LVRT control strategy for asymmetric faults of DFIG based on improved MPCC method

CAN DING, YUNWEN CHEN, TAIPING NIE
1College of Electrical Engineering and New Energy, China Three Gorges University, Yichang, CO 443002 China

Corresponding author: Can Ding (e-mail: dingcan@ctgu.edu.cn).

ABSTRACT In the case of asymmetric faults, modern new power grids require a double-fed induction generator for the grid-connected operation of wind turbines to still have good low voltage ride-through capabilities. To solve this problem, it proposes a low voltage ride-through control strategy based on an improved model predictive current control strategy in the two-phase stationary coordinate system. First, it analyzes the transient characteristics of a double-fed induction generator and proposes an improved flux extraction method based on the analysis results. The method simplifies the traditional flux linkage measurement link and solves the one-beat delay problem of model predictive control by controlling the step length. Then, the paper also introduces the induced voltage and flux attenuation into the predictive control, which can effectively eliminate the double-frequency oscillation component in the DC bus voltage and electromagnetic torque. Therefore, the grid-connected power quality is improved. Finally, by building a model as a case, it is verified that the control strategy has a good effect on the realization of low voltage ride-through under asymmetric faults. It can achieve the two control goals of self-preservation and support of a double-fed induction generator during low voltage ride-through operation.

INDEX TERMS doubly-fed induction generator, low voltage ride-through, predictive current control, flux measurement, two phases stationary coordinate system

I. INTRODUCTION

Wind energy has the characteristics of randomness and volatility. In the process of grid-connected power generation, it presents shortcomings such as strong output power fluctuations and large impacts on the grid, which will affect the normal operation of the grid [1]. Therefore, modern power grids place high requirements on the grid-connected operation of wind turbines, requiring wind turbines to have high reactive power control capabilities [2]-[7] and low voltage ride-through capabilities during faults [8]-[10]. The technical difficulty of a double-fed induction generator (DFIG) operating in low voltage ride-through (LVRT) is to achieve the following two control goals at the same time, namely self-protection and support. Self-protection mainly suppresses stator and rotor overcurrent, rotor overvoltage, and intermediate DC bus overvoltage, and protects the safety of the rotor side converter (RSC) and DC bus capacitor. The support is to continuously and stably provide reactive power to assist the grid voltage recovery and reduce the possibility of grid voltage collapse [11].

To reduce the action of hardware equipment, the current domestic usually improves the control strategy of the excitation converter to achieve the purpose of protecting the wind turbine. Its advantage lies in making full use of the converter’s capacity to achieve LVRT. Some new control technologies such as internal model [12], hysteresis [13]-[14], and sliding mode [15] control have been proposed one after another. Compared with traditional PI controllers, these control techniques have great advantages in suppressing rotor overcurrent, but they cannot accelerate stator transient flux decay. The concept of optimal demagnetization was proposed from the paper [16]. Optimal de-excitation refers to the selection of a suitable de-excitation coefficient to minimize the current peak value of the RSC during LVRT. In order to support the restoration of the grid voltage, scholars superimposed the de-excitation current command with the normal rotor current command [17]. It completed de-excitation control and reactive power support while controlling the rotor converter, but required a larger current capacity of the generator-side converter. Paper [18] introduced
a de-excitation control method based on grid voltage-oriented vector control. This method can speed up the attenuation speed of the stator flux linkage, but only the simulation study on the control of the three-phase symmetrical drop of the grid voltage was carried out, and the study of the asymmetric drop condition was not carried out.

Model Predictive Control (MPC) is an optimization algorithm [19]. Its principle is to predict the future state quantity and output quantity according to the built system model, and carry out the rolling optimization of the control quantity according to the evaluation function, and finally select the optimal control algorithm. Scholars introduced a model predictive control method applied to the field of power electronics [20]. This paper described in detail the application of Finite Control Set Model Predictive Control (FCS-MPC) to power converters. Some scholars have designed a predictive control strategy based on the maximum wind energy tracking model of the DFIG. This strategy kept the output power of the wind turbine stable when the wind speed changes, but did not apply the MPC to the excitation converter of the wind turbine. Some scholars combined MPC with demagnetization control, but the flux linkage measurement link is complicated, which affected the demagnetization effect [21]-[22]. Other scholars proposed improved demagnetization control [23]. The demagnetization control strategy dynamically adjusted the scale factor of demagnetization according to the depth of the grid voltage drop under symmetrical faults, but it is only suitable for symmetrical faults.

