in Figure 3.

### 3 INFLUENCE ANALYSIS OF DIFFERENT MODEL PARAMETE

#### 3.1 Modelling of electromechanical system and the influence of its parameter

##### 3.1.1 Mathematical model of electromechanical system

The stator and rotor of doubly-fed induction generator (DFIG) contain symmetrical three-phase winding. The symmetrical three-phase power supply with adjustable frequency excites the rotor winding while its constant frequency excites the stator winding. The slip frequency between the stator and rotor determines the generator speed. Figure 4 shows the schematic of the stator and rotor.

The mathematical model of DFIG in two-phase synchronous rotating coordinate system can be obtained through coordinate...
where \( H_{\omega t} \) and \( H_{g} \) are the inertia time constants of wind turbine and generator, \( D_{sh} \) and \( K_{sh} \) are the damping coefficient and stiffness coefficient of shafting respectively, \( \theta_{sh} \) is the torsional angle of shafting, \( \omega_{\omega t} \) and \( \omega_{r} \) are the angular velocities of wind turbine and generator, \( T_{m} \) and \( T_{e} \) are the electromagnetic torque of wind turbine and generator respectively.

### 3.1.2 Influence of electromechanical system parameters

The electromechanical system parameters are mainly wind turbine parameters, shafting parameters and generator parameters, which reflect the inherent physical characteristics of wind power. Aerodynamic model parameters are used to simulate the blade, converting wind energy into mechanical energy. Shafting model parameters reflect the oscillation process generated between the blade and generator, including wind wheel inertia, generator inertia, damping coefficient and gearbox ratio. Generator parameters affect the electrical behaviour of the generator, including stator and rotor impedance and excitation reactance.

The shafting model mainly affects the oscillation process between the wind turbine and the generator under the disturbance. In order to analyze the specific influence of shafting parameters, the output characteristics of DFIG-WT with the same capacity, different models and manufacturers are compared. Table 1 shows the corresponding shafting parameters of 1.5MW DFIG-WT produced by two different manufacturers. It can be seen that the two groups of parameters are at the same level.

Keep other parameters the same, use the two sets of shafting parameters in Table 1 to make a model simulation comparison of three-phase short circuit fault, and the results are shown in Figure 6. It can be seen that different shafting parameters have little influence on the active power of DFIG-WT under steady-state, and the two curves almost coincide in steady-state. The shafting parameters mainly affect the initial period of fault occurrence and the recovery period after fault disappearance. During the two periods, the oscillation amplitude of the two power curves is slightly different, but the oscillation trend and the recovery time are the same. Because the order of magnitude of the shafting parameters are large, the parameter can be obtained from the wind turbine manufacturer without parameter identification.

The generator parameters that affect the electrical behaviour of DFIG-WT mainly include impedance, reactance and excitation reactance of stator and rotor. To determine the influence of generator parameters, the output power characteristics of DFIG-WT model, which use two sets of generator parameters provided by different manufacturers, in case of three-phase short circuit fault are compared.

It can be seen from Figure 7 that the generator parameters of DFIG-WT have little influence on the system's active power and reactive power under steady-state and transient state, and the two sets of data almost coincide in the whole simulation process. It is known that the control system determines the output characteristics, and DFIG-WT has the characteristics of small capacity and fast response speed. Even though the generator parameters of the specific capacity DFIG-WT are different, the
response speed are equivalent, so the overall output active and reactive power are not different.

From the above analysis, it can be known that different electromechanical parameters may cause local fluctuations of DFIG-WT output power. Still, its impact on the overall output power is small.

3.2 Influence of DFIG-WT control system parameters

3.2.1 Vector control model of rotor side converter

As the main part of the converter, rotor side converter control is the core of DFIG-WT control. So this paper mainly introduces the rotor side converter control model in detail. It is known that the difference between DFIG-WT stator voltage and flux is 90° under steady-state and symmetrical faults state. If the direction of stator flux is taken as the d-axis's positive direction, then the stator voltage vector is in the q-axis direction. Furthermore, it can be deduced that the stator voltage in d-axis is 0 and the stator voltage in q-axis is constant. Then the stator voltage and flux linkage equation of DFIG-WT can be simplified as:

\[ \begin{align*}
\psi_{sd} & = \psi_s \\
\psi_{sq} & = 0 \\
u_{sd} & = 0 \\
u_{sq} & = u_s
\end{align*} \]  

(4)

The stator current expression is obtained by substituting the above formula into the flux equation:

\[ \begin{align*}
i_{id} & = \frac{\psi_s - L_{m}\psi_{id}}{L}i_s \\
i_{iq} & = \frac{L_{m}i_{id}}{L_s}
\end{align*} \]  

(5)

In dq coordinate system, the stator power can be expressed as:

\[ \begin{align*}
P_s & = u_{sd}i_{sd} + u_{sq}i_{sq} \\
Q_s & = u_{sq}i_{sd} - u_{sd}i_{sq}
\end{align*} \]  

(6)

