Transient Analysis of a Superconducting AC Generator Using the Compensated 2-D Model

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***Abstract*—This paper presents a 2-D transient analysis of a superconducting AC generator(SCG) using the finite element method(FEM). The compensated 2-D model obtained by lengthening the airgap of the original 2-D model is proposed for the accurate and efficient transient analysis. The accuracy of the compensated 2-D model is verified by the small error 6.4% compared to experimental data. The transient characteristics of the 30KVA SCG model have been investigated in detail and the damper performance on various design parameters is examined.**

***Index Terms*— Finite element method, Superconducting AC generator, 2-D transient analysis.**

I. INTRODUCTION

A SCG has many advantages over conventional generators, such as reduction in width and size, improvement in efficiency, and better steady-state stability. However, the SCG still has been unnoticed for commercial applications, from the view point of reliability and maintainability since it requires expensive liquid helium refrigeration plant [1].

In addition, the superconducting winding of the rotor in the SCG is extremely sensitive to the induced alternating currents during various operations of the power system such as unbalanced loading, harmonics, and transient state. Accordingly, it is necessary to shield the superconducting winding of the SCG by double damper structures [2], [3].

The outer damper, outermost shell of the rotor, is subjected to high centrifugal and electromagnetic forces. It also removes transient magnetic fields due to fluctuation in the load. The inner damper prevents the heat radiation and reduces the transient magnetic field over the stator.

It is important to calculate the transient state accurately with respect to the current, the magnetic flux distribution, and the heat loss of eddy current. SCG has a very large lateral leakage flux due to the air-cored structure of the rotor and stator. Therefore, 3-D analysis is necessary to calculate the transient state and predict the SCG performance accurately [4].

However, 3-D analysis requires a long computation time and large memory size due to the accuracy of the analysis. Especially, 3-D transient analysis is much more difficult because of mesh processing at each relative movement between stator and rotor. Consequently, considering the lateral leakage flux, the 2-D analysis using equivalent airgap length is more efficient than 3-D analysis with respect to the computation time and accuracy in the transient analysis of the SCG.

In this paper, the compensated 2-D model is obtained by lengthening the airgap of the primary 2-D model. The airgap length of the compensated 2-D model is calculated by the airgap flux difference between the 2-D and the 3-D magnetostatic analysis.

In the transient analysis, the eddy current of the inner and outer damper have been investigated in detail with respect to the various materials and widths of the damper. The eddy current losses in the damper structures have been calculated also. The efficiency and accuracy of the compensated model is verified by the comparison between computed electromotive force(EMF) and measured EMF.

II. SCG MODEL AND FEM FORMULA

A. 30KVA SCG Model

Fig. 1 shows the experimental equipment of 30KVA SCG which is designed and constructed by KERI(Korea Electro technology Research Institute). The SCG consists of superconducting field winding, armature winding, inner damper, and outer damper. Table I presents the specifications of the SCG.

B. 3-D FEM Formulation

In order to describe the static magnetic field using the scalar potential, its rotational part should be modified by the magnetic field intensity

$$\vec{H} = \vec{T} - \nabla\Omega \quad (1)$$

where $\vec{T}$ is an arbitrary function describing input current density $\vec{J}$, and Ω is a magnetic scalar potential.
Equation (1) satisfies Ampere's law and the solenoidal condition of flux density.

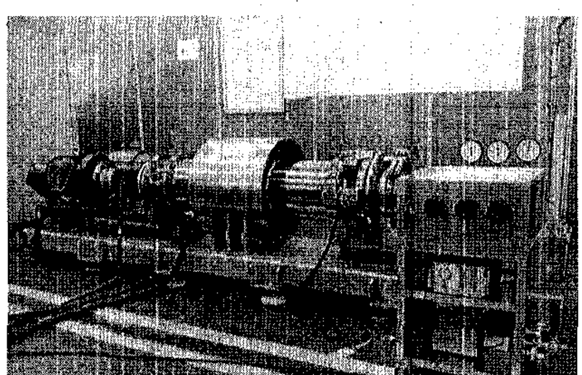

Fig. 1. Experimental equipment of 30KVA SCG.

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TABLE I. SPECIFICATIONS OF THE SCG

Armature		Field	
Rated output	30/3φ(KVA)	Turns of field winding	532
Rated speed	1,800 (rpm)	Strand	NbTi
Frequency	60 (Hz)	Critical current	580(A)
Turns per phase	72	Pole number	4
Slot number	36	Input current	200(A)
Permeability of flux shield 1000			

$$\nabla \cdot \mu(\vec{T} - \nabla \Omega) = 0 \tag{2}$$

After discretizing (2) by FEM, the next equation is derived as

$$\mu \cdot [S][\Omega] - [F] = 0 \tag{3}$$

where S is the system matrix and F is the force matrix.

