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Crowbar Resistance Setting and its Influence on DFIG Low Voltage Based on Characteristics

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ABSTRACT

In the case of low voltage fault cases,doubly fed induction generator (DFIG) with Crowbar protection circuit to realize low voltage ride through (LVRT), and the choice of crowbar resistance of unit LVRT effects is very large.In this paper, from the DFIG wind power system steady state and transient mathematical model of voltage drop down, using space vector analysis method and Laplace transform, deduced the time domain transient current expressions of voltage drop Put forward the method for calculating the maximum fault current and the rotor side crowbar resistance setting method, solve the crowbar protection circuit for tilting rotor current and DC bus over-voltage problems. Numerical example and simulation shows that, The proposed method, effectively suppress the transient component of fault current, significantly improved the automation level of the wind power system.

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1. INTRODUCTION

The energy crisis and environmental problems is human facing two big problems. In order to solve these two contradictions, to implement sustainable development strategy, development of renewable, clean and pollution-free new energy received unprecedented attention.Resolutely carry out the scientific outlook on development, taking the path of sustainable development, using advanced technology to develop renewable energy, has become the world to explore and deal with the two big crisis measures actively.Relative to the conventional non-renewable energy, new types of renewable energy including solar energy, wind energy, geothermal energy, tidal energy, biomass, etc.Among them, the wind energy as an inexhaustible, inexhaustible energy, clean and no pollution, is the most cheap renewable energy, the most promising "green energy".Wind energy is more and more brought to the attention of the countries all over the world and received extensive development and utilization.

When the grid short-circuit fault occurs, will inevitably affect the normal operation of the wind turbines near.The physical structure of the stator side are connected to the grid directly, also determines its failure in the face of the power grid show some sensitivity and vulnerability.When grid voltage drop occurs, the stator voltage will ensue, in flux larger transient dc component, and along with the electromagnetic coupling effect makes the rotor side show current and over voltage.In addition, because of a malfunction during the voltage of the generator set machine is reduced, can not be normal to grid electricity, plus net side converter ac power voltage change, make dc bus voltage fluctuations;At the same time, because of the converter capacity is limited, in the face of the fault caused by the change, can only limited ability to automatically adjust, unit under fault ability is poor.

In the case of low wind capacity, failure occurs when the power grid, to protect the converter equipment, at the same time avoid the fan blade is damaged, usually directly to the wind generating set to take off the network operation.But with the wind turbines installed capacity increases, the transient characteristics of power grid has inevitably changed.Once the wind turbines because of short circuit fault and a massive network, is bound to aggravate the instability of the power grid.In this case, the requirements of wind power generation system in the power grid failure condition of the continuous automatic ability becomes extremely important.

In view of the continuous expansion of wind power development, in order to reduce or eliminate the adverse impact of the crew to take off the net, the wind power on grid specifications developed countries reached a consensus: require networking operation of wind turbines in a certain range and certain duration shall not to take off the net under the voltage of power grid failure, namely the LVRT ability, when necessary, also need to provide fault power grid voltage and frequency of coordinated control, assist power grid voltage recovery.Grid at present, many developed countries according to their own situation, has low voltage after the wind power grid through the performance has a strict technical standards, and through the actual operation situation of continuous improvement.So the LVRT technology has become one of the large-scale wind power generation technology bottleneck.

The relevant domestic and foreign scholars have done relevant research in this field, in view of the grid fault under the automatic operation mode of the doubly-fed wind power generation system, the current mainstream research direction is mainly divided into two categories: 1) By adding the transient component to optimize converter excitation control; 2) Crowbar device of double PWM converter is adopted to improve the rotor over current protection. In converter control aspects: Wang and Jiang the master-slave control system, the rotor side converter as the main system, the network side converter, as from the system, is decided by the main system power from the power of a given system, to achieve the balance of power [1].

Shi-jie *et. al.* by using the small signal model analysis method, this paper puts forward a optimized feed-forward control strategy, inhibits caused by load and power grid change bus voltage fluctuation, the system dynamic response ability improved [2], but there can't suppress the mutation caused by power grid busbar voltage fluctuation shortcoming; Chi *et.al.* considering the dynamic process of stator magnetizing current of generator transient model and the establishment of the relevant control strategy, realizes the effective control of transient currents, and by improving the rotor voltage compensation term in the equation, finished the dynamic quantity in the model of real-time correction, improve the ability of dynamic response of voltage fluctuation [3].

