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Estimation of Effective Coil Length of Superconducting Generator using 3D FEM

Pan-Seok Shin and Doh-Young Park

Abstract - This paper presents a method to estimate an effective length of a 1000-kVA superconducting generator using three-dimensional FE analysis. Flux linkage of stator coil and the induced voltage are calculated with FEM program and Faraday's law. An effective length of the stator coil is estimated using the calculated voltage and geometric configuration of the machine. In order to verify the estimation method, 30-kVA superconducting generator is built and tested. The test result agrees reasonably well with the estimation.

Keywords - superconducting generator, finite element method, electric machinery

1. Introduction

The application of superconductors to electric power systems has been pursued for more than 30 years. As one of key technologies for the 21st century, research activities on superconductivity have been undertaken in a wide range of fields. Research and development on the application of superconducting technology to electrical generation is expected to yield significant benefits in energy savings, resources conservation and preservation of our environment. Superconducting generators will be vital apparatuses in the power generating stations. The features of the generator are high efficiency, smaller and lighter weight, and large capacity. Comparing to the conventional generators, the superconducting generators have a very large airgap between field winding and stator coil. It has been an interesting research topic to estimate effective length of the armature coil because the exact calculation of the effective flux linkage is very difficult. The actual electromagnetic field distribution of an air-core machine is a complex three dimensional problem dependent upon the rotating and stationary winding geometry, electromagnetic shields and machine frames.

Thus, this paper presents a method to estimate an effective length of a 30-kVA and a 1000-kVA superconducting generator using three-dimensional(3D) FE analysis. 3D analysis allows more accurate calculation of parameters of the end winding region, which is impossible to calculate by 2-D FE analysis. Superconducting generators have several different aspects than the conventional ones, such as very high magnetic flux density, absence of magnetic material in the main magnetic flux path and so on. By 3D FE analysis, the airgap flux density and the flux linkage of stator coil are calculated, and the induced voltage is computed using Faraday's law. Also, the effective length of the generator can be estimated by using 3D FE analysis because the flux density distribution can be observed along both the axial and radial directions.

2. Numerical Formulation

2.1 3-D Finite Element Formulation

In 3D magnetostatic FEM analysis, scalar and vector potential formulation methods are available depending on the material properties, source types, coil shapes and so on. The scalar potential formulation is defined in the current source free region where **J** is zero. As $\nabla \times H$ is zero by Ampere'law, the governing equation in this region is defined by the scalar potential as (1).

$$\mathbf{H} = -\nabla\ \Phi \tag{1}$$

where, Φ is scalar potential. The field lines of H are orthogonal to Φ and permanent magnet can be a source in this formulation. When there is a current source in a region, the total magnetic field intensity ($\mathbf{H}_{\text{tot}}$) is expressed as (2); $\mathbf{H}_{\text{red}}$ is reduced magnetic field ($-\nabla\ \Phi_{\text{red}}$)[4] and $\mathbf{H}_{\text{j}}$ is the field from Biot-Savart law .

$$\mathbf{H}_{\text{tot}} = \mathbf{H}_{\text{red}} + \mathbf{H}_{\text{j}} \tag{2}$$

In the absence of magnets, the reduced field ($-\nabla\ \Phi_{\text{red}}$) is a part of the field not represented by the source field $\mathbf{H}_{\text{j}}$. Thus the reduced field represents the reaction of the material to this source field. Also, the vector potential formulation employs Maxwell equations that lead to flux density and vector potential ***A***. The vector potential formulation can solve the various problems, but it has three unknowns at each node and requires large computing system of (3).

$$\nabla \times \nu(\nabla \times \mathrm{A} - \mathrm{B}_r) = \mathrm{J} \tag{3}$$

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where, ν is permeance of the concerned region and $\mathbf{B}_r$ is residual flux density of permanent magnet. The conventional Weighted Residual Method is applied to (2) and (3) in a discretized domain to yield FE system equations. The pre- and post- processors of a commercially available software, FLUX3D, are used for the modeling and analyzing the superconducting generators.

