III-21. TWO DIMENSIONAL FINITE-ELEMENT SIMULATION OF A HIGH TEMPERATURE SUPERCONDUCTING SYNCHRONOUS GENERATOR DURING THREE-PHASE SHORT-CIRCUIT FAULT CONDITION USING FULL TRANSIENT NON-LINEAR ROTATING MACHINE MODEL

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Abstract - **This paper describes fault analysis of a 100kVA high temperature superconducting synchronous generator (HTSSG) using two dimensional (2D) finite element modelling. The 100 kVA generator dimensions are based on the actual machine under construction in the Electrical Power Engineering Research Group at University of Southampton, United Kingdom. The non-linear transient modelling was simulated taking into account the relative movement between the stator and rotor. The high temperature superconducting field windings were analysed using external circuit equations as the equivalent supply voltage and resistance.**

Introduction

It is important for electrical machine designer to understand the causes of instability in a machine especially due to sudden three-phase short-circuit condition. This will provide essential stability margins and hence suitable specification of control system and protective devices can be decided upon before the machine is built. In the past most designers relied on the use of complicated equivalent circuit machine models whose parameters are difficult to obtain with good accuracy during the design stage. The finite-element method provides better facilities to model complicated geometry of electrical machines, including saturation effects in iron, thus leading to better understanding of the short-circuit phenomenon. Many researchers, in particular Turner [1], has proved that numerical analysis using finite-element method gives answer consistent with test results for various machine designs.

The short-circuit analysis is of particular importance when considering devices operating in very low temperature environment. In this case the field winding of the HTSSG is made of silver clad $(BiPb)_2Sr_2Ca_2Cu_3O_x$ or better known as BSCCO tapes which operate in a temperature range 73-77 K. During fault condition, large transport currents are expected to be induced in these windings; these cause large loss densities which may lead to thermal runaway and could damage the winding.

The design reported in this paper is based around an existing stator which has 48 slots and a balanced 2-pole 3-phase winding. The stator winding is short pitched (14/24) with two parallel circuits connected in each phase. The rotor of the generator (with hybrid salient pole design) is made of 9% Nickel steel plates of various sizes and shapes. The superconducting field winding consists of ten 40-turn identical flat coils placed in between 9% Nickel steel flux diverters. The flux diverters made of 9% nickel steel are placed between the coils to reduce the normal field in the coils by diverting flux around them. The required low temperatures are provided using a purpose built closed circuit liquid cryogen cooling system with pipe-network feeding liquid cryogen to the rotor body of the generator and to the copper radiation screen. Details of the design of the HTSSG may be found in [2].

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2D Transient Rotating Machine Model

The generator is modelled by a transient 2D finite-element model which includes rigid body rotation of the rotor. External circuits are linked to the 2D model to simulate the connections between the coils. The resistance of the armature winding and the end winding leakage inductance are included in the definition of the external circuits. The value of the end winding leakage inductance was estimated using a formula based on Kilgore [3]; this gave a value of 0.125 mH. The rotor is set to rotate at a fixed speed of 3000 rpm and the time-step was chosen to hide the effects of tooth ripple, which in this case are believed not to be significant. Therefore, a fixed time step of 0.417 ms was used which is equivalent to a period for the rotor to pass one stator slot. Non-linear analysis was used throughout because the saturation of the rotor core was thought to be important. For simplicity, the coils are considered as being constructed from filamentary wires such that skin and proximity effects in the turns are ignored.

The symmetry of the machine is exploited to halve the area that needs to be modelled; regions are bounded by the rotor inter-polar axis and the back of the stator core: the later was taken as flux line with A=0 and the former had a periodicity boundary condition with A at 180° = $-A$ at 0°. The model was discretised into 24496 elements in order to obtain a solution with minimal error. The simulation of this time stepping rotating machine model was carried out using available finite-element OPERA software. Figure 1 shows the extent of the models used and the mesh near the coils.

