Three-phase short circuit calculation method based on pre-computed surface for doubly fed induction generator

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Abstract. This paper presents an improved short circuit calculation method, based on pre-computed surface to determine the short circuit current of a distribution system with multiple doubly fed induction generators (DFIGs). The short circuit current, injected into power grid by DFIG, is determined by low voltage ride through (LVRT) control and protection under grid fault. However, the existing methods are difficult to calculate the short circuit current of DFIG in engineering practice due to its complexity. A short circuit calculation method, based on pre-computed surface, was proposed by developing the surface of short circuit current changing with the calculating impedance and the open circuit voltage. And the short circuit currents were derived by taking into account the rotor excitation and crowbar activation time. Finally, the pre-computed surfaces of short circuit current at different time were established, and the procedure of DFIG short circuit calculation considering its LVRT was designed. The correctness of proposed method was verified by simulation.

1. Introduction

When the initiative distribution network occurs short circuit fault, a large number of circuit current of distributed generation injecting increase current of the fault point, and that will result in distribution equipment facing higher requirements of dynamic and thermal stability [1]. Doubly fed induction generator (DFIG), with its flexible control performance and small capacity of the converter, is widely used in wind power generation system. Compared with Fixed-speed induction generator with no external excitation, DFIG uses the converter to adjust the rotor excitation for achieving power control [2]. This makes the injected short circuit current and power control closely, especially for meeting the low voltage ride through requirements, more complex control and protection schemes should be introduced, so the effect on the characteristics of the short circuit current will be more significant [3,4]. Therefore, the dynamic characteristics and short-circuit current calculation method of DFIG considering its LVRT process needs for further research.

When the grid short circuit makes DFIG terminal voltage dropping, the generator stator flux appears transient DC component, and that will generate short circuit inrush current in stator, then through the interaction between the magnetic field of the stator and rotor, the over current and over voltage phenomenon will appear in rotor winding of DFIG. When the grid occurs remote fault, the rotor-side converter will regulate the output of DFIG, the transient response of DFIG unit is analyzed with the rotor excitation in [3], but does not consider that DFIG needs to run at reduced power compensation mode, and at the same time must to provide reactive power support during LVRT [2]. When the grid occurs proximal fault, the substantially dropping voltage will cause rotor current over limiting value, so the crowbar protection of DFIG will be activated. The calculation formula of short circuit current of
DFIG is derived after crowbar activation, but without taking into account the delayed impact of crowbar activation on the short circuit current in [4].

The interactive iterative of short circuit calculation models and network equations of distributed generation is used to get short-circuit calculation result accurately, but the multi coupling variables and large amount of iterative calculation cannot meet the requirements of engineering calculations [5]. Existing the computing curve method of domestic and the calculation coefficient method of foreign are mainly for synchronous generators and induction motors in engineering practical algorithm, yet the practical processing method of short circuit calculation of DFIG is not given [6].

With the change of grid fault condition, different characteristics of the LVRT control and protection of DFIG not only will be exhibited, but also the injected short circuit current will be changed. This paper works for practical calculation, calculation formulas of short circuit current of DFIG are derived with before and after crowbar activation, the develop method of complete computing surface of period component of short circuit current, calculating impedance and open-circuit voltage of DFIG is proposed, then the calculation surface method of DFIG three phase short circuit taking LVRT control and protection into account is put forward, and the way of the development computing surface and calculation step is given.

2. The calculation surface method of short circuit current of DFIG

Conventional generators, points of DFIG and failure are kept in complex power systems, through the network simplification, and dual power networks can be got with a short circuit point as the center in figure 1(a). $Z_k, Z_s$ and $Z_f$ are the equivalent impedances of DFIG side, system side and the point of failure, and $E_s$ is the emf of conventional generator. The star network is further simplified to the triangular networks, and a radial networks is shown in figure 1(b), in which $Z_{sk}, Z_{sf}$ and $Z_{kf}$ are the transfer impedances of different nodes of the triangle network.

![Figure 1](image_url)

**Figure 1.** Equivalent circuits of short circuit calculation. (a) Star network. (b) Triangle network. (c) Thevenin equivalent circuit.

