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Fault Ride-Through Capability Enhancement of DFIG-Based Wind Turbine With a Flux-Coupling-Type SFCL Employed at Different Locations

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Abstract—Doubly fed induction generators (DFIGs) have attracted a wide interest for wind power generation, but they suffer from high sensitivity to grid disturbances, particularly grid faults. In this paper, a modified flux-coupling-type superconducting fault current limiter (SFCL) is suggested to improve the fault ride-through (FRT) capability of DFIGs. The SFCL's structure and principle is first presented. Then, considering that the SFCL can be installed at a DFIG's different locations, its influence mechanism to the DFIG's FRT capability is analyzed, and some technical discussions on the design of the SFCL are carried out. Furthermore, the simulation model of a 1.5-MW/690-V DFIG integrated with the SFCL is built, and the performance analysis is conducted. From the results, introducing the SFCL can effectively limit the fault currents across the DFIG's stator and rotor sides, and when the stator side is selected as the installation site, the terminal-voltage sag can be also improved, which helps prevent the disconnection of the DFIG from the power grid. Doubly fed induction generator (DFIG), fault ride-through capability, flux-coupling-type SFCL, short-circuit current, transient simulation.

I. INTRODUCTION

WIND energy is the fastest growing source of renewable energy in the power industry, and its large scale application can contribute to solve the global problems such as environmental pollution and energy shortage. In regards to wind power generation, doubly-fed induction generator (DFIG) has attracted a wide interest . Actually, one of the main demands for DFIG is to guarantee its fault ride-through (FRT) capability, but DFIG suffers from high sensitivity to grid disturbances,especially grid faults When a short-circuit fault occurs in an electric grid with DFIG, stator current increases and a voltage dip will appear at the generator terminals. Further, the rotor side converter (RSC) may be blocked, and the wind turbine will be tripped .Currently, several solutions have been proposed to improve the FRT capability of DFIG . A brief comparison of three typical solutions is stated as follows. Introducing a static synchronous compensator (STATCOM) can only adjust the reactive power after fault occurrence. Employing a superconducting magnetic energy storage (SMES) can provide voltage protection of the RSC, but it may not suppress the overcurrent and electromagnetic torque oscillations. In contrast,installing a superconducting fault current limiter (SFCL) can restrict the fault current, prevent the disruption of protective equipment and affect the DFIG more directly.

In this paper, a modified flux-coupling type SFCL is adopted to enhance the transient performance of DFIG during a fault. presents the SFCL's structural principle, and discusses its influence mechanism to the DFIG's FRT capability as well as some technical issues about the device design. the model of a 1.5 MW/690 V DFIG integrated with the SFCL is built in MATLAB, and simulation analyses are carried out to access the SFCL's behaviors.

II. THEORETICAL ANALYSIS

A. Structure and Principle of the SFCL

The schematic configuration of the modified flux-coupling type SFCL is shown in Fig. 1(a). This SFCL is mainly composed of a coupling transformer (CT), a controlled switch S_1 and a superconducting coil (SC). The switch S_1 and the superconducting coil are respectively connected in series with the CT's primary and secondary windings, which are wound in reverse directions. The metal oxide arrester (MOA), which can be used to suppress switching overvoltage, is connected in parallel with the CT's primary winding. L_1, L_2 are the winding selfinductances, and M is the mutual inductance. In addition, Z_s is the circuit impedance and S_{load} is the circuit load. R_{SC}/R_{moa} is recorded as the SC/MOA's normal-state resistance. Since it is convenient to analyze the CT's characteristics by using the equivalent circuit whose parameters are expressed in terms of the mutual-inductance and self-inductances of the

(B) Electrical equivalent circuit.

windings the SFCL's impedance characteristic can be studied more clearly. According to the CT's equivalent circuit, the SFCL's electrical equivalent structure is shown in Fig. 1(b),where the series and parallel connections among the coupling windings, SC, MOA and S_1 become more intuitive.In normal (no fault) condition, the switch S_1 is closed and the SC is maintained in the zero-resistance/superconducting state.The SFCL's impedance is determined by the CT's operating impedance, which can be calculated as:

Supposing that the coupling coefficient k and transformation ratio n can be respectively expressed as figure 1

