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Distance protection for transmission lines of DFIG-based wind power integration system

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ABSTRACT

This paper proposes a distance relay in time domain based on the R-L differential-equation algorithm which is suitable for wind power integration system. However, the conventional R-L differential-equation algorithm cannot detect the correct fault direction if the fault point is very close to the relay location. Therefore, this paper mainly focuses on this problematic conditions and proposes a solution. The instantaneous value equivalent model of DFIG is established and characteristics of the transient electromotive force (EMF) of DFIG after the faults are also analyzed, which shows that the EMF of DFIG has the inertia within a short time after the faults. The memory voltage drop and actual voltage drop on equivalent impedance from relay location to back-side and opposite-side equivalent power sources are introduced in this paper to detect the fault direction. Meanwhile, the characteristics of the memory voltage drop and actual voltage drop under forward and reverse fault conditions are deduced, respectively. With the differentiated correlation coefficient between the memory voltage drop and actual voltage drop under different fault conditions (forward and reverse fault), the fault direction identification criterion is formed accordingly. Finally, an extensive performance evaluation using PSCAD/EMTDC simulation corroborates the effectiveness of the proposed method. Results show that the proposed method can detect the fault direction quickly with high sensitivity during zero-voltage fault conditions.

1. Introduction

Environmental concerns have led to rapid growth of wind energy all around the world [1]. The installed capacity of wind power is increasing rapidly in recent years in China, and the majority of wind power is connected to high-voltage transmission grids.

The wind farms based on double fed induction generators (DFIGs) are widely employed in modern power system, due to various advantages, such as its low cost, variable speed-constant frequency operation and reduced converter size [2]. In practice, DFIGs are equipped with crowbar circuits to protect the converters during severe voltage drops. If the fault locations are very close to the DFIG-based wind farm, i.e., the scope of this paper, it is the most severe fault conditions and the crowbar protection may be activated. Once the crowbar is activated, the main peak of the fault current spectrum of a DFIG-based wind farm may not be centered around the fundamental frequency, which depends on the machine slip of the DFIG before the fault. Therefore, the fault behavior of the DFIG-based wind power integration system is quite different from that of conventional synchronous generators [3–7], which greatly affects the performance of traditional relay protections [8–13].

To improve the performance of distance relays used in wind power integration system, many different methods have been proposed in recent studies [14–21]. Most of those studies are still established in frequency domain based on the fault behavior of wind farms. Due to the exclusive fault behavior of DFIGs-based wind farms, the distance relay in time domain based on the R-L differential-equation algorithm may be a more suitable solution [22]. The main advantage of the R-L differential-equation algorithm based distance relay is that only the transmission line model has a great impact on the performance of the relays. Therefore, this method will not be affected by the complex fault behavior of DFIG-based wind farm. However, one of the greatest challenges of the R-L differential-equation algorithm based distance relays is the zero-voltage fault. The zero-voltage fault is defined as the fault point to be very close to the relay location, producing zero voltage at the relay location during the fault. To overcome the problem of zero-voltage faults, a directional element is necessary to the R-L differential-equation algorithm based distance relays.

The common directional element of the distance relay to solve the zero-voltage fault conditions is memory-polarized, i.e., the angle of

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each phase fault current is compared with that of the pre-fault voltage in the same phase. However, the voltage and current frequencies of DFIG-based wind farms might become different if the crowbar protection was activated during the faults. On the other hand, considering the effect of the converter control system of DFIGs, the behavior of DFIGs is quite complex during the fault. So phase oscillations may occur when the current phasor measurement techniques is used to compute the current phasor, because the data windows may contain different state data [14]. As a result, the conventional approach of finding the phase angle between the fundamental fault current and a voltage signal may fail to provide the correct fault direction under such conditions. Therefore, the directional element of distance relays in wind power integration system still needs to be further studies.

In [23], a fault direction identification method based on waveform correlation in time domain was proposed. However, the proposed method could not defeat zero-voltage fault. In [24], a fault direction identification method based on model recognition was proposed. However, this method could not overcome the problem of zero-voltage fault as well. A novel three-phase fault direction identification method for distribution systems with DFIG-based wind distributed generation was proposed in [25]. The decaying pattern of the ac component for DFIG fault currents was used as the feature in discriminating fault directions. However, this proposed method can be only used during balanced faults.

In order to solve the direction identification problem of zero-voltage faults in DFIG-based wind power integration systems, a novel directional element in the time domain is proposed. Based on the differentiated characteristics of the memory voltage drop and actual voltage drop on equivalent impedance from relay location to back-side and opposite-side equivalent power sources under forward and reverse fault conditions, the correlation coefficient is introduced in this paper to detect the fault direction. Then, an improved distance relay in time domain based on the R-L differential-equation algorithm is proposed in this paper. Extensive simulation results indicated that the proposed method can detect the fault direction quickly with high sensitivity under zero-voltage fault conditions in wind power integration systems.