In literature [4-12] the proposed neural network control, artificial neural network has any approaching any nonlinear model of nonlinear mapping ability, using the study and the convergence can be adaptive controller design, can improve the control precision of the system, enhance the system's ability to adapt to the environment, therefore also has the corresponding application in wind power generation system research.Neural network control can also be combined with fuzzy control, designed a fuzzy neural network controller to control the wind turbine.But complicated control system design, parameters of positive definite is difficult, difficult to large-scale application. In addition to the above said intelligent control method, and the sliding mode variable structure control and H∞ control, a new type of intelligent control method in the wind power system control also has a certain application research, with the development of new technology and people's emphasis on wind power, wind power control technology will get a bigger development.

In the Crowbar protection technical aspects: literature [13-14] from the viewpoint of time domain, the detailed analysis of the rotor side after adding Crowbar protection circuit of DFIG, dynamic characteristics of rotor current, and compared with the results of the simulation analysis.Literature [15-25] DFIG was deduced in parallel operation conditions issued after life end symmetrical short circuit, the expressions of the rotor current under the static coordinate system, and according to the rotor current expression of initial setting is derived by the Crowbar protection circuit of resistance, but more complex expression, between various physical quantities did not give a clear and precise meaning. Literature [26-34] from the angle of flux linkage gives the DFIG is derived on the parallel operation of distributed vitality end after three phase short circuit fault of rotor current expression, and considering the size of the Crowbar resistance and low investment, exit time of DFIG voltage through the influence of dynamic characteristics.

This paper deduced the transient current time-domain expressions of voltage sags;Put forward the method for calculating the maximum fault current and the rotor side Crowbar resistance of a complete set of setting method, solve the Crowbar protection circuit for tilting rotor current and dc bus over-voltage after problems.Simulation and experimental results show that this method can effectively improve the automation level of wind power generation system.

2. A MATHEMATICAL MODEL OF DFIG WIND POWER SYSTEM STEADY STATE

Under the three-phase symmetric winding, the DFIG rotor to convert to the stator side, therefore, reduced after each phase of the number of turns are equal. Each winding of voltage, current and magnetic chain the positive direction of the motor common practice. In the synchronous rotating coordinate system dq0 speed, but the following steady-state mathematical model of DFIG is established. For DFIG voltage equation (1)

$$\begin{cases} u_{ds} = R_s i_{ds} - \omega_s \psi_{qs} + \dfrac{d\psi_{ds}}{dt} \\ u_{ds} = R_s i_{qs} + \omega_s \psi_{ds} + \dfrac{d\psi_{ds}}{dt} \\ u_{dr} = R_r i_{dr} - (\omega_s - \omega_r)\psi_{qr} + \dfrac{d\psi_{ds}}{dt} \\ u_{qr} = R_r i_{qr} + (\omega_s - \omega_r)\psi_{dr} + \dfrac{d\psi_{qr}}{dt} \end{cases}. \tag{1}$$

ψ as the flux, L_s and L_r as the self inductance of the stator and rotor respectively; ω_s the angular frequency of the stator, ω_r the rotor angular frequency;

For DFIG flux equation (2)

$$\begin{cases} \psi_{ds} = L_{1s} i_{ds} + L_m(i_{ds} + i_{dr}) \\ \psi_{qs} = L_{1s} i_{qs} + L_m(i_{qs} + i_{qr}) \\ \psi_{dr} = L_{1r} i_{dr} + L_m(i_{ds} + i_{dr}) \\ \psi_{qr} = L_{1r} i_{qr} + L_m(i_{qs} + i_{qr}) \end{cases}. \tag{2}$$

L_m for the mutual inductance between stator and rotor. Subscript s, r, q, d, respectively of the motor stator and rotor axis, d, q axis component. All the above quantities have been reduced to the stator rotor side.