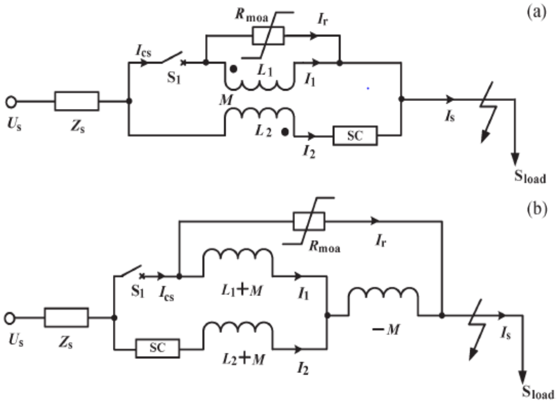

FIGURE 1 Modified flux-coupling-type SFCL

is obtained. In the case that an iron core is used to maximize the coupling, k will be approximate to 1 and $Z_{CT} \approx 0$. The non-inductive coupling is achieved, and the MOA is "shortcircuited".Consequently, the SFCL will not affect the main circuit.

After the fault happens, S_1 will be opened rapidly. Hence, a freewheeling circuit consisting of L_1 and R_{moa} will be formed, so as to restrain the switching overvoltage. Once the overvoltage is eliminated, the freewheeling circuit will be interrupted owing to the MOA's high resistance effect. Further, since the flux between the CT's two windings can no longer cancel out each other, the non-inductive coupling will be destroyed,and the superconducting coil will as well quench to its high resistance state. Right now the SFCL will play the role, andits current-limiting impedance can be calculated as

$$z_{CT} = jw[\frac{L_1+M}{L_2+M} - M]..............(1)$$

the modified SFCL is a resistive-inductive type (hybridtype) SFCL, which absorbs the merits of the two types of SFCLs and can theoretically enhance the transient performance of a power system more efficiently Besides, the use of the coupling transformer can make the AC current across the superconducting coil be adjusted flexibly, which helps to promote the SFCL's application in a high-voltage electric grid. The schematic diagram of a DFIG-based wind turbine with the SFCL is shown in Fig. 2, where the SFCL is designed to be installed at the DFIG's different locations. When a threephase short-circuit happens at the electric power grid, a series of transient electromagnetic changes will be caused, and the changes of stator and rotor fluxes are critical. Due to the power transformer, the DFIG's terminal voltage will not drop to zero. Herein a voltage-drop coefficient A_1 $(0 \leq A_1 \leq 1)$ is provided, and the terminal voltage is recorded as V_s.In accordance with the DFIG's equivalent circuit for transient analysis the fault currents across the DFIG's stator and rotor windings can be expressed .When the SFCL is respectively installed at the stator side or rotor side of the DFIG, the contributions of introducing Z_{SFCL} is to improve rotor windings of the DFIG can both be limited.

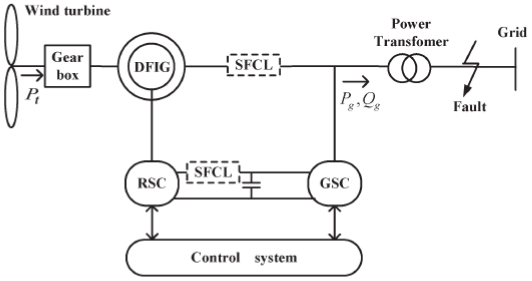

FIGURE 2 DFIG Based Wind Turbine With SFCL

Regarding the voltage compensation caused by the SFCL, the desired voltage boosting level should be considered. At the same time, it should be noted that if the voltage dip is too serious, the SFCL can undertake part compensation which is determined by its design parameters, and the remaining voltage compensation can be provided through DFIG converters as injected reactive current to fulfill grid code requirements.

C. Technical Discussion on Design of the SFCL

- Superconducting material**.** In regards to the superconducting coil included in the SFCL, it will suppress the DFIG's fault currents by the resistance generated at the superconducting-normal (S-N) transition. In a sense, this superconducting coil can be treated as a resistive SFCL, and the main HTS materials that have been employed in the resistive SFCL are: bulk Bi-2212 and YBCO 2G tapes .In view of that the YBCO 2G components may actuate faster than the Bi-2212 components, and the expected current-limitation is higher for the YBCO 2 components after the S-N transition . The YBCO 2G tapes may be more suitable for making the modified fluxcoupling type SFCL. At present, considering the commercial YBCO 2G tapes with high resistivity matrix with a linear resistance of 0.354 Ω/m, the transition to the normal state occurs from 2 ms up to 4 ms after the start of fault current when the current peak was limited to 8 times I_c.