Taking the stator current into the stator power expression and then into the voltage equation, we can get:

\[ \begin{align*}
u_{rd} & = R_{r}i_{rd} + \sigma L_{r}i_{rd} - \omega_{s}\sigma L_{r}\psi_{s} \\
u_{rq} & = R_{r}i_{rq} + \sigma L_{r}i_{rq} + \omega_{s}\sigma L_{r}\psi_{s}
\end{align*} \]  

(7)

where, \( p \) is the differential operator, \( u_{rd} \) is the voltage reference value of RSC’s voltage interior loop in d-axis, \( u_{rq} \) is the voltage reference value of RSC’s voltage interior loop in q-axis, \( \sigma = 1 - \frac{i_{sd}^2}{L_{s}i_{sq}} \). The stability of the system can be improved by calculating the cross-coupling term through the internal variables of the rotor current and the stator flux. And the cross-coupling term is:

\[ \begin{align*}
\Delta u_{rd} & = \omega_{s}\sigma L_{r}i_{rq} \\
\Delta u_{rq} & = -\omega_{s}\sigma L_{r}i_{rd} + \frac{L_{m}}{L_{s}}\psi_{s}
\end{align*} \]  

(8)

The control block diagram of RSC (Rotor-Side Converter) built by the above formula is shown in Figure 8.

3.2.2 Power control mode of DFIG-WT

In this paper, the measured active and reactive power curves of a 1.5 MW DFIG-WT in West Inner Mongolia Power Grid during low voltage ride-through are shown in Figure 9(a–c), which corresponding to the condition that the voltage of the grid-connection point drops to 35%, 50% and 75% respectively. The figure shows that under normal operation condition, the
active output power are all 1.5 MW and reactive power are all 0 MVar, from which the conclusion can be deduced that DFIG-WT realizes the maximum power tracking control under normal operation, and it is in full power operation. Besides, DFIG-WT is in unit power factor operation when the reactive power is zero. 9 shows that DFIG-based wind turbine (DFIG-WT) generates a certain capacity of reactive power during low voltage ride-through (LVRT), which measure 0.87, 0.87, and 0.435 MVar respectively to support the grid voltage during the experiment. In comparison to the above-mentioned drop, the terminal voltage of the wind turbine increased slightly to 0.42, 0.56, and 0.78 pu, respectively. Therefore, the output reactive power of DFIG-WT during LVRT is proportional to the level of voltage drop. Thus, the reactive power control is voltage drop control. According to \( \Delta Q = k_u \times \Delta U \), where \( \Delta Q \) is the reactive power delivered by the wind turbine to the grid and \( \Delta U \) is the difference in voltage drop, \( k_u \) is 1.32 (\( k_u = 0.29 \) pu/\((1-0.78 \) pu)). When the voltage drop is large, the reactive power output is limited to 0.87 MVar, considering the current carrying capacity of the wind turbine converter. Thus, when the voltage drop depth reaches 35%, the reactive power output remains at 0.87 MVar. During the LVRT, the Crowbar protection device consumes the excess active power for active power control. In Figure 9, the active oscillation during steady state is caused by the transient shock impact on the system after removing Crowbar, at which point the current on the rotor side of the DFIG-WT is redistributed. The rotor-side converter current also produces an impulse component at the moment when the Crowbar circuit stops operation. Affected by the superposition of two transient components, the system also fluctuates within certain amplitude while restoring stability. Mechanical oscillations may also simultaneously occur. After comparing the experimental results, the voltage drops of the grid and the active power output (different wind speeds) during the steady state of DFIG-WT also affect the amplitude of the active power oscillation. The greater the voltage drop and the higher the output active power of the DFIG-WT, the greater the oscillation amplitude of the active power after the Crowbar is removed.

**3.2.3 Active power control parameters of DFIG-WT**

When the active power control is maximum power tracking control in normal operation, it adopts the speed control mode, that is, the generator speed is taken as the input control signal. And the main control parameters are the proportion coefficient and an integral coefficient of PI controller. In order to analyze the influence of different control parameters on the active power output characteristics, two groups of typical PI control parameters are selected to simulate DFIG-WT three-phase short circuit fault. When the PI control parameters \( K_p \) and \( K_i \) are 0.1, 100 and 1.4, 60 respectively, the comparison curves of active power are shown in Figure 10.

It can be concluded from Figure 10 that in the speed control mode, different typical PI parameters only have a slight impact on the transient active power, mainly reflecting in the beginning stage and the end recovery stage of low voltage ride-through. But on the whole, different parameters have little effect on the active output power, and the two curves are almost the same. And the research method of reactive power control’s PI control parameters is similar, so this paper will not describe it in detail.

**3.3 Influence of DFIG-WT protection system parameters**

**3.3.1 Low voltage ride-through protection device**

During the voltage drop, the phenomenon of transient rotor over-current, over-voltage and rotor speed rising sharply will
appear, seriously the power electronic devices will be damaged. At present, the implementation methods of low voltage ride-through for DFIG-WT are mainly divided into two categories, including additional protection control strategy and installing hardware protection devices. While the most commonly used method in the actual wind farm is installing a Crowbar protection circuit or Chopper protection circuit, and the circuit diagram is shown in Figure 11.

