Abstract

The present thesis covers some aspects of the design of magnetic shield, taking core saturation into account, and presents some studies on the steady-state analysis and transient analysis of superconducting generator using *direct field approach.* The air-gap flux density is of the order of 0.9 to 1 Tesla for a normal 500 MW turbogenerator. In case of a superconducting generator, this value can go up to 1.5 Tesla, so that the generator becomes compact and there is considerable reduction in size and weight. There is every possibility that this alternating flux can link with the nearby metallic structure and cause heating. Moreover, the flux being alternating can cause harm to the operating personnel if not prevented from escaping into the surroundings of the generator. Too thick a shield may prevent the flux from escaping, but it adds to the generator weight; and too thin a shield will minimize the weight of the generator, but may not fully prevent the flux from escaping beyond shield region. So the magnetic shield, being a component having the maximum weight in case of a superconducting generator, needs optimization in order to have weight and cost advantage over a normal generator. This is taken care of by the proper design of shield, so that the '10G' line is kept well within the prescribed distance beyond the shield. The thesis also discusses the design of multiple and thick dampers under fast rise in field current, and the machine performance under negative sequence loading and three-phase short-circuits, which need to be studied for a large superconducting generator.

First, the thesis gives the flux distribution inside iron shield, as well as in other regions of SC generator, taking into account the non-liner B-H characteristic of the magnetic shield material. A mathematical model has been developed to represent the superconducting generator under no-load and full-load cases with suitable boundary conditions using field approach. For the analysis of superconducting generator under transient condition, the field equations are to be solved in r, θ and time in cylindrical co-ordinate system. It is quite complicated and time consuming to solve the field equations when all these three dimensions are involved. There are several transient electrical problems in superconducting generator, which will involve all these dimensions for calculating generator performance. It is convenient to solve them, if the dimensionality of the problem can be reduced. One can either follow FEM or FD methods to solve the problem. In case of superconducting generators, the geometry is very much suitable for following FD method. The main aim in the thesis is not only to solve static problems but also the transient problems in case of superconducting

generator, where the boundary conditions are dynamic (time varying), and hence, the conventional FEM packages do not help much, since such boundary conditions are too special. For solving the field equations, even the existing FEM techniques can be used, but that would be a lengthy exercise in itself. So, at least, for this type of machine, where the geometry is simple, one can follow methods like FD. For the sake of illustration of solving such transient problems, one may like to reduce the order of equations to the extent possible without much loss of accuracy. Hence, the variable 'θ' needs to be eliminated. Again, when saturation is present, this separation or elimination of one variable is mathematically difficult unless a procedure like Galerkin's method is followed. This reduces the dimensionality of the field equations. Its application has been demonstrated in Chapter-3 for a steady-state case with non-linear magnetic shield. The method described in this thesis can not only be applied to steady-state conditions but also for the analysis of large superconducting generators under transient conditions, if saturation is present. This is one of the significant contributions of the thesis.

The proposed method predicts the field outside the magnetic shield by taking into account the infinite boundary conditions. The optimum thickness values of magnetic shields have been computed for 500 MW and 1000 MW SC generators keeping the '10 G' line well within the prescribed distance beyond the magnetic shield. The method has also been used to calculate accurately the values of flux densities inside the shield, for accurate calculation of the core losses. The results obtained by the proposed 1-D method have been compared with a standard FEM electromagnetic 2-D programme, like Maxwell. The results of flux densities along pole-axis, the permeability variation along peripheral direction and the flux plots in quarter section of the machine, obtained using the proposed method for the 500 MW SC generator, have shown good correlation with those obtained by using the standard FEM programme.

One of the main contributions of the present thesis has been to give a method of analysis using direct field approach for arriving at an optimum damper thickness, which will permit the required flux build-up during field forcing or ramp excitation for a SC generator. The method has been applied to the 200 kVA and 500 MW SC generators in order study the effect of dampers during fast response excitation, to calculate the field voltage required for field forcing, and to compute the rate-of-charge of flux density near the superconducting field winding. These computations could not be done using the available standard FEM software.

