# Fault Ride-through Capacity Enhancement of Doubly Fed Induction Generator Based Wind Farm by Saturated Core Fault Current Limiter

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*Abstract*—**The increase of short-circuit fault capacity and fault ride-through (FRT) are the main issues of doubly fed induction generator (DFIG) based wind farm. In this paper, a new method of using saturated core fault current limiter (SCFCL) to improve FRT capability of DFIG-based wind farm is proposed. During fault condition in the grid, SCFCL not only limits the fault current but also contributes to maintain the stability of the generator terminal voltage and decrease the peak value of DC-link overvoltage at the instant of fault occurring. Accuracy and capability of the proposed method are confirmed by simulating a sample power system in MATLAB/Simulink software. Moreover, enhancement of different SCFCL impedance values and different installation locations are compared.**

*Index Terms*—**Saturated core fault current limiter (SCFCL), fault ride-through (FRT), doubly fed induction generator (DFIG), wind farm.**

## I. INTRODUCTION

The wind power, as a significant clean and renewable energy source, has bright prospects of development [1]. With the increase of stand-alone wind turbine capacity, the wind power generation system has evolved from the original distributed energy sources to a centralized large-scale wind farm. However, the emergence of large-scale centralized wind farms has also brought new technical issues to the power system. The short-circuit level increase and fault ride-through (FRT) are considered as two main problems under the fault condition.

On one hand, for short-circuit faults occurring in power systems, the short-circuit current is not only provided by the power system source, but also supplied by the large wind farm wind turbines, which could lead to the increase of the power system capability of short-circuit, and thus the short-circuit current may not be effectively blocked by the existing equipment alone. On the other hand, the decrease of generator voltage caused by the system short-circuit fault brings a series of transient processes, which will cause great harm to the wind turbines. Doubly fed induction generator has become the most popular wind turbine due to their high energy efficiency, variable speed, and reduced mechanical stress [2]. However, DFIG has high sensitivity to disturbances on the power grid, especially grid faults. Faults can cause voltage dips at the connection point, which in further result in a substantial increase in the DC link voltage of the power converter.

In order to prevent the damage of the converter, a crowbar system was applied to block the rotor side converter (RSC). However, once the crowbar circuit is active, the DFIG loses the ability to control both active and reactive power and even consumes reactive power from the system to prevent voltage recovery after the fault is removed. In addition, hardware modifications were proposed to increase DFIG FRT capability with a static series compensator (SSC), or STATCOM. However, this method is generally more expensive and has limited effectiveness in the event of a serious fault

Fault current limiter (FCL) is one of the most effective measures to limit the overcurrent when a fault occurs. The application of fault current limiter can also improve the transient performance of fan failure by reducing voltage sag. In order to run DFIGs uninterruptedly during grid faults, the quiescent current limiter was applied to the rotor circuit.in [7]. In [8], a comparison of FCL and STATCOM showed that FCL was more effective than STATCOM in raising FRT. In [9] based on the steady-state equivalent circuit analysis, qualitative analysis of enhancement of FCL with different current-limiting impedance transformations was put forward.

Compared with other FCLs, saturated core fault current limiter (SCFCL) has the advantages of low cost, simple structure, rapid response, high impedance amplification and no control device [10]. In this paper, a novel solution to FRT capacity enhancement of DFIG-based wind farm by SCFCL is proposed. Moreover, the enhancement of FRT by SCFCL of different limiting impedance values and on different installation positions are investigated and compared.

The article is organized as follows. Section □ introduces the DFIG wind turbine and the SCFCL, and an equivalent model of the grid connected to the wind farm is established. Section □ investigates the effect of SCFCL on the dynamic performance of wind farm and compare the influence of SCFCL of different limiting impedance values and on different installation locations. In section □, applicability and accuracy of this method is confirmed by simulating a sample power system in MATLAB/Simulink framework. In section □, conclusions are summarized.

## II. MODELING

### A. DFIG

A generalized machine mode in a synchronous frame reference of DFIG is established based on the following assumptions [11].

