Fundamental Electrical Design Method for Superconducting Synchronous Generators

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Abstract. A fundamental electrical design methodology using electrical equations for superconducting synchronous generators, taking into consideration the size of the machine components and the performance of the superconducting field winding, has been developed. A fundamental electrical design of a 70 MW superconducting generator developed as part of the Super-GM project was conducted and it was found that the design predictions were in good agreement with the test results.

1. Introduction
A 70 MW superconducting synchronous generator (SCG) employing low-temperature superconductors was developed in Japan. Nowadays, small-scale superconducting synchronous machines employing high temperature superconductors have many significant advantages and active development of these machines has been carried out in the USA, Germany and other countries.

Such superconducting generators (SCGs) consist of superconducting field windings, cryogenic rotors and air gap armature windings, with the design method differing from that of conventional machines. Bearing in mind that the establishment of a design methodology is very important in the development of SCGs, fundamental design programs have been developed.

This paper presents the main electrical design equations for SCGs, together with a fundamental design methodology using these electrical equations and a comparison study between the design predictions and the test results of the 70 MW SCG.

2. Electrical design equations
The main electrical design equations for SCGs, derived from two-dimensional electromagnetic analysis, taking into consideration the winding thickness and edge effects, are presented as follows.

1) Operating point in the superconducting field windings (steady state current density \( J_s \) and flux density \( B_s \)) are expressed by

\[
J_s = A_1[B - 5(k_1 / k_2)] + (k_1 / k_2)A_2
\]

\[
B_s = (k_1 / k_2)k_3B
\]

where, \( A_1 \): gradient of \( J_s \) to \( B \) \([\text{A/mm}^2/\text{T}]\), \( A_2 \): current density at \( B=5[\text{T}] \), \( k_1 \): load factor, \( k_2 \): transient current rate, \( k_3 \): flux concentrated coefficient in the field winding

2) Flux density and magnetomotive force (MMF) of the field windings: the experienced maximum flux density under no-load condition \( B_{mf} \) may be expressed by

\[
B_{mf} = \left[3\sqrt{3}/2\pi^2\right]\mu_0 k_s \left[I/N_f r_f / (r_f / r_{fo})\right]^{-1} \left[1 + (r_f / r_c)^2\right]^2
\]

where, \( \mu_0 \): permeability of the air gap, \( I/N_f \): MMF of the field winding /pole pair, \( r_c \): inner radius of
the stator core, \( r_{fo}, r_{fi}, r_{ci} \) outer, inner and mean radii respectively of the field windings

The maximum armature reaction flux density \( B_{ma} \) is expressed by

\[
B_{ma} = \left( 9\sqrt{2} / 2\pi^2 \right) \mu_0 \left( \zeta_a N_a / r_{ci} \right) \left( r_{ai} / r_{ao} \right)^{p-1} \left[ 1 + \left( r_{ai} / r_{ci} \right)^2 \right]
\]

(4)

where, \( \mu_0 \): MMF of the armature winding /pole/phase, \( r_{ao}, r_{ai}, r_{ci} \): outer, inner and mean radii of the armature windings, \( \zeta \): winding coefficient of the armature windings, \( p \): pole number

The maximum flux density of the superconducting windings under load condition \( B_m \) is expressed by the following equation, using equations (3), (4), with a phase angle of \( \theta \) and a load angle \( \delta \).

\[
B_m = (3\sqrt{3} / 2\pi^2) \mu_0 k_3 (I_a N_a / r_f) - 2B_{mf} B_{ma} \sin(\theta + \delta)
\]

(5)

Since \( B_{mf} \approx B_{ma} \), \( (r_f r_c)^2 \ll 1 \), \( r_{ao} r_{fo} \approx 1 \), the MMF of the field winding per pole is expressed by the following equation as a first approximation.

\[
B_m = (3\sqrt{3} / 2\pi^2) \mu_0 k_3 (I_a N_a / r_f)
\]

(6)

3) The thickness of the field winding \( t_f \) is obtained from the following equation.

\[
I_f N_f = (2/3)\pi c \delta \xi \sin \theta
\]

(7)

where, \( c, \delta \): current density and the space factor of the field windings

4) The active length of the machine \( l_s \) is expressed by the following equation from the standpoint of synchronous reactance.

\[
p_a = \left[ 27\sqrt{6} / 2\pi^2 \right] \mu_0 f (r_f / r_c) \left[ 1 + \left( r_{ai} / r_{ci} \right)^2 \right] I_f N_f \zeta_a l_s \sqrt{1 + x^2 + 2x \sin \theta}
\]