DFIG is not only connected to the point of failure via the transfer impedance $Z_{kf}$, but also connected with conventional power via the transfer impedance $Z_{sk}$ in figure 1(b), and after fault conventional power will play a voltage supporting role in DFIG, but the injected short circuit current will be altered by the change of DFIG terminal voltage. Thevenin equivalent network of DFIG system except accessed node $k$ is shown in figure 1(c), where $Z_{sk}$ and $U_{oc}$ are the calculating impedance and open circuit voltage. Before grid fault $Z_{jk} = Z_k + Z_i$ and $U_{oc} = E_s$, when the node $f$ occurs fault $Z_{sf}$ and $U_{oc}$ in figure 1 can be given as

\[
\begin{align*}
Z_{jk} &= Z_k + Z_i + Z_f + Z_{kf} \\
U_{oc} &= E_s + Z_f E_s
\end{align*}
\]

In actual grid the coupling between the conventional power and DFIG is often stronger when $Z_{sk}$ is smaller, and the open circuit voltage value of Thevenin equivalent is not zero after fault, moreover, it is gradually approaches to $E_s$ when $Z_{sk}$ is decreased. Therefore, when the short-circuit current of DFIG is did in engineering calculation, the relationship of short circuit current and $Z_{sk}$, $Z_{sf}$ and $E_s$ in figure 1(b)
is obtained in advance by extending the computing curve method of short circuit current. In order to reduce associated variables of DFIG short circuit current, the computing surface of short circuit current periodic component and calculating impedance $Z_{js}$, open circuit voltage of DFIG is developed by using Thevenin equivalent circuit of figure 1(c), so the computing surface method of short circuit current of DFIG connected into grid is formed.

3. Formulate computing surfaces of short circuit current of DFIG

Crowbar switching of DFIG rotor is determined by grid fault condition, when the crowbar deactivation the short circuit current is mainly affected by rotor excitation regulatory role, but after the crowbar activation the fluxes coupling of stator and rotor of DFIG short circuit transient process will be affected with the rotor resistance increasing. In computing surface making of the short circuit current, the crowbar activation condition is determined according to the calculating impedance $Z_{oc}$ and the open circuit voltage $U_{oc}$ of DFIG accessed point after grid fault, then the computing surface of DFIG three-phase short circuit current is targeted to develop.

3.1. The computing curved surface of DFIG short circuit current during crowbar deactivation

The stator short circuit current of DFIG is decided by the change of the stator flux and the rotor excitation control with crowbar deactivation. According to the relationship of the current and the flux of the stator and rotor and the calculated formulas of the stator flux and the rotor current after fault, the three-phase short circuit current space vector $i_s(t)$ of DFIG can be given as

$$i_s(t) = \frac{1}{L_s} \psi_s(t) - \frac{L_m}{L_s} i_m(t) = \frac{U_{s}'}{j\omega L_s} e^{j\omega t} + \frac{U_{r}'}{j\omega L_s} e^{j\omega t} - \frac{L_m}{L_s} [i_{st}(t) + i_m(t) + i_n(t)]$$

$$= \left[ \frac{U_{s}'}{j\omega L_s} - \frac{L_m}{L_s} \right] e^{j\omega t} + \left[ \frac{U_{r}'}{j\omega L_s} - \frac{L_m}{L_s} \right] e^{j\omega t} - \frac{L_m}{L_s} i_{st}(t)$$

$$i_s = \frac{-2P_s}{3L_m U_{oc}(1-s)} + \left[ \frac{2Q_s L_m}{3L_m U_{oc}'} + \frac{U_{r}'}{\omega L_m} \right] i_{st} = \frac{L_m}{L_s} \left[ (s-1)T - \frac{1}{(s\omega)} \right] \left[ U_{s}' - U_{r}' \right]$$

The complex analysis is not considered in practical engineering calculations, and the short circuit computing surfaces are formulated by using the following assumptions: 1) On normal operation DFIG is three-phase symmetrical, and the open voltage of Thevenin equivalent circuit of the unit accessed node before fault is $U_{oc} = E_s = 1.0\text{pu}$; 2) the flux circuit saturation of system components and the impedance resistances in network are ignored; 3) the pre-fault unit output is $P_0 + jQ_0 = 1.0 + j0\text{pu}$, and the load is processed as without load case.

