Adaptive analysis of main transformer protection in hybrid wind farms

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Abstract. With the development of wind power technology, wind farms have gradually formed a mixed operation pattern dominated by DFIG and PMSG. By analyzing the short-circuit current characteristics when a fault occurred in the main transformer protection zone of the wind farm and the hybrid wind farm is connected to the grid, the possible impacts of the short-circuit current of the hybrid wind farm on the protection of the transformer is studied. The results show that after mixing different unit types, when the fault occurs in the main transformer protection zone of the wind farm, the short-circuit current contains the second harmonic component, and its attenuation speed is related to the number of PMSG, the number of DFIG, the fault location, and the severity of the fault. Under the influence of above factors, the blocking time of the second harmonic blocking protection will be prolonged, thereby increasing the operating time of the ratio differential protection.

1. Introduction
Transformer is one of the most important equipment in power system. The reliable action of transformer protection determines the safe and stable operation of power system. At present, the transformer protection is mainly differential protection, and the second harmonic blocking protection is configured to identify the inrush current. In order to make the transformer protection operate reliably in the event of a serious internal fault, differential quick-break protection is usually configured.

Factors such as the electromagnetic coupling of wind turbines and the regulation of power electronics will cause the harmonic components of the fault current to change, resulting in the transformer differential protection refusing to operate. References [1-2] pointed out that the influence of the frequency shift of the fault current of the DFIG would cause a delay in the transformer protection action. Reference [3] takes into account the low-voltage ride-through technology of DFIG, and analyzes the effect of DFIG fault current on the transformer differential protection.

In view of the lack of research on the impact of short-circuit current from hybrid wind farm on transformer protection, this article analyzes the short-circuit current characteristics of hybrid wind farm, studies its impact on transformer protection, and uses the RTDS simulation platform to verify.

2. Short-circuit current characteristics of hybrid wind farm
When a fault occurred in the main transformer protection zone of the wind farm, the short-circuit current will include the fundamental frequency component, the DC component and the second harmonic
component. Among them, the content of the second harmonic component content is the key to determine whether the transformer differential protection is operating correctly.

Overcurrent occurs in the rotor of the DFIG when the power grid is deeply faulted. Crowbar circuits are usually provided to bypass the rotor to protect the converter. At this time, the second-harmonic current in the short-circuit current of the DFIG contains almost no second harmonic current [4]. When the crowbar circuit is not turned on, the field winding of the DFIG rotor remains connected to the rotor-side converter. Because the stator transient short-circuit current contains a DC component, after the rotor-side converter's double closed-loop PI control, the stator short-circuit current will include the second harmonic component [5]. The magnitude of the DC component and the attenuation speed are the main factors that determine the content of the second harmonic and the attenuation speed. Therefore, to analyze the characteristics of the second harmonic of the short-circuit current, the DC Analysis.

In the synchronous rotating coordinate system, the DFIG voltage and the flux equation can be expressed as:

\[
\begin{align*}
    u_s &= R_s i_s + D \psi_s + j \omega_p \psi_s \\
    u_r &= R_r i_r + D \psi_r + j \omega_p \psi_r \\
    \psi_s &= L_s i_s + L_m i_r \\
    \psi_r &= L_r i_r + L_m i_s
\end{align*}
\] (1)

In the formula, \(u_s\), \(i_s\), \(\psi_s\), \(u_r\), \(i_r\), \(\psi_r\) represents the stator and rotor side voltage, current, and flux linkage space vectors; \(R_s\), \(R_r\) represents the stator and rotor side winding resistances; \(L_s\), \(L_r\), \(L_m\) represents the stator and rotor side self-inductance and the mutual inductance between the stator and rotor, respectively, \(L_s = L_m + L_{s\sigma}\), \(L_r = L_m + L_{r\sigma}\), where \(L_{s\sigma}\), \(L_{r\sigma}\) is the leakage inductance on the stator and rotor sides respectively; \(\omega_s\), \(\omega_p\) is the synchronous angular velocity and slip angular velocity; \(D\) is the differential operator.

