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Abstract—Direct drive high temperature superconducting (HTS) wind turbine generators have been proposed to tackle challenges for ever increasing wind turbine ratings. Due to smaller reactances in HTS generators, higher fault currents and larger transient torques could occur if sudden short circuits happen at generator terminals. In this paper, a finite element model that couples magnetic fields and the generator's equivalent circuits is developed to simulate short circuit faults. Afterwards, the model is used to study the transient performance of a 10 MW HTS wind turbine generator under four different short circuits, i.e., three-phase, phase-phase clear of earth, phase-phase-earth, and phase-earth. The stator current, fault torque, and field current under each short circuit scenario are examined. Also included are the forces experienced by the field winding under short circuits. The results show that the short circuits pose great challenges to the generator, and careful consideration should be given to protect the generator. The results presented in this paper would be beneficial to the design, operation and protection of an HTS wind turbine generator.

Index Terms—Finite element analysis, force, high temperature superconducting generator, short circuit, transient.

I. INTRODUCTION

HIGH temperature superconducting (HTS) generators have higher torque densities compared to their conventional counterparts. Therefore, HTS generators are expected to provide a competitive drive train for wind turbines with large power ratings [1]. Studies of HTS wind turbine generators in 10 MW rating and above have been of great interest, and several designs have been proposed [2]–[4].

Given the high price of HTS tapes commercially available in the market, a cost-effective design option is to employ a salient-pole iron rotor and an iron-toothed stator [5]. This topology results in to a partially superconducting machine, i.e., a copper AC armature winding and an HTS DC field winding, in which a large magnetic air gap exists because of needed space for a cryostat wall and thermal insulation [6]. Consequently, the reactance is lower than that in a conventional machine [7]. A lower reactance, on one hand, provides a faster dynamic response and a higher load capacity. On the other hand, it leads to a higher fault current and a larger transient torque under short circuit conditions [8], [9]. For instance, a peak value of the fault torque could be as high

as ten times the rated value. It would be very challenging to design the mechanical structure of a generator to withstand such a high peak torque since usually the generator structure is designed for three times the rated torque [10].

Unlike conventional generators in which the interests under short circuit conditions are mainly focused on stator currents and fault torques, in superconducting generators field currents are also of vital importance since they may exceed critical values and permanent damage to superconducting windings is possible [7]. Besides, large forces experienced by superconducting windings during short circuits cause excessive stresses and strains, which influence critical currents adversely.

Superconducting generators' performance under short circuit conditions has been studied in several publications. An analytical model and a finite element (FE) model were introduced in [8] and [11], respectively, to simulate short circuits in HTS machines. [12] reported influences of a series of generator parameters on stator currents and fault torques, assuming a constant rotating speed. [13] dealt with effects of electromagnetic (EM) shields and different armature teeth on stator currents and torques as well as field currents. Both [12] and [13] considered a three-phase short circuit under no load condition. The performance of HTS field windings under fault conditions was presented in [14] and [15], either focusing on over-current capabilities and thermal transient responses, or on magnetic fields.

Nevertheless, further improvements can be made. For example, it makes more sense to consider mechanical dynamics than assuming a constant rotating speed. Assuming a constant rotating speed means the drive torque always equals to the electromagnetic torque, which is unrealistic since the latter changes significantly during short circuits. In addition, different short circuits have different consequences, therefore, a systematic study of different short circuits is necessary to find the worst-case scenarios.

In this paper, a model that couples magnetic fields and generator's equivalent circuits is developed to study the transient performance of a 10 MW HTS wind turbine generator. Four different short circuit scenarios, i.e., three-phase, phase-phase clear of earth, phase-phase-earth, and phase-earth, are investigated. The stator current, fault torque, and field current under each short circuit scenario are investigated, and the forces experienced by the field winding under short circuits are also examined.