2.2 Modeling of 30 kVA Superconducting Generator

The cross-section of the 30-kVA superconducting generator is shown in Fig. 1. Its main specifications are 60 Hz, 4 poles, 1800 rpm and 220 volts as sited in Table 1. The field winding has 532 turns and its no-load field current is 200 A. The shield core is formulated as a scalar potential region and the air as the total one ($\mathbf{H}_{tot}$). Fig. 2 shows a model of the field winding (left) and 30-kVA superconducting generator (right). The field winding consists of superconducting wires whose diameter is 1 mm and critical current at 5 K is 580 A. Fig. 3 shows a field winding with stainless steel field core and the assembled rotor.

Table 1 Specifications of 30 kVA superconducting generator

Specifications	Unit	Values
Power capacity	kVA	30
Rated voltage	V	220
Rated field current	A	200
Frequency	Hz	60
Speed	rpm	1800
poles		4
Radius of stator coil	mm	227
Radius of field coil	mm	115
Number of slots		36
Coil pitch	slot	8

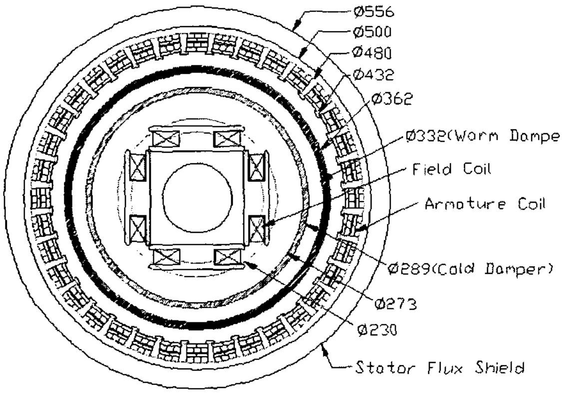

Fig. 1 Cross section of 30 kVA superconducting generator

The armature winding is modeled to calculate flux linkage and induced voltage. The armature coil has 3 turns/pole-phase and its design length is 288 mm. The coil is supported by a fiber composite bore cylinder. Fig. 4 shows an armature winding model to calculate flux linkages. The flux through the coil can be computed by the integral of flux density over a surface as (4). The surface approximately corresponds to the geometry of the coil.

$$\Phi = \int_S B \; dS = \sum_{e=1}^{N} B_e \; ds_e \qquad (4)$$

where, B_e is flux density in an element, s_e is area of the element, and N is total number of element in the coil geometry.

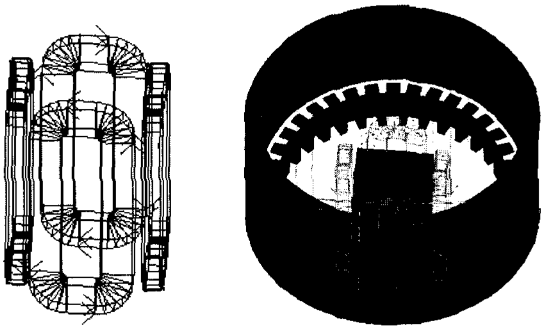

Fig. 2 3D Model of field winding (left) and 30 kVA generator

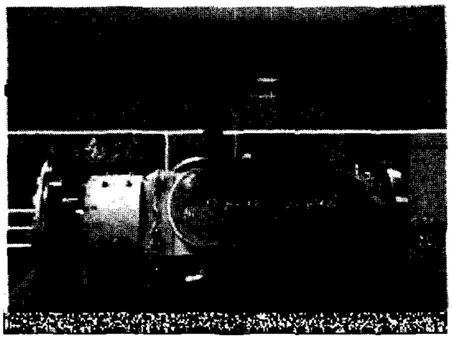

Fig. 3 Fabricated field winding and assembled rotor

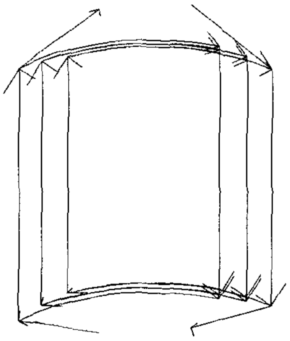

Fig. 4 Rectangular model of armature coil to calculate flux linkage

2.3 Modeling of 1000 kVA Superconducting Generator

Fig. 5 shows the cross-section of a 1000-kVA superconducting generator. Its main specifications are 60 Hz, 2 poles, 3600 rpm and 3300 volts. The field winding has 964 turns with the no-load field current of 884 A. The airgap length is 170 mm. Fig. 6 shows the simulation model of the field winding and the generator. The shield core is formulated as a scalar potential region and the air region as the reduced one. As shown in Fig.6, for reduction of computing time, half model of the generator is chosen to analyze the magnetic field of the generator. The model has 31,786 nodes and 192,916 elements and it takes about one and half hours to solve the model by SUN Enterprise-3500.