The YBCO 2G tapes with stainless steel reinforcement can provide good mechanical properties, such as tensile strength above 250 MPa at room temperature, essential for designing the SFCL .

- AC loss. In a way, the AC loss of the HTS coil will be an important factor affecting the SFCL's engineering application. application. Its AC loss can be measured with a standard electrical technique, and also be calculated by finiteelement simulations. Theoretically, the superconductor's electrical properties may be modeled with a nonlinear power law where voltage varies as $(J/J_c)_n$, and the critical current density J_c and the power index n can be derived from the measured DC current-voltage characteristics.Accordingly, the AC loss can be computed in:

$$P = f \iint_{0}^{1/f} J.Ed \dots\dots\dots (2)$$

where *f* is the frequency, *S* is the superconductor's crosssection, and **J** and **E** are the current density and the electric field at each FEM node. From the simulation and experimental results in the AC loss will be reduced in the presence of externally applied AC magnetic field, but be increased in the presence of AC transport current. To reduce the SFCL's AC loss asmuch as possible, the coupling transformer should adopt an optimized transformation ratio, where the balance between the HTS coil's AC transport current and the controlled switch's breaking current is expected to be achieved.

- Operating temperature and cooling system.

SFCL is designed maximum temperature reached of about 300 K because thermal shock can degrade the HTStape. YBCO has limited temperature reached up to about 450 K which is melting point of solder in it. To achieve more thermally stable operation, the SFCL can be designed 190 K . Regarding the cooling system which is used to provide a low temperature environment for the SFCL, it should can diffuse the generated energy caused by the fault current and have a higher reliability.

MAIN SIMULATION PARAMETERS OF THE SYSTEM MODEL

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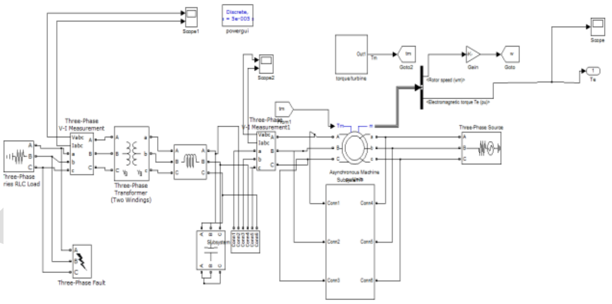

FIGURE 3 Simulink for DFIG With SFCL

In general, the HTS coil is immersed in liquid nitrogen (LN2), and a cryocooler can be used for keeping liquid nitrogen under boiling temperature . Based on the treatment of evaporating nitrogen, the cryogenic system can be divided into two kinds: open system and closed system . By comprehensively considering the cost, reliability and maintainability, the open cryogenic systemmay be adopted for the SFCL.The detailed engineering design of the SFCL for an actual wind power system will be performed in anther paper, and this article's next section is devoted to the simulation analysis.

III. SIMULATION STUDY

To quantitatively evaluate the SFCL's effects on the FRT capability of a DFIG, the simulation model corresponding is built in MATLAB, and parts of simulation parameters are indicated as Table I. In regards to the simulation case that the SFCL is respectively installed at the DFIG's stator side/rotor side, it is recorded as case I /case II, and the simulation conditions are set as that, a three-phase fault happens at $t = 1$s, and the fault duration/resistance is 0.1 s/0.1 Ω. Fig. 3 shows the quench and recovery model of the imitated superconducting coil . The SC will enter the normal state within 4 ms, and after the fault is removed, it does not recover the superconducting state at once due to the thermally accumulated joule energy.The recovery time is set to the value less than 0.5 s, so as to match up the auto-reclosing's operation.show the stator current and stator voltage of the DFIG for the case I. After installing the SFCL, the first peak values of the fault currents (i_{Af}, i_{Bf}, i_{Cf}) can be limited to 2.13 kA, 2.69 kA, 2.74 kA, respectively, in contrast 6.91 kA, 9.26 kA, 6.59 kA without SFCL. The inhibition rates of the expected fault currents will be 69.1%, 70.9%, 58.4%, respectively. Moreover, introducing the SFCL can make the DFIG's terminal voltage be maintained at 76% of normal value, which may prevent the disconnection of the DFIG from the main grid indicates the DFIG's stator current and stator voltage for the case II. Applying the SFCL can make the fault currents (i_{Af}, i_{Bf}, i_{Cf}) be limited to 3.15

kA, 5.92 kA, 5.08 kA, respectively. Compared with the two cases, the difference between their current-limiting rates will be respectively 14.7%, 34.8%, 35.5%. Obviously, the SFCL equipped at the rotor side cannot bring a positive effect on the DFIG's stator voltage.