An improved Model Predictive Current Control (MPCC) strategy based on a two-phase stationary (αβ) coordinate system under asymmetrical power grid faults is proposed in this paper. This strategy is mainly for DFIG to solve the problems of complicated flux measurement links during LVRT and the delay and a large amount of calculation for MPCC. First, a reference model was established based on the structure of the DFIG to analyze its dynamic process in the case of asymmetrical faults in the power grid. Then built the predictive model based on dynamic analysis, and set the control step length to the most suitable step length that can offset the delay problem. And this paper proposed a new method of flux linkage measurement. This method controlled the rotor flux linkage to track the stator flux linkage decay, so as to achieve the purpose of suppressing the rotor overcurrent and suppressing the flux linkage fluctuation. The fault ride-through control strategy was designed as described above. Finally, it was verified on the MATLAB/Simulink simulation platform that the control strategy can guarantee the feasibility of support while protecting itself.

II. ANALYSIS OF TRANSIENT CHARACTERISTICS OF DFIG IN POWER GRID FAILURE

A. MATHEMATICAL MODEL OF DFIG IN αβ COORDINATE SYSTEM

In order to obtain a complete doubly-fed fan model, the parameters are equivalent to the stator coordinate system, and the motor convention is adopted. The mathematical model of DFIG in the three-phase stationary coordinate system can be written as

\begin{align}
  u_s &= R_s i_s + \frac{d\varphi_s}{dt} \\
  u_r &= R_r i_r + \frac{d\varphi_r}{dt} - j\omega \varphi_r \\
  \varphi_s &= L_s i_s + L_m i_r \\
  \varphi_r &= L_r i_r + L_m i_s
\end{align}

Among them, \(u_s\) and \(u_r\) are the stator and rotor side voltages, \(i_s\) and \(i_r\) are the stator and rotor side currents, \(R_s\) and \(R_r\) are the stator and rotor resistances, \(\varphi_s\) and \(\varphi_r\) are stator and rotor flux linkages respectively, \(L_s\) and \(L_r\) are the stator and rotor inductances respectively, \(L_m\) is the stator and rotor mutual inductances, and \(\omega\) is the rotor speed.

According to the mathematical model of the DFIG in the three-phase stationary coordinate system, it can be seen that the model is not only a time-varying or coupled, but also a nonlinear equation. These characteristics make the design of the controller more complicated, so coordinate transformation is needed to simplify the model. The DFIG is transformed from the three-phase stationary coordinate system to the two-phase stationary coordinate system, and a mathematical model of vector control is built for its stable operation. The subsequent optimization control algorithms in this paper are all carried out in the αβ coordinate system. In the two-phase stationary coordinate system, the control strategy can save Parker coordinate transformation and reduce the introduction of parameter \(\theta_r\) in the calculation. In addition, the conventional stator flux orientation method is affected by the cross-coupling term of the positive sequence component in the counterclockwise rotating synchronous coordinate system. When the load is unbalanced, it appears as harmonics in the d-q coordinate system. Therefore, it is necessary to control the current in the d-q coordinate system. The feedforward decoupling of the cross-coupling is performed, and the controller design at this time becomes complicated. Rewriting equation (1). The mathematical model of the stator side and rotor side of the built DFIG in the αβ reference frame is expressed as follows:

\begin{align}
  u_{s\alpha} &= R_s i_{s\alpha} + \frac{d\varphi_{r\beta}}{dt} \\
  u_{r\alpha} &= R_r i_{r\alpha} + \frac{d\varphi_{r\beta}}{dt} - j\omega \varphi_{r\beta}
\end{align}

Rewritten equation (2) expresses the stator and rotor flux linkages in the αβ reference system as follows:

\begin{align}
  \varphi_{r\alpha} &= L_s i_{s\alpha} + L_m i_{r\alpha} \\
  \varphi_{r\beta} &= L_r i_{r\alpha} + L_m i_{s\alpha}
\end{align}
According to the state space equations of stator flux linkage and rotor flux linkage, it can be deduced that the following relationship exists:

$$\varphi_{\text{raf}} = \frac{L_m}{L_{\text{r}}} \varphi_{\text{raf}} + \sigma L_s i_{\text{raf}}$$  \hspace{1cm} (5)