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II. TYPES AND MODELLING OF SHORT CIRCUITS

A. Types of Short Circuits

Four different short circuit faults (SCF) could happen at generator terminals, i.e., three-phase (L-L-L), phase-phase clear of earth (L-L), phase-phase-earth (L-L-Earth), and phase-earth (L-Earth), as illustrated in Fig. 1 [16]. Note that normally the neutral line of a generator is not grounded. In L-L-Earth and L-Earth short circuits, the worst case is that the neutral line is accidentally grounded, as depicted by the dashed lines in Fig. 1 (c) and (d). Although the occurrence is rare, the fault currents are so large that they could exceed a three-phase fault current. Therefore, in this paper the neutral line is grounded while studying L-L-Earth and L-Earth short circuits.
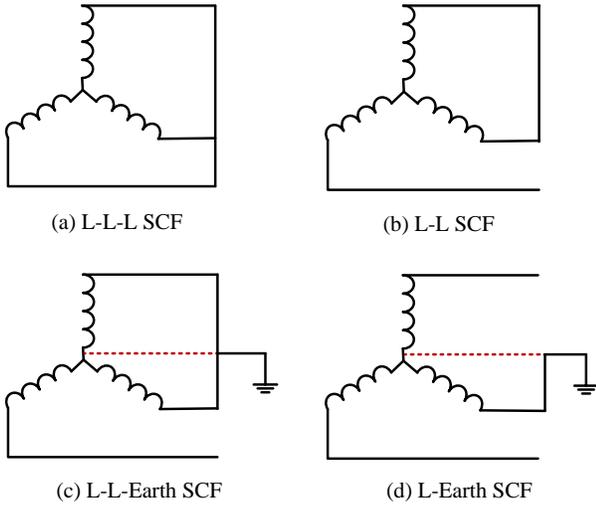

(a) L-L-L SCF   (b) L-L SCF

(c) L-L-Earth SCF   (d) L-Earth SCF

Fig. 1. Types of short circuit faults at generator terminals.

B. Modelling of Short Circuits

A two dimensional (2-D) model which couples the computation of magnetic fields and generator's equivalent circuits is developed to simulate short circuit faults in a superconducting generator.

The flux linkages in three phases λ_a, λ_b, λ_c, and their time differentials $\frac{d\lambda_a}{dt}$, $\frac{d\lambda_b}{dt}$, $\frac{d\lambda_c}{dt}$ are computed in a finite element model, and then coupled with the generator's equivalent circuits to get three phase currents i_a, i_b, and i_c. The flux linkage in the field winding λ_f and its time differential $\frac{d\lambda_f}{dt}$, as well as the field current i_f, can be obtained in the same way.

The generator's equivalent circuits are given by [8] [13]:

$$u_a = \frac{d\lambda_a}{dt} - r_s i_a - L_{\sigma s}\frac{di_a}{dt} \tag{1}$$

$$u_b = \frac{d\lambda_b}{dt} - r_s i_b - L_{\sigma s}\frac{di_b}{dt} \tag{2}$$

$$u_c = \frac{d\lambda_c}{dt} - r_s i_c - L_{\sigma s}\frac{di_c}{dt} \tag{3}$$

$$u_f = \frac{d\lambda_f}{dt} + r_f i_f + L_{\sigma f}\frac{di_f}{dt} \tag{4}$$

where u_a, u_b, and u_c are the phase winding terminal voltages; u_f is the field winding terminal voltage; r_s and r_f are the resistances for the phase winding and the field winding, respectively. The end winding leakage inductances $L_{\sigma s}$ and $L_{\sigma f}$ for the phase winding and the field winding are also included. It is necessary to point out that it is more practical to excite the field winding by a voltage source rather than a current source. The reason is that an unrealistic over voltage and instantaneous power should be provided by the current source if a short circuit happens [13].

By assigning proper constraints to u_a, u_b, and u_c, different short circuits can be achieved. For example, $u_a = 0$ realizes an L-Earth short circuit, while $u_a = u_b$ realizes an L-L short circuit.