C. 2-D FEM Formula

In the transient field, if the magnetic vector potential has only z-axis component, end-ring of the secondary conductor is short, and the magnetic material is isotropic, the governing equations for the 2D finite element analysis are given (4) and (5).

$$-\frac{1}{\mu}\left[\frac{\partial}{\partial x}\left(\frac{\partial \vec{A}}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\partial \vec{A}}{\partial y}\right)\right]+\vec{J}_e-\vec{J}_0=0 \tag{4}$$

$$\vec{J}_e=-\sigma\left(\frac{\partial \vec{A}}{\partial t}+\upsilon_\phi \frac{\partial \vec{A}}{\partial \phi}\right)=-\sigma \frac{d\vec{A}}{dt} \tag{5}$$

where μ is the permeability, $\vec{A}$ is the magnetic vector potential, $\vec{J}_e$ is the eddy current density, $\vec{J}_0$ is the input current density, σ is the electrical conductivity, and υ_ϕ is the velocity of the angular direction.

The electrical circuit equation of the voltage source is expressed as

$$V = R_m I + L_m(dI_m/dt) + E_m \tag{6}$$

where V is the voltage source, R_m is the phase resistance, L_m is the leakage inductance of the end coil and E_m is the emf induced in the coil.

After applying the Galerkin method to (4), and combining (6), then the system matrix equation (7) using the inverse difference scheme is obtained as

$$\begin{bmatrix}[s]+1/\Delta t[C] & Q_m \\ 1/\Delta t[F_m] & R_m + L_m/\Delta t\end{bmatrix}\begin{bmatrix}A^{t+\Delta t} \\ I_m^{t+\Delta t}\end{bmatrix}= \begin{bmatrix}1/\Delta t[C] & 0 \\ 1/\Delta t[F_m] & L_m/\Delta t\end{bmatrix}\begin{bmatrix}A^t \\ I_m^t\end{bmatrix}+\begin{bmatrix}0 \\ V^{t+\Delta t}\end{bmatrix} \tag{7}$$

The moving line technique is introduced to carry out the transient 2-D FEM analysis efficiently without mesh processing at each moving step between stator and rotor [5].

III. RESULTS AND DISCUSSION

The SCG has a large lateral leakage flux due to its air-cored structure in the rotor and stator. Consequently, the error ratio of 2-D analysis compared to 3-D analysis is remarkably large.

Thus, the modified 2-D analysis method which can account for the lateral leakage flux should be introduced. Among the modified 2-D analysis methods, the method using equivalent airgap length that is calculated by comparing the difference between airgap flux in the original 2-D model and 3-D model of SCG is applied.

In this paper, the compensated 2-D model is obtained by lengthening the airgap of the primary 2-D model to the equivalent airgap length. In the 3-D magnetostatic analysis using FEM, the airgap(gap length : 16.5 mm) flux is 0.004 Wb the same as that of the 2-D magnetostatic analysis(gap length : 44.6 mm). Therefore, the equivalent airgap length of the compensated 2-D model is 44.6 mm, while the original 2-D model is 16.5 mm.

Fig. 2 shows the 3-D finite element mesh of the SCG which has 116,624 elements and 21,317 nodes.

Fig. 3 shows the phase voltage calculated using the compensated 2-D model. The maximum phase voltage is 187.9 V and the phase angle with the three phases has 120 degrees each.

Fig. 4 shows the results of the 2-D FEM and experiment of the line voltage between the u-v phase. The maximum EMF value of the primary 2-D model(model 1) and compensated 2-D model(model 2) is 405.6V and 325.8V, respectively. The experimental result is 306.1V. The analysis error between the simulated and experimental result is 32.5% in model 1, 6.4% in model 2. By the result, it clarifies that the compensated 2-D model can be efficiently used for the accurate analysis of the SCG.

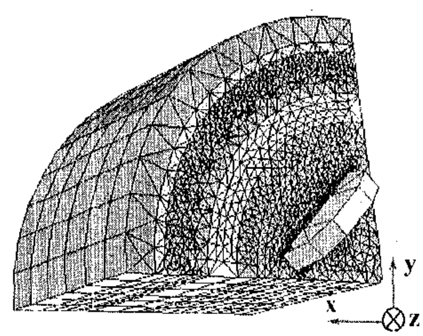

Fig. 2. 3-D finite element mesh.