Where $\sigma$ is the leakage inductance coefficient, $\sigma = \frac{1-L_m}{L_{\text{r}}}$. The relationship of the rotor flux linkages is

$$\varphi_{\text{rab}} = \varphi_{\text{ra}} + j\varphi_{\text{rb}}.$$

In the same way, the relationship between the rotor voltage and the stator flux linkage is obtained:

$$u_r = \frac{L_m}{L_s} \frac{d\varphi_r}{dt} + \left(\sigma L_s + R_s\right) i_r$$  \hspace{1cm} (6)

In the $\alpha\beta$ coordinate system, the active and reactive power output from the stator side of the DFIG are respectively:

$$P_s + jQ_s = -\frac{3}{2} u_{\text{saf}} \times i_{\text{saf}}$$ \hspace{1cm} (7)

$$P_s = -\frac{3}{2} \left( u_{\text{sas}} i_{\text{sas}} + u_{\text{sbs}} i_{\text{sbs}} \right)$$

$$Q_s = -\frac{3}{2} \left( u_{\text{sbs}} i_{\text{sas}} - u_{\text{sas}} i_{\text{sbs}} \right)$$

According to the above, the state space equations of the DFIG after grid connection are obtained, and these equations can be used as the model basis of the improved MPCC strategy.

DFIG often uses steady-state stator flux orientation vector control during LVRT. However, this control strategy ignores the transient process of the stator flux linkage of the DFIG, and the stator flux linkage cannot be accurately oriented when the fault occurs, so it is not suitable for the operation of the DFIG when the fault occurs.

B. DYNAMIC ANALYSIS OF ASYMMETRICAL POWER GRID FAULTS

Compared with the three-phase symmetrical drop, the stator flux contains a negative sequence component during an asymmetrical drop of the power grid. The existence of the negative-sequence component of the flux linkage makes the negative-sequence component of the grid voltage relative to the rotor have a greater slip rate, which will lead to more serious rotor overvoltage and overcurrent. Therefore, the LVRT control under asymmetric faults should be paid more attention.

Equation (3) is also valid under unbalanced faults, and can be written in the following form:

$$u_{\text{ra}} = R_s i_{\text{ra}} + \frac{d\varphi_{\text{ra}}}{dt} + \omega_s \varphi_{\text{rb}}$$ \hspace{1cm} (8)

Combining equation (3) and equation (5) and eliminating the rotor flux, equation (8) can be rewritten as:

$$u_{\text{ra}} = R_s i_{\text{ra}} + \left( L_m - \frac{L_m}{L_{\text{r}}} \right) \frac{di_{\text{ra}}}{dt} + \omega_s \varphi_{\text{rb}}$$

$$u_{\text{rb}} = R_s i_{\text{rb}} + \left( L_m - \frac{L_m}{L_{\text{r}}} \right) \frac{di_{\text{rb}}}{dt} - \omega_s i_{\text{ra}}$$

Equation (9) analysis shows that the rotor voltage is composed of two parts. They are the rotor back electromotive force related to the stator flux and the rotor loop voltage drop determined by the rotor current and rotor winding parameters. That is to say, the vector of the rotor voltage is determined by both the stator flux linkage and the rotor current. This is consistent with the influence factor of equation (6) on the rotor voltage.

When an asymmetric fault occurs in the power grid, the stator flux linkage can be divided into three flux linkages. Two of them are determined by the stator voltage, which are the positive sequence flux $\varphi_{\text{sa}}$ rotating in the positive sequence of $\omega_s$ and the negative sequence flux $\varphi_{\text{sb}}$ rotating in the negative sequence of $-\omega_s$. The remaining part is free flux $\varphi_{\text{sf}}$. The slip rate of the stator transient DC flux linkage and negative sequence AC flux linkage is much greater than that of the normal stator flux linkage, which will induce a large transient back electromotive force in the rotor winding. This back electromotive force eventually leads to overcurrent of the rotor and also causes larger electromagnetic torque pulsation. The traditional PI controller only controls the positive sequence component, and cannot realize the simultaneous control of the positive and negative sequence components. Therefore, this paper improves the control method of the sequence component. The total stator flux is derived from the mathematical model equation (1) of DFIG in the three-phase static coordinate system [24], which is obtained by an integral term:

$$\varphi_s = \int (u_{\text{r}} - R_s i_{\text{r}}) dt$$ \hspace{1cm} (10)

