A Method for FRT Capacity Enhancement of DFIG Based Wind Farm Using Saturated Core Fault Current Limiter

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***Abstract*—The short circuit level increase 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.**

Keywords—saturated core fault current limiter (SCFCL), fault ride-through (FRT), doubly fed induction generator (DFIG), wind farm.

I. INTRODUCTION

With the exhaustion of fossilized energy and the intensification of environmental pollution, the wind power has bright prospects of development as a significant clean and renewable energy source. The International Energy Agency (IEA) projects that by 2050, about 15-18% of global electricity will be generated from wind. With the increase of single capacity of wind turbines, the wind power generation system develops from the original distributed energy source to the centralized large-scale wind farm. However, the emergence of large-scale centralized wind farms has also brought new technical issues to the stable operation of the system.

On one hand, the short-circuit current is not only provided by the power system source, but also supplied by the large wind farm wind turbines, thus the short-circuit current may not be effectively blocked by the existing equipment. On the other hand, the generator voltage reduction caused by the system short-circuit fault brings a series of transient processes to the wind turbine, which would present significant harm to the safe operation of the wind turbines. Now the doubly fed induction generator (DFIG) is the most popular wind turbine system because of its various advantages such as high energy efficiency, variable speed and reduced mechanical stress on turbines [1]. But DFIG suffers from high sensitivity to grid disturbances, especially grid faults [2]. The fault can lead to a voltage dip at the connection point of DFIG even if it is far from turbine location. The dip results increasing of the stator current. Further, it may damage the rotor side converter (RSC) and cause a large increase in the DC-link voltage of the power converter.

To prevent over-current damage of the RSC, a crowbar system is applied to block the RSC. But once the crowbar circuit is active, the DFIG wind turbine loses the ability of controlling active and reactive power, and even consumes reactive power from the main grid, which prevents voltage recovery after fault clearance. In addition to crowbar approach, a hardware modification is put forward to improve the FRT capability of DFIG wind turbines by using static series compensator (SSC), or STATCOM [3]. However, this approach usually costs much more and has a limited effect in case of serious faults.

Fault current limiter (FCL) is one of the most effective measure to limit excess current when a fault occurs. The application of fault current limiter can also improve the transient performance of wind turbine during the fault by reducing the voltage dip. In [4], a static current limiter (SCL) was applied in the rotor circuit for uninterrupted operation of wind turbines equipped with DFIGs during grid faults. In [5] and [6], two different bridge-type FCLs were proposed for

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FRT enhancement. In [7], the direct comparison of FCL and STATCOM suggested that FCL is more effective than STATCOM in FRT enhancement. In [8], an analytical method based on the steady-state equivalent circuits to qualitatively analyze the enhancement of FRT with different limiting impedances of FCL is proposed.

Compared with other FCLs, the saturated core type FCL (SCFCL) has the advantages of low cost, simple structure, rapid response, high impedance magnification and no control device. In this paper, a new 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

This section deals with the model of DFIG in synchronous reference frame. The generalized machine model is developed based on the following conditions and assumptions [9].

- Positive direction for the stator and rotor currents is assumed into the generator, and for the grid filter current is out of the grid-side converter.
- The equations are derived in synchronous reference frame using direct (d) and quadrature (q) axes representation.
- All system parameters and variables are in per unit and referredto the stator side of DFIG.
- The rotation speed of the rotor is assumed to stay constant during the electrical transients.

1) Basic equations

a) Flux equation

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

b) Volitage equation

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

c) Electromagnetic torque equation

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

Where Ψ, 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. ω 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

Ignoring the nail winding transient and assuming the symmetry of d and q axis parameters for convenience, the simplified and practical dynamic equivalent model of DFIG is deduced as follows.

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

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

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.

The equivalent circuit expressed by the generator equivalent transient electromotive force E' and the transient impedance Rs+jXs' is shown in Fig. 1.