Table 2 Specifications of 1000 kVA superconducting generator

Specifications	Unit	Values
Power capacity	kVA	1000
Rated voltage	V	3300
Rated field current	A	884
Frequency	Hz	60
Speed	rpm	3600
Poles		2
Radius of stator coil	mm	320
Radius of field coil	mm	151
Number of slots		48
Coil pitch	slot	10

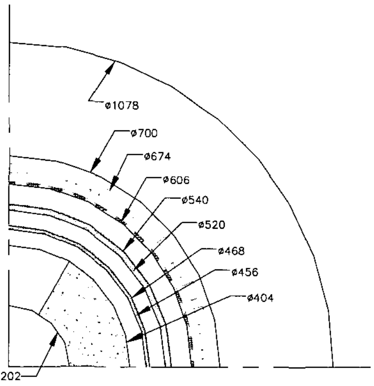

Fig. 5 Cross section of the 1000 kVA superconducting generator

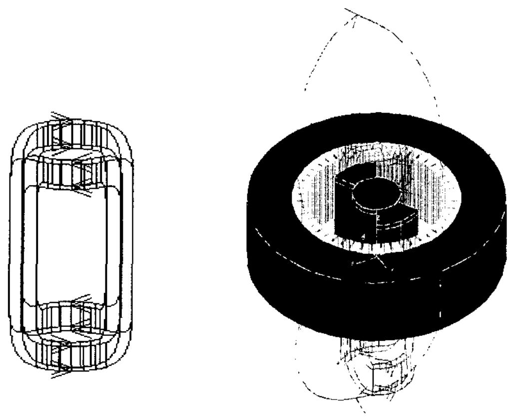

Fig. 6 3D model of field winding and 1000 kVA generator

3. Simulation Results

3.1 30 kVA Superconducting Generator

Fig.7 shows the assembled 30-kVA prototype superconducting generator which was developed by the Korea Electrotechnology Research Institute (KERI) in Korea. Using the simulation model, the flux linkage is calculated to compute the induced voltage on the coil. First of all, the airgap flux density distribution is analyzed on the field

Fig. 7 30-kVA prototype superconducting generator

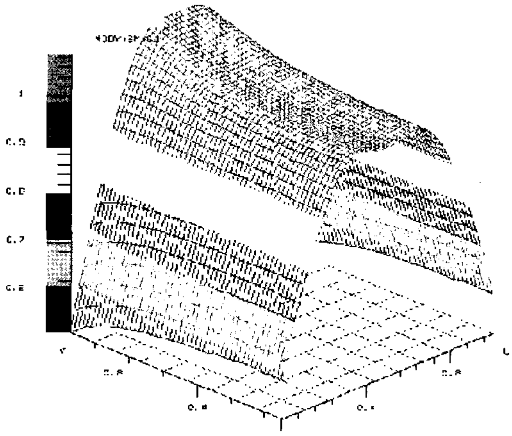

Fig. 8 Flux density distribution at field winding (30 kVA, v: axial direction, u: radial direction along r=115 mm)

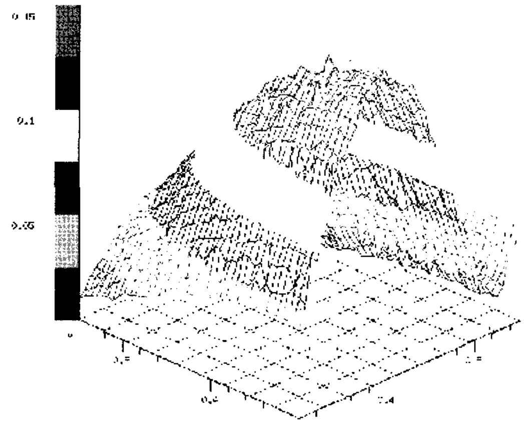

Fig. 9 Flux density distribution at stator winding (30 kVA, v: axial direction, u: radial direction along r= 228 mm)

winding and on the armature coil. Fig. 8 shows the flux density distribution along the center of the field winding (r = 115 mm) and Fig. 9 on the armature coil that is 107 mm apart from the center of field winding (r=228 mm).