(8)

where, \( f \): frequency, \( x \): synchronous reactance

Active and leakage reactance \( x_{ad}, x \) are expressed by

\[
x / x_{ad} = \left( I_e / I_s \right) \left[ 1 - t_a / 3r_a \right] / \left[ 1 - t_a / 3r_a + \left( r_{ai} / r_{ci} \right)^2 \right], \quad x = x_{ad} + x_i
\]

(9)

where, \( I_a, I_c \): active and equivalent edge length of the armature windings

5) MMF of the armature winding / pole / phase is obtained by the following equation from the standpoint of synchronous reactance.

\[
I_f N_f / \zeta_a N_a = \sqrt{B_a (r_f / r_c) \left[ 1 - t_a / 3r_a + \left( r_{ai} / r_{ci} \right)^2 \right] / \left[ 1 + \left( r_{ai} / r_{ci} \right)^2 \right]} \sqrt{1 + x^2 + 2x \sin \theta / x_{ad}}
\]

(10)

6) The thickness of the armature winding \( t_a \) is obtained from the following equation.

\[
\zeta_a N_a / r_a = (1/3) \pi \beta \xi \delta \xi t_a
\]

(11)

where, \( \delta, \beta \): current density and space factor of the armature winding

3. Fundamental design methodology

Figure 1 shows the flowchart of the fundamental design program developed using the electrical equations, and the computing process of the design program is explained as follows.

1) Specifications and basic parameters of the SCG such as effective power and space factor of the windings, as well as the basic size of each component are given.

2) Field windings parameters: Since \( r_f \) is given as the coefficient of the field windings radius multiplied by the output power function, the required \( N_f I_f \) is calculated using equation (6) for the first computation and equations (3)-(5) for the iterative computations. The required thickness of the field windings \( t_f \) may be determined from equation (7).

3) Armature windings parameters: The thickness of the armature windings is given as the coefficient of the armature winding radius multiplied by the output power function.

4) Active length of the machine is determined from equation (8) in order to satisfy the required output power. For a given synchronous reactance, the active reactance \( x_{ad} \) and end leakage reactance \( x_i \) are determined using equations (9).

5) Armature MMF: Using the supposed thickness, the current density and space factor of the
armature winding, the armature MMF \( a_1 \) may be obtained. The armature MMF \( a_2 \) is obtained from equation (10), and therefore the thickness of the armature winding is adjusted to make assumed value \( a_1 \) coincide with the proper value \( a_2 \). Since \( a_1 \) is affected by the generator parameters, which vary as \( a_1 \) is adjusted, several iterative computations may be needed.

6) Experienced magnetic flux density of superconductors: The experienced magnetic flux density of superconductors \( B_{m1} \) obtained from equations (2), is the assumed value, and the thickness of the field windings is adjusted so that \( B_{m1} \) coincides with the proper \( B_{m2} \) of the calculated value based on the generator parameters. Since the value of \( B_{m2} \) is affected by the generator parameters, which vary as \( B_{m1} \) is adjusted, several iterative computations may be needed for the adjustment. The required thickness of the armature windings \( t_a \) may be determined from the equation (11).

7) Output such as the required MMF of the field and armature windings, magnetic flux density, machine losses and efficiency, machine weight, various reactance are printed out.

The features of the developed fundamental design program are as follows.

- For given generator specifications, a logical fundamental design may be realized using repeated iterative adjusting computations for the thickness of the armature and field windings.
- The influence of various parameters such as synchronous reactance, the field winding diameter and maximum magnetic flux density on superconductors may be easily obtained.

Figure 1. Flowchart of the fundamental design program
4. Fundamental design predictions of 70 MW class SCM

Fundamental design predictions of a 70 MW class SCM using this design program are shown compared with the test results, in Table 1. Since the output power of 74.7 MW (10kV) was attained with this 2-pole 60 Hz SCM, a line current of 4792 A was produced. From a B-Jc short sample performance of the used NbTi superconductor attaining 420 A/mm² at 5 T and 145 A/mm² at 8 T, A₁ and A₂ is fixed at 92 A/mm²/T, and 420 A/mm². An external rotor diameter of 0.808 m and a synchronous reactance of 0.409 pu are provided as initial conditions. From Table 1, the following may be clearly observed:

- The design values of external rotor and stator diameter and stator core length are in good agreement with the manufactured SCM, except that the field winding diameter is a little bit larger.
- The design values of the field MMF, armature electric loading, maximum experienced magnetic flux density are in good agreement with the test results.
- The design values of various reactance are in approximately agreement with the test results.
- The design values of generator weight and efficiency are in good agreement with the test results.

Consequently