The Crowbar protection circuit is parallel with the rotor side converter, usually using a rotor current or DC bus voltage as the input control signal. When the current or voltage exceeds the set threshold, crowbar will start. At the same time, rotor circuit is shorted by the bypass resistance in Crowbar, rotor side converter loses control, and DFIG-WT absorbs reactive power from the grid. Therefore, Crowbar device will have a great impact on the output reactive power of DFIG during the fault period. Chopper protection circuit is parallel with the bus capacitor on the DC side, usually using the DC voltage as the input control signal. After the Chopper circuit starts, it is equivalent to parallel a resistance on the DC bus capacitor. At this time, the Chopper protection circuit absorbs redundant energy to suppress the rise of the DC side bus voltage, so that the rotor side converter and grid side converter can operate normally. Therefore, the Chopper device has little effect on the active and reactive power of DFIG-WT during the fault period.

Based on the analysis of power control mode in Section 2.2, it can be seen that the active power and reactive power of DFIG-WT with protection device fluctuate greatly during the fault period, which is consistent with the Crowbar control characteristics; in the low voltage ride-through experiment of an actual wind farm, the output current of DFIG-WT grid-connection point does not exceed the limiting current value no matter how much the voltage drop degree is, which is consistent with the characteristics of Crowbar circuit suppressing output current. Combing with the installation information of the DFIG-WT protection device provided by West Inner Mongolia Power Grid simultaneously, it can be concluded that only Crowbar device is installed in the studied DFIG-WT, and the low voltage ride-through operation of DFIG-WT can be realized.

### Table 3

| $R_{cb}/\Omega$ | $I_{r,max}/pu$ | $U_{r,max}/pu$ |
|----------------|---------------|---------------|
| 0.5            | 0.997         | 0.351         |
| 0.7            | 0.902         | 0.452         |
| 0.9            | 0.860         | 0.535         |

#### 3.3.2 Impact of crowbar resistance on the system

The rotor-side converter current and the grid-side converter voltage constrain the setting of the Crowbar resistance of DFIG-WT. When a short-circuit fault occurs in the power grid, an excessively small Crowbar resistance cannot effectively suppress the short-circuit current on the rotor side, which may damage its converter. If the Crowbar resistance is too large, overvoltage on the DC side of the grid-side converter may occur and damage its converter. Generally, the larger the Crowbar resistance within a reasonable value range, the more noticeable the effect of suppressing the overcurrent on the rotor side.

During grid fault, the maximum rotor voltage is:

$$U_{r,max} = I_{r,max}R_{cb} \tag{9}$$

where, $R_{cb}$ is the Crowbar resistance value. This value must meet the following constraints to prevent overvoltage on the DC side of the grid-side converter:

$$U_{r,max} < U_{r,lim} \tag{10}$$

where, $U_{r,lim}$ is the maximum voltage that the grid-side converter can withstand. Thus, the maximum Crowbar resistance estimation formula [24] is:

$$R_{cb} = U_{r,lim}/I_{r,max} \tag{11}$$

The grid-side converter has rated an operating voltage of 480 V for the 1.5 MW DFIG-WT used in this study. Generally, the DC side voltage is not allowed to exceed 10%–15% of the rated voltage due to the limited voltage resistance of the converter. The most unfavourable situation is considered and converted to the standard unit value because the rated voltage of DFIG is 690 V. Thus,

$$U_{r,lim} = \frac{480}{690\sqrt{2}}(1 + 10\%) = 0.54 \tag{12}$$

For 1.5 MW DFIG-WT, the rotor side current and voltage after Crowbar input are simulated by introducing different Crowbar resistance values (0.5, 0.7, and 0.9 Ω) to determine the maximum value. Table 3 shows the simulation results.

Table 3 shows that as the Crowbar resistance increases, the maximum rotor current value gradually decreases but the rotor side voltage gradually increases. Under the premise of
ensuring that the grid-side converter does not exceed the voltage \((U_{r,\max} < U_{r,\lim})\), the larger the Crowbar resistance, the more noticeable is the effect of suppressing the short circuit current. Thus, the maximum value of the Crowbar resistance is approximately 0.9 \(\Omega\).

A short-term three-phase short-circuit fault is set at \(t = 3\) s to analyze the impact of Crowbar with different resistances on the LVRT of the system. When the time is 3.15 s, the fault is cleared and the Crowbar exit time is set to 3.068 s. Figure 12 shows the simulation results of the rotor current of the DFIG-WT corresponding to \(R_{cb} = 0.7\) \(\Omega\) and \(R_{cb} = 0.9\) \(\Omega\).