- Positive direction is assumed into the generator for the stator and rotor currents, and out of the grid-side converter for the grid filter current.
- All system parameters and variables are in per unit and referred to the stator side.
- The rotation speed of the rotor is assumed to stay constant during the electrical transients.

#### 1) Basic equations

- Flux equation

$$\begin{cases} \Psi_{sd} = L_{ss} i_{sd} + L_m i_{rd} \\ \Psi_{sq} = L_{ss} i_{sq} + L_m i_{rq} \\ \Psi_{rd} = L_{rr} i_{rd} + L_m i_{sd} \\ \Psi_{rq} = L_{rr} i_{rq} + L_m i_{sq} \end{cases} \tag{1}$$

- Voltage equation

$$\begin{cases} u_{sd} = \dfrac{d\Psi_{sd}}{dt} - \omega_0 \Psi_{sq} + R_s i_{sd} \\ u_{sq} = \dfrac{d\Psi_{sq}}{dt} - \omega_0 \Psi_{sd} + R_s i_{sq} \\ u_{rd} = \dfrac{d\Psi_{rd}}{dt} - s\omega_0 \Psi_{rd} + R_r i_{rd} \\ u_{rq} = \dfrac{d\Psi_{rq}}{dt} + s\omega_0 \Psi_{rd} + R_r i_{rq} \end{cases} \tag{2}$$

- Electromagnetic torque equation

$$T_e = n_p L_m \left( i_{sq} i_{rd} - i_{sd} i_{rq} \right) \tag{3}$$

where $\Psi$, $v$ and $i$ represent the flux, voltage and current. Subscripts $s$ and $r$ denote the stator and rotor quantities, respectively. $L_s$ and $L_r$ are the stator and rotor self-inductances, $L_m$ is the mutual inductance. $\omega_0$ is the speed of d-q reference frame and $s$ is the slip ratio. $n_p$ is number of pole-pairs. Also, $R_s$ and $R_r$ are the stator and rotor resistances.

#### 2) Equivalent circuit

The simplified equivalent model of DFIG is deduced as follows.

$$\begin{cases} \dfrac{dE_d'}{dt} = -\dfrac{1}{T_0'}\left[ E_d' + \left( X_s - X_s' \right) i_{sq} \right] - \omega_0 u_{rq}' + s\omega_0 E_q' \\ \dfrac{dE_q'}{dt} = -\dfrac{1}{T_0'}\left[ E_q' + \left( X_s - X_s' \right) i_{sd} \right] - \omega_0 u_{rd}' - s\omega_0 E_d' \end{cases} \tag{4}$$

$$\begin{cases} u_{sd} = R_s i_{sd} - X_s' i_{sq} + E_d' \\ u_{sq} = R_s i_{sq} - X_s' i_{sd} + E_q' \end{cases} \tag{5}$$

Where, $E_d'$ and $E_q'$ are d axis and q axis components of the equivalent transient electromotive force, $T_0'$ is electrical time constant and $X_s'$ is transient reactance. $\omega_0$ is the speed of d-q reference frame and $s$ is the slip ratio.

The equivalent circuit expressed by the generator equivalent transient electromotive force $E'$ and the transient impedance $R_s$+j$X_s'$ is shown in Fig.1.

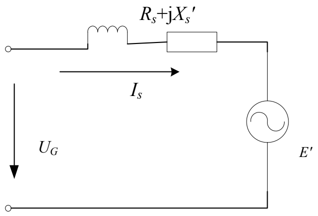

Fig. 1. Equivalent circuit of DFIG

### B. SCFCL

The SCFCL limits the short-circuit current by using the nonlinear variation of the magnetic permeability of the core material. The SCFCL has the low impedance ($Z_f$) in normal stare and the high impedance ($Z_F$) during fault. With features of fast transition and zero reset time, it is effective to model SCFCL as current dependent variable impedance. In this paper, a mathematical model as in Eq. (6) is used to simulate the dynamic response of the SCFCL in MATLAB/Simulink [12], where $i_Q$ is the critical quenching current, $n$ is a constant related to transition time.