Since the free component of the flux linkage is a relatively slow DC component, it can be obtained by filtering with a low-pass filter. At this time, the combined value of the free component and the negative sequence component of the flux linkage can be obtained, as shown in the following equation:

$$\varphi_s = \frac{1}{j\omega_s} \frac{d\varphi_s}{dt} = 2\varphi_{\text{sa}} + \varphi_{\text{sf}}$$ \hspace{1cm} (11)

Rewrite the above equation as:
\[
\varphi_s = \omega_s \int \left(2\varphi_{s2} + \varphi_d\right)^2 - \varphi_d^2 dt
\] (12)

Discretize equation (12), and the sampling period is \(T_s\), where \(T_s = 50\mu s\). Then introduce the trapezoidal equation. The results will be used as the \(k\)th flux linkage value in the subsequent predictive control process, and the following flux linkage measurement method can be obtained:

\[
\begin{align*}
\alpha(k) &= \left(2\varphi_{s2(k)} + \varphi_d(k)\right)^2 - \varphi_d^2(k) \\
\varphi_{s2(k)} &= \frac{1}{2} [\alpha(k) - \varphi_{s1(k)}] \\
\varphi_s(k) &= \varphi_{s1(k)} + \varphi_{s2(k)} + \varphi_d(k)
\end{align*}
\] (13)

The flux measurement process is shown in figure 1

**FIGURE 1.** Flux link measurement link structure.

### III. IMPROVED MODEL PREDICTIVE CURRENT CONTROL

The principle of predictive control is divided into three basic steps. First establish a predictive model, then predict the future dynamics of the system, and finally control the constraints and act on the system.

**A. Build a predictive model**

According to the principle of model predictive control, the time interval \(P\) in the forecast time domain should not be less than the time interval \(M\) in the control time domain, that is, \(P \geq M\). Considering the delay problem of model predictive control, this paper shortens the time interval of control time domain. Paper [25] mentioned that the model predictive current control has the characteristic that it is almost impossible to obtain the control current of the next 3 cycles in the \(k\)th cycle. No matter if the sampling time of the converter is shortened to \(1/2T_s\) or \(1/4T_s\), its control current is consistent with the current moment \(k\). Moreover, the model prediction can only make a trade-off in terms of stability and rapidity, and cannot be perfectly compatible with the two [26]. The sampling frequency is too high will put forward higher requirements for the control chip, at this time the control system will have a large error [27]. In order to make the excitation converter have as fast response speed as possible, and taking into account the one-beat delay problem in the timing control [28], this paper shortens the sampling time of the excitation converter to \(1/2T_s\). At this time, the prediction time domain \(P\) is equal to \(2M\). It applies the optimal combination of switching functions at time \(t(k + 1)\) determined at time \(t(k)\) to time \(t(k + 2)\), thereby obtaining an ideal combination of switching functions. The derivation of the prediction equation is shown in figure 2. Among them: \(x(k)\) is the sampling time; \(i(k)\) is the sampling current corresponding to the sampling time; \(i(4)\) is the current sampling value; \(i(m)\) is the predicted current value; \(x(k)\)-\(x(k-1)\)=\(T_s/2\); \(x(m)\)-\(x(4)\)=\(T_s/2\). The working principle of figure 2 is to sample at time \(x(3)\) to obtain \(i(3)\), and predict the control value at time \(x(4)\) to act on it at time \(x(m)\). The obtained control value \(i(4)\) will directly pass through the value function Compare to obtain the final control signal. The current value of the fault itself fluctuates in a large range, and the repeated iterations of the model prediction make the value at each moment be effectively processed. The predicted value is essentially the result of processing based on the value obtained at the current time \(x(3)\), and the predicted value belongs to the future value and will not affect the prediction model at the current time.