As signified in they show the SFCL's effects on the DFIG's rotor fault current and output power. It is observed that no matter the SFCL is placed at the stator or rotor side of the DFIG, the rotor fault current's change can be suppressed, and it contributes to provide the overcurrent protection for thebRSC. But on the whole, the SFCL's performance behaviors will be better under the case I, where the SFCL can more effectively consume the DFIG's active power and smooth its reactive power, and the operational stability of the wind powerintegrated system can be well enhanced.

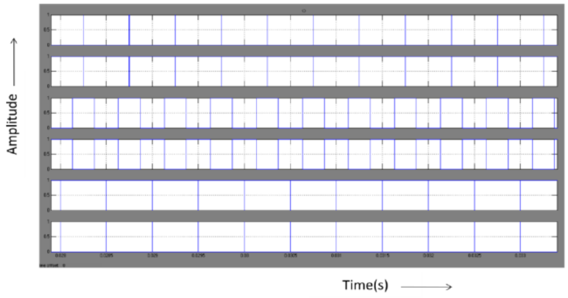

FIGURE 4 Wave for Pulse

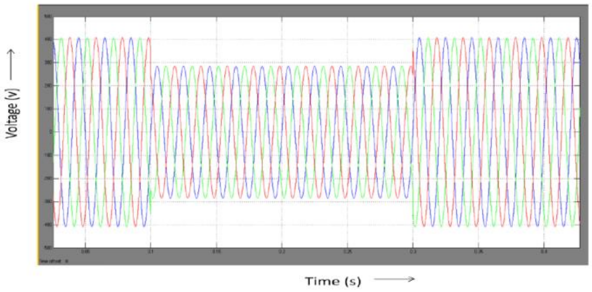

FIGURE 5 With Fault Wave form

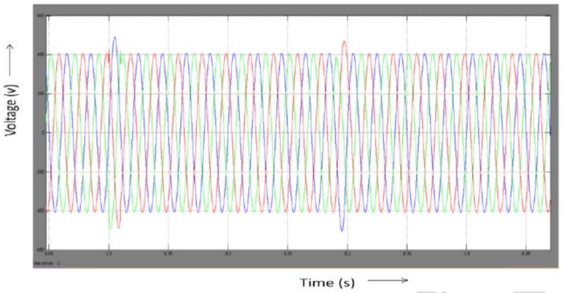

FIGURE 6 After using SFCL

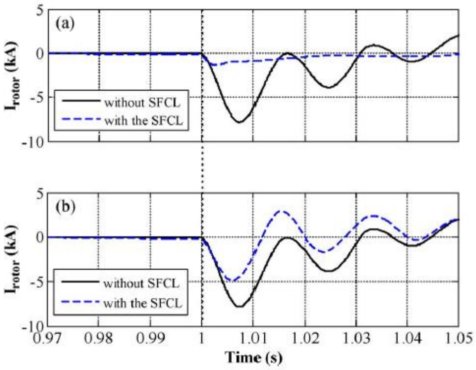

FIGURE 7 Waveform of without SFCL and with SFCL

IV. CONCLUSION

In this paper, a modified flux-coupling type SFCL is suggested to enhance the FRT capability of DFIG. Theoretical derivation, technical discussion and simulation analysis are performed.From the demonstrated results, introducing the SFCL can effectively limit the fault currents across the DFIG's stator and rotor sides, and when the stator side is selected as the installation site, the DFIG's terminal-voltage sag can also be improved, which helps to prevent the disconnection of the DFIG from the main grid and meanwhile enhance the wind power integrated system's operational stability. Regarding the modified SFCL's parameter optimization, AC loss calculation and engineering design, follow-up studies will be carried out and reported in the near future.

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