Equivalent calculation of aperiodic component of thermal effect of DFIG with short circuit fault

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Abstract. The temperature rise caused by three-phase short current at stator side of doubly fed induction generator (DFIG) may damage DFIG and its adjacent electrical equipment. By using the step-by-step integration, the thermal effect may be quantified, but the contribution of periodic component and aperiodic component of thermal effect cannot be distinguished, and the amount of calculation is large. In this paper, the steady-state component of rotor flux is considered to reduce the error of analytical expression of short current. The components of short current are decomposed and the square of the short current is integrated. The calculation method of equivalent duration of aperiodic component of thermal effect is proposed, and the effect of equivalent duration on different crowbar resistance and stator voltage drop ratio is quantified. The simulation results are provided to validate the accuracy of the proposed models.

1. Introduction

As a sustainable and pollution-free green energy, the wind power wins increasing installed capacity [1-2]. Most of the areas with abundant wind energy are located at sea or desert, so the short circuit fault is common. If the short current is large, the wind turbine equipment will be damaged in light, and the power grid will be endangered in severe cases [3-4].

The doubly-fed induction generator (DFIG) is widely used for wind energy conversion [5-6]. With three-phase short-circuit outside of the stator, the short current is the largest with the most serious impact on DFIG winding and its adjacent equipment. At present, there are many studies on the short current and low-voltage ride of the DFIG. The short current calculation method of DFIG is proposed in [7-8] under the premise of considering low-voltage ride through. The transient characteristics of DFIG with crowbar in and without crowbar are considered in [7], and the relationship between the periodic component of the short current and the calculated reactance and open circuit voltage is used. In [8], the mathematical model of doubly fed generator with crowbar input and reactive power control of rotor side converter is established, and the expression of stator short current in two stages is derived. In [9-10], the calculation model of short current affected by excitation regulation characteristics is established on the basis of considering the grid scale fault. Ref. [11] considers the equivalent circuit of power frequency and rotor frequency sequence network of DFIG with the crowbar, and the differential equation of DFIG flux is derived. In [12], the dynamic influence of rotor current is considered, and the rotor flux is calculated. A calculation method of short current is proposed in [11-12].

Compared with synchronous generators, the structure and control characteristics of DFIG are quite different [13], and the analytical expression of thermal effect is rarely published. Ref. [14] establishes a
new model of the DFIG with crowbar protection and derives the analytical expression of the short current, but ignores the rotor magnetism the influence of the steady state component on the short current. The dynamic equation of rotor current affected by rotor converter control in transient process of motor was derived [15], and the analytical expression of fault current was obtained. However, its form is relatively complex and it is difficult to derive the analytical expression of thermal effect. In [16], the analytical expression of DFIG short current was derived considering the influence of steady-state component of rotor flux, and the analytical expression of thermal effect of DFIG short current was further derived by square integration.

For engineering purpose, the product of the square of the periodic short current and time is usually used to estimate the thermal effect, but this method is relatively rough and optimistic, since it ignores the thermal effect of aperiodic current. Following [16], this paper newly quantifies the equivalent duration of the aperiodic component of the thermal effect. The sensitivity of equivalent duration to the crowbar resistance and the stator voltage is newly quantified. The simulation results are provided to validate the accuracy of the proposed model.

2. Analytical Expression of Periodic/Aperiodic Components of Short current of DFIG

2.1. Assumptions to derive analytical expression of short current

The DFIG is shown in Fig. 1(a) [17]. When the rotor current is too large, the crowbar acts to introduce the current to the earth [18]. At this time, the equivalent circuit is shown in Fig. 1(b), where \( u, I, R \) and \( L \) are voltage, current, resistance and inductance respectively. \( R_{cb} \) is the crowbar resistance, \( L_s = L_{s\sigma} + L_m, L_r = L_{r\sigma} + L_m, L_{s\sigma} \) and \( L_{r\sigma} \) are stator leakage inductance and rotor leakage inductance respectively, and \( L_m \) is excitation inductance. The subscripts \( s \) and \( r \) represent the stator and rotor respectively. Even if the crowbar acts, the current is still large after the fault, so it is necessary to quantify the thermal effect.

