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Mal-operation risk assessment for the feeder overcurrent protection in large-scale clustering wind farms

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ABSTRACT

Conventionally, the Doubly-fed Induction Generator (DFIG) has no impacts on the arrangement and the setting of the feeder overcurrent protection in the large-scale, concentrated wind farm, since the DFIG has long been regarded as a normal load under the fault conditions. As a result, existing overcurrent protection equipped on a sound feeder may mal-operate when a fault occurs on adjacent feeders, if the DFIG feeding current on the corresponding sound feeder is high enough. To prevent this, further investigation is thereby undertaken in this paper. The characteristics of the DFIG feeding current is analyzed under various fault conditions in the first place. Secondly, the feeder overcurrent protection is set according to currently-applied principles, based on which the corresponding mal-operation zone and the mal-operation risk are calculated under different system operation conditions. It can be deduced from the results that a reasonable DFIG crowbar resistance value and an optimized wind farm arrangement can be of positive effect to limit the mal-operation risk. Directional element must be configured for the existing protection if above countermeasures are not available and the mal-operation risk still exists.

Introduction

With higher penetration of renewable energy into the power grid, the centralized, large-scale wind farms have received much attention. In comparison with other type of wind turbines, the Doubly-fed Induction Generator (DFIG) has become the most popular one for its low-size power convertor [1].

The Jiuquan wind farm in China, which has the aforementioned type of structure, includes five clusters, naming Qiaodong, Qiaoxi, Ganxi, Gandong and Guazhou. Two of the clusters, Ganxi and Guazhou, are named as cluster-1 and cluster-2, as shown in Fig. 1. As seen, the wind farm is divided into different parts according to the voltage level. They are respectively: the low-voltage zone (LV, 0.69 kV), the middle-voltage zone (MV, 35 kV) and the high-voltage zone (HV, 220 kV) [2]. A certain cluster containing numbers of wind turbines nearby is connected to a subordinate collector bus. The feeders performs as bridges for energy from the subordinate collector buses to the main collector bus. This type of wind farms is also provided and studied by several literatures [3–8].

Two-staged overcurrent protection is the common arrangement for switch S_1 and S_2 equipped on each feeder respectively, with Stage-1 being the instantaneous overcurrent protection [2]. Its protection range covers the whole length of the corresponding feeder and all the DFIG in Cluster-1. Staged-2 is the definite-time overcurrent protection and usually set based on the maximal load current. Conventionally, their setting principles have no relationship with the DFIG, since that under the fault conditions, the DFIGs are regarded as normal loads. Above method show great performance in previous applications. However, it is currently no longer the case as the low-voltage-ride-through (LVRT) capability of the DFIGs are greatly enhanced recent years.

While numerous LVRT schemes have been proposed for the DFIG, both on the stator side [9–11] and the rotor side [12–14], the crowbar protection [15] shows the best performance and is currently used as a proven technique. As shown in Fig. 2, the crowbar is switched in once the rotor current exceeds the threshold, which is mainly caused by a stator side voltage dip, to keep the rotor-side convertor (RSC) from severe damages. By this means, the DFIG becomes able to keep connected within the faulted duration. As a result, once a fault occurs on a feeder L_1 (or L_2), the DFIGs on adjacent feeders will provide feeding current continuously to the fault location due to their enhanced LVRT capability. This feeding current, if high enough, may result in the mal-operation of the overcurrent protection, and may leads to abnormal disconnection of those clusters from the wind farm. To the best of the author's knowledge, recent studies unfortunately, do not tend to solve

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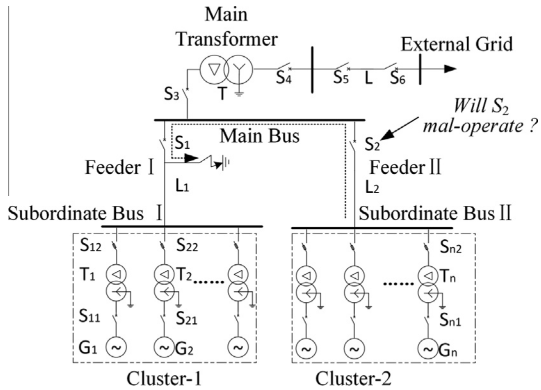

Fig. 1. The typical structure of the wind farm.

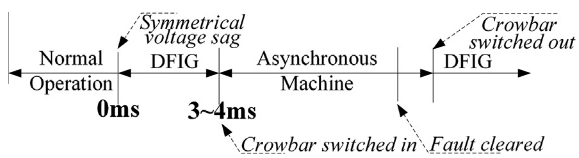

Fig. 2. The crowbar protection for the DFIG.

above problem directly, as the interest is mainly placed on the electro-magnetic transient analysis [1,16,17], the modeling and the short circuit current calculation [18], or other similar topics for a certain DFIG. That how much impact the DFIGs with LVRT capability will have on the feeder overcurrent protection is an area of intense investigation we focus on in this paper.

This paper is organized as follows: Section 'Theoretical study for the DFIG feeding current' starts with the study for the DFIG feeding current under various fault conditions by theoretical analysis. In Section 'Time–frequency Domain Analysis and the Reciprocal Effect', the characteristics of the power frequency component within the feeding current, which is the meaningful one for the feeder overcurrent protection, is extracted and calculated by time–frequency domain analysis. The reciprocal effect of the DFIG feeding current and the feeder overcurrent protection is therefore studied. In Section 'Mal-operation risk analysis under various conditions', the reciprocal effect is further investigated in various conditions. Optimized coordinate strategy between DFIGs and the feeder overcurrent protection is also put forward. The specific goal of this paper is to prevent the possible mal-operation risk by providing a complete setting strategy for the feeder overcurrent protection, which will enhance the LVRT capability of the whole wind farm.