2. Characteristics of EMF of DFIG-Based wind farm

2.1. Instantaneous value equivalent model of DFIG

In a *d-q* synchronous reference frame, the stator and rotor voltage equations of the DFIG in space vector notation can be written as

$$\begin{cases} \boldsymbol{U}_{\mathrm{s}} = R_{\mathrm{s}}\boldsymbol{I}_{s} + \frac{d\boldsymbol{\psi}_{\mathrm{s}}}{dt} + j\omega\boldsymbol{\psi}_{\mathrm{s}} \\ \boldsymbol{U}_{\mathrm{r}} = R_{\mathrm{r}}\boldsymbol{I}_{\mathrm{r}} + \frac{d\boldsymbol{\psi}_{\mathrm{r}}}{dt} + j\omega_{s}\boldsymbol{\psi}_{\mathrm{r}} \end{cases} \tag{1}$$

where R_{s} is the stator resistance, R_{r} is the rotor resistance, ω is the fundamental angular frequency and ω_s is the slip angular frequency. The stator and rotor flux equations can be given by

$$\begin{cases} \boldsymbol{\psi}_{\mathrm{s}} = L_{\mathrm{s}}\boldsymbol{I}_{\mathrm{s}} + L_{\mathrm{m}}\boldsymbol{I}_{\mathrm{r}} \\ \boldsymbol{\psi}_{\mathrm{r}} = L_{\mathrm{m}}\boldsymbol{I}_{\mathrm{s}} + L_{\mathrm{r}}\boldsymbol{I}_{\mathrm{r}} \end{cases} \tag{2}$$

where L_{s} is the stator inductance, L_{r} is the rotor inductance and L_{m} is the mutual inductance.

Substituting (2) into (1) yields

$$\boldsymbol{U}_{\mathrm{s}} - R_{\mathrm{s}}\boldsymbol{I}_{\mathrm{s}} - \left(j\omega\boldsymbol{I}_{\mathrm{s}} + \frac{d\boldsymbol{I}_{\mathrm{s}}}{dt}\right)\left(L_{\mathrm{s}} - \frac{L_{\mathrm{m}}^2}{L_{\mathrm{r}}}\right) = \frac{L_{\mathrm{m}}}{L_{\mathrm{r}}}\frac{d\boldsymbol{\psi}_{\mathrm{r}}}{dt} + j\omega\frac{L_{\mathrm{m}}}{L_{r}}\boldsymbol{\psi}_{\mathrm{r}} \tag{3}$$

Then, the right side of (3) is defined as the EMF of DFIG

$$\boldsymbol{E} = \frac{L_{\mathrm{m}}}{L_{\mathrm{r}}}\frac{d\boldsymbol{\psi}_{\mathrm{r}}}{dt} + j\omega\frac{L_{\mathrm{m}}}{L_{r}}\boldsymbol{\psi}_{\mathrm{r}} \tag{4}$$

Under normal operation conditions, the rotor flux space vector $\boldsymbol{\psi}_{\mathrm{r}}$ is constant. So the EMF of DFIG under normal operation conditions is

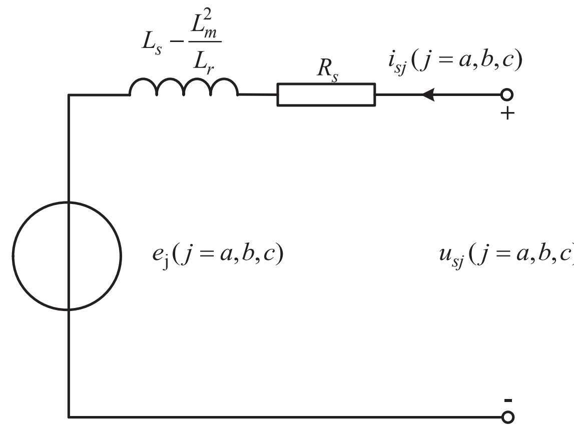

Fig. 1. Instantaneous value equivalent model of DFIG.

$$\boldsymbol{E} = j\omega\frac{L_{\mathrm{m}}}{L_{r}}\boldsymbol{\psi}_{\mathrm{r}}. \tag{5}$$

In a *abc* stationary frame, (3) can be rewritten as

$$\begin{cases} e_a = u_{sa} - R_{\mathrm{s}}i_{sa} - (L_{\mathrm{s}} - \frac{L_{\mathrm{m}}^2}{L_{\mathrm{r}}})\frac{di_{sa}}{dt} \\ e_b = u_{sb} - R_{\mathrm{s}}i_{sb} - (L_{\mathrm{s}} - \frac{L_{\mathrm{m}}^2}{L_{\mathrm{r}}})\frac{di_{sb}}{dt}. \\ e_c = u_{sc} - R_{\mathrm{s}}i_{sc} - (L_{\mathrm{s}} - \frac{L_{\mathrm{m}}^2}{L_{\mathrm{r}}})\frac{di_{sc}}{dt} \end{cases} \tag{6}$$