The calculating impedance $Z_{js} = jX_{js} = j\omega L_{js}$ of the equivalent circuit in figure 1(c) is appended to the stator leakage inductance of DFIG, namely $L_{js} = L_{ls} + L_{js}$, while $U_{s}'$ and $U_{r}'$ in formula (2) are respectively replaced by the pre-fault and post-fault open-circuit voltages, so the short-circuit current of DFIG can be calculated with crowbar deactivation. The DFIG active power $P''$ injected into the equivalent voltage source in figure 1(c) is equal to the machine terminal output power $P'$, but the reactive power $Q''$ shall be subtracting the reactive power loss of the calculated inductance $L_{js}$, and studies consider that the reactive power is only absorbed by the equivalent voltage source after fault. By the formula (2) and figure 1(c) the formula of computing curved surface of DFIG short circuit current periodic component can be obtained as

$$I_s = \frac{2P_s}{3U_{oc}(1-s)} + \frac{2Q_s}{3U_{oc}'} - \frac{2P_s}{4(\omega L_m)} + \frac{Q_s U_{oc}^2}{\omega L_m} - \frac{P_s}{3U_{oc}}$$

The formula (2) shows that the transient component changed with time in the DFIG short circuit current is mainly from the DC component with crowbar deactivation, and the periodic component is directly transiting to the steady state value after fault.
3.2. The computing curved surface of DFIG short circuit current during crowbar activation

After the grid fault DFIG stator flux $\Psi_s(t)$ not only has the forced component with synchronous frequency $\Psi'_s(t)$ as well as the DC transient component $\Psi_{sdc}(t)$. The equivalent circuit of the stator synchronous frequency component is shown as figure 2(a) in the stator reference frame, due to the difference of frequency between the stator and rotor, so the equivalent circuit of the rotor shall be imputed to the stator side according to the frequency. The DC component of the stator is not easy to be analyzed in the stator reference frame, therefore it shall be imputed to the rotor side according to the frequency, and the equivalent circuit of the stator is shown as figure 2(b).

![Figure 2. Steady-state equivalent circuits of DFIG. (a) Equivalent circuit in the stator reference frame. (b) Equivalent circuit in the rotor reference frame.](image)

According to the relationship of the stator current and rotor current in figure 2, and combining $\Psi_s(t)=L_s\dot{i}_s(t)+L_m\dot{i}_r(t)$ and $\Psi_r(t)=L_m\dot{i}_r(t)+L_r\dot{i}_r(t)$ the forced component $\Psi'_s(t)$ and the transient component $\Psi_{sdc}(t)$ of the rotor flux can be obtained as

$$\Psi'_s(t) = \frac{L_m}{L_s} R_s i_s - \frac{\eta'}{L_r} \Psi_{sdc}(t) = \eta' \Psi'_s(t),$$

$$\Psi_{sdc}(t) = \frac{L_m}{L_r} R_s i_s - \frac{\eta}{L_r} \Psi_{sdc}(t)$$

(5)

When the rotor current exceeds the threshold value $I_{r\lim}$, the crowbar resistance will be put into though some time delay (the required time of from fault detection to activation is usually within 10ms [4]). The exciting current regulation of the rotor converter before the crowbar activation will affect the initial conditions of the rotor flux after the crowbar activation. It is assumed that the crowbar activation after $T_c$ delay makes the rotor current reach the limit $i_r(T_c)=I_{r\lim}$, according to the relationship of the rotor flux, the stator flux and the rotor current, the initial phasor $\Psi_{s0}$ of the rotor flux can be obtained as

$$\Psi_{s0} = \frac{L_m}{L_r} \Psi_s(T_c) + \sigma L_r i_r(T_c) = \frac{L_m}{L_r} \frac{U_r}{\omega L_s} e^{j\omega T_c} + \frac{L_m}{j\omega L_s} \frac{U_s - U_r}{\sigma L_r} e^{-j\omega T_c} + \sigma L_r I_{r\lim}$$

(6)