The thesis also covers the analysis of a superconducting generator under negative sequence currents in the armature winding. First, analysis has been done using generalised direct field approach (using numerical method), formulating Laplace's equations in air-gap regions, Poisson's equation in current carrying regions and diffusion equation where damper is present. This numerical approach covered in the thesis can be regarded as a simple and convenient method for analyzing SC generators with multiple thick dampers under negative sequence loading or a.c. flux screening. By the numerical analysis given in this thesis, it has been shown that the selection of number of dampers and their thickness in large superconducting generators are very important for limiting the a.c. fluxes near the superconductng field winding. The thesis also gives an approximate analytical (closed-form) solution to this problem. The results obtained using this analytical method have compared well with the results obtained by the numerical method using the generalised field approach.

Another significant contribution of the thesis has been to propose a numerical method for analysing the performance of superconducting generator with thick dampers (where the damper parameters are frequency-dependant) under sudden three-phase short-circuit condition using direct field approach. The method automatically takes into account the distributed and frequency-dependant nature of dampers. The method of approach has been to formulate Laplace's equations in air-gap regions, Poisson's equation in current carrying regions and diffusion equation where damper is present.. *The d-q axes equations at the machine terminals under fault conditions are suitably translated as constraints for the vector potential and its normal derivative in field equations representing the armature and field winding. The current densities in armature and field regions are expressed in terms of (unknown) vector potentials to solve the Poisson's or diffusion equations in the field, armature and damper zones. The originality in this method includes translation of the terminal conditions of machine into vector potential and current density for inclusion into the field oriented equations.* Such computations for large superconducting generators under transient and with time varying boundary conditions are not possible by the available software.

To summarize the work, when the transient circuit problems like sudden 3-phase short circuit, ramp excitation etc. are to be solved from direct field approach, enormous amount of computational work is involved. Hence, reduction of dimensionality is attempted in the thesis. The problem, in general, involves four independent variables, i.e., r, θ, z (length) and

time. Assuming the machine to be long, the problem is reduced to the conventional 2-D problem. By considering only space fundamental, θ *parameter can be eliminated. This elimination is possible, even in the presence of magnetic saturation if Galerkin's method is used. This method helps in writing down the d and q axes equations correctly, including saturation-based coupling terms by defining two equivalent permeabilities in d and q axes in the magnetic shield. The analysis also takes care of distributed nature of thick dampers, since the dampers are represented by a number of thin elements and field equations are written for each element. Thereby, the frequency-dependant nature of damper parameters is taken into account in all transient cases. The translation of circuit-oriented boundary conditions into the field equations, proposed in the thesis, helps to solve various transient cases using direct field approach. The proposed work in the thesis includes the development of reduced order equations for the analysis of SC generator in presence of saturated magnetic shield. These reduced order equations are used to solve numerically all the steady-state and transient cases of SC generator with the help of finite difference method. The steady-state problems solved include the optimization of the saturated magnetic shield and analysis of SC generator under loaded condition using Galerkin's method. The specific transient problems solved are: (i) flux-time response due to ramp excitation in presence of damper(s), (ii) attenuation of negative sequence flux due to dampers, and damper optimization; and finally (iii) behaviour of SC generator under sudden 3-phase short-circuit Thus, the proposed generalized calculation method, using reduced order equations and direct field approach, takes care of saturation of the magnetic shield and frequency-dependant nature of the dampers during transient conditions and can be used for the steady-state as well as transient analysis of SC generators.*

Using the general numerical methods presented in the thesis, steady-state and transient analyses have been carried out and results have been presented for a 200kVA SC generator designed and developed at BHEL, R&D, and the 500 MW, 1000 MW and 1300 MW SC generators data of which are available in the literature. The calculated results compared well with the test values obtained for the 200kVA SC generator.