The mechanical dynamics can be integrated into the model by:

$$T_m - T_e = J\frac{d\omega_m}{dt}, \tag{5}$$

where T_m is the mechanical torque driving the generator; T_e is the electromagnetic torque produced by the generator; J is the moment of inertia of the whole drive train including the blades, hub, shaft and generator itself; ω_m is the mechanical rotating speed of the rotor. Under no load conditions, T_m equals zero; under rated load conditions, T_m equals the rated electromagnetic torque of the generator.

The model described above is implemented both in Ansoft Maxwell and Comsol to study L-L-L and L-L short circuits of a 10 MW low temperature superconducting (LTS) wind turbine generator proposed by General Electric (GE) Global Research. The results obtained from Ansoft Maxwell and Comsol are in good agreement with each other, and also with those in [10].

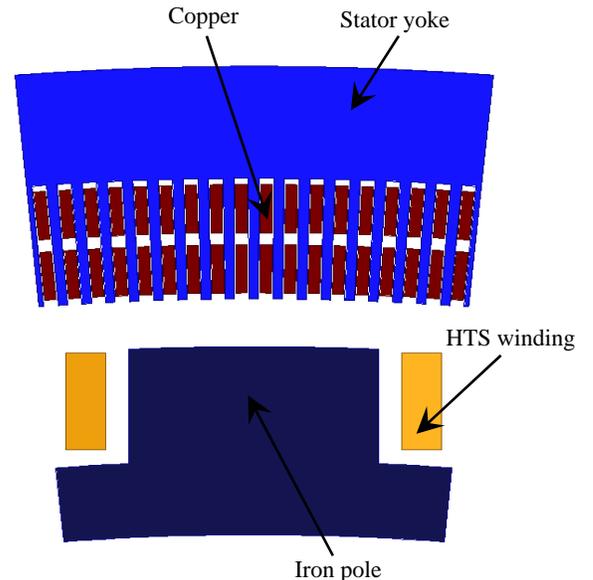## III. SHORT CIRCUITS OF A 10 MW HTS WIND TURBINE GENERATOR

A. Generator Model

Fig. 2. Illustration of a one-pole segment of the modified 10 MW HTS wind turbine generator.

Width of the HTS tape (mm)	12
Thickness of the HTS tape (mm)	0.2
No. of layers per coil	8
No. of tapes per layer	110
Operating temperature (K)	30
Operating current (A)	388
Critical current (A)	550

Types of short circuits	Peak values of F_τ (Per unit)	Peak values of F_r (Per unit)
L-L-L	9.47	4.6
L-L	10.7	4.4
L-L-Earth	10.4	4.5
L-Earth	9.7	3.8

A 10 MW direct drive LTS wind turbine generator introduced in [10] has been modified to an HTS generator. A one-pole segment of the HTS generator is illustrated in Fig. 2. By replacing the LTS field winding with the HTS field winding, the specifications of the field winding change accordingly, as listed in Table I.

The HTS generator has the same output power and stator specifications as the original LTS generator, except the changes in the air gap, EM shield, and rotor. The magnetic air gap of the generator is decreased from 84 mm to 50 mm since the HTS field winding has a less demanding requirement of thermal insulation than the LTS field winding does. The EM shield is eliminated in the HTS generator as it has very limited influence on short circuits [13]. Also, an iron pole is adopted in the rotor to reduce the usage of HTS tapes.

B. Stator Currents and Faults Torques

The generator operates at the rated condition from 0 to 1 s. The short circuits then take place at the instant of 1 s when the voltage in phase A is passing through zero and the flux linkage in phase A is maximum. Therefore, maximum fault currents occur in phase A. Fig. 3 and Fig. 4 respectively show the current waveforms in phase A and the torque waveforms of the generator five seconds after the instant of short circuits.

As shown in Fig. 3, the stator currents increase to their peak values within the first half circle after the instant of short circuits. The maximum peak value of the stator currents is 18 times the rated value, and occurs in an L-L-Earth short circuit. Fig. 4 indicates that the generator produces a maximum torque of 10 times the rated value when an L-L short circuit happens at the generator terminals. Such high stator currents and fault torques pose a great challenge to the generator. For instance, the insulation of the stator winding might get burnt due to intense heating during short circuits; or the generator mechanical component could collapse if, for instance, protective devices fail to clear short circuits fast enough.