**FIGURE 2.** Schematic diagram of prediction formula derivation.

To realize MPCC of LVRT, the voltage and current are firstly sampled discretely to obtain:

\[
\frac{d}{dt} \begin{bmatrix} u(k) \\ i(k) \end{bmatrix} = \frac{1}{T_s} \begin{bmatrix} u(k) - u(k-1) \\ i(k) - i(k-1) \end{bmatrix}
\] (14)

Compared with other controllers, the improved MPCC strategy proposed in this paper does not need to separate the positive and negative sequence of voltage and current. This makes the problem that the positive and negative sequence separation cannot be accurately controlled when the voltage drops will no longer exist. Consider the state-space model of a linear discrete-time system as follows:

\[
\begin{align*}
x(k+1) &= Ax(k) + Bu(k) + Bd(k) \\
y_c(k+1) &= Cx(k)
\end{align*}
\] (15)

Where \(x(k)\) is the state variable, \(u(k)\) is the input control variable, \(y_c(k)\) is the controlled output variable, and \(d(k)\) is the measurable external disturbance variable. The current \(i_{\alpha}(k), i_{\beta}(k)\) and other information are used as the state
variable matrix $\mathbf{x}(k)$, combined with the mathematical model $u(k)$ of the DFIG as the input control variable. Based on the above parameters, predict the current values $i_{r\alpha}(k+1)$ and $i_{r\beta}(k+1)$ corresponding to the next moment, and use them as the controlled output variable $y_c(k)$. First of all, this paper assumes that all the state variables of the system can be measured, and all the above equations are rewritten as an incremental model:

$$\Delta x(k+1) = A\Delta x(k) + B_x\Delta u(k) + B_d\Delta d(k)$$  \hspace{1cm} (16)$$

$$y_c(k) = C_x\Delta x(k) + y_c(k-1)$$

$$\Delta x(k) = x(k) - x(k-1)$$

Where $\Delta u(k) = u(k) - u(k-1)$

$$\Delta d(k) = d(k) - d(k-1)$$

The measured value of kth at the current moment is $x(k)$, and $\Delta x(k) = x(k) - x(k-1)$ can be calculated. $\Delta x(k)$ can be used as the starting point for predicting the future dynamics of the system, from which the state at the k + 1 th can be predicted. This value is actually the state increment:

$$\Delta x(k+1 | k) = A\Delta x(k) + B_x\Delta u(k) + B_d\Delta d(k)$$ \hspace{1cm} (17)$$

In the above equation, " $k+1 | k$ " represents the prediction of time $k$ at time $k+1$, and the $k$ after the symbol "|" represents the current time, where the value of the $k + 1$ th has no effect on the output at time $k$. After the state-space model is established, the conduction current prediction equation is derived. Then, different command values are given to the rotor converter through constraint conditions.

**B. Current predictive control algorithm**

In the case of voltage asymmetry faults, since the stator transient flux linkage is not much and it will automatically attenuate, its impact on the overvoltage is limited. For the sake of simplicity, this paper temporarily ignores the influence of the stator's transient DC flux in the analysis. That is, only the positive and negative sequence flux linkage and current of the stator are considered.

Equation (9) can be rewritten as:

$$\frac{di_{r\alpha}}{dt} = (u_{r\alpha} - e_{r\alpha} - R_i i_{r\alpha}) \left( L_{r\alpha} - \frac{L_m^2}{L_{r\alpha}} \right) - \omega i_{r\beta}$$

$$\frac{di_{r\beta}}{dt} = (u_{r\beta} - e_{r\beta} - R_i i_{r\beta}) \left( L_{r\beta} - \frac{L_m^2}{L_{r\beta}} \right) - \omega i_{r\alpha}$$ \hspace{1cm} (18)$$

Ignoring the change of the free component of the flux linkage, calculate the induced electromotive force $e_{r\alpha}$, $e_{r\beta}$ at this time. The incremental method is used to take $\Delta i_{r\alpha}$ and $\Delta i_{r\beta}$ as the output, and the forward Euler method is introduced to replace the difference quotient with the difference value. The results are the current control increment at the $k + 1$ th moment:

$$\Delta i_{r\alpha}(k) = T_s \left[ \frac{\Delta u_{r\alpha}(k) - \Delta e_{r\alpha}(k) - R_i \Delta i_{r\alpha}(k)}{L_{r\alpha} - \frac{L_m^2}{L_{r\alpha}}} - \omega \Delta i_{r\beta}(k) \right] + \Delta i_{r\alpha}(k-1)$$

$$\Delta i_{r\beta}(k) = T_s \left[ \frac{\Delta u_{r\beta}(k) - \Delta e_{r\beta}(k) - R_i \Delta i_{r\beta}(k)}{L_{r\beta} - \frac{L_m^2}{L_{r\beta}}} - \omega \Delta i_{r\alpha}(k) \right] + \Delta i_{r\beta}(k-1) \hspace{1cm} (19)$$