The Figure 12 shows that after the fault occurs, the maximum rotor current is 0.86 pu when the Crowbar resistance \(R_{cb}\) is 0.7 \(\Omega\), which is less than 0.902 pu when the Crowbar resistance \(R_{cb}\) is 0.9 \(\Omega\). At this point, the rotor current tends to stabilize more quickly after the fault is removed. This result indicates that the Crowbar resistance value is relatively large within a reasonable range, which more effectively suppresses the rotor-side short circuit. At the same time, the rotor-side current stabilizes more quickly after the fault is removed.

3.3.3 | Temperature effects of crowbar resistance

During the short-circuit fault of DFIG-WT, the Crowbar resistance is affected by the thermal effect of the short-circuit current, which increases the temperature of the Crowbar and therefore its resistance. The short-circuit time is short, the heat dissipation conditions are poor, the heat generated by the thermal effect converts into a temperature rise to increase the Crowbar temperature conditions are poor, the heat generated by the thermal effect converts into a temperature rise to increase the Crowbar temperature rise of the crowbar resistance, as shown in the

The stator current \(i_s\) [25] under grid voltage drop fault is:

\[
i_s = \frac{(1-K)U_{s0}e^{\omega_s(t-t_0)}}{j\omega_s(I_s - I_{m1}^2/I_s)} + \frac{KU_{s0}e^{\omega_s t}}{j\omega_s(I_s - I_{m1}^2/I_s)} - \frac{I_m}{L_s(I_s - I_{m1}^2/I_s)}\left(\psi_{f0} e^{\omega_s(t-t_0)} - \psi_{f00} e^{\omega_s t}\right) - \frac{L_m}{L_s} \psi_{f00} e^{\omega_s(t-t_0)}\]

where the instantaneous value \(\psi_{f0}\) of the rotor flux linkage at the fault moment is:

\[
\psi_{f0} = \frac{I_m}{j\omega_s(I_s + 1/T_s')}\left(R_{ch} + R_{r}\right)(1-K)U_{s0}
\]

The steady-state component \(\psi_{f00}\) of the rotor flux linkage after the fault is:

\[
\psi_{f00} = \frac{I_m}{j\omega_s(I_s + 1/T_s')}\left(R_{ch} + R_{r}\right)(1-K)U_{s0}
\]

In the formula of the voltage drop coefficient \(K = (U_{s0} - U_{s1})/U_{s0}\), \(i_{s0}\) and \(i_{s1}\) are the stator voltage and current before and after short circuit, respectively. \(U_{s0}\) and \(U_{s1}\) are the amplitudes of the stator voltage before and after short circuit, respectively. Stator decay time constant is \(T_s' = (I_s - I_{m1}^2/I_s)/R_s\), rotor transient time constant with Crowbar resistance is \(T_{s1}' = (I_s - I_{m1}^2/I_s)/\left(R_{ch} + R_{r}\right)\), and \(\omega_s\) is the synchronous angular velocity. All of the above formulas are derived from the rotating coordinate system. Equation (14) is converted to the instantaneous value of a-phase current in the abc coordinate system using coordinate transformation:

\[
i_{sa} = \frac{(1-K)U_{s0} \cos(\omega_s(t-t_0) + \alpha)}{j\omega_s(I_s - I_{m1}^2/I_s)} + \frac{KU_{s0} \alpha}{j\omega_s(I_s - I_{m1}^2/I_s)} - \frac{I_m}{L_s} \psi_{f00} e^{\omega_s(t-t_0) + \alpha} - \frac{L_m}{L_s} \psi_{f00} e^{\omega_s(t-t_0) + \alpha} - \frac{L_m}{L_s} \psi_{f00} e^{\omega_s(t-t_0) + \alpha} - \frac{L_m}{L_s} \psi_{f00} e^{\omega_s(t-t_0) + \alpha}
\]

where \(\alpha\) is the initial phase angle. The heat generated by the DFIG-WT short-circuits fault does not immediately propagate to the surrounding medium, and its heat is converted into the temperature rise of the Crowbar resistance, as shown in the
TABLE 4  Identification results of actual system parameters

| Category                                | Name                        | Parameter | Identification result |
|-----------------------------------------|-----------------------------|-----------|-----------------------|
| Generator parameters                    | Stator resistance [pu]      | $R_s$     | 0.005231              |
|                                         | Stator reactance [pu]       | $L_s$     | 0.085124              |
|                                         | Rotor resistance [pu]       | $R_r$     | 0.005481              |
|                                         | Rotor reactance [pu]        | $L_r$     | 0.140167              |
|                                         | Excitation reactance [pu]   | $L_m$     | 4.9896                |
| Control parameters                      | Active power control [pu]   | $K_p$, $K_i$ | 1.3, 70              |
|                                         | Reactive power control [pu] | $K_p$, $K_i$ | 0.8, 100             |
| Low voltage ride-through protection device | Crowbar resistance [Ω]    | $R_{cb}$  | 0.91                  |

following formula:

$$
\int_0^t \frac{i^2_{sa}}{R} dt = \int_{T_w}^{T_h} \rho S C_T dT \tag{18}
$$

where $T$ is the temperature, $C_T$ is the specific heat capacity, $T_w$ is the starting temperature after short-circuit, $T_h$ is the highest temperature after the short-circuit current heating, $\rho$ is the density, $i/s$ is the length, and $S$ is the cross-sectional area. During short circuit, the conductor has a large temperature range and resistance that can no longer be constant but rather a function of temperature. Thus,

