LOAD CHARACTERISTICS ANALYSIS OF A 100KVA SYNCHRONOUS GENERATOR WITH HIGH TEMPERATURE SUPERCONDUCTING FIELD WINDING USING FINITE ELEMENT MODELLING

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In the development of a high temperature superconducting synchronous generator it is important to analyse the magnetic saturation of the machine so that its internal state during load operation prior to the disturbance is accurately predicted. Furthermore, the use of a superconducting field winding makes the machine more vulnerable to system instability. A modest increase in the field current may cause large loss densities in the winding, leading to thermal runaway. This would require the machine to be shut down while the winding temperature returned to normal, which would compromise the reliability of machine. In this paper a method, employing finite element analysis, is established to calculate the saturated reactances of synchronous machines under steady state operation.

1 Introduction

It is well known that superconducting generators have many advantages in the terms of economic and technical benefits over the conventional generators. The ability to predict accurately the electrical response of the machine ensures that the performance is within stability margin. In the case of a high temperature superconducting (HTS) synchronous generator, two particular areas of concern can be identified both associated with losses generated in the 'cold' regions. The losses in the superconductor increase rapidly as functions of both temperature and current density. Consequently it is necessary to determine the temperature and current that may occur in the field winding due to transient events. A two dimensional finite element model is employed. Direct and quadrature axis reactances, are evaluated by finite element analysis taking saturation into account.

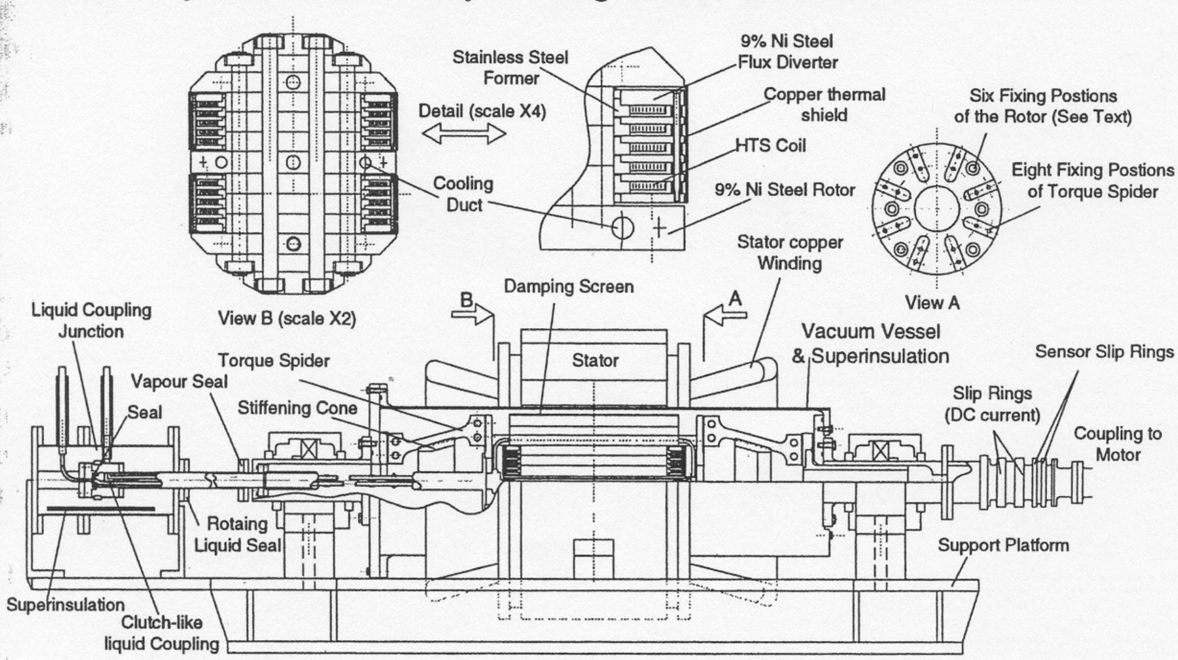

Figure1 Sketch of the 100kVA HTS generator.

The machine used in this evaluation is a 3-phase 2-pole 100-kVA 3000-rpm synchronous generator with a hybrid salient pole rotor. The stator winding is short pitched (14/24) with two parallel circuits. The design of the machine is shown in Figure 1 and the superconducting generator will be built at University of Southampton, United Kingdom [1]. The rotor will operate in the temperature range 73-77K and be equipped with a high-temperature superconducting field winding made of stainless steel reinforced Ag-clad Bi-2223 tapes. Since most ferromagnetic materials are brittle at liquid nitrogen temperatures, the rotor of the generator will be made of 9% Ni steel. The use of Invar (36% Ni, 64% Fe) was also considered, but the low thermal expansion coefficient of Invar presented great difficulty in connecting it to non-magnetic structural materials.

