AC Loss Calculation of Synchronous Generators Made of HTS Superconducting Armature Windings and Permanent Magnet Rotor

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Abstract

In this study, a novel FEM calculation method based on A-Formulation of Maxwell Equations was proposed to evaluate the transient AC current losses of superconducting generators. The calculations are carried out in 2-Dimensions. The model generator under consideration is a three-phase synchronous generator with a 12-pole and 12-slot rotor made of permanent magnets and the stator windings made of high-temperature superconducting coils. Superconducting coils are wound with 2G HTS coated conductors and the critical current intensity is around 300 A at T = 77 K. Rotor magnets generate magnetic fields in the xy-plane and only current is induced in the z-direction inside the HTS coils. The Loss calculation of the superconducting generator were then repeated with the H-formulation and the A-H Hybrid model. AC loss was calculated for different rotor speeds using all three calculation approaches. The induced current distributions and magnetic field distributions in HTS coils for various time instants for 60 rpm rotor sped are presented.

Acknowledgments: Fedai Inanir acknowledges the financial support of the Scientific and Technological Research Council of Turkey (TUBITAK) under the contract number 114F424.

Introduction

There is a general trend that superconducting rotationary machines of small sizes and high power are more viable commercially. The main reason is that the cryogenic subsystem required to be added to the system constitutes a much smaller part of the total machine weight and cost. The commercial availability of stranded NbTi superconductors since the late 1960s made it possible to start applications for superconducting rotating machines (Woodson et al., 1966). Since these superconductors are only suitable for carrying direct current (DC), they were originally designed to replace the DC field windings in existing rotating machines. The ideal applications for these designs were large synchronous motors, generators and unipolar DC machines.

The magnetic field strength in the air gap of conventional rotary machines is generally limited by the saturation of the iron core teeth on the rotor and stator. However, the high current carrying capacity of superconductors made it possible to generate much higher air gap field strength with a small volume field winding and very little energy loss. First, the resistance losses are equal to the field and armature windings. From this, the promised efficiency improvement can be achieved by replacing the superconducting windings with the copper field windings (representing about half of the total copper losses). In this sense, large synchronous generator designs are General Elekcric (Keim, 1985), Westinghouse (1977), Super-GM (Nitta, 2002; Rogalla & Kes, 2011) etc. has been implemented by companies. Although Super-GM implemented the project in the 1990s in which it tested three different rotors 70 MVA generators using three different NbTi field windings, none of them were found economically attractive due to technical problems such as inadequacy and cost of low temperature cooling systems, instability of the superconductor wire.

The discovery of HTS in 1986 provided an impetus for the development of various electrical machines based on these new superconductors. In particular, the fact that these superconductors offer the opportunity to operate at higher temperatures (between 25 K and 77 K) with lower cost cooling systems has enabled applications where YSS technologies such as full-scale high or low speed motors and generators are used worldwide.

Framework of Modelling

New calculation methods have been developed for electromagnetic analysis of superconductor generators. The calculations were made in two dimensions and the model generator was designed. Figure 1. The model design considered is a three-phase synchronous generator with 12 poles and 12 slots made of permanent magnets and the stator windings made of superconducting coils. Superconducting coils are 2G coated conductors wound and the critical current intensity is around 300 A at T = 77 K. Rotor magnets generate magnetic fields in the *xy*-plane and only current is induced in the z-direction from the HTS coils. Parameters used for model generators are given in Table 1. Firstly, A-V formulation was used for calculations. According to the A-V formulation, the current induced in the generator is calculated according to the Ampere equation as follows:

$$\sigma \frac{\partial \boldsymbol{A}}{\partial t} + \frac{1}{\mu_0 \mu_r} \nabla \times \nabla \times \boldsymbol{A} = 0 \tag{1}$$

where σ represents the conductivity of the superconductor and the materials used with the generator, A represents the vector potential, μ_0 the magnetic permeability of the cavity, and μ_r the relative magnetic permeability. A new method was developed to solve the time dependent partial differential equation with the finite element software COMSOL Multiphysics software.

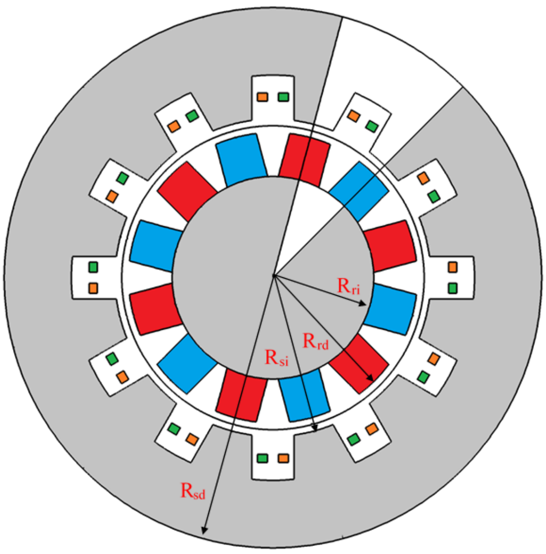

Figure 1. Model generator used in calculations. The rotor of the generator is designed from permanent magnets and the magnets are positioned to generate magnetic fields in the radial direction inward and outward.