$$
R = \rho_0(1 + \beta T)l/S \tag{19}
$$

where $\rho_0$ is the resistivity and $\beta$ is the temperature coefficient. The following can be obtained from Equations (13), (18) and (19):

$$
\frac{M_k}{S^2} = \frac{C_T \rho}{\rho_0 \beta} \left( \ln(1 + \beta T_h) - \ln(1 + \beta T_w) \right) \tag{20}
$$

where $M_k$ is the moment of inertia, $S$ is the cross-sectional area, $\beta$ is the temperature coefficient of rotation, $\rho$ is the density of the conductor material, $\rho_0$ is the resistivity at the reference temperature, $T_w$ is the starting temperature after the short-circuit current heating, $T_h$ is the highest temperature after the short-circuit current heating, $C_T$ is the specific heat capacity of the conductor material, $S$ is the cross-sectional area of the conductor, $\alpha$ is the initial phase angle, $\omega_0$ is the synchronous angular velocity, $\omega_s$ is the slip angular velocity, $\rho_0$ is the resistivity at the reference temperature, $S$ is the cross-sectional area of the conductor, $\beta$ is the temperature coefficient of resistance, $L$ is the inductance, $R$ is the resistance, $I$ is the current, and $\omega$ is the angular velocity.

Although the increase in Crowbar resistance suppresses the current on the rotor side, an overvoltage situation in the grid-side converter shortly occurs. The Crowbar resistance value of the proposed DFIG-WT set is limited by the current technology. The effect of Crowbar resistance on temperature was not considered. The technician selected the Crowbar resistance value as the maximum value within the feasible range. Therefore, in subsequent research, considering the thermal effect is of great importance to the selection of Crowbar resistance.

3.4  Parameter identification of DFIG-WT

The level of agreement between the simulation model and the actual system operation is increased to accurately obtain the structure and control parameters of DFIG-WT in the Mengxi Power Grid. The time domain simulation and improved genetic algorithm are used to identify the independent variable parameters. The improved genetic algorithm can obtain the optimal solution by improving the selection operator, crossover, and mutation operator in the process of repeated evolution. The relevant parameters of the DFIG-WT power control parameters and resistance of the Crowbar protection circuit are used as the independent variables of the improved genetic algorithm.
The three-phase short circuit fault of DFIG-WT, which leads to the 20% \( U_a \) voltage drop for 0.625 s, is taken as the system excitation. The deviation between actual and model simulation curves of DFIG-WT in the entire LVRT are taken as the objective function of the improved genetic algorithm. Continuously correcting the values of the above independent variables can lead to accurate identification of their corresponding independent variables.

In addition, the “Weight Modelling and Verification Method for Wind Turbine Low Voltage Ride Through” proposed that the weighted mean deviation reflecting the overall curve fitting difference is the most appropriate. Therefore, the same is used as the fitness standard for parameter identification. A weight division problem occurs when selecting the objective function. In this study, the weighted mean absolute deviations of active and reactive powers are used as the objective function of the improved genetic algorithm. It refers to the German model verification standard FGW TR4 (Federation of German Wind power and other Renewable Energies) [27], where the principle of obtaining the error \( F \) [28] is determined as follows:

\[
F = F_p + F_Q
\]

\[
F_p = 0.1F_{PA} + 0.6F_{PB} + 0.3F_{PC}
\]

\[
F_Q = 0.1F_{QA} + 0.6F_{QB} + 0.3F_{QC}
\]  

(21)

where, \( F_p \) and \( F_Q \) are the absolute deviations of active and reactive powers. \( F_{PA}, F_{PB}, \) and \( F_{PC} \) are the active power deviations between the measured and simulated systems in the pre-failure, failure, and failure recovery phases, respectively. \( F_{QA}, F_{QB}, \) and \( F_{QC} \) are the reactive power deviations between the measured and the simulated systems in the pre-failure, failure, and failure recovery phases, respectively.

Taking active power as an example, the formula of active absolute deviation for each phase is expressed as:

\[
F_{PX} = \frac{\sum_{{t}_{start}}^{{t}_{end}} |P_R(t) - P_X(t)|}{{t}_{end} - {t}_{start} + 1}, X = A, B, C
\]

(22)

where \( P_R \) and \( P_X \) are the active output power values of the measured and simulated system, respectively, and \( {t}_{start} \) and \( {t}_{end} \) are the start and end time of each phase, respectively.