$$Z_{FCL} = Z_F \frac{\left( \frac{i}{i_Q} \right)^n}{1 + \left( \frac{i}{i_Q} \right)^n} + Z_f \tag{6}$$

### C. GRID-CONNECTED WIND FARM

As the fault is not inside the wind farm, it is reasonable to adopt the comprehensive model of the wind farm to reduce the model complexity and the calculation time. Thus, assuming that all the wind turbines in the wind farm are in the same running state, the whole wind farm is equivalent to a single DFIG. Fig. 2 shows a conventional DFIG wind farm connected to a strong grid via two step-up transformers and double-circuit lines. The SCFCL is installed on the location A or the location B.

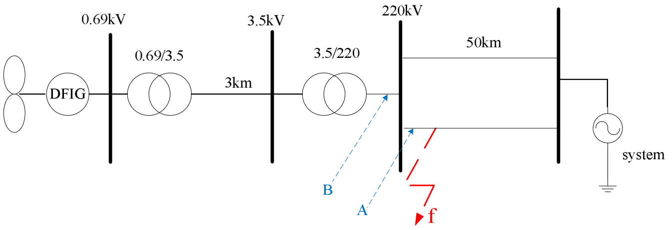

Fig. 2. Grid-connected wind farm model

## III. THEORETICAL ANALYSIS

### A. LOCATION A

Assume that the three-phase short-circuit fault in the system occurs at the head of a 220kV line and that the SCFCL is installed on the location A. The equivalent circuit is shown in Fig. 3 (a). $U_s$ is the grid voltage, $Z_L$ is the impedance of one transmission line, $Z_{T1}$ and $Z_{T2}$ are the impedances of transformers. To simplify the analysis, by ignoring the system impedance and

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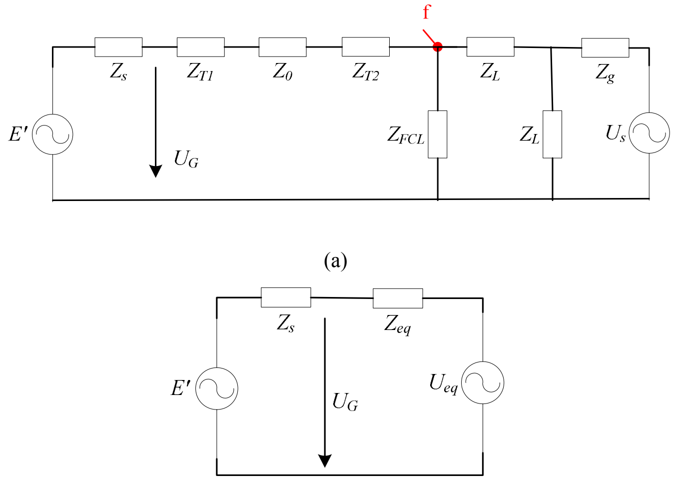
grounding impedance, the circuit is further equivalent in Fig. 3 (b) according to David theorem.



(b)

Fig. 3. Equivalent circuit of location A

By stacking theorem, the generator terminal voltage $U_G$ can be expressed as in Eq. (7). It can be proved that $U_G$ increases as $x$ increases (the SCFCL impedance value increases). It shows SCFCL application helps to maintain the stability of the generator terminal voltage.

$$\begin{cases} U_G = \dfrac{Z_{T1}+Z_0+Z_{T2}+\dfrac{xZ_L}{1+x}}{Z_{T1}+Z_0+Z_{T2}+\dfrac{xZ_L}{1+x}+Z_s}E' \\ \quad +\dfrac{Z_s}{Z_s+Z_{T1}+Z_0+Z_{T2}+\dfrac{xZ_L}{1+x}}\dfrac{x}{x+1}U_s \\ x=\dfrac{Z_{FCL}}{Z_L} \end{cases} \tag{7}$$

## B. LOCATION B

Assume that a three-phase short-circuit fault in the system occurs at the head of a 220kV line and that the SCFCL is installed on the location B. The equivalent circuit is shown in Fig. 4.