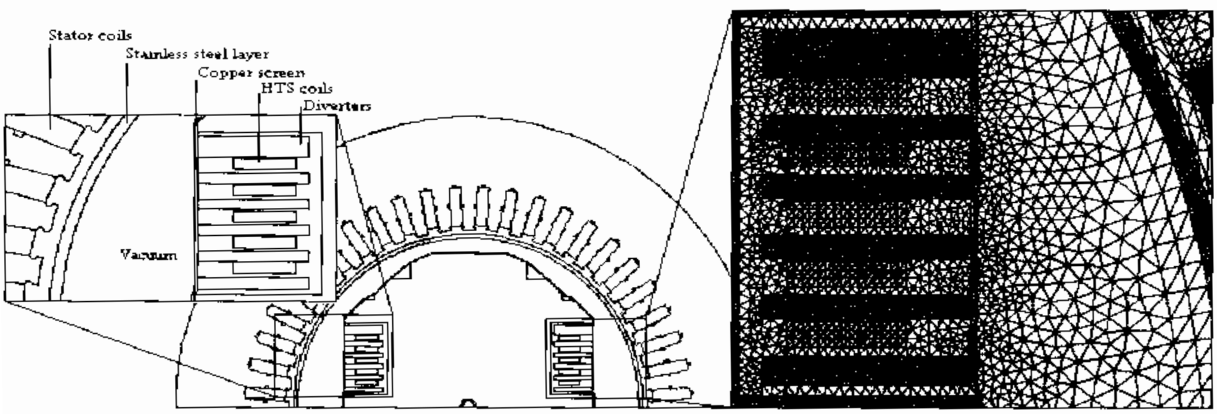

Fig. 1. 2D model of the high temperature superconducting synchronous generator.

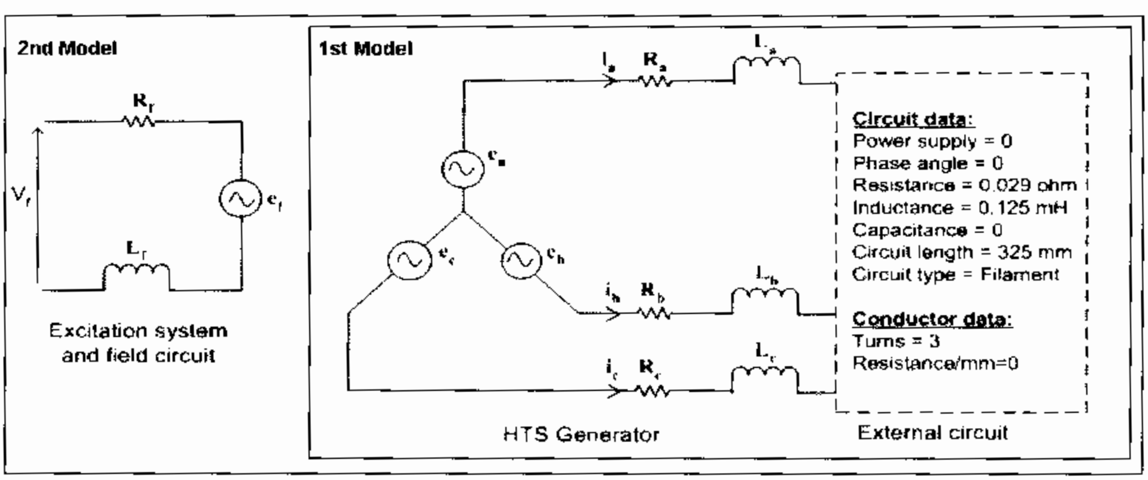

Fig. 2. The circuit arrangement for finite element modelling.

The generator was subjected to a three-phase balanced short-circuit at the terminals, starting from the no-load condition. Important parameters, such as direct axis reactances and time constants, were derived from the predicted waveforms. Finally, the use of a substantial negative field voltage to reduce the large fault currents in the field circuit was investigated.

Since it was unclear what value of resistance should be used for the field circuit, two models were produced. In the first approach, a constant value of field current was imposed by removing the field circuit from the model. In the second model, a low value of resistance (10 mΩ) was used to represent the resistance of the field circuit under normal operating conditions. Figure 2 shows the external circuit arrangement for the two models used for short-circuit analysis.

Results

The envelope of the AC component is high at the instant of short-circuit and decays ultimately to the sustained value I_S. If I_S is subtracted from the AC wave, the remainder is found to consist of two exponential components: transient component I' with long time constant, T_d', and subtransient component I'' with short time constant, T_d''. In addition to these AC currents, the waveforms of the stator currents each include a decaying DC component. The waveforms of the stator currents for the first and second model are shown in Figure 3 (a) and (b) respectively. In general, each short-circuit armature current waveform consists of a unidirectional or DC component and three AC components, and is given by an expression of the form

$$I_{SC} = I_{DC} e^{(-t/T_a)} + I_S \cos(\omega t + \phi_0) + I' e^{(-t/T_d')} \cos(\omega t + \phi_1) + I'' e^{(-t/T_d'')} \cos(\omega t + \phi_2) \qquad (1)$$