C. Field Currents

Similar to the stator currents, the field currents also increase after the instant of short circuits. This phenomenon can be understood by the fact that the flux linkage in any winding can not change instantaneously. Short circuits tend to decrease the flux linkage, thus both the stator current and the field current increase to maintain the flux linkage.

Fig. 5 depicts the variations of the field currents in 2 seconds after the instant of four different types of short circuits. The increase of the field currents leads to elevated magnetic fields experienced by the HTS tapes, and the critical currents decrease consequently. It can be seen that the field currents have peak values about 40% higher than the rated ones in L-L-L, L-L, and L-L-Earth short circuits, and about 30% higher in an L-Earth short circuit. Fig. 5 shows that the field currents obviously exceed the critical currents in L-L-L, L-L, and L-L-Earth short circuits, which means resistive losses occur in HTS tapes. Also noted is that the field currents vary with respect to time, which means AC losses exist. The resistive losses and AC losses yield a temperature rise, which in turn decrease the critical currents.

A straightforward approach to mitigate the temperature rise is operating superconducting windings with a lower load factor, i.e., giving enough safety margin. However, it is not economically satisfying to operate superconducting windings with a lower load factor. A better solution could be allowing the field currents to exceed the critical currents to a reasonable extent on condition that the temperature rise is limited and superconducting windings can fully recover after short circuits are cleared [14].

D. Forces

The tangential force exerted on the rotor that produces the torque significantly increases owing to the occurrence of short circuits, so does the force experienced by the field winding. Table II lists the peak values of both tangential forces F_τ and radial forces F_r applied on the field winding during short circuits. The reason for the large forces is that the main magnetic flux becomes larger due to increased field current.

As revealed in Table II, the tangential forces could be as high as ten times the rated values, and the radial forces could be four to five times the rated values. Due consideration needs to be given to these large forces since excessive stresses and strains are generated in HTS tapes, which influence critical currents negatively. In addition, these large forces need to be handled by the supporting elements of the field winding. From an economic perspective, it is not advisable to design the supporting elements to withstand such large forces at nominal operation. A better way could be designing the supporting elements with a reasonable safety factor at nominal condition, and limiting the peak forces through a fast acting protection system.
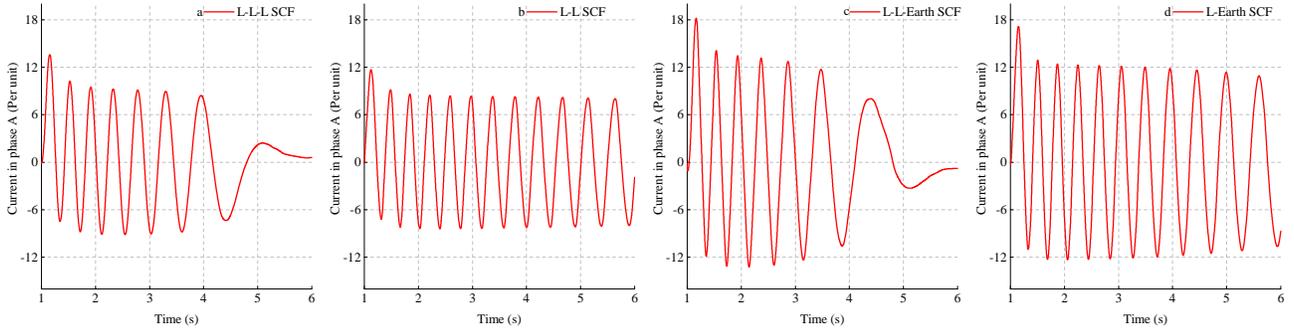
Fig. 3. Current waveforms in phase A in 5 seconds after the instant of (a) L-L-L; (b) L-L; (c) L-L-Earth; (d) L-Earth short circuit faults.
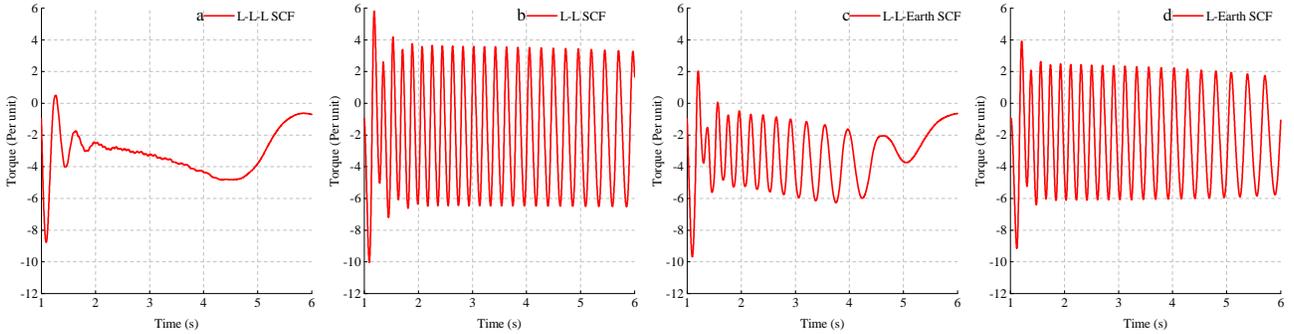