Figure 14 shows the block diagram of the multi-variable parameter identification method combining time-domain simulation and improved genetic algorithm. First, the measured data \( F_R \) of the wind farm is imported and the population is initialized. Thus, the value of the above multi-parameter independent variable is expressed in the form of gene coding. The system structural and control parameters identified above are placed into the simulation model to obtain the simulation output \( F_s \). Then, the fitness of the independent variables in the above population is calculated. The objective function determines whether the termination condition is reached. If the condition is met, the value of the above-mentioned optimal independent variable is obtained. Regenerative individuals are selected according to the distribution of fitness, and the probability of selection is determined by the level of corresponding fitness. This study adopts the Rank method for fitness distribution function, which overcomes the scale and premature convergence problems of proportional fitness calculation. Then, based on the principle of linear crossover, an improved heuristic crossover operator is proposed to generate new sub-individuals, \( C = P_1 + R \times (P_1 - P_2) \), where \( R \) is a random value between 0 and 1. \( P_1 \) and \( P_2 \) are father individuals 1 and 2, respectively, and \( P_1 \) is more adaptable than \( P_2 \). Then, an improved adaptive mutation operator \( M = P + \delta \times D \) is proposed based on the Gaussian mutation principle, where \( M \) is the sub-individual resulting from the mutation of the father individual, \( P \) is the father individual, \( \delta \) is the mutation step, and \( D \) is the evolution direction. The mutation step and evolution direction are not fixed, and are rather adaptively adjusted with the degree of diversity of the independent variables. A new generation of population is generated from crossover and mutation, which runs in a reciprocating cycle.

After the simulation operation, the respective variable identification results in Figure 15 are obtained. The target function value corresponding to the independent variable at the 19th/20th generation of the population is the smallest. Thus, the deviation between the measured and the simulated curves is the smallest, and the individual fitness is optimal. The individuals evolved at this time are the global optimal solution obtained by the improved genetic algorithm, and the curve matching degree of the measured data is the highest. Table 4 shows the system parameter identification results.
4 | ACCURATE MODELING OF DFIG-WT

4.1 | Model initialization

In order to make the model reach stability quickly after start-up, the initialization technology of the established simulation model is studied. According to the maximum power tracking curve of DFIG-WT, the rotor speed at a stable state under different wind speeds is obtained. Then the slip rate $s$ at initial state can be got. Through recording a large amount of data, the stator current at the initial state of the generator is determined. And the initial state electrical angle of the generator $\theta = \text{number of pole pairs} \times \text{mechanical angle} \times 2\pi$.

The speed of DFIG-WT and wind speed have the following relationship:

$$\omega_\text{wi} = \lambda \frac{v}{R}$$

(23)

where $\omega_\text{wi}$ is the wind turbine speed, $\lambda$ is the tip speed ratio, $v$ is the wind speed, and $R$ is the wind turbine blade radius. It can be seen from the above formula that the wind turbine speed and the wind speed are basically linear. Combing the wind turbine speed data at different wind speed and the maximum power tracking curve of DFIG-WT, the specific relationship of wind speed and wind turbine speed is obtained, which is shown in Equation (24).

$$\omega_\text{wi} = 0.0997v - 0.0278$$

(24)

Similarly, the rotor speed has different initial speeds $\omega_r$ at different wind speeds. Besides, it is known that when DFIG-WT rotor speed exceeds the maximum speed, it will be limited at the rated speed and operates at a constant value of 1.2 pu. According to the statistical data at a stable state in different wind speeds, the relationship between rotor speed and wind turbine speed is as Equation (25). Then the initial slip of the generator $(1 - \omega_r)$ at the corresponding wind speed can be found.

$$\omega_r = 0.9672\omega_\text{wi} + 0.0202$$

(25)

Take high-power state ($v = 14$ m/s) and low-power state ($v = 7.3$ m/s) as an example; compare and analyze the simulated results with or without initialization technology. In high-power operation conditions, the rotor speed is more than its rated speed according to Equations (24) and (25), so the rotor speed is limited at 1.2 pu and the corresponding slip rate is $-0.2$ pu. Substituting the above parameters as initialization data into simulation model, the curve of DFIG-WT active power with initialization (blue curve) can be obtained, as shown in Figure 16. It greatly improves the stable running time of DFIG-WT compared with the active power curve without initialization (orange curve). In the same way, the comparison curve of active power with and without initialization under low-power operation condition is shown in Figure 17. It proves
that the initialization technology of quickly entering the initial steady-state in the DFIG-WT model is valid and correct.

### 4.2 Full wind speed model

The active power captured by the wind turbine can be expressed as:

\[
P_w = \frac{1}{2} \rho A C_p(\beta, \lambda) v^3
\]  

(26)

\[
C_p(\beta, \lambda) = 0.22 \left(\frac{116}{\lambda^1} - 0.4\beta - 5.0\right) e^{\frac{12.5}{\lambda^i}}
\]  

(27)

\[
\lambda_i = \left(1 - \frac{0.035}{\beta + 1}ight)^{-1}
\]  

(28)

\[
\lambda = \frac{\omega_r R}{v}
\]  

(29)

where \(\lambda\) is the tip speed ratio, \(\beta\) is the pitch angle, \(R\) is the wind turbine blade radius, \(\rho\) is the air density, \(v\) is the wind speed, \(A\) is the blade swept area, \(\lambda_i\) is the intermediate variable in the formula simplification, \(C_p(\beta, \lambda)\) is the power coefficient of a wind turbine, and \(\omega_r\) is the rotor speed.