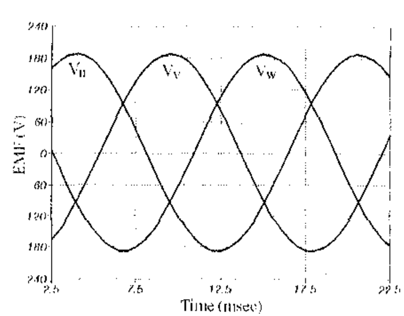

Fig. 3. The 3 phase EMF in the stator.

Fig. 5 shows the flux distribution in the transient state when the value of the exciting current reached at mid-value of the steady state. Therefore, it can illustrate that the inner damper protects the time varying magnetic flux in the transient state.

Fig. 6 represents the analyzed results of eddy currents in the inner damper by five different conducting materials such as copper(5.80×10^7s/m), aluminum(3.82×10^7s/m), tungsten (1.82×10^7s/m), brass(1.5×10^7s/m) and iron(1.03×10^7s/m). From the results, the more conducting materials are used for the outer damper, the more protection of the inner damper from the transient magnetic flux due to the magnetic fluctuation both in space and time occurs.

Fig. 7 shows other transient analysis results by the different outer damper widths. In case 4, the width of the outer damper does not change. Cases 1, 2, and 3 have shorter widths than that of case 4 that is to say -24mm, -20mm and -10mm respectively. Cases 5 and 6 have longer widths than that of case 4 that is to say 10mm and 20mm respectively. As shown in Fig. 7, the more longer width of the outer damper is used, the less eddy current of the inner damper occurs.

The eddy current losses in the inner damper of the SCG with the outer damper(model 3) and the SCG without the outer damper(model 4) have been investigated and the results are shown in Fig. 8. The eddy current losses in the inner damper of the SCG with the outer damper structure are about 10^6 times smaller than that of the model without the outer damper. From these results, the role of the outer damper which protects the transient magnetic field is clarified.

IV. Conclusions

In this paper, the transient characteristics of the damper in the SCG are analyzed using the 2-D FEM. The results show that the compensated 2-D model is efficient and accurate for analyzing the transient analysis of the SCG. The accuracy of the compensated 2-D model is verified by a small analysis error 6.4% compared to the experimental result. Using the compensated 2-D model, the transient characteristics of the outer and inner damper are made clear by various conducting materials and outer damper widths.

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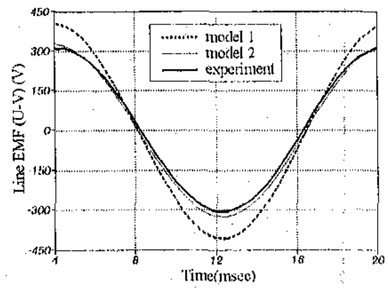

Fig. 4. The comparison of EMF between simulation and experiment.

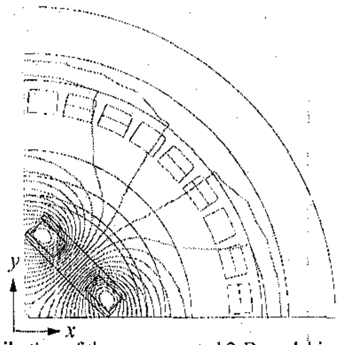

Fig. 5. Flux distribution of the compensated 2-D model in transient state.

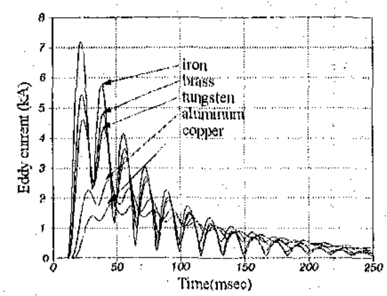

Fig. 6. Eddy current in inner damper by the material variation of outer damper.

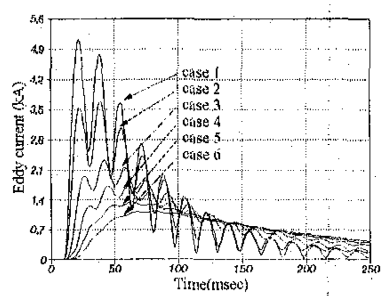

Fig. 7. Eddy current in the inner damper by the width variation of outer damper.

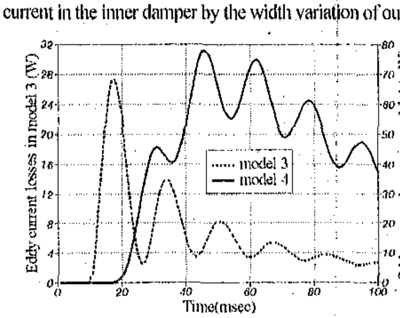

Fig. 8. Eddy current losses in inner damper in model 3 and model 4.