According to the predicted future state, the output of the controlled object in the predicted time domain are calculated. And adjust the feedback proportional coefficients $f_1$ and $f_2$ according to the depth of the grid voltage drop. At this time, the feedback current can be written as:

$$\Delta i_{r\alpha}^*(k) = f_1 \Delta i_{r\alpha}(k)$$

$$\Delta i_{r\beta}^*(k) = f_2 \Delta i_{r\beta}(k) \hspace{1cm} (20)$$

From the above analysis, the predicted current expression is obtained as:

$$i_{r\alpha}(k+1) = i_{r\alpha}(k) + \Delta i_{r\alpha}^*(k)$$

$$i_{r\beta}(k+1) = i_{r\beta}(k) + \Delta i_{r\beta}^*(k) \hspace{1cm} (21)$$

Among them, the predicted value of the rotor current in equation (21) consists of two terms. They are the reference value and the incremental value. The reference values $i_{r\alpha \text{ref}}(k)$ and $i_{r\beta \text{ref}}(k)$ are the reference values obtained after the coordinate transformation of the original control strategy. The increment value $\Delta i_{r\alpha}^*(k)$ and $\Delta i_{r\beta}^*(k)$ are the increments of each step considering the induced voltage change and negative sequence flux linkage compensation. Finally, $u_{r\alpha}(k+1)$ and $u_{r\beta}(k+1)$ are obtained according to the relationship between the rotor current and the voltage, and the results are used as the converter control signal at the $k + 2$ time. The improved RSC control scheme is shown in the figure 3. The green area is the traditional MPC control measurement, and the yellow area is the proposed improved MPCC strategy based on the $\alpha \beta$ coordinate system.
C. Value function establishment

The control strategy in this paper needs to achieve two goals: to achieve low voltage ride through, and to ensure grid-connected power quality. These goals need to be achieved through a value function, and other goals such as reducing switching losses are not considered in this paper. Based on the above, the predicted value and reference value of the current are obtained. Figure 4 shows the waveforms of the predicted current value and the reference current value for single-phase grounding, two-phase short-circuit, and two-phase grounding fault.

\[
g_a = \|i_{ra}^*(k+1) - i_{ra}(k+1)\| + \|i_{rb}^*(k+1) - i_{rb}(k+1)\|
\]

The predicted value of the current and the reference value are compared through the value function, and the switch combination corresponding to the current vector that minimizes the value function is selected as the RSC trigger pulse signal to realize the control of the RSC. The DC bus voltage is very important for the stable operation of GSC and RSC, and the stability of the DC bus voltage is directly related to the power flowing through the bus [29]. To prevent the delay of the system from deteriorating the performance of the system, the delay is compensated according to the above-mentioned shortening of the sampling time to \(1/2T_s\). And considering that the DC bus voltage is kept stable under the fault, the new value function is constructed at this time as:

\[
g_a = \|i_{ra}^*(k+2) - i_{ra}(k+2)\| + \|i_{rb}^*(k+2) - i_{rb}(k+2)\| + \lambda|u_{dc}^* - u_{dc}|
\]

The improved model predictive current control scheme is shown in Figure 5.
IV. CASE SIMULATION AND ANALYSIS

A. SIMULATION OF CLSSCB BREAKING FAULT CURRENT

To verify the proposed improved MPCC strategy, this paper sets up an asymmetric timing fault at the connection between the wind turbine outlet and the grid. The following three working conditions of single-phase ground fault, two-phase short-circuit fault and two-phase ground fault are analyzed as examples. The improved control strategy is compared with the traditional PI control and the control scheme used in the paper[30] to directly output PWM to the power converter without modulation. Later, the control strategy of the paper[30] is expressed as traditional model predictive control. The grid-connected topology of the DFIG is shown in figure 6.