2 2D Finite Element Model

The symmetry of the machine is exploited to halve the area that needs to be modelled. This reduces the amount of work needed to create the model and reduces the number of elements and nodes required. Figure 2 shows the extent of the models used. The losses in the cold region may be greatly reduced by introducing a thin layer of copper placed over the rotor surface to provide a low resistance path for the eddy currents. The design also includes 9% nickel steel rings placed between the superconducting coils to divert flux away from the coils and the effectiveness of the diverters is shown in Figure 3.

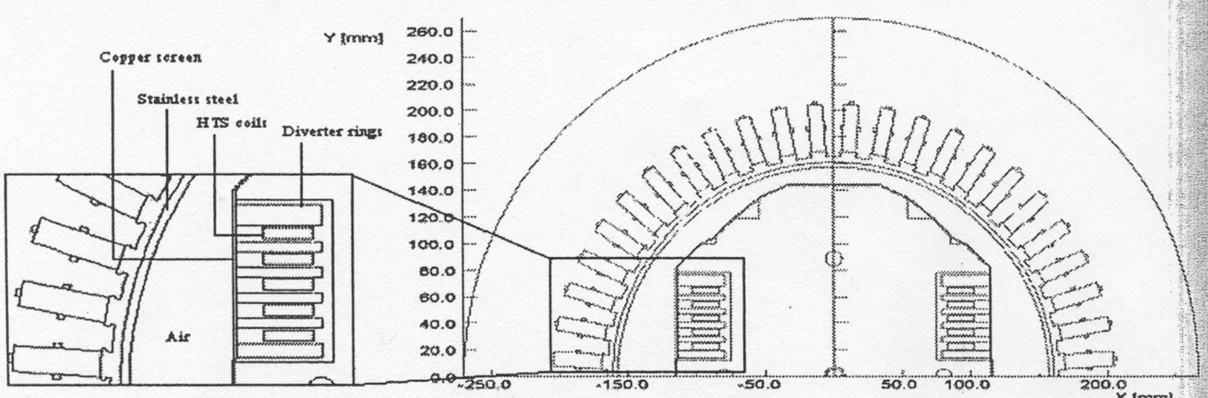

Figure 2 The high temperature superconducting synchronous generator 2D model.

3 Finite Element Analysis

In 2D finite element modelling, field current and armature current were used as the input. A nonlinear Poisson equation is solved to determine the permeability of the iron in the steady state condition. The finite element solution is iterative in order to account for nonlinear BH characteristics of the generator magnetic circuits. Linear finite element computations using the permeabilities from the previous solution were then used for calculation of the saturated reactances. In these models, the field winding is unexcited and a current of 1A is applied to the main phase winding with -0.5A in the other two phases.

In a model with XY symmetry, there will be X and Y components of flux density and Z directed currents. The flux linking a rectangular loop with two sides parallel to the Z direction is simply given by the product of the length of these sides and the difference in the vector potential (A_z) between the points in the XY plane. The flux linkage λ is given by

$$\lambda = \frac{N}{a_1} \int_{a_A} A_z da - \frac{N}{a_2} \int_{a_{A'}} A_z da$$

Where a_A is the region occupied by outward half of the coils in phase A, $a_{A'}$ is the return half of the coils, a_1 is the area of each outward coil, a_2 is the area of the return coil and N is the number of turns in each coil. The flux linkage of an armature phase per ampere of armature current is the synchronous inductance, L, thus the synchronous reactance is simply $x = \omega L$.

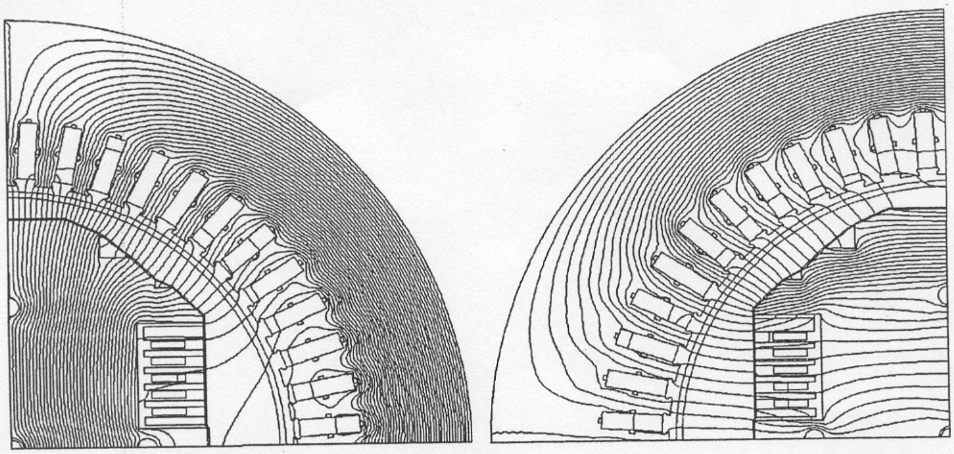

Figure 3 Distribution of flux lines for direct and quadrature axis investigations