![DFIG with crowbar](image)

According to the practice of motor, the stator and rotor voltage and flux are shown in (1) and (2), where \( \psi \) is the flux, \( \omega \) is the synchronous angular velocity, \( s \) is the slip, and \( p \) is the differential operator.

\[
\begin{align*}
    u_s &= R_s i_s + p \psi_s + j\omega \psi_s \\
    u_r &= R_r i_r + p \psi_r + j s \omega \psi_r = 0 \\
    \psi_s &= L_s i_s + L_m i_r \\
    \psi_r &= L_{r\sigma} i_s + L_r i_r
\end{align*}
\]

(1)

(2)

The relationship between the current and the flux can be derived,

\[
\begin{align*}
    i_s &= \psi_s / L'_s - k_s \psi_r / L'_r, \\
    i_r &= -k_r \psi_s / L'_r + \psi_r / L'_r
\end{align*}
\]

(3)

where \( k_s = L_m / L_s \) and \( k_r = L_m / L_r \) are the inductance coupling coefficients of stator and rotor respectively; \( L'_s \) and \( L'_r \) are the transient parameters of stator and rotor respectively [16].
In steady state, the stator voltage and flux are in synchronous rotating coordinate system, so the differential term of stator flux is zero. By ignoring the stator resistance, the initial value of the stator flux is derived,

\[ \psi_{st} = -u_{st}/\omega \] (4)

It is assumed that DFIG has three-phase short circuit at t0 and stator voltage drops suddenly. Since the stator and rotor flux of DFIG cannot change suddenly, the initial value of parameters after fault can be determined according to the initial value of parameters before and after fault,

\[ u_{sf} = (1 - G)U_{st}e^{j\omega t} \] (5)

where f represents fault, usf is stator side voltage after short circuit, G=(Us0−Usf)/Us0 is stator voltage drop ratio, Us0 and Usf are stator voltage amplitude before and after fault respectively.

From (4) and (5), the expression of stator flux after fault can be deduced,

\[ \psi_{sf} = -(1 - G)U_{st}e^{j\omega t}/\omega \] (6)

The stator flux has been reduced to a certain extent after the fault. However, the instantaneous current after the fault cannot change suddenly, so the direct-current component appears. The accurate expression of stator flux after fault can be deduced,

\[ \psi_{st} = (1 - G)U_{st}e^{j\omega t}/\omega + GU_{st}e^{j\omega t}/\omega \] (7)

where T_s=L_s/R_s is the stator transient time constant.

When the grid fault occurs and the DFIG stator voltage drops deeply, the crowbar acts. It can be seen from Fig. 2 that the stator and rotor resistances are small and negligible compared with the crowbar resistance. The equivalent impedance of the stator side is given by the Thevenin theorem,

\[ Z_s = R_{cb} + j\omega(L_s - L_m)/L_s = R_{cb} + j\omega L_s' \] (8)

At the moment of failure, the instantaneous value of the rotor flux is,

\[ \psi_{ro} = (u_{ro} - Z_{ro}L_m)/j\omega L_m \] (9)

where is0=Is0e^jα is the stator side current before the fault.

If the stator voltage does not fall to zero, the steady-state component of the rotor flux is not zero, and the steady-state component of the rotor flux is,

\[ \psi_{rs} = NR_s'/(1 - G)U_{st}e^{j(\omega t + 1/T_r')}) \] (10)

where N=Lm/(LsLr−L_m^2), R_s'=Rcb+R_r, T_r'=L_s'/R_s' is the rotor transient time constant.

The steady-state component of the rotor flux is related to the voltage at the stator side after fault. According to the conservation law of flux, the rotor flux after fault is given by,

\[ \psi_{ro} = \psi_{ro}e^{j(\omega t - t_0)} + (\psi_{ro} - \psi_{rs})e^{j(\omega t - t_0)}e^{-(\omega t - t_0)T_r'} \] (11)

The post-fault rotor current in the abc frame is given by (13), where \( \alpha \) is the initial phase angle.

\[ i_a = (1 - G)U_{st}cos(\omega(t-t_0) + \alpha)/(j\omega L_s') + GU_{st}cos(\alpha)e^{-j\omega t/T_r'}/(j\omega L_s') - k_s(\psi_{st} - \psi_{stc})cos(\omega(t-t_0) + \alpha)e^{-j\omega t/T_r'}/L_s' \] (12)

2.2. Periodic and aperiodic components of short current

The short current consists of 4 components. The 2nd and the 4th terms contain the stator transient time constant T_s' and the rotor transient time constant T_r' respectively, and the two gradually decay with the increase of short-circuit time, which are aperiodic components of short current, and the first and third terms are periodic components of short current. Therefore, (12) can be rewritten as follows,

\[ i_a = I_p + I_{ap} \] (13)

where Ip is the sum of periodic components and Iap is the sum of aperiodic components,

\[ I_p = (1 - G)U_{st}cos(\omega(t-t_0) + \alpha)/(j\omega L_s') - k_s(\psi_{st} - \psi_{stc})cos(\omega(t-t_0) + \alpha)e^{-j\omega t/T_r'}/L_s' \]
\[ I_{ap} = GU_{st}cos(\alpha)e^{-j\omega t/T_r'}/(j\omega L_s') - k_s(\psi_{st} - \psi_{stc})cos(\omega(t-t_0) + \alpha)e^{-j\omega t/T_r'}/L_s' \] (14)
3. Analytical Expression of Periodic/Aperiodic Components of Thermal Effect