It can be seen from equation (26) that the mechanical power output by the wind turbine is related to the wind speed and the power coefficient \(C_p\). In the range of full wind speed, the operating state of DFIG-WT will be divided into three phases: (1) Phase of constant power coefficient and variable rotor speed: when the wind speed is greater than cut-in wind speed, the power coefficient is the maximum value \(C_{p_{\text{max}}} = 0.438\) in order to achieve maximum wind energy capture. As is shown in Figure 18, at this time \(\beta = 0, \lambda_{\text{opt}} = 8.1\). And the rotor speed \(\omega_r\) will increase with wind speed to achieve maximum power point tracking control until the rated speed of DFIG-WT is reached. (2) Phase of constant rotor speed and variable power coefficient: when wind speed is still increasing but does not exceed rated wind speed, the rotor speed will remain at the rated value \(\omega_{\text{m}} = 1.2pu\). The maximum power in this phase is the output power of DFIG-WT when the rotor speed is rated. Simultaneously, tip speed ratio and power coefficient will decrease, pitch angle will keep constant, and output power will continue increasing to the rated power. (3) Phase of variable pitch angle and constant power: when wind speed continues to increase, the output power will also increase. If the wind speed exceeds the rated speed of 12.5 m/s, DFIG-WT will start up the pitch angle control to keep the output power constant, which is near the rated value. During the three phases, the variety of DFIG-WT parameters are shown in Figure 19. When wind speed is less than the cut-in wind speed or greater than the cut-out wind speed, DFIG-WT does not work. Therefore, the actual operation of DFIG-WT can be determined according to the output power and the change of pitch angle.

To verify the correctness of the control strategy under the full wind speed range proposed in this paper, the variation of the DFIG parameters is analyzed. The change of simulated wind speed is shown in Figure 20, and the cut-in wind speed is set as 4.5 m/s. In the simulation process, the initial wind speed is 4.5 m/s, then wind speed changes to 7, 11, 12.5, 13, 15 and 10 m/s. During the simulation time of 10 s, the wind speed first increases above the rated wind speed and then falls below the rated wind speed. By analyzing the changes of DFIG parameters, the validity and correctness of the control strategy can be judged. The simulation results are shown in Table 5.
It can be obtained from the simulation result, when wind speed is less than 10.8 m/s, DFIG operates at the phase of constant power coefficient and variable rotor speed. When the wind speed is greater than 10.8 m/s and less than 12.5 m/s, DFIG operates at the phase of constant rotor speed and variable power coefficient. When the wind speed is greater than 12.5 m/s, DFIG operates at the phase of variable pitch angle and constant power operation.

As shown in Table 5, when the wind speed is 4.5 and 7 m/s, $C_p$ is 0.438, rotor speed is 0.561 and 0.6656 pu respectively, which proves that DFIG achieve maximum power tracking control. The output power is 0.015 pu and 0.17 pu less than the rated power, so the pitch control system does not work and the pitch angle keep 0°. Therefore the parameters meet the operating state of the constant power coefficient and variable speed phase.

When the wind speed is 11 and 12.5 m/s, $C_p$ is 0.436 and 0.416 respectively, and the rotor speed are both rated speed of 1.2 pu. In the case, the optimal tip speed ratio cannot be maintained to maximize the power coefficient. The output power is 0.71 pu and 1 pu, both exceeding the rated power, and the pitch control system does not work. Therefore, each parameter meets the operating state of the constant rotor speed and variable power coefficient phase. When the wind speed is 13 and 14 m/s, $C_p$ is 0.37 and 0.25 respectively, which decreases with the increasing of wind speed. The reference value of the rotor speed is still 1.2 pu, making the generator rotor not over-speed. In the case, the output power exceeds the rated power, so the pitch control system starts up, and the pitch angle increases to 1.34° and 2° respectively to keep the output power stable at 1 pu. Therefore the parameters meet the operating state of the pitch constant power phase.

When the wind speed drops to 10 m/s, the rotor speed is 0.971 pu, and the power coefficient $C_p$ can reach 0.438. In the case, the output power is 0.53 pu and the pitch angle is restored to 0°. Based on the above analysis, the correctness and effectiveness of the maximum power point tracking control strategy and the pitch control strategy in the full wind speed range are verified.

## 5 COMPARISON RESULTS OF SIMULATION MODEL AND EXPERIMENTAL DATA

### 5.1 Field test system

LVRT test was performed on the #42 DFIG-WT of the wind farm. The test system is shown in Figure 21, where the LVRT test unit is located in the dashed blue box. The positions of the measuring points (MP) are shown in the green dashed box in Figure 21(b).

On the basis of the principle of impedance voltage division, $Z_1$ and $Z_2$ are configured in accordance with a certain proportion to realize a voltage dip within the range of 0–0.9 pu [29]. During normal operations, switch $Q_1$ is closed while switch $Q_2$ is off. During a fault, switch $Q_1$ is off while switch $Q_2$ is closed.