2.1. DFIG under the Voltage Drop of Transient Analysis

In the study of the impact of the power grid voltage drop of DFIG system, need to derive the DFIG system of the stator voltage and rotor current under the condition of voltage drop of transient mathematical expressions. Due to the power grid voltage drop DFIG rotor circuit usually be Crowbar circuit short circuit, so using the superposition principle of the circuit is analyzed, by the case DFIG transient current expression. Symmetrical stator three phase line voltage drop can be considered in the process of applying a set of stator end with the original bus voltages in the opposite direction and amplitude of voltage drop amplitude of the process. Set the short circuit current space vector for (3)

$$i_s = i_{s0} + i_{s1}. \tag{3}$$

In the type, $i_{s0}$for the stator voltage drop before steady state of the stator current space vector; i_{s1} reverse three phase is applied at the end of the stator voltage generated by the stator current.

In the rotor synchronous rotating MT coordinate system, the stator current vector is before the voltage drop (4)

$$i_{s0}{}' = \frac{u_s{}'}{R_s + j\omega_1 L_s} = \frac{-jU_m e^{j(\omega_s t + \varphi)}}{R_s + jX_s}. \tag{4}$$

for this type, R_s as the stator resistance, $\omega_1$for the stator synchronous rotation angular velocity; ω_s for the slip frequency angular velocity. In the rotor coordinate system, set the stator and rotor initial value is 0, using Laplace transform, available for stator voltage equation s domain expression (5)

$$AU_{s1}' = [R_s + (s + j\omega_1)L_s(s)]I_{s1}'. \qquad (5)$$

In the type, A is the voltage drop degree (0 < A < 1), Characterization of the size of the voltage drop, $L_s(s)$ for the operation of the stator side inductance in the rotor coordinate system, among them;

$$L_s(s) = L_s(1+sT_r') \;/\; (1+sT_r);$$

The available for the stator current where is (6):

$$I_{s1}' = \frac{jAU_m e^{j\varphi}}{(s - j\omega_s)(\alpha + s + j\omega_1)\; L_s(s)}. \qquad (6)$$

In the type, α as the attenuation coefficient of the stator dc component parts, and $\alpha \approx R_s / L_s'$ .Will type (6) into partial fraction form and take the Laplace inverse transform, we can get i_{s1}', and to consider $\omega_r >> \alpha$, $-\frac{1}{T_r'} + \alpha << \omega_r$, $(s - j\omega_s)(\alpha + s + j\omega_1) \approx s(\alpha + s + j\omega_r)$ available, the i_{s1}' where is (7):

$$i_{s1}' \approx \frac{AU_m e^{j(\omega_s t+\varphi)}}{X_s}[1 - e^{-(\alpha + j\omega_1 + j\omega_s)t}] + AU_m e^{j\varphi}(\frac{1}{X_s'} - \frac{1}{X_s})[e^{-\frac{t}{T_r'}} - e^{-(\alpha + j\omega_r)t}]. \qquad (7)$$

In the DFIG no-load or with slight load, can be assumed that $\omega_r \approx \omega_1$ is available, we can get i_s' . Available in stator coordinate system and the rotation of the stator current space vector for time domain expression (8)

$$i_s = i_s' e^{j\omega_r t} = (A-1)\frac{U_m e^{j(\omega_1 t+\varphi)}}{X_s} - \frac{AU_m e^{j\varphi}}{X_s'} e^{-t\alpha} + AU_m e^{j\varphi}(\frac{1}{X_s'} - \frac{1}{X_s})e^{-\frac{t}{T_r'}} e^{jt\omega_r}. \quad (8)$$

By type (8) you can see, the result of the stator current is composed of three parts: the first part $(A-1)\mathrm{U_m}\cos(\omega_1 \mathrm{t}+\varphi)/\mathrm{X}_s$ is the steady-state component of stator current, its size is determined by the amplitude of voltage drops A. The second part $AU_m e^{-\alpha t}\cos\varphi / X_s'$ is the transient current of dc component, its amplitude depends on the short circuit of the phase angle φ, This component for the continuous attenuation trend time constant T_a of the stator, among them $T_a = 1/\alpha$; $AU_m(1/\mathrm{X}_s' - 1/\mathrm{X}_s)\mathrm{e}^{-\frac{t}{T_r'}}\cos(\omega_r \mathrm{t}+\varphi)$ is the AC component, accounts for most of the transient current, with the transient time T_{r}' constant attenuation change.

3. CROWBAR CIRCUIT RESISTANCE SELECTION AND EXAMPLE ANALYSIS

By the rotor side mounted to the Crowbar protection circuit in the power grid voltage drop failure can increase the generator rotor resistance, can effectively restrain the ac component part of transient fault current, make the DFIG system can not took off network under low voltage failure. But due to the increase of Crowbar circuit protection resistance may cause the inverter DC bus voltage on the pump, so you need to properly choose the resistance value. Therefore, it is necessary to calculate the voltage drop, the rotor side of time-domain current expression.

