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.

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.

Modeling Framework

New computational methods have been developed for electromagnetic analysis of superconducting generators. Calculations were performed in two dimensions and the model generator was designed (Figure 1). The model design considered is a three-phase synchronous generator the rotor of which has 12 poles and 12 slots and is made of permanent magnets and the stator windings of which are made of superconducting coils. Superconducting coils were wrapped on 2G coated conductors and the critical current density is approximately 300 A at T=77 K. The rotor magnets generate magnetic field in the xy- plane and current is induced in the YSS coils only in the z-direction. The parameters used for model generators are given in Table 1. A-V formulation was primarily used for the calculations. According to the A-V formulation, the current induced in the generator is calculated according to the Ampere equation as follows:

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

In this formula, represents the conductivity of the superconductor and the materials used with the generator, the vector potential, the magnetic permeability of free space, and the relative magnetic permeability. A new method has been developed to be solved with COMSOL Multiphysics software.

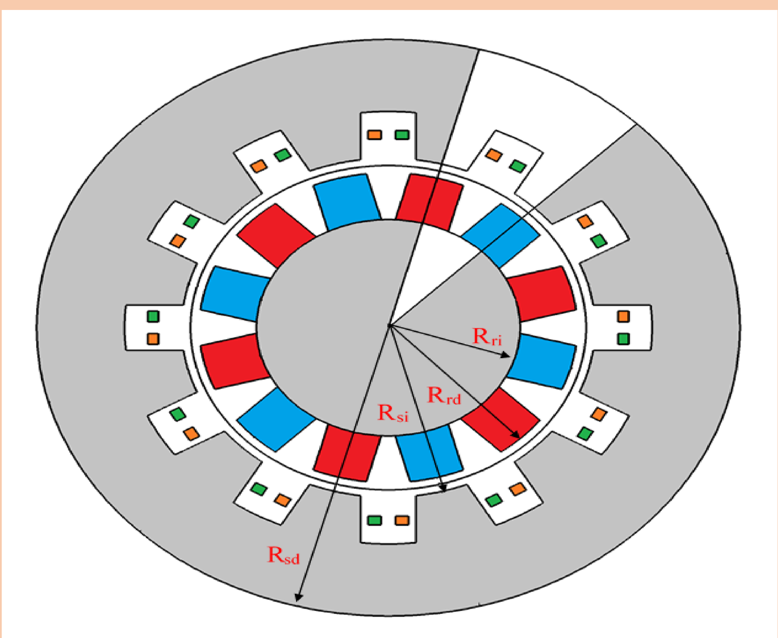

Figure 1. Model generator used in calculations. The rotor of the generator was designed from permanent magnets, and the magnets were placed in a radial direction to produce an inward and outward magnetic field.

Governing Equations

$$J = J_c tanh\left(\frac{E}{E_c}\right)$$

$$E = E_c \left(\frac{J}{J_c}\right)^n$$

$$\sigma = \frac{J_c}{E_c}\left(\frac{E}{E_c} + \Delta\right)^{\frac{1}{n}-1}$$

with

$$\boldsymbol{E} = -\frac{\partial \boldsymbol{A}}{\partial t}$$

$$\boldsymbol{A} = A_z \hat{k}$$

Table 1. Parameters used for the model generator

Parameter	Definition	Value
R_{so} (mm)	Outer Radius of Stator	320
R_{si} (mm)	Inner Radius of Stator	188
R_{ro} (mm)	Outer Radius of Rotor	172
R_{ri}	Inner Radius of Rotor	12
D_{ag} (mm)	Air Void	16
L (mm)	Length of Generator	600
p	The Number of Poles of the Generator	12
s	The Number of Slots of the Generator	12
B_r (T)	The Magnetic Field of Permanent Magnet	1.2
ω (rpm)	The Angular Velocity of Generator	10,30…180
I_c (A)	The Critical Current density of the Strip	300
w_{sc} (mm)	The Width of the Strip	12
h_{sc} (?m)	The Thickness of the Strip	100
E_c (V/m)	Critical Electric Field	$1x10^{-4}$
n	Exponent parameter	25
N_s	The Number of the winding of stator coils	100