4 Numerical Results

A synchronous generator under load exhibits an interesting symmetry condition. Even though the geometry of the generator is symmetric about direct and quadrature axes, the magnetic field is not symmetric about these axes but does retain rotational symmetry about the centre of the generator, with a period of 180° for a two pole generator. The direct-axis reactance, x_d and quadrature-axis, x_q reactance were found to be 0.195 per unit and 0.132 per unit respectively. The low values obtained are due to the large air gap that is needed to accommodate the thermal insulation. Calculations were also carried out based on the constants defined by Kilgore and Walker [2,3] and it was found to be consistent although some assumptions have been made to the dimension of the rotor pole. A comparison is given in Table 1.

Table 1 Reactances of the generator

Parameters	Finite element	Calculations
x_d (direct-axis reactance)	0.195 p.u.	0.226 p.u.
x_q (quadrature-axis reactance)	0.132 p.u.	0.148 p.u.
x_d' (direct-axis transient reactance)	0.041 p.u.	0.052 p.u.
x_d'' (direct-axis sub-transient reactance)	0.015 p.u.	0.019 p.u.
x_q'' (quadrature-axis sub-transient reactance)	0.013 p.u.	0.016 p.u.
x_2 (negative sequence reactance)	0.015 p.u.	0.013 p.u.

During transient conditions, the synchronous machine exhibits further parameters that need to be considered: transient reactances (direct-axis, x_d' and quadrature-axis, x_q'); and sub-transient reactances (direct-axis, x_d'' and quadrature-axis, x_q''). The direct-axis transient reactance is lower than the corresponding synchronous reactance since eddy currents in the field winding prevent any instantaneous change in its flux linkage. There is no difference between the corresponding quadrature-axis reactances, since flux can pass sideways through the field coils without linking them. The sub-transient reactances are lower than transient reactances, since eddy currents in the damper winding (which in this case is the copper screen used to reduce high frequency eddy current losses) excludes the flux from the rotor. The direct and quadrature axis reactances at different frequencies are shown in Figure 4. The values at appropriate frequencies are included in Table 1.

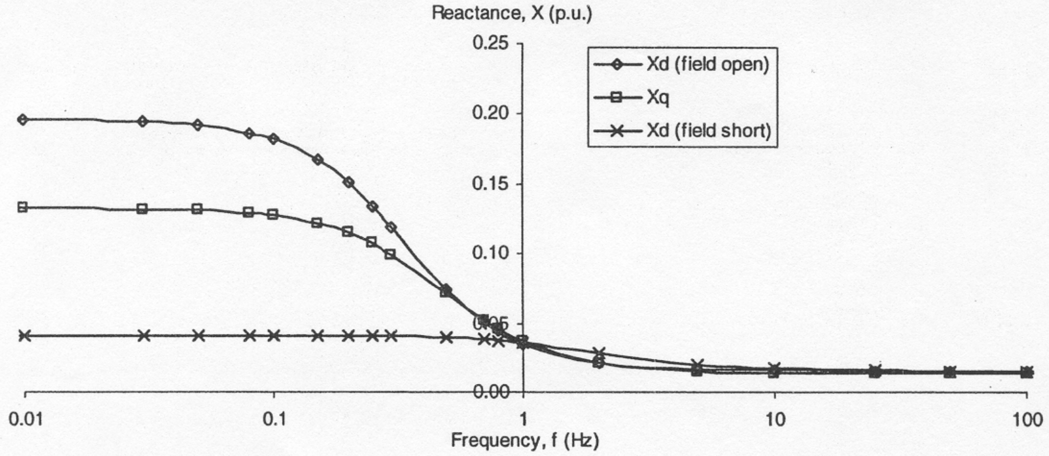

Figure 4 Direct and quadrature axis reactances of the generator at different frequencies

5 Discussion

The direct and quadrature axis reactances were calculated for range of frequencies. The direct axis reactance was calculated with the field winding open circuit to give the synchronous reactance, and with the field winding short circuit to give the transient reactance. All three graphs converge to the sub-transient reactance at high frequencies. The values of the saturated reactances calculated using the above method are most appropriate for modelling small transients. If fault currents were to be considered, a non-linear AC model might be more appropriate.

6 Acknowledgements

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