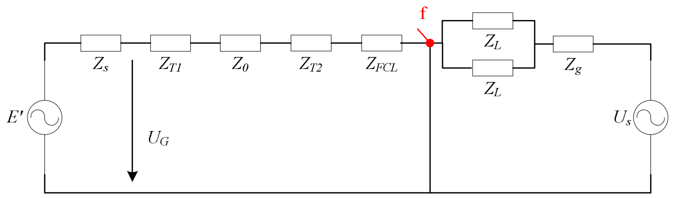


Fig. 4. Equivalent circuit of location B

The generator terminal voltage $U_G$ can be expressed as in Eq. (8). It can be seen that $U_G$ increases as the SCFCL impedance increases. But compared to installation on the location A with the same SCFCL impedance value, the effect is much less.

$$U_G=\frac{Z_{T1}+Z_0+Z_{T2}+Z_{FCL}}{Z_s+Z_{T1}+Z_0+Z_{T2}+Z_{FCL}}E' \tag{8}$$

## C. SUMMARY & COMPARISON

Analyzing and comparing Eq. (7) and Eq. (8), conclusion can be drawn that SCFCL contributes to maintain the stability of the generator terminal voltage at the instant of fault occurring by restricting the short-circuit current. The larger impedance value of SCFCL, the greater effect. Moreover, the SCFCL installed on the location A is more effective than the SCFCL of the same impedance value installed on the location B. This is because that SCFCL can effectively restrict the current from the grid to the short-circuit point and the current from the wind farm to the short-circuit point when SCFCL is installed on the location A. But when installed on the location B, SCFCL can only restrict the current from the wind farm. That leads to a larger voltage dip in transmission lines and results in a lower generator terminal voltage.

## IV. SIMULATION STUDY

## A. EFFECT OF DIFFERENT IMPEDANCE VALUES

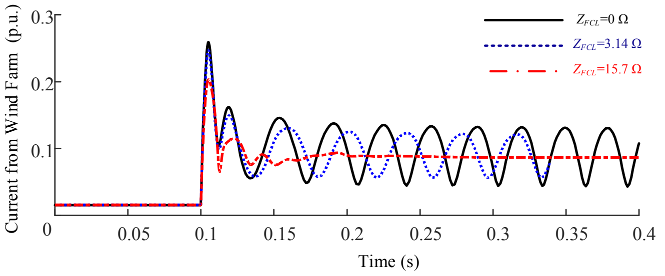
To illustrate the effectiveness of the method and to make a performance comparison among different SCFCL impedance values, a system as shown in Fig. 2 is modeled by MATLAB/Simulink. The system parameters used in the simulation are listed in Table □. The SCFCL of different limiting inductances (0, 10mH, and 50mH) are installed on the location A in sequence, where $Z_{FCL}$= 0, 3.14Ω, and 15.7 Ω.

TABLE I. SYSTEM PARAMETERS

| **Parameters** | | **Values** | **Parameters** | | **Values** |
|---|---|---|---|---|---|
| **Grid** | $U_s$ | 220kV | **DFIG** | $P$ | 9MW |
| | $f$ | 50Hz | | $R_s$ | 0.00706pu |
| | $Z_g$ | 0.005pu | | $R_r$ | 0.005pu |
| | $Z_0$ | 0.23+j0.66 | | $L_s$ | 0.171pu |
| | $Z_{T1}$ | 0.05pu | | $L_r$ | 0.156pu |
| | $Z_{T2}$ | 0.16pu | | $L_m$ | 2.9pu |
| | $Z_L$ | 2.53+j15.71Ω | | $H$ | 5.04s |

### 1) Limiting Current

In Fig. 5, $I_G$ is the current flow from the wind farm to the short-circuit point, and $I_S$ is the current flow from the grid to the short-circuit point.