As the boundary condition, it was considered that the vector potential and the scalar potential were anti-periodic on the right and left of the generator sector whose calculation was made and given in Figure 1:

$$A_{left} = -A_{right}$$

$$V_{m,left} = V_{m,right}$$

In addition, the sector symmetry boundary condition for the glide plane separating the rotor and stator was defined as:

$$\boldsymbol{B} \cdot \hat{n}. = 0$$

Magnetic isolation boundary condition was used for the outer envelope.

Results

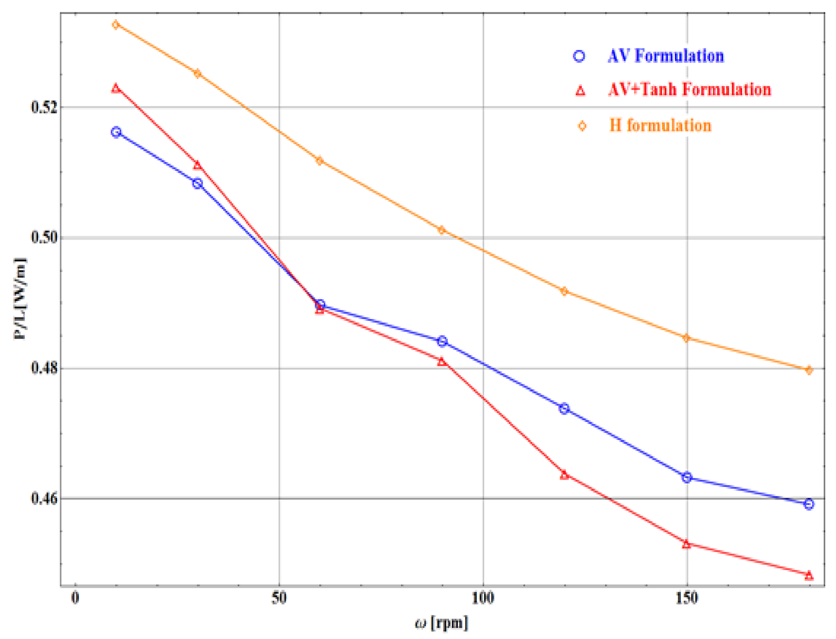

Figure 2. The Variation of AA losses that were calculated by the three developed methods as a function of generator rotational speed.