After fault, the short circuit current of DFIG stator can be obtained by formula (1):

\[i_{sf} = \frac{1}{L_s} \psi_{sf} - \frac{L_m}{L_s} i_{rf}\] (2)

In the formula, the subscript \(f\) represents the electrical quantity after the fault.

It can be known from formula (2) that the short-circuit current after the fault can be obtained from the stator flux and the rotor current after the fault. According to the law of conservation of magnetic flux, the stator flux cannot change abruptly after a fault, and the stator flux cannot go directly from the steady state value before the fault to the steady state value after the fault. If a three-phase fault occurs at \(t = 0\), the stator flux linkage can be expressed as [6]:

\[\psi_{sf} = \frac{U_{s2}}{j \omega_s} e^{j \omega_s t} - \frac{k U_{s1}}{j \omega_s} e^{-t / T_s}\] (3)

Where \(U_{s1}\), \(U_{s2}\) is the stator voltage before and after the voltage drop, \(k U_{s1} = U_{s1} - U_{s2}\), and \(T_s\) is the stator decay time constant.

According to the rotor voltage equation in the synchronous rotating coordinate system, and the rotor flux is expressed by the stator flux and the rotor current:

\[u_r = R_r i_r + (D + j \omega_p) \left( i_r - \frac{L_m}{L_s} \psi_s \right)\] (4)

Substitute the stator flux expression (3) into (4) after the fault and sort it out:
Among them, $\sigma$ is defined as the DFIG leakage coefficient, and $\sigma = 1 - \frac{L_m}{L_s}$.

When the crowbar circuit is not put into operation after the fault, the RSC maintains a regulating function, and its inner loop current control equation is

$$u_r^* = k_p (i_r^* - i_r) + k_i \int (i_r^* - i_r) dt + j \omega_s \sigma L_i i_r$$

In the formula: $u_r^*$, $i_r^*$ is the RSC output voltage and current reference value, and $k_p$, $k_i$ is the proportional and integral coefficients of the PI controller of the current inner loop.

It is considered that the converter can ideally track the modulated wave, that is, $u_r = u_r^*$, the simultaneous equations (5) and (6), and the second-order differential equation of the rotor current can be obtained.

$$\sigma L_r D^2 i_r + (R_r - j \omega_r \sigma L_r + k_p) D i_r + k_i i_k i_r^* = \frac{L_m}{L_s} \left[ j \omega_s (s + 1) U s_2 e^{j \omega s t} - \frac{1}{T_s} (sk - \frac{k}{T_s \omega_s}) U s_1 e^{-j \omega s t} \right]$$

Equation (7) is the second-order differential equation of the rotor current. The general and special solutions of the differential equation are the rotor current. Substituting the rotor current and the stator flux expression into equation (2), the rotor-side converter current can be taken into account as follows:

$$i_s = i_{s1} + i_{s2} + i_{s3} + i_{s4}$$

In the formula:

$$i_{s1} = \left( \frac{U s_2}{\omega_s L_s} - \frac{L_m}{L_s} \left( \frac{a_1 \sigma L_r}{\omega_s^2 - a_3} \right) \right) i_r, i_{s2} = \left( \frac{k U s_1}{\omega_s L_s} - \frac{L_m}{L_s} \frac{a_2 T^2 \sigma L_r}{k_1 T + 1 - a_3 T} \right) e^{-j \omega s t},$$

$$i_{s3} = \frac{-L_m}{L_s} i_r^*, i_{s4} = \frac{-L_m}{L_s} \frac{a_4 T e^{a_5^2 - a_5} e^{-a_5 t}}{a_4 - a_5}$$

Among them:

$$a_1 = -\frac{L_m}{\sigma L_r L_s} (s + 1) U s_2, a_2 = \frac{L_m}{\sigma L_r L_s} (sk - \frac{k}{T_s \omega_s}) U s_1, a_3 = \frac{R_r + k_p}{\sigma L_r} - j \omega_r, a_4 = -\frac{a_3^2 - 4 a_2}{2}, a_5 = -\frac{a_3 \sqrt{a_3^2 - 4 a_2}}{2}$$

It can be known from equation (9) that the DC component of the stator transient short-circuit current attenuation is determined by the voltage drop depth and the parameters of the PI controller, and it is attenuated by the stator attenuation time constant.