Theoretical study for the DFIG feeding current

The state equation of the DFIG under the d–q coordinate system is given by literature [19] as:

$$\begin{cases} \frac{d\boldsymbol{\psi}}{dt} = A\boldsymbol{\psi} + \mathbf{u} \\ \mathbf{i} = L^{-1}\boldsymbol{\psi} \end{cases} \tag{1}$$

where $\boldsymbol{\psi}$, $\mathbf{u}$ and $\mathbf{i}$ are vectors of the stator flux, stator voltage and the stator current, which can be expressed as the following equations:

$$\begin{cases} \boldsymbol{\psi} = \begin{bmatrix} \psi_{sd} & \psi_{sq} & \psi_{rd} & \psi_{rq} \end{bmatrix}^T \\ \mathbf{u} = \begin{bmatrix} u_{sd} & u_{sq} & u_{rd} & u_{rq} \end{bmatrix}^T \\ \mathbf{i} = \begin{bmatrix} i_{sd} & i_{sq} & i_{rd} & i_{rq} \end{bmatrix}^T \end{cases} \tag{2}$$

Matrix A and L^{-1} is given by:

$$\begin{cases} A = \begin{bmatrix} -\omega_s & \omega_1 & \omega_{sm} & 0 \\ -\omega_1 & -\omega_s & 0 & \omega_{sm} \\ \omega_{rm} & 0 & -\omega_r & -\omega_2 \\ 0 & \omega_{rm} & -\omega_2 & -\omega_r \end{bmatrix} \\ L^{-1} = \frac{1}{L_sL_r - L_m^2} \begin{bmatrix} L_r & 0 & -L_m & 0 \\ 0 & L_r & 0 & -L_m \\ -L_m & 0 & L_s & 0 \\ 0 & -L_m & 0 & L_s \end{bmatrix} \end{cases} \tag{3}$$

where ω_1 and ω_2 are the synchronous speed and the slip speed respectively. Other parameters are expressed as follows:

$$\begin{cases} \omega_s = \frac{R_sL_r}{L_sL_r - L_m^2} \\ \omega_r = \frac{R_rL_s}{L_sL_r - L_m^2} \\ \omega_{sm} = \frac{R_sL_m}{L_sL_r - L_m^2} \\ \omega_{rm} = \frac{R_rL_m}{L_sL_r - L_m^2} \end{cases} \tag{4}$$

where R_s and L_s are the stator resistance and inductance, R_r and L_r are the rotor resistance and inductance, and L_m is the mutual inductance converted to the stator side, respectively.

Suppose that a symmetrical fault occurs at $t = 0$ s, and the pre- and post-fault stator side voltage is u_- and u_+. p represents the depth of the voltage dip, and they satisfy the following equation as:

$$u_+ = pu_- \tag{5}$$

At the fault moment, the rotor parameter in matrix A changes dramatically as ω_r changes to ω_{rc}, and ω_{rm} to ω_{rmc} for that the crowbar is switched in, and the crowbar resistance is added into the rotor winding. As a result, the coupling from stator side to the rotor side is enhanced, whereas the coupling from rotor side to stator side stays almost the same. Therefore, the stator flux has great impact on the rotor current, and on the opposite, the impact of the rotor flux on the stator current is less obvious. As we focus on the feeding current from the stator side in this study, equation can be written as follows with the impact of the rotor flux neglected:

$$\begin{bmatrix} \frac{d\psi_{sd}}{dt} \\ \frac{d\psi_{sq}}{dt} \end{bmatrix} = \begin{bmatrix} -\omega_s & \omega_1 \\ -\omega_1 & -\omega_s \end{bmatrix} \begin{bmatrix} \psi_{sd} \\ \psi_{sq} \end{bmatrix} + \begin{bmatrix} u_{sd} \\ u_{sq} \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} = \frac{1}{L_sL_r - L_m^2} \begin{bmatrix} L_r & 0 \\ 0 & L_r \end{bmatrix} \begin{bmatrix} \psi_{sd} \\ \psi_{sq} \end{bmatrix} \tag{7}$$

Since the stator flux oriented control is applied before the fault occurrence moment, it is no harm to suppose that the initial stator flux satisfies the following equation:

$$\begin{bmatrix} \psi_{sd} \\ \psi_{sq} \end{bmatrix} \Bigg|_{t=0} = \begin{bmatrix} \frac{u_-}{\omega_1} \\ 0 \end{bmatrix} \tag{8}$$

From (6)–(8) we can get:

$$\boldsymbol{\psi}_s = \frac{u_-}{\omega_1} \left[(1-p) e^{-\omega_s t} e^{-i\omega_1 t} + p \right] \tag{9}$$

$$\mathbf{i}_s = \frac{L_r}{L_sL_r - L_m^2} \times \frac{u_-}{\omega_1} \left[(1-p) e^{-\omega_s t} e^{-i\omega_1 t} + p \right] \tag{10}$$

As demonstrated in (10), stator current in d–q coordinate system consists of the AC component in power frequency and the DC component during the electro-magnetic transient, according to this simplified model. Here the former one is the free component, and the latter one is the forced component. The angular speed of them is $-\omega_1$ and 0 respectively. Therefore, in the a–b–c coordinate system,