![Diagram of DFIG](image)

**FIGURE. 6 Basic structure of DFIG.**

Before the grid fault occurs, DFIG runs in a stable state; at 3s, an asymmetrical fault occurs on the grid with a duration of 0.625s. The main parameters of DFIG are shown in the following table:

| Parameter                              | Numerical value |
|----------------------------------------|-----------------|
| Stator and rotor mutual inductance (mH)| 0.0025          |
| Rotor leakage inductance (mH)          | 0.002587        |
| Stator leakage inductance(mH)          | 0.002587        |
| DC bus voltage reference value (kV)    | 1.2             |
| Rated Capacity (MW)                    | 2               |
| Rated voltage (kV)                     | 0.69            |
| Stator resistance(mΩ)                  | 0.0026          |
| Rotor resistance(mΩ)                   | 0.0029          |

| Parameter                              | Numerical value |
|----------------------------------------|-----------------|
| Stator and rotor mutual inductance (mH)| 0.0025          |
| Rotor leakage inductance (mH)          | 0.002587        |
| Stator leakage inductance(mH)          | 0.002587        |
| DC bus voltage reference value (kV)    | 1.2             |
| Rated Capacity (MW)                    | 2               |
| Rated voltage (kV)                     | 0.69            |
| Stator resistance(mΩ)                  | 0.0026          |
| Rotor resistance(mΩ)                   | 0.0029          |

After the fault occurs, the excitation converter first detects the voltage drop at the grid connection point. At this time, the system switches from the original PI control to the model predictive control strategy in the paper[30] or the improved MPCC strategy. When a single-phase ground fault occurs and the grid voltage drops to 40%, the simulation waveform is shown in figure 7; when a two-phase short-circuit fault occurs and the grid voltage drops to 50%, the simulation waveform is shown in figure 8; when a two-phase-to-ground short-circuit fault occurs, the grid voltage drops to 50%, the simulation waveform is shown in figure 9. It can be seen from (a), (b), and (c) of figures 7, 8, and 9 that the quality of the rotor current waveform is stable when there is no fault. After the fault occurs, the rotor current generates a surge current due to the existence of the negative sequence component of the stator flux linkage. The model predictive control strategy does not use space vector control directly sends the PWM control signal to the converter device through the minimized value function, so that it can directly track the rotor current to realize the control under the fault. During the fault process, the model predictive current control proposed in this paper suppresses the rotor current under traditional PI control and the rotor current under the traditional model predictive control.

When the terminal voltage drops, the stator voltage will also drop, and the flux linkage will change accordingly. At this time, there will be a surge current in the stator current. The improved MPCC suppresses the flux linkage so that the stator current is suppressed. The (d), (e), and (f) of Figs. 7, 8, and 9 show the a-phase waveform of the stator current. It can be seen that the improved MPCC has a more obvious effect on the stator and rotor current than the traditional PI control and the traditional predictive control. This is also conducive to controlling the stator to send reactive power through the rotor current after the voltage drops, to provide reactive power support to the grid.

To suppress the over-voltage and over-current phenomenon on the rotor side when the grid voltage drops, it is necessary to suppress the induced electromotive force on the rotor side. This induced electromotive force is generated by the AC component of the stator flux and the DC component of the rotating and cutting rotor windings. In the above analysis, the DC component and its influence have been ignored. Therefore, the essence of fault control is to suppress the AC component of the flux linkage caused by the fault. It can be seen from figures 7, 8, and 9, where (i) indicates that the electromagnetic torque under the traditional PI control has a large number of double-frequency AC components generated by the flux cutting. PI control cannot be effectively suppressed due to its control limitations. The traditional model predictive control represented by (h) has a certain inhibitory effect on the electromagnetic torque, so although the amplitude is large, it will also have a restraining effect over time. But because it does not suppress the double frequency AC component, the control is not stable enough. The improved MPCC shown in (g) suppresses the double-frequency AC component so that the electromagnetic torque decays quickly and the oscillation amplitude is small. At this time, the fluctuation is unavoidable but relatively stable.