Fig. 4. Torque waveforms of the generator in 5 seconds after the instant of (a) L-L-L; (b) L-L; (c) L-L-Earth; (d) L-Earth short circuit faults.
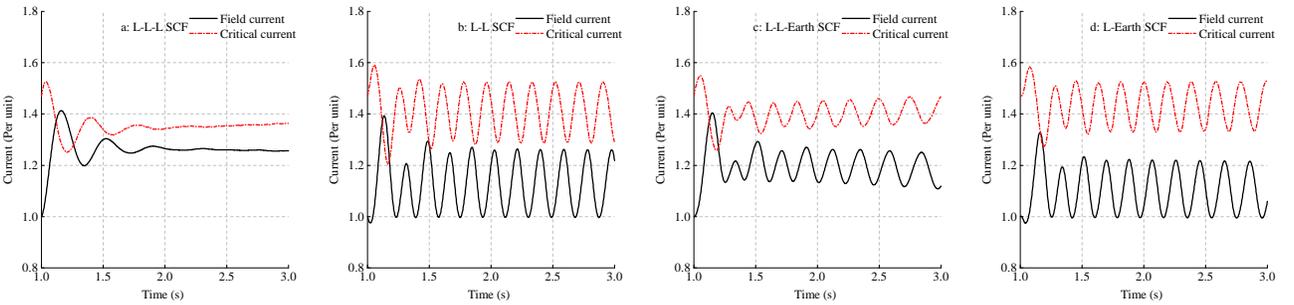

Fig. 5. Field current waveforms in 2 seconds after the instant of (a) L-L-L; (b) L-L; (c) L-L-Earth; (d) L-Earth short circuit faults. The solid lines represent the field currents while the dash lines represent the critical currents.

IV. CONCLUSION

Four types of short circuits of a 10 MW HTS wind turbine generator are systematically studied in the paper. The findings reveal that the extent of influence of short circuits on the generator depends on the types of short circuits. When rating a circuit breaker to interrupt fault currents, it is advisable to refer to a phase-phase-earth short circuit which produces a maximum fault current. A phase-phase short circuit, which results in a maximum fault torque, should be considered for the safety of the generator mechanical structure. The field currents in the HTS field winding under short circuits increase by 30% to 40%, depending on the types of short circuits. The over currents and the associated temperature rise should be handled properly to avoid damages to the field winding. The results also indicate that the field winding experiences excessive forces under short circuits, and these forces tend to overload the supporting elements and decrease the current-carrying capacity of the field winding.

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