The crowbar delay times $T_c$ of different units are different, and the periodic component of DFIG short circuit current is gradually increased with $T_c$ increase. When $T_c<5$ms, the rotor flux phasor at the moment of crowbar activation can be considered to equal with at the moment of the grid fault $\Psi_{s0} = \eta' \Psi'_s$; and when $T_c\geq5$ms, the initial rotor flux at the moment of crowbar activation shall be calculated by the formula (6). The stator and rotor fluxes are imputed from the stator side to the rotor side though the same reference frame transformation, and the proportionality coefficient $\eta$ between the pre-imputed and the post-imputed is approximately equal in figure 2(b). According the flux conservation at the moment of crowbar activation, in the stator reference frame the post-fault rotor flux $\Psi(t)$ can be given as

$$\Psi(t) = \eta' \Psi'_s(t) + \eta \Psi_{sdc}(t) + \left[\eta'_s - \eta \Psi_{sdc}(t) - \eta \Psi_{sdc}(T_c)\right] e^{-(T_c-T_c)j\omega} + \left[\frac{L_m}{L_s} \frac{U_r}{\omega L_s} e^{j\omega T_c} + \frac{L_m}{L_r} \frac{U_s - U_r}{\sigma L_r} e^{-j\omega T_c} + \frac{L_m}{j\omega L_s} \frac{U_r}{\sigma L_r} e^{-j\omega T_c} + \sigma L_r I_{r\lim}\right] e^{-(T_c-T_c)j\omega}$$

(7)

$$\Psi(t) = \eta' \Psi'_s(t) + \eta \Psi_{sdc}(t) + \left[\eta'_s - \eta \Psi_{sdc}(t) - \eta \Psi_{sdc}(T_c)\right] e^{-(T_c-T_c)j\omega} + \left[\frac{L_m}{L_s} \frac{U_r}{\omega L_s} e^{j\omega T_c} + \frac{L_m}{L_r} \frac{U_s - U_r}{\sigma L_r} e^{-j\omega T_c} + \frac{L_m}{j\omega L_s} \frac{U_r}{\sigma L_r} e^{-j\omega T_c} + \sigma L_r I_{r\lim}\right] e^{-(T_c-T_c)j\omega}$$

Where: $T_c = (L_r^2+L_m^2)/\sigma R_c$ is the decay time constant of the rotor flux DC component. Though relations of the stator and rotor flux and the current can obtain $\dot{i}_d(t)=[L_s \Psi(t)-L_m \Psi(t)]/(\sigma L_r L_r)$, then the formulas of $\Psi(t)$ and $\Psi(t)$ are substituted into it to obtain the vector expression $\dot{i}_d(t)$ of DFIG three-phase short circuit current after the crowbar activation such as in (5).
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\[ I_s(t) = \frac{1}{\sigma} \left[ \left( L_s - L_{oc} \right) e^{j\omega t} - L_{oc} \left( L_s - L_{oc} \right) e^{j\omega t} + \left( L_s - L_{oc} \right) e^{j\omega t} \right] \]

At this time, DFIG short-circuit current periodic component contains two parts: a) steady-state periodic component with synchronous frequency, b) transient periodic component with rotor speed frequency. By the pre-fault open-circuit voltage \( U_{oc} = 1.0 \text{pu} \) and the formula (8) the two parts of the periodic component \( I_{sa} \) and \( I_{sa}' \) can be obtained as

\[ I_{sa} = \frac{U_{sa}}{\sigma} - \frac{L_{sa}^2 R_{sa}}{\sigma \omega L_s (\sigma \omega L_s - j R_s)} \]

\[ I_{sa}' = \frac{1}{\sigma} \left[ \frac{s L_{sa}^2 U_{sa} e^{j\omega t}}{L_s} + \frac{L_{sa}^2 (1-s)(1-U_{sa}) e^{-j\omega t}}{L_s} \right] e^{-j\omega t} \]

The post-fault rotor speed range of DFIG can’t exceed the allowable range, otherwise the over-speed protection activation will make the unit out of operation, so the RMS of DFIG short-circuit current period component can be obtained as \( I_s = (I_{sa} + I_{sa}')^{1/2} \) combining the periodic component \( I_{sa} \) with \( I_{sa}' \) after the crowbar activation.

4. Short circuit calculation steps of DFIG short circuit current account LVRT

Assuming that there are \( m_1 \) conventional generator, \( m_2 \) sets DFIG, the grid node \( f \) fault, and the procedure of computing surface of calculated DFIG short circuit current is summarized as follows.