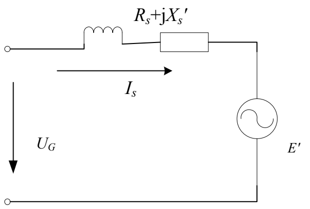


Fig. 1. Equivalent circuit of DFIG

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 state and the high impedance (Z_F) during fault. With the characteristics of fast transition and zero reset time, it is valid to model a SCFCL as a 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 [10].

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

C. Grid-connected wind farm

As the fault is not inside the wind farm, it is reasonable to adopt the comprehensive model of the large 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 large DFIG wind farm connected to a grid via two step-up transformers and double-circuit lines. The SCFCL is chosen to be installed on the location A or the location B.

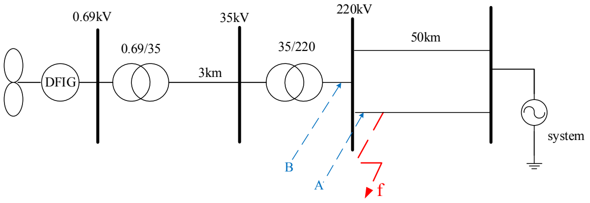
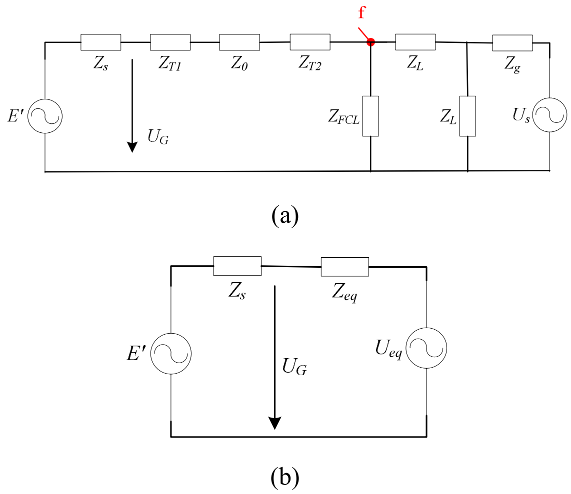


Fig. 2. Grid-connected wind farm model

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 grounding impedance, the circuit is further equivalent in Fig. 3 (b), where the equivalent voltage source U_{eq} and the equivalent impedance Z_{eq} can be obtained based on David theorem.



(a)

(b)

Fig. 3. Equivalent circuit of location A

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

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

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.

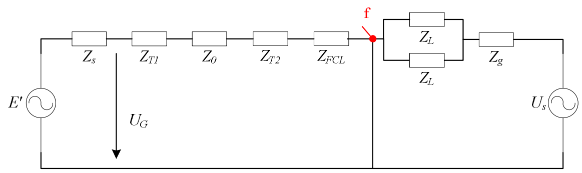


Fig. 4. Equivalent circuit of location B

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 and 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

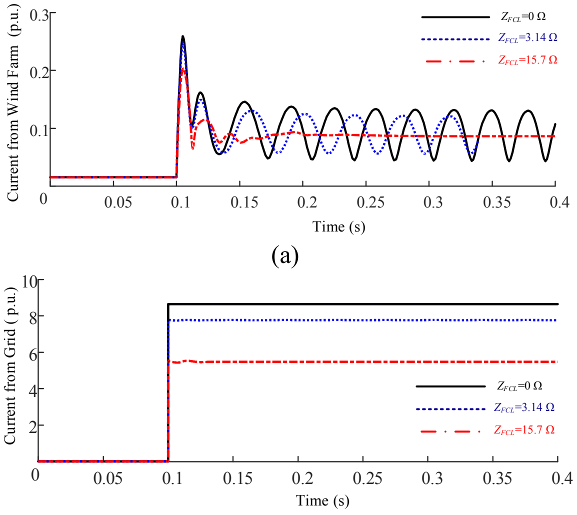
To illustrate the effectiveness of the method and to make a performance comparison among different SCFCL impedance values, a system as shown in Fig. 2 is modeled by MATLAB/Simulink. The system parameters used in the simulation are listed in Table □. The SCFCL of different limiting reactance values (0Ω, 3.14Ω, and 15.7Ω) are respectively installed on the location A.