(a)

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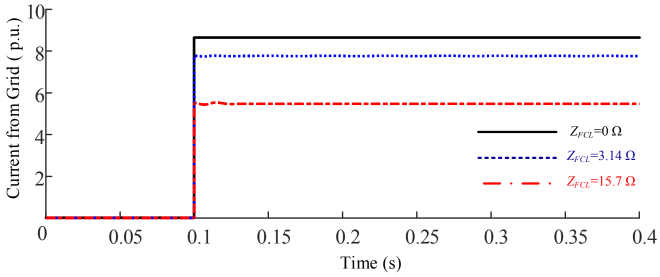


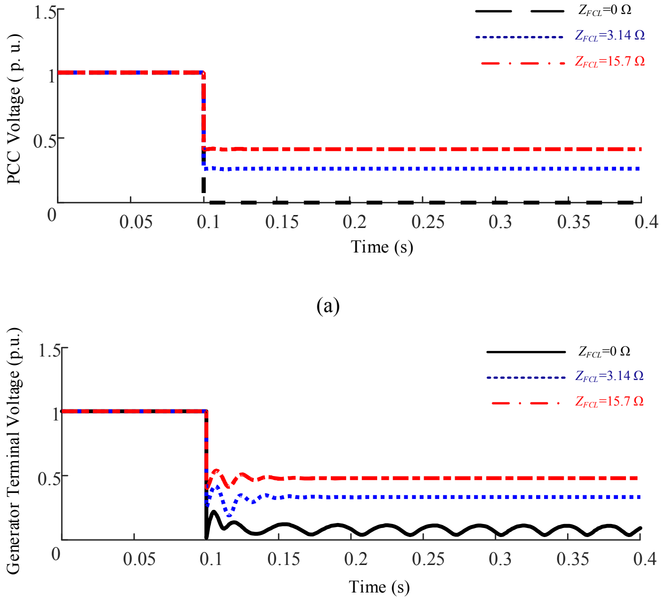
(b)

Fig. 5. (a) Current from wind farm (b) Current from gird

It can be seen that the currents under normal operation are quiet small relatively, while during the fault without SCFCL, the peak value of $I_G$ reaches 0.262p.u. and the peak value of $I_S$ reaches 8.63p.u.. By contrast, with SFCL impedance values of 3.14Ω and 15.7Ω, the peak values of are 0.248p.u. and 0.204p.u. and the peak values of $I_S$ are 7.79p.u. and 5.55p.u.. Moreover, with SFCL impedance value of 15.7Ω, the $I_G$ stabilizes quickly within 0.15s. It is verified that SCFCL can effectively restrict the short-circuit current and SCFCL installed on the location A can effectively restrict both the current from the grid to the short-circuit point and the current from the wind farm to the short-circuit point.

### 2) *Maintaining voltage*

In Fig. 6, $U_{PCC}$ is the voltage of the point of common connection (PCC), and $U_G$ is the generator terminal voltage.



(a)

(b)

Fig. 6. (a) PCC voltage (b) Generator terminal voltage

As shown in Fig. 6. (a), when the most serious system fault occurs, the value of $U_{PCC}$ can drop to nearly zero without SCFCL. But with SFCL impedance values of 3.14Ω and 15.7Ω, the $U_{PCC}$ can be maintained in 0.18p.u. and 0.42p.u. during the fault. As shown in Fig. 6. (b), when the most serious system fault occurs, the peak value of $U_G$ drops to 0.12p.u. without SCFCL. But with SFCL impedance values of 3.14Ω and 15.7Ω, the peak values of $U_G$ can be maintained in 0.34p.u. and 0.48p.u. during the fault. Moreover, with SFCL impedances of 3.14Ω and 15.7Ω, the $U_G$ stabilizes quickly within 0.1s. This confirms the theoretical study in Section □ that SCFCL helps to maintain the stability of the PCC voltage and the generator terminal voltage.

It is confirmed that both the voltage dips are effectively limited by installing a SCFCL on the 220kV transmission line and the limiting effect increases along with SCFCL impedance value increasing.