**Step 1:** Form the original node impedance matrixes, add \( z_i \) of \( m_1 \) sets conventional generator to access point, obtain \( n \times n \) node impedance matrix \( Z \) of the fault component network, and from node 1 to \( m_1 \) are conventional power points, then from \( m_1+1 \) to \( m_1+m_2 \) are accessed points of DFIGs.

**Step 2:** Calculate the transfer impedance \( z_{ij} \) of \( m_1 \) sets conventional power points to the short circuit node \( f \) according formula (2), set \( k=1 \), go to **Step 3**.

**Step 3:** Calculate the transfer impedance \( z_{ik} \) of \( m_1 \) sets conventional power points to \( k-th \) set accessed point of DFIG and the transfer impedance \( z_{ij} \) of \( k-th \) set DFIG to short circuit node.

**Step 4:** Merge \( m_1 \) sets conventional power points, obtain the three-terminal network transfer impedance \( Z_{ik}, Z_{it} \) and \( Z_{ti} \) of \( k-th \) set DFIG, solve (1) to obtain the calculating impedance \( Z_{Is} \) and the open circuit voltage \( U_{oc} \) of \( k-th \) set DFIG accessed point.

**Step 5:** Check the computing surface of \( k-th \) set DFIG by the fault time \( t \), \( Z_{it} \) and \( U_{oc} \) to obtain the circuit current periodic component per-unit value of \( k-th \) set DFIG injecting fault node, and calculate the short circuit current actual value by the criterion parameter.

**Step 6:** If \( k \leq m_2 \), set \( k=k+1 \) and go to **Step 3**, otherwise, stop iteration and output the short circuit calculation result of \( k-th \) set DFIG.

5. Simulation studies

The short circuit current periodic components for different fault locations at different times are calculated with this proposed algorithm and compared with the simulation results of the electromagnetic transient model of MATLAB / Simulink in the multi-machine grid example (figure 3). Where the first and the second units rated capacities are 1.5MW, and the remaining two units both are 2MW, the rated voltage is 0.69kV and DFIGs are connected to the grid by the step-up transformer.

Assuming normal operation, each DFIG output is \( P_{g0} = 1.0+0+j0 \text{pu} \), the rotor speed is \( \omega_0 = 1.211 \text{pu} \), the crowbar resistance is 20Rr, the activation delay is \( T_c = 5 \text{ms} \), the rotor current control parameters are \( k_p = 0.6, k_i = 8 \) and \( I_{lim} = 2 \text{pu} \), and the simulation and calculation results of DFIG short circuit current period component when a three phase fault occurs at node 6 are shown in figure 4. The crowbar resistances of DFIG1 and DFIG4 of the electrical distance which is far from the fault node do not activate after fault, so the short circuit current is gradually increased to a new steady-state value. While the remaining two units are close to the fault node, the crowbar will activate by delay and the short circuit currents decay rapidly after rising to the peak value, then the short circuit currents of DFIG2 and DFIG3 respectively transit to the steady-state values after three cycle and one cycles, and in figure the calculated results of
the short circuit currents by this proposed method are basically consistent with the dynamic simulation results.

The interactive process of the DFIG short circuit current with the network is simplified by this method, ignoring the influence of the rotor speed variation, and greater change of the unit terminal voltage and the rotor speed after the crowbar activation makes the calculation errors of DFIG2 and DFIG3 relatively large.

6. Conclusion
This paper proposes a method to calculate the computing surface of DFIG short circuit current, taking into account the control and protection of LVRT, and using the numerical example of multi-DFIG system to verify that the period component of each unit short circuit current can be calculated effectively by this proposed method, when the three-phase short circuit fault occurs at different nodes. The studies show that the periodic component of short circuit current is determined by the open circuit voltage and the calculating impedance between the access point of DFIG and the fault point. The proposed method only need to obtain the calculating reactance and the open circuit voltage when DFIG is not connected to the grid, and the method is simple in principle, a small amount of calculation and applied to the engineering calculation of short circuit current, for the asymmetric short circuit current also can be calculated further using the equivalent theory of positive sequence.

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