TABLE I. SYSTEM PARAMETERS

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

1) Current limiting

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)

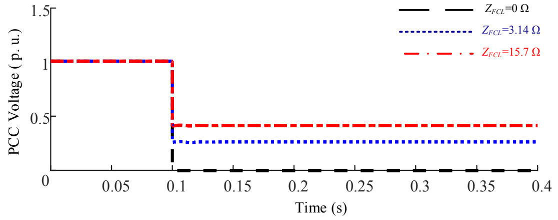
(b)

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

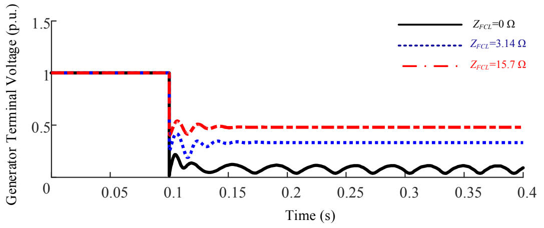
It can be seen that the currents under normal operation are quiet small relatively, while during the fault without SCFCL, the peak value of I_G reaches 0.262p.u. and I_S reaches 8.63p.u.. By contrast, with SCFCL impedance values of 3.14Ω and 15.7Ω, the peak values of I_G are 0.248p.u. and 0.204p.u. while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

2) Voltage maintaining

In Fig. 6, U_{PCC} is the voltage of the point of common connection (PCC), and U_G is the 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 SCFCL 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 minimum value of U_G drops to 0.12p.u. without SCFCL. But with SCFCL impedance values of 3.14Ω and 15.7Ω, the minimum values of U_G can be maintained in 0.34p.u. and 0.48p.u. during the fault. Moreover, with SCFCL 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.



(a)



(b)

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

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 SCFCL 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.

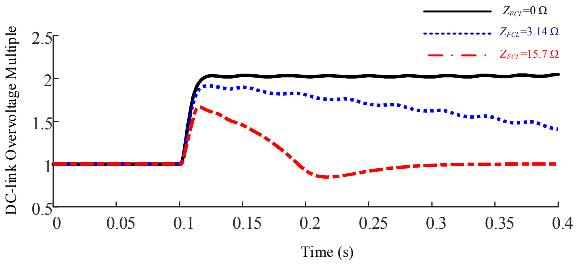


Fig. 7. Overvoltage of DC-link

The simulation results confirm the FRT capacity enhancement of DFIG-based wind farm with SCFCL maintaining the stability of the generator terminal volt-age and decreasing the peak value of DC-link overvolt-age during the fault. Also, the SCFCL reduces the oscilla-tion 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

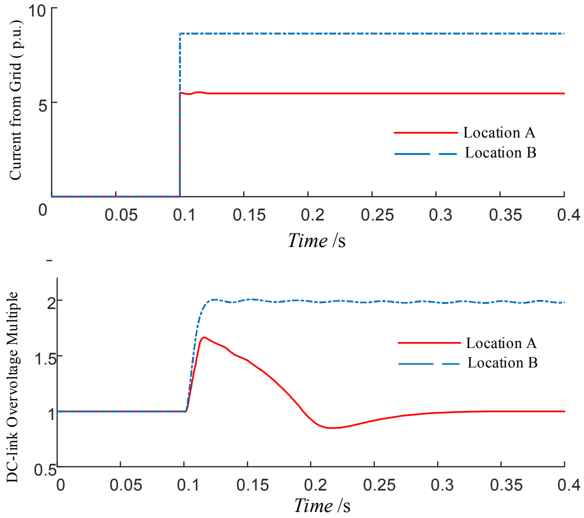


Fig. 8. Comparison between location A and location B

V. CONCLUSION

In this paper, a new method of using SCFCL to im-prove FRT capability of DFIG-based wind farm is pro-posed. 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 oc-curring. In this way, SCFCL is efficient in both fault cur-rent limiting and FRT capacity enhancement of DFIG-based wind farm. Moreover, the enhancement of different SCFCL impedance values and different instal-lation locations are compared. The enhancement in-creases with SCFCL impedance value increasing, and the transmission line close to PCC is a better location for SCFCL installation.

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