3.1. Value Choice

According to the stator voltage, current equation(9) and considering type (10) to the rotor side of the fault current time-domain expression is given as (9):

$$i_r^{'} = \frac{1}{j(L_s L_r - L_{\mathrm{m}})}[\frac{L_s}{s}\sqrt{u_{dr}{}^2 + u_{qr}{}^2}e^{j\delta t} + L_m U_s]e^{-t/T_r^{'}} + \frac{U_s}{j\omega_s}[-\frac{L_m e^{-j(1-s)\omega_s t}e^{-t/T_s^{'}}}{(L_2 + L_m)L_s^{'}} + \frac{e^{-t/T_r^{'}}}{L_r^{'}}]. \quad (9)$$

By the type of (9), Crowbar protection circuit in the selection of resistance value r_{crow} is very important, the greater the r_{crow}, rotor under low voltage fault current is small; nature, power and torque oscillation amplitude is small, but too much r_{crow} can lead to network side and generate overvoltage on rotor winding of the converter, eventually led to the dc bus voltage on the margin of the oscillation of the pump and motor.

The available method for calculating the maximum fault current and the rotor side Crowbar resistance setting method is as follows:

a. After the input Crowbar protection circuit, the rotor side of the fault current maximum value I_m should be less than the rotor current, usually I_m take about 2 p.u., and so are (10):

$$\frac{U_s}{\sqrt{(\omega_1 L_s^{'})^2 + r^2_{crow}}} < I_{\mathrm{m}}. \quad (10)$$

By the type (10), the Crowbar resistance within the reasonable value range, the greater the resistance, the inhibition effect of tilting to the rotor current is more obvious.

b. In order to avoid after input Crowbar protection circuit, overvoltage appears on the dc bus, should satisfy (11):

$$\frac{\sqrt{3}R_{crow}U_s}{\sqrt{(\omega_1 L_s^{'})^2 + r^2_{crow}}} < U_{dc}. \quad (11)$$

By type (10) and (11) can be the minimum and maximum for (12):

$$\begin{cases} r_{crow\_\min} = \sqrt{(\frac{U_S}{I_m})^2 - (\omega_1 L_s^{'})^2} \\ \mathrm{r}_{crow\_\max} = \frac{U_{dc}\omega_1 L_s^{'}}{\sqrt{3U_s{}^2 - U_{dc}{}^2}} \end{cases}. \quad (12)$$

Type (12) showed that the guarantee network side without appear over voltage of the converter, if within scope of the Crowbar resistance setting and proper slants big, and its exit before fault removal, DFIG LVRT effect will be better.

3.2. The Example Analysis

For 2 MW DFIG, in order to determine the appropriate value of Crowbar resistance, in the type (12) in different r_{crow}, can have different maximum short-circuit current $I_{r\ max}$ and voltage $U_{r\ max}$ corresponding to the rotor. The specific calculation results are shown in table 1.

Table 1. The Calculation Results of $I_{r\ max}$, $U_{r\ max}$ under different Crowbar values

r_{crow}	$I_{r\max}$	$U_{r\max}$
0.01	8.86	0.081
0.03	7.92	0.161
0.05	6.89	0.345
0.07	6.15	0.490
0.09	5.98	0.535
0.10	5.77	0.577

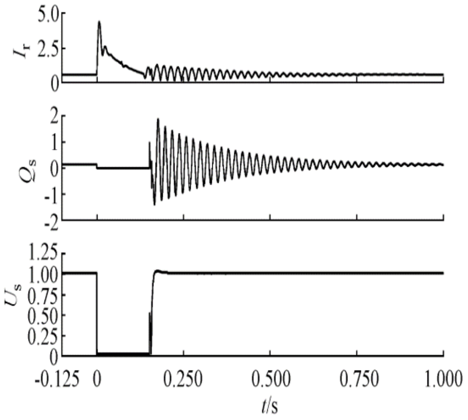
It can be seen from Table 1: with the increase of Crowbar resistance, maximum rotor current decreases, but the maximum voltage increased rotor side. Usually, in within a reasonable scope, Crowbar resistance, the greater the tilting to the rotor current suppression effect is more obvious. In addition, it can be seen that when $r_{crow}=0.10$, $U_{rmax}<U_{rlim}$, no longer established, therefore the Crowbar resistance should not be more than 0.09.