3.1. Analytical expression of thermal effect of DFIG short circuit

Considering the most serious case, when the initial phase angle is zero and t=0, the three-phase short circuit outside the stator is taken. After the crowbar acts, the time integral of the square short current is expanded into the sum of 10 components, the analytical expression of thermal effect $Q$ of short current is obtained,

$$Q = \int_0^{t_f} i_d^2 dt = \sum_{i=1}^{10} Q_i$$

(15)

where $t_f$ is the short circuit duration and $\tau$ is the number of thermal effect components. The expression of each component is as follows,

$$Q_i = \begin{align*}
Q_1 &= (1-G)U_{ad}^2 t_f / 2 \omega^2 L_s^2 \\
Q_2 &= -G^2 U_{ad}^2 T_s (1-e^{-\frac{2t}{T_p}}) / 2 \omega^2 L_s^2 \\
Q_3 &= (1-G)k U_{st}^2 \psi_{st} / \omega T_s \\
Q_4 &= k^2 \psi_{st}^2 t_f / 2 L_s^2 \\
Q_5 &= 2Gk U_{ad}^2 (1-e^{-\frac{2t}{T_p}}) \psi_{st} / \omega L_s^2 \\
Q_6 &= 2Gk U_{ad}^2 (1-e^{-\frac{2t}{T_p}}) \psi_{st} / \omega L_s^2 \\
Q_7 &= (\psi_{so}^2 - \psi_{st}^2) (1-e^{-\frac{2t}{T_p}}) T_s k^2 L_s^2 \\
Q_8 &= 2Gk U_{ad}^2 (1-e^{-\frac{2t}{T_p}}) \psi_{st} / \omega L_s^2 \\
Q_9 &= k^2 \psi_{st}^2 (1-e^{-\frac{2t}{T_p}}) (\psi_{so}^2 - \psi_{st}^2) T_s^2 \\
Q_{10} &= -2(1-G)U_{ad}^2 (1-e^{-\frac{2t}{T_p}}) K U_{ad} / \omega L_s^2 \\
Q_{10} &= k^2 \psi_{st}^2 (1-e^{-\frac{2t}{T_p}}) (\psi_{so}^2 - \psi_{st}^2) T_s^2
\end{align*}$$

(16)

3.2. Short circuit thermal effect components of DFIG

It is clear that Q3, Q4, Q6, Q7, Q8, Q9 and Q10 contain $\psi_{rf \infty}$. Obviously, Q1, Q3 and Q6 are directly proportional to the short-circuit duration, and belong to the periodic component. The aperiodic components Q2, Q4, Q5, Q7, Q8, Q9 and Q10 attenuate exponentially, among which Q2, Q4 and Q8 attenuate slowly according to $T_p$, Q4, Q7 and Q9 attenuate faster according to $T_p$, Q9 is based on the transient time constant of stator and rotor parallel structure, the time constant is less than $T_p$, and the attenuation rate is the fastest. Therefore, the thermal effect may be given by Qp (sum of the periodic components) and Qap (sum of aperiodic components) of the thermal effect.

$$Q = Q_p + Q_{ap}$$

(17)

$$\begin{align*}
Q_p &= Q_1 + Q_3 - Q_6 \\
Q_{ap} &= Q_2 + Q_4 + Q_5 - Q_7 - Q_8 - Q_9 + Q_{10}
\end{align*}$$

(18)

4. Equivalent duration Constant of Aperiodic Component of Thermal Effect

4.1. Analytical expression of equivalent duration constant of aperiodic component of thermal effect

Equipment thermal stability calibration can effectively avoid equipment damage and secondary failure caused by fault heating. In engineering application, the product of the square of short current and time is usually used to calculate the thermal effect. However, if the calculation results are close to the rated check value, the results obtained by this method are optimistic because the thermal effect ignores the aperiodic component of thermal effect.

Fig. 2 (a) shows the accurate calculation of thermal effect. The thermal effect is composed of the periodic and aperiodic components. But the aperiodic component is often difficult to calculate. Hence to quantify the thermal effect with the periodic component only, the equivalent duration of the aperiodic component is quantified, as shown in Fig. 2 (b). It is seen that,

$$\left(t_p + t_{ap\text{eq}}\right) = \left(t_e + t_{ap\text{eq}}\right) t_e$$

(19)

where $t_{ap\text{eq}}$ is equivalent duration of aperiodic component of short circuit thermal effect.