It is found that the peak value of the flux density is reduced by 80 % (1.12 T to 0.18 T) and the average reduced by 90 % (0.794 T to 0.073 T). It means that about 65 % of the flux is leakage due to the large airgap. Average flux density in the airgap is calculated along the radial direction as shown in Fig. 10. As the calculating points become far apart from the field winding, the average flux density is gradually reduced in inversely proportional to the distance. The average value is reduced from 0.87 T to 0.11 T. In order to compute the induced voltage on armature coil, the calculated flux linkage of the armature coil is applied to (5).

$$e_{peak} = \omega N\Phi = 2\pi f N\Phi \text{ [V]} \tag{5}$$

where, ω is angular velocity, N is number turns per phase, Φ is flux linkage of armature coil. Because the computed value by (5) is a peak voltage of a phase, the 3 phase rms voltage of the generator can be calculated by (6).

$$V_{rms} = \left(\frac{\sqrt{3}}{\sqrt{2}}\right)e_{peak} \tag{6}$$

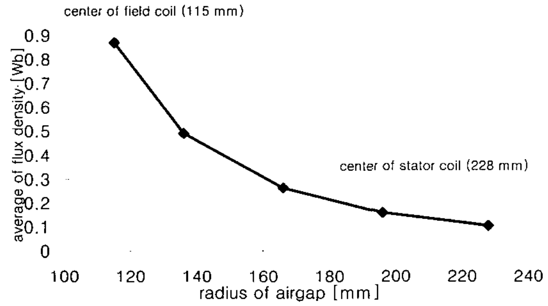

Fig. 10 Flux density in airgap to radial direction (30 kVA)

As the rotor is rotated by 10 degrees along the axis, the flux density and induced voltage are calculated as shown in Fig. 11. The voltage varies sinusoidally and its peak value is 240 volts, which is 4 % higher than the test results.

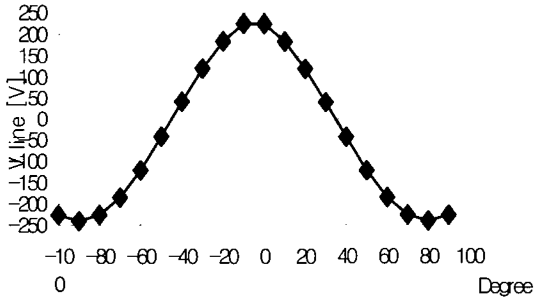

Fig. 11 Induced voltage as function of rotor angle(30 kVA)

When the axial length of the stator coil varies from 250 mm to 450 mm, the induced voltages are calculated as shown in Fig. 12. The voltages are linearly increased up to 380 mm, and above 400 mm the voltage seems to be saturated because the length of field winding and the flux linkages are constant. Also, the induced voltages are calculated as function of field current, and compared with those of the 2D FEM and the test result as shown in Fig. 13. As expected, 2D FEM result is proportional to the field current and 3D FEM result has a little nonlinear portion due to the axial and radial variation of the flux density. When the field current is low, the measured induced voltage is higher than the computed one by 2D FE analysis. The induced voltages were measured at only three different field currents, however it provides fairly good information. The 3D FEM results show good agreement with the test results.