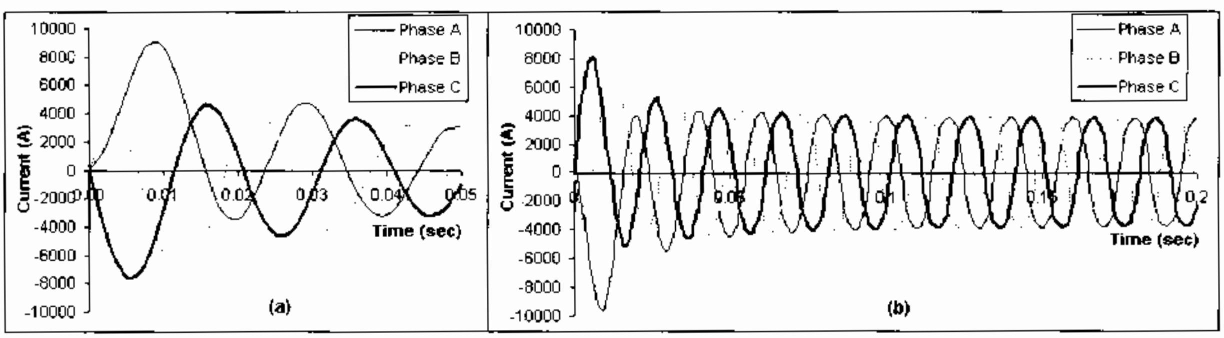

Fig. 3. Currents as a function of time for HTSSG short-circuited while running at no-load: (a) With constant value of field current and (b) With low resistance applied to the external field circuit.

The DC current components arise because, at the instant of short-circuit, the flux linking the stator windings differs from the value required to drive the sustained current. The DC components drive this additional flux, and are driven by the decay of the flux. The algebraic sum of the DC components is zero and they all decrease to zero exponentially with the same armature time constant, T_a. The transient and sub-transient currents arise from similar mechanism due to the flux trapped in the field winding and damper winding (radiation screen) respectively.

Due to the low resistance of the field circuit in the second model, the transient time constant is very long; the length of the simulation is therefore too short to give any estimate of the synchronous reactance or transient time constant. The synchronous reactance was therefore obtained by fitting the results from the first model into Equation 1 with the 3rd term removed. The difference between synchronous and transient reactances is due to eddy currents in the field circuit which are not allowed in the first model. This is due to the fact that the constant field current applied does not affect the transient term. Other parameters were obtained by curve fitting Equation 1 into the second model, and their values are shown in Table 1.

When a transient that is caused by a short-circuit, is induced into the field, a large positive fault current results. In order to investigate the voltage required to control this large current, a negative voltage was applied externally to the field winding 5 ms after fault initiation. It can be seen from Figure 4 that, with -175 V, the field fault current was successfully reduced.

Table 1. The direct reactances and time constants of the HTSSG

Reactances (p.u.)		Time Constants (sec)	
xd	0.1191	Td'	-
xd'	0.0729	Td"	0.0206
xd"	0.0408	Ta	0.0120

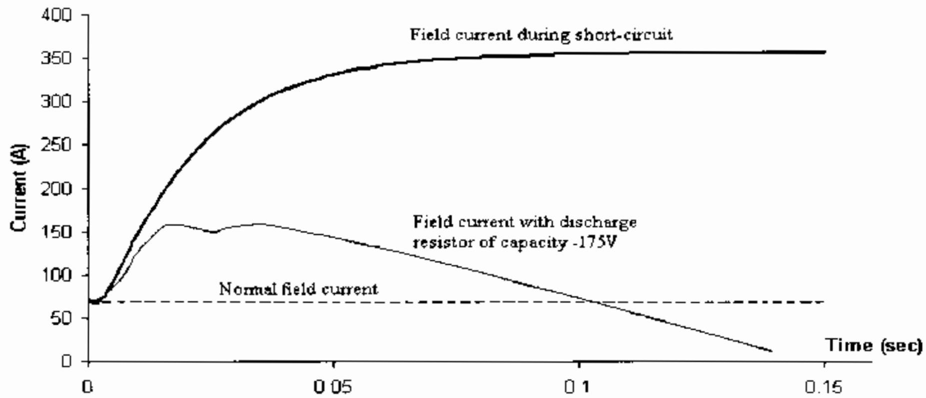

Fig. 4. The unidirectional component in the field current of the HTSSG

Conclusions

The simulation of the HTSSG during symmetrical three-phase short-circuit was successfully analysed using full transient rotating machine model. As expected the reactances were found to be of very low value compared to conventional generators. This is due to the large air gap needed to accommodate the thermal insulation. The field current during the fault condition was also analysed due to the anticipated large current that may cause damages to the superconducting field windings.

Acknowledgement

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References

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