### 5.2 Model validation

Figure 22 shows a simulation model of a 1.5 MW DFIG-WT with LVRT control established via MATLAB/Simulink to verify the correctness of the parameter testing method and the
TABLE 6  DFIG-WT model Parameters

| Parameter                        | Value   |
|----------------------------------|---------|
| Rated power [MW]                 | 1.5     |
| Rated voltage [V]                | 690     |
| Wind wheel inertia [kg m²]       | 116     |
| Generator inertia [kg m²]        | 2.95 × 10^6 |
| Damping coefficient [ms/rad]     | 195,000 |
| Gearbox ratio                    | 103.5:1 |
| Wind wheel inertia [kg m²]       | 123     |
| DC side normal voltage [V]       | 1100    |
| Wind wheel diameter [m]          | 77      |
| Rated wind speed [m/s]           | 12.5    |

proposed model. The topology and main circuit parameters of the simulation model are consistent with those in the physical diagram of the DFIG-WT testing system in Figure 21(b). Model parameters are composed of the values provided by the DFIG-WT manufacturer as shown in Table 6 and optimal values identified as shown in Table 5.

First, the basic parameters from wind turbine manufacturer are obtained in preparation for the construction of the DFIG-WT. Table 6 shows the parameters.

Figure 23 shows the comparison between the simulated and measured waveforms of the established DFIG-WT model according to the above parameters and control mode. It includes the active output power and reactive output power of the DFIG-WT, the value of the terminal voltage and current and the value of the dq axis component of the voltage and current. In the Figure 23, the orange and blue curves are the measured and simulated waveforms, respectively. The power values during normal and LVRT states in four operation conditions (high/low-power running at different voltage drop) are well matched, and the falling process of LVRT is also well fitted. Therefore, the built model of DFIG-WT based on LVRT testing is accurate.

5.3  |  Error evaluations

In Germany joint measurement requirements for renewable power sources like wind energy, solar energy and biomass have been in the FGW TR4 (Federation of German Wind power and other Renewable Energies). It is the model validation guideline that corresponds to the measurement guideline. Literature [30] provides the evaluation content and error requirements of model verification according to FGW codes. The assess-

FIGURE 22  1.5 MW-Connected DFIG-WT

FIGURE 23  Comparison of DFIG-WT measured and simulated curve under LVRT testing. (a) Voltage drop to 20% under heavy-power operation condition. (b) Voltage drop to 35% under heavy-power operation condition. (c) Voltage drop to 75% under low-power operation condition. (d) Voltage drop to 90% under low-power operation condition
The absolute error between the simulation waveform and the field test data is shown in Figure 24 under the conditions of voltage drops to 20% and 35% under heavy-power operation and 75% and 90% under low-power operation. Figure 24 shows the preset maximum values for $F_1$, $F_2$, $F_3$, and $F_G$. The error of each electric quantity ($P$, $Q$, $I_q$) is less than the maximum value set by the specification. Thus, the validity and accuracy of the identification method and model are further verified.

### 6 CONCLUSIONS

This work considers a 1.5 MW DFIG-WT of a wind farm in West Inner Mongolia Power Grid as the research object. On the basis of the measured data obtained from LVRT testing, an accurate electromagnetic transient simulation model is established. The following conclusions can be derived:

1. Based on the electromechanical system, control system and protection system of DFIG-WT, the DFIG-WT transient model on full operation condition and rapid starting period is established. This model can operate in the full wind speed range and quickly enter stable state within 1 s after start-up.

2. Considering that different system parameters of DFIG-WT have different influence degrees, the integrated parameter identification method is adopted. For the action characteristics and control strategy of DFIG-WT, the active and reactive power control mode in normal or fault conditions are determined by the curve fitting method. For the generator parameters, power control parameters, and resistance of Crowbar of DFIG-WT, an improved genetic
algorithm is used to identify the resistance value to accurately reflect the output characteristics of DFIG-WT during LVRT.

(3) The comparison results of simulated and measured data show that the proposed integrated parameter identification method is effective, reasonable, and provides a reference for the modelling of DFIG-WT. Moreover, the built model can be transformed into the power system simulation software PSD-BPA through the interface algorithm for electromagnetic transient simulation calculation of the regional power grid.

(4) The following work in this paper will focus on the research of the asymmetric faults of the built model. It includes the operating characteristics and improved control methods of DFIG-WT under asymmetric grid faults.

ACKNOWLEDGEMENTS

This paper was supported by the Science and Technology Project of China State Grid Headquarters (SGTYHT/18-JS-206) and Natural Science Foundation of Hebei Province (E2018502134).

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How to cite this article: Yan X, Cui S, Sun X, Sun Y. Transient modelling of doubly-fed induction generator based wind turbine on full operation condition and rapid starting period based on low voltage ride-through testing. *IET Renewable Power Generation*. 2021;15:1069–1084. https://doi.org/10.1049/rpg2.12090