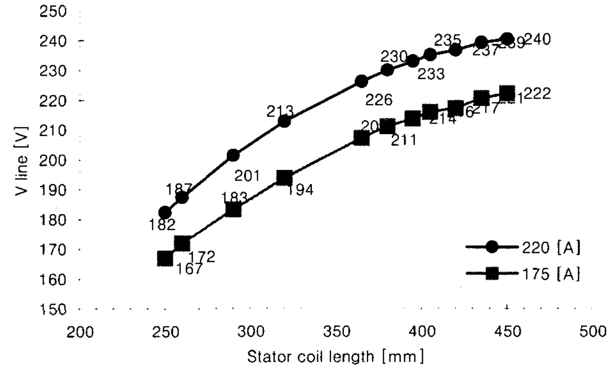

Fig. 12 Induced voltage as function of axial length(30 kVA)

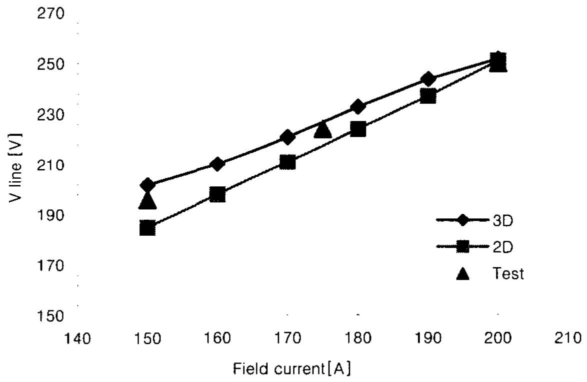

Fig. 13 Induced voltage as function of field current(30 kVA)

3.2 1000-kVA Superconducting Generator

Using the simulation model, the flux linkage is calculated to compute the induced voltage of the coil. First of all, the airgap flux density distribution is analyzed on the field winding and on the stator. Fig.14 shows the flux density distribution along the center of the stator winding for the no-load rated field current. The average flux density in the airgap along the radial direction is shown in Fig. 15. It is found that the average value is reduced by about 80 % (1.3 T to 0.26 T). It means that about 58 % of the flux is leakage due to the large airgap (170 mm).

The induced voltage of the 1000-kVA generator is calculated as a function of field current as shown in Fig.16. In the figure, the 'rectangular' line represents the voltage of design length of the stator coil and the 'triangular' represents 10 % reduced coil length. As expected, the induced voltage is linearly proportional to the coil length.

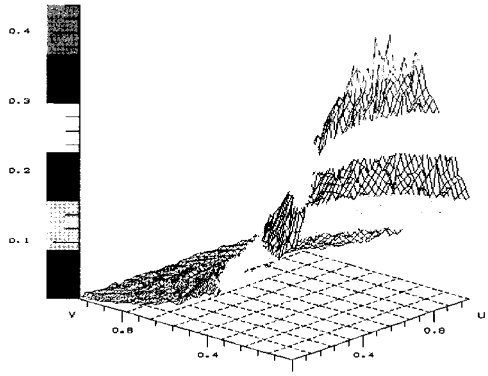

Fig. 14 Flux density distribution of armature end winding region (1000-kVA, v: axial direction, u: radial direction along r= 320 mm)

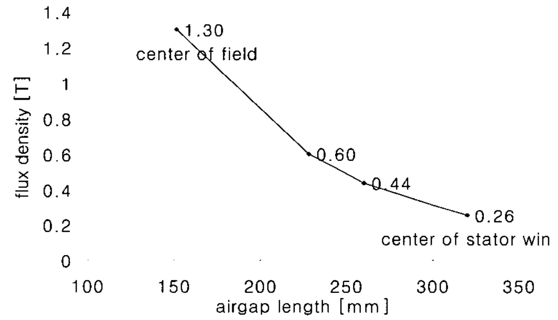

Fig. 15 Flux density distribution of airgap to radial direction (1000 kVA)

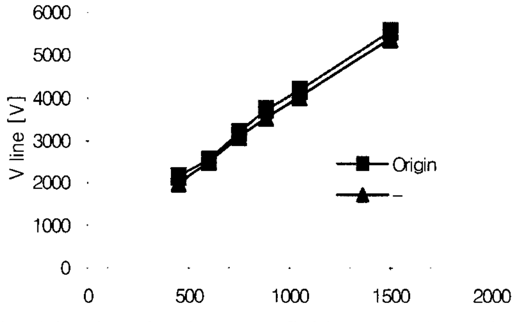

Fig. 16 Induced voltage vs. field current (1000 kVA)