The expression of equivalent duration of aperiodic component of short circuit thermal effect can be deduced by expanding the above formula,
(20)

\[
t_{ap, eq} = \frac{I_{ap}^2 t_f}{I_{p}^2} = \frac{Q_{ap} / I_{p}^2}{Q_{ap} t_f / Q_{p}}
\]

4.2. Sensitivity of equivalent duration of aperiodic component of thermal effect

The sensitivity of the equivalent duration may be also quantified by the perturbation method,

\[
SE_{t_{ap, eq}} = \left| \frac{I_{ap, eq} (\zeta + \mu) - t_{ap, eq} (\zeta)}{\mu} \right|
\]

where \(\mu\) is the perturbation value and \(\zeta\) is the short circuit parameter.

5. Example Analysis

The parameters of the DFIG are shown in Table 1, where \(U_R\) is the rated voltage, \(S_R\) is the rated power, \(r\) is the radius of the wind turbine, \(H_r\) is the inertia of the generator, \(H_{wt}\) is the inertia of the wind turbine, \(D_s\) is damping coefficient, \(C_f\) is direct current capacitor, \(U_{dc}\) is direct current voltage, \(c_1\)~\(c_9\) are the coefficients.

| Parameter | Value | Parameter | Value | Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|-----------|-------|-----------|-------|
| \(U_R\)   | 690 V | \(C_f\)   | 0.5 p.u. | \(D_s\)   | 20.5 p.u. | \(c_6\)   | 13.2  |
| \(S_R\)   | 1.5 MW| \(U_{dc}\) | 1200 V | \(c_1\)   | 0.73   | \(c_7\)   | 18.4  |
| \(r\)     | 32.1276 m| \(L_{st}\) | 0.182 p.u. | \(c_2\) | 121 | \(c_8\) | -0.02 |
| \(R_s\)   | 0.011 p.u. | \(L_{st}\) | 0.144 p.u. | \(c_3\) | 0.58 | \(c_9\) | -0.03 |
| \(R_t\)   | 0.009 p.u. | \(H_r\)   | 0.5 s   | \(c_4\) | 0.002 | \(c_10\) | 5.89 p.u. |
| \(L_{st}\) | 3.5 s | \(H_{wt}\) | 5.89 p.u. | \(c_5\) | 2.14 | \(c_11\) | 3.5 s |

5.1. Analytical expression of short current and its error

According to the grid codes, when the stator voltage drops to 0.2 p.u., the crowbar will act. With air density \(\rho=1.225\text{kg/m}^3\), wind speed \(u_w=8\text{m/s}\), \(R_{cb}=0.1\text{p.u.}\), \(U_{s0}=1\text{p.u.}\), \(G=0.8\text{p.u.}\), \(\mu=0.0001\text{p.u.}\), \(\zeta\) take stator voltage drop ratio, crowbar resistance, grid short circuit start time \(t_0=0.02\text{s}\). Fig. 3(a) shows the comparison of DFIG short current analysis and step-by-step integration results, which are relatively close. Fig. 3(b) shows the periodic and aperiodic components of the short current. The aperiodic component increases rapidly at the beginning of short-circuit, and then decreases to zero with the increase of short-circuit time.
5.2. Periodic and aperiodic components of short circuit thermal effect

Fig. 4 shows the variation of the components of the thermal effect. The periodic components in Fig. 4 (a) are roughly proportional to short-circuit duration, and the value is relatively large. The aperiodic component (including attenuation component) in Fig. 4 (b) increases rapidly at first then saturates. The values are small except Q2.

5.3. Equivalent duration and sensitivity analysis of aperiodic component of thermal effect

Fig. 5(a) shows the equivalent duration of the aperiodic component with time. With the longer time, the equivalent duration increases and gradually saturates. Figs. 5(b) and 5(c) describe the sensitivity of equivalent duration to the stator voltage and the crowbar resistance respectively. It is found that the sensitivity increases at first with time and then saturates. Compared with crowbar resistance, stator voltage drop proportion is proportional to thermal effect, resulting in higher sensitivity. However, with the increase of short-circuit time, the aperiodic short current decays to zero, the thermal effect does not change, and the sensitivity tends to saturate.

6. Conclusion

Based on the analytical thermal effect model of the DFIG previously proposed by the authors, the analytical expressions of the periodic and aperiodic components of the thermal effect of the DFIG are newly proposed. The equivalent duration of the aperiodic component is newly defined, whose sensitivities to the stator voltage and the crowbar resistance are studied. It is found that,

(1) The analytical expression of DFIG short current can effectively distinguish the influence of periodic component and aperiodic component on equipment.

(2) The equivalent duration of aperiodic component of short circuit thermal effect can accurately reflect the contribution of aperiodic component of thermal effect.
(3) The sensitivity of the thermal effect to stator voltage drop ratio and crowbar resistance increases with time, and finally tends to be stable.

(4) Compared with the crowbar resistance, the stator voltage drop ratio has a greater influence on the equivalent duration of the aperiodic component of the thermal effect.

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