4. THE SIMULATION AND EXPERIMENTAL ANALYSIS

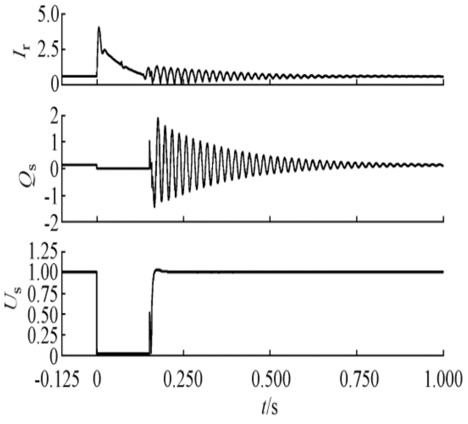
To test and verify the low voltage of doubly-fed wind power generator through the function, and the reasonable value of Crowbar resistance. The MATLAB/Simulink simulation and the low power test system is built in the laboratory.

4.1. The Simulation Analysis

This paper select as 0.06, 0.06, after the Crowbar into the rotor side of the current, the stator reactive power and voltage of the machine are simulated, the simulation results are shown in figure 1.Can be seen from the diagram, Failure after=0.06, the biggest rotor side current is 4.82, when=0.088, the rotor side current is about 3.80, and the failure after removal of the rotor current can be faster to stabilize. The wind generator at low voltage failure after resection, from the grid to absorb the maximum instantaneous reactive power were 1.4 and 1.44 respectively. Comprehensive numerical example and simulation analysis, it is suggested that in the practical engineering, the Crowbar resistance can effectively restrict the rotor over current, on the basis of its Crowbar big resistance should be appropriate.



(a) r_c=0.06



(b) r_c=0.088

Figure 1. Under the different r_c values of DFIG, accordingly I_r, Q_s, U_s

4.2. Experimental Verification

To test and verify the rationality of the simulation results, set the power rating of 10 kw low power test system, the Crowbar resistance under the different values of the experiment, the main circuit of DFIG parameters are shown in Table 2.

Table 2. 10KW DFIG Parameters

parameter	values	Convert value
The stator line voltage U/V	380	/
Stator resistance$R$/Ω	0.105	0.0073
Rotor resistance$R$/Ω	0.105	0.0073
Stator leakage inductance L/H	0.0032	0.0680
Rotor leakage inductance L/H	0.0034	0.7320
Mutual Inductance L/H	0.105	2.2500

This experiment take r_{crow}=0.085, 0.086, 0.087, 0.088, 0.089, 0.090 six conditions, the corresponding DFIG rotor current, stator reactive power and voltage of the machine of the experimental results are shown in table 3.

Table 3. Under Different Crowbar Values, the Experimental Results of $I_{r\max}, U_{r\max}$

r_{crow}	$I_{r\max}$	$U_{r\max}$
0.085	6.13	0.492
0.086	6.11	0.500
0.087	6.09	0.530
0.088	6.08	0.535
0.089	6.06	0.538
0.090	6.04	0.540

Contrast table 1 and table 3 can be seen, the change trend of each parameter under different Crowbar resistance, the simulation results with the experimental results are basically identical. Thus verified the reasonable value range, the greater the resistance Crowbar, the inhibition effect of tilting to the rotor current is, the more obvious conclusion.

5. CONCLUSION

1) From the perspective of space vector using the Laplace transform of DFIG wind power system is analyzed under the machine terminal voltage drop of transient characteristics;

2) By the rotor side mounted to the Crowbar protection circuit in power grid voltage drop increase the generator rotor resistance,can effectively restrain the transient fault current;

3) Within the scope of the reasonable value, the greater of the Crowbar resistance,the inhibition effect of tilting to the rotor current is more obvious.

The efficiency and practicability of DFIG determines its inevitable popular attention, from the perspective of the model of wind power equipment manufacturers in the world in recent years, wind power equipment has dominated in the market.As wind turbines within the grid capacity continue to improve, in view of the wind power generation system in LVRT the technical research, especially in the power grid failure under continuous automatic technology study, have important theory meaning and practical value.

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