When the field current is 884[A], the no-load voltage is about 3700[V], which is 400 V higher than the design value: it means that the effective length is a little longer than the length of the initial design (430 mm). Also, the design margin of the coil seems to be a little large. On the assumption that the shape of the armature coil is rectangular, the induced voltage is calculated as a function of axial length varied from 480 mm to 950 mm as shown in Fig 17. The voltages are linearly increased up to 650 mm, and above 800 mm the induced voltage seems to be saturated because the length of the field winding and the filed current is fixed. From the simulation results, the effective length of the generator coil is estimated to be 680 mm to have the rated voltage at the no-load rated field current.

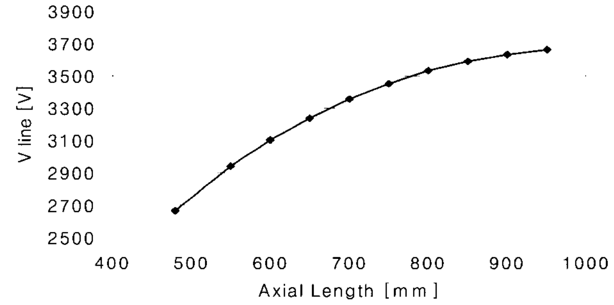

Fig. 17 Induced voltage vs. axial length (1000-kVA)

4. Estimation of the effective length

The effective length of the generator can be calculated by the various design parameters. The effective area of the armature coil depends on the shape of coil and its supporting structure as shown in Fig. 18. Consequently, the effective length of the generator, l_e, can be derived from the function of the flux density, stator coil length, shape of the end winding and other values as described in (7).

$$\begin{aligned} l_e &= l + f(b, W, \theta, \lambda) \\ &\approx l + k_{elf}\, b\pi \ \cos\theta \end{aligned} \tag{7}$$

where, l is the armature coil length (straight part), k_{elf} is an effective length factor which depends on various parameters of the generator such as leakage flux, winding shape and field current, b is the effective length of the end winding, W is the coil pitch, θ is the angle between the end winding and axial direction, and λ is the flux linkage.

For 30 kVA generator, the effective length is estimated to be about 350 mm by using the simulated data (l = 288 mm, b = 65mm). k_{elf} for 30 kVA generator is derived as 0.415. In case of 1000 kVA generator, the effective length is 680 mm (l = 430 mm, b = 503mm) and its k_{elf} is 0.172.

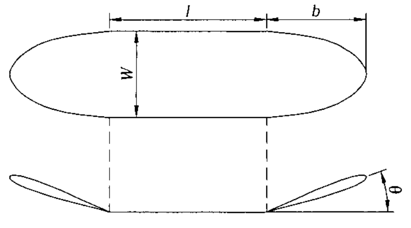

Fig. 18 Schematic diagram of armature winding

In both cases, the effective length is much longer than the design data. It gives very useful design information to correct the parameters of the generator.

5. Conclusions

By using a three-dimensional FEM program, the effective lengths of 30 kVA and 1000 kVA superconducting generators are estimated for providing a valuable information to machine designers. Scalar and vector potential formulations are employed for 3D FEM program. Flux linkage of the stator coil is calculated with the FEM program and the induced voltage is computed using Faraday's law. In the case study of the 30 kVA superconducting generator, the simulation results are compared with those of 2D FE analysis and those of the measured, which are in good agreement with each other.

Finally, the effective length of the 1000 kVA superconducting generator is estimated using the derived equation, the calculated voltage and the geometric configuration of the machine. From the results of the simulation, the effective length of the stator coil is estimated about 350 mm in case of 30 kVA generator and about 680 mm in case of 1000 kVA generator. The effective length factor, k_{elf} , is between 0.15 and 0.45 for the two cases, which will provide a useful information to the machine designers. The estimated effective length will be very useful to redesign the final model of 1000 kVA generator. Further works seem to be necessary to verify the program and the estimation method for the different machines, preferably large ones.

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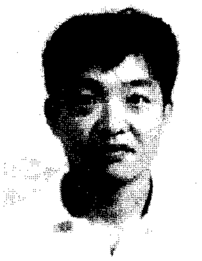

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