Since the DC component is the main cause of the second harmonic, the second harmonic will also be attenuated by the stator decay time constant and it can be known from equation (9) that its content increases with the PI controller integral coefficient.

For PMSG, taking into account the effects of low-voltage ride-through control strategy, the PMSG output short-circuit current after a symmetric fault occurs is [7]:

$$I_p = \frac{2}{3} \frac{P_{p, PMSG}}{u_{p1}} - \frac{2}{3} j \frac{Q_{0, PMSG}}{u_{p1}} + j K_d (0.9 - k_u u_{p1}) i_N$$
2.1. Hybrid wind farm equivalent circuit

According to the DFIG and PMSG short-circuit current expressions (8) and (11), their equivalent values after the fault are controlled sources. The single-machine equivalent circuit after its failure is shown in Figure 1. The equivalent circuit diagram of the hybrid wind farm is shown in Figure 2. Among them: $Z_G$ is the transformer impedance, and $Z_{DP}$ is the equivalent impedance between DFIG and PMSG.

Since the decay time constant is related to the equivalent external circuit impedance from the generator to the fault point, if the short circuit occurs outside the line of the machine or there is a fault impedance, the influence of the equivalent impedance of the external circuit from the generator to the fault point on the short circuit current should also be considered. The stator decay time increases with the decrease of the external circuit impedance. The circuit impedance is merged into the resistance and leakage reactance of the stator winding[8]. So it is necessary to analyze the change trend of the impedance of the circuit from the DFIG to the fault point after a short-circuit fault. Take a DFIG in the wind field as an example, analyze the external circuit impedance and its influencing factors.

The equivalent impedance of the external circuit of the hybrid wind farm is:
In the formula: $Z_{DDeq}$ is equivalent impedance of DFIG, $Z_{Peq}$ is equivalent impedance of PMSG.

From the above equation, it can be seen that when the fault occurs in the high-voltage side of the transformer in the hybrid wind farm, the equivalent impedance of the external circuit is affected by the number of PMSG, the number of DFIG, the fault location and the fault severity. Since the second harmonic attenuation speed is affected by the size of $Z_{DDeq}$, the attenuation speed slows down with the decrease of $Z_{DDeq}$, therefore, the second harmonic protection locking time of the transformer after failure is also affected by the above factors.

3. Simulation analysis

The topology of the hybrid wind farm is shown in figure 3.

![Figure 3. Primary wiring diagram of mixed wind farm](image)

In case of point 1 fault (fault duration 0.2s), the braking coefficient of the transformer’s second harmonic locking protection is set at 15%, and the influence of various factors on the transformer's second harmonic locking protection is analyzed respectively.

a. Nothing changes  
b. Increase the number of PMSG  
c. Increase the number of DFIG
It can be seen from the simulation results that increasing the number of PMSG or DFIG will increase the protection blocking time; the low-voltage side fault protection blocking time of the transformer is shorter; increasing the transition resistance makes the protection blocking time shorter, and the ratio differential protection action is faster.

4. Conclusion
The second harmonic protection blocking time of a hybrid wind farm is affected by the number of DFIG and PMSG, the location of the fault, and the severity of the fault. The more the number of DFIG and PMSG, the slower the second harmonic attenuation speed and the longer the protection blocking time; The protection blocking time is shorter when fault occurs on the low-voltage side of the transformer; the larger the fault transition resistance, the shorter the protection blocking time.

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