From (6), the instantaneous value equivalent model of DFIG can be established as shown in Fig. 1. From Fig. 1, we can see that the DFIG is represented by a voltage source in series with an impedance. Eq. (4) shows that the EMF of DFIG depends on variation of the rotor flux, which means that the voltage source is controlled by the rotor flux. To analyze the characteristic of the EMF of DFIG after the fault, it is necessary to discuss the variation characteristics of rotor flux of DFIG under fault conditions.

2.2. Variation Characteristics of the Rotor Flux

Based on (2), the current vectors can be rewritten as

$$\begin{cases} \boldsymbol{I}_{\mathrm{s}} = \frac{L_{\mathrm{r}}}{L_{\mathrm{t}}}\boldsymbol{\psi}_{\mathrm{s}} - \frac{L_{\mathrm{m}}}{L_{\mathrm{t}}}\boldsymbol{\psi}_{\mathrm{r}} \\ \boldsymbol{I}_{\mathrm{r}} = -\frac{L_{\mathrm{m}}}{L_{\mathrm{t}}}\boldsymbol{\psi}_{\mathrm{s}} + \frac{L_{\mathrm{s}}}{L_{\mathrm{t}}}\boldsymbol{\psi}_{\mathrm{r}} \end{cases} \tag{7}$$

where $L_{\mathrm{t}} = L_{\mathrm{s}}L_{\mathrm{r}} - L_{\mathrm{m}}^2$.

Substituting (7) into (1) yields

$$\begin{cases} \boldsymbol{U}_{\mathrm{s}} = R_{\mathrm{s}}\left(\frac{L_{\mathrm{r}}}{L_{\mathrm{t}}}\boldsymbol{\psi}_{\mathrm{s}} - \frac{L_{\mathrm{m}}}{L_{\mathrm{t}}}\boldsymbol{\psi}_{\mathrm{r}}\right) + \frac{d\boldsymbol{\psi}_{\mathrm{s}}}{dt} + j\omega\boldsymbol{\psi}_{\mathrm{s}} \\ \boldsymbol{U}_{\mathrm{r}} = R_{\mathrm{r}}\left(-\frac{L_{\mathrm{m}}}{L_{\mathrm{t}}}\boldsymbol{\psi}_{\mathrm{s}} + \frac{L_{\mathrm{s}}}{L_{\mathrm{t}}}\boldsymbol{\psi}_{\mathrm{r}}\right) + \frac{d\boldsymbol{\psi}_{\mathrm{r}}}{dt} + j\omega_{s}\boldsymbol{\psi}_{\mathrm{r}} \end{cases}. \tag{8}$$

It is assumed that a three-phase short-circuit occurs at time t = 0. According to [27], considering the effect of stator flux transient time constant, the stator flux after the fault before the crowbar is activated can be expressed as

$$\boldsymbol{\psi}_{\mathrm{s}} = \frac{\boldsymbol{U}_{\mathrm{s}}}{j\omega} + \left(\frac{\boldsymbol{U}_{\mathrm{s}}(0\_)}{j\omega} - \frac{\boldsymbol{U}_{\mathrm{s}}}{j\omega}\right)e^{-j\omega t}e^{-\frac{t}{T_{\mathrm{s}}}}, \quad 0 < t \leqslant t_0. \tag{9}$$

where $\boldsymbol{U}_{\mathrm{s}}$ is the stator voltage vector after the fault, $\boldsymbol{U}_{\mathrm{s}}(0\_)$ is the pre-fault stator voltage vector and $T_{\mathrm{s}} = \frac{L_{\mathrm{t}}}{L_{\mathrm{r}}R_{\mathrm{s}}}$ is stator flux transient time constant. The crowbar protection is activated at t_0 moment.

From (8), the rotor flux equation can be rewritten as

$$\frac{d\boldsymbol{\psi}_{\mathrm{r}}}{dt} + (j\omega_{s} + R_{\mathrm{r}}\frac{L_{\mathrm{s}}}{L_{\mathrm{t}}})\boldsymbol{\psi}_{\mathrm{r}} = \boldsymbol{U}_{\mathrm{r}} + R_{\mathrm{r}}\frac{L_{\mathrm{m}}}{L_{\mathrm{t}}}\boldsymbol{\psi}_{\mathrm{s}}. \tag{10}$$

Assuming that the rotor voltage vector does not change after the