In fact, no matter what control strategy is adopted by the rotor side converter and the grid side converter (Grid Side Converter, GSC) during the fault period, it is required to ensure the stability of the DC bus voltage. To ensure the stability of the DC bus voltage is to ensure the controllability of the GSC. This is a prerequisite for the normal operation of the excitation converter and the effectiveness of the improved control strategy. Figures 7, 8, and 9 (l), (k), and (j) correspond to the DC bus voltage changes of the converter based on PI
control, traditional model predictive control and improved MPCC, respectively. It can be seen from the waveform before 3s that the DC bus voltage is stable at about 1.2kV when there is no fault. When a fault occurs, energy will accumulate at the DC bus, causing the DC bus voltage to oscillate. It can be seen from the waveforms before 3s that the DC bus voltage is stable at about 1.2kV when there is no fault. When a fault occurs, energy will accumulate at the DC bus, and the DC bus voltage will oscillate. Moreover, the voltage oscillation under a two-phase fault is more serious than a single-phase ground fault. The improved MPCC strategy can effectively suppress its fluctuations and accelerate the suppression rate over time during the fault period. Taking the DC bus voltage into consideration in the improved MPCC will make the suppression effect better than the traditional model predictive control, and the harmonic content will be reduced. It can be seen that no matter for single-phase ground fault, two-phase short circuit or voltage drop under two-phase ground short circuit, the improved MPCC strategy proposed in this paper is better than the traditional PI-based controller and the traditional MPC. In addition, the suppression effect of two-phase short-circuit and two-phase-to-ground short-circuit is more obvious than that under single-phase-to-ground fault. At 3.625s, the grid voltage is restored, and the magnetic field will suddenly change again to make the current oscillate. Since the early model predictive control has a certain inhibitory effect on the electromagnetic torque, the electromagnetic torque is in a relatively stable state when switching to PI control, so the fluctuation is not large. Therefore, the DC bus voltage is not affected too much, and its fluctuation cannot be effectively suppressed under the control of traditional PI for a long time.

FIGURE 7 Comparison of LVRT performance between improved MPCC and traditional MPC and PI for single-phase grounding.
FIGURE 8 Comparison of LVRT performance between improved MPCC and traditional MPC and PI in two-phase short circuit.

FIGURE 9 Comparison of LVRT performance between improved MPCC and traditional MPC and PI in two-phase short grounding fault.

Figures 10, 11, and 12 are the grid-side current, voltage and output reactive power waveforms in the d-q coordinate system. They are the waveforms of improved MPCC, traditional model predictive control and traditional PI control when the single-phase fault voltage drops to 40%, the voltage drops to 50% under a two-phase short circuit, and the voltage drops to 50% under a two-phase grounding short circuit. In the case of a grid failure, the MPCC strategy proposed in this paper can improve the quality of the grid-connected voltage and current waveforms. The q-axis reference value $u_{q_{ref}}$ of the GSC is based on the DC bus voltage as the control target. Figures 10, 11, and 12 (d), (e), and (f) show that both the traditional model

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predictive control and the improved MPCC control can suppress the $u_{dq}$ oscillation, which is consistent with the above-mentioned DC bus voltage analysis. The above analysis shows that the improved model predictive control effectively guarantees the stability of the DC bus voltage. At this time, the GSC is in a controllable state and the control effect is better. Therefore, the suppression effect on the grid-side voltage and current waveforms is more obvious than that of the traditional model predictive control.

Figures 10, 11, and 12 (g), (h), and (i) are reactive power waveforms. It can be seen from the figure that when the voltage drops, DFIG will inject a certain amount of reactive power into the grid, and the reactive power will increase at this time. The fault is cleared at 3.625s, and the reactive power will directly recover to the steady-state value before the fault occurs after a short-term transient. The above analysis analyzes the effective suppression of the improved MPCC on the stator and rotor overcurrent, which makes the stator reactive power in a controllable state under a single-phase fault. Although the traditional model predictive control has a certain inhibitory effect, it cannot effectively track the reactive power.

**FIGURE. 10** Comparison of LVRT performance between improved MPCC and traditional MPC and PI for single-phase grounding.

**FIGURE. 11** Comparison of LVRT performance between improved MPCC and traditional MPC and PI in two-phase short circuit.
V. CONCLUSION

This paper analyzed the transient characteristics of DFIG under asymmetric faults and proposed an improved model predictive current control method without adding hardware protection equipment. Based on the above analysis, the following conclusions are obtained:

1) The proposed improved MPCC strategy based on the unbalanced voltage of the grid in the αβ coordinate system can greatly reduce the amount of calculation, and the strategy did not require current positive and negative sequence separation. A new measurement structure of flux linkage was proposed, which simplifies the links of flux linkage. Setting the model sampling time as the smallest step length that offsets the delay of predictive control effectively solved the problem of one-beat delay in MPCC.

2) The simulation verification was carried out for the single-phase ground fault, the two-phase short-circuit fault, and the two-phase short grounding fault. The results showed that the control strategy can make DFIG meet the two control objectives of LVRT, namely, self-protection and support.

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