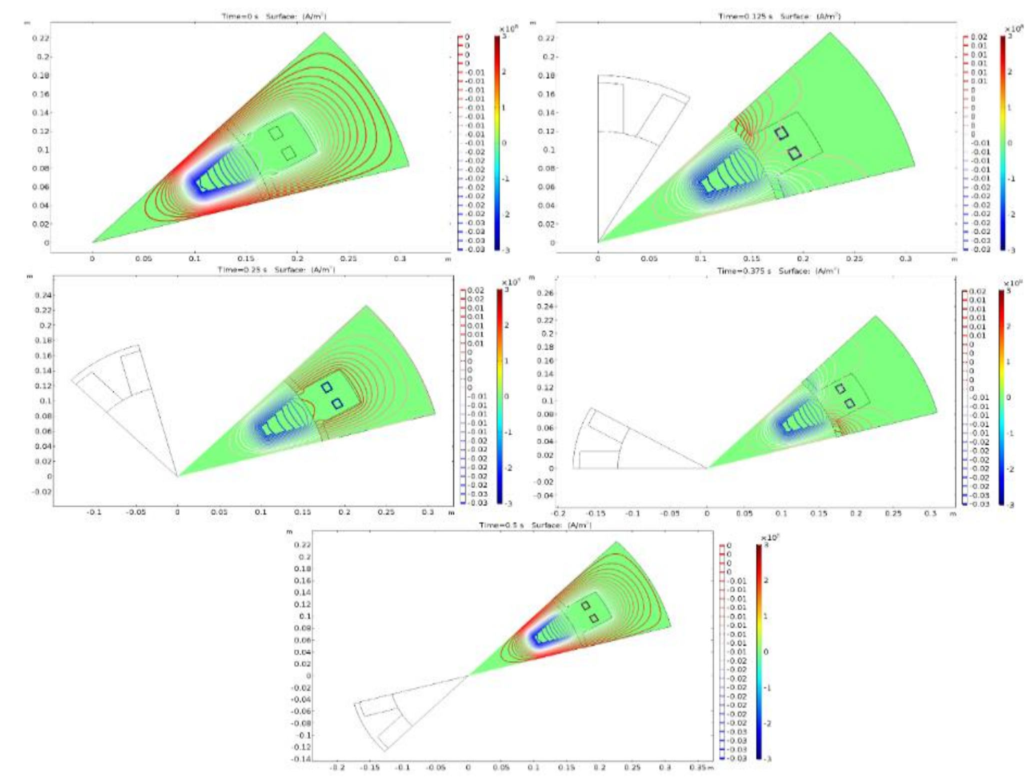

Figure 3. The distributions of the current that was induced in the superconducting coils when the rotor rotates a quarter round for ω= 10, 30, 150, 180 rpm velocities and magnetic field distribution.

In Figure 2, AA losses that were calculated using all three methods for different generator velocity were shown. As it can be seen in the figure, AA losses decreased almost linearly as the angular velocity increased. The reason for this can be easily understood by looking at Figure 4 because the penetration depth of the induced current decreases as the rotational speed increases. Therefore, the losses decrease proportionally. These values indicate instantaneous losses. For actual loss values, these values should be multiplied by the frequency corresponding to the speed.

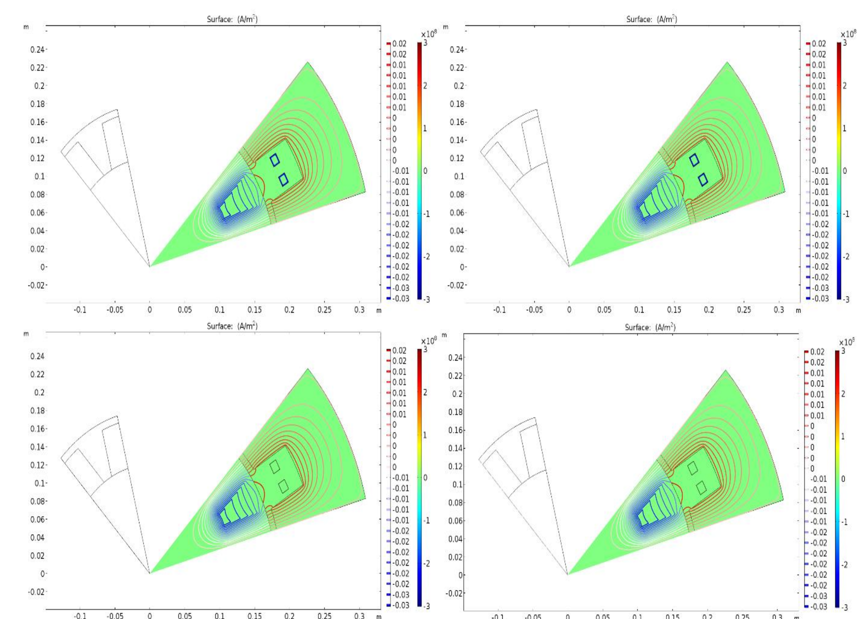

Figure 4.The magnetic field distributions of the stator and rotor of the model generator for ω=60 rpm during t=0, 0.125, 0.25 0.375, 0.5 s.

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