### 3) *FRT*

The coefficient $K$ is used to depict the overvoltage multiple of DC-link. As shown in Fig.7, the fault leads to an overvoltage of DC-link. Without SCFCL, the peak value of overvoltage rapidly increases to more than 2 times of the normal operation voltage within 0.05s and keeps increasing in further. While with SFCL impedances of 3.14Ω and 15.7Ω, the peak values of $K$ are reduced to 1.92 and 1.67. And with SCFCL, the overvoltage begins to decrease shortly after the increase. Moreover, with SCFCL impedance value of 15.7Ω., the overvoltage decreases to the normal operation voltage within 0.2s.

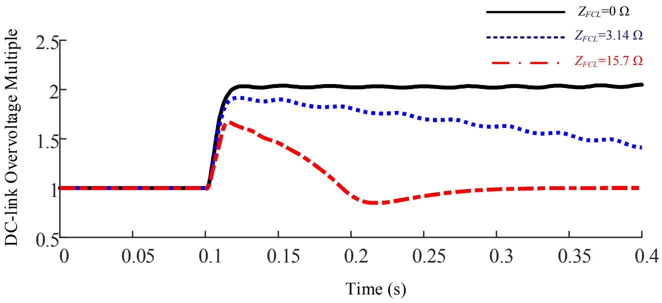


Fig. 7. Overvoltage of DC-link

The simulation results confirm the FRT capacity enhancement of DFIG-based wind farm with SCFCL maintaining the stability of the generator terminal voltage and decreasing the peak value of DC-link overvoltage during the fault. Also, the SCFCL reduces the oscillation and settling time of DFIG transient response during the fault.

## *B. EFFECT OF DIFFERENT INSTALLATION LOCATIONS*

To make a performance comparison between different SCFCL installation locations, a system as shown in Fig. 2 is modeled by MATLAB/Simulink. The limiting impedance value is set to 15.7Ω. The SCFCLs are respectively installed on location A and location B.

When the fault occurs, it leads to a short circuit current from grid to the fault point and then causes an overvoltage of DC-link. As shown in Fig. 8, with SCFCL installed on location A, the peak value of the short circuit current from the grid is reduced to 5.55 p.u. and the peak of the DC-link overvoltage multiple is reduced to 1.67. While with SCFCL installed on location B, the peak value of the short circuit current from the grid is 8.62 p.u. and the peak of the DC-link overvoltage multiple is more than 2. It suggests that the installation position of SCFCL has a significant impact on current limiting and FRT capacity enhancement. Moreover, the SCFCL installed on the location A is more effective than the SCFCL of the same impedance value installed on the location B.

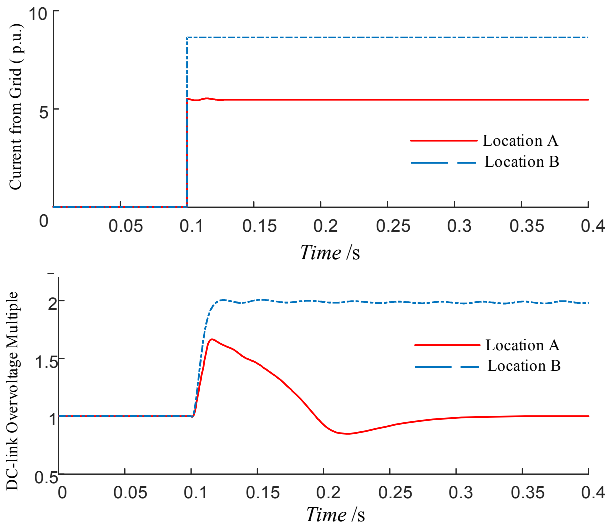


Fig. 8. Comparison between location A and location B

## V. CONCLUSION

In this paper, a new method of using SCFCL to improve FRT capability of DFIG-based wind farm is proposed. SCFCL contributes to maintain the stability of the generator terminal voltage and decrease the peak value of DC-link overvoltage at the instant of fault occurring. In this way, SCFCL is efficient in both fault current limiting and FRT capacity enhancement of DFIG-based wind farm. Moreover, the enhancement of different SCFCL impedance values and different installation locations are compared. The enhancement increases with SCFCL impedance value increasing, and the transmission line close to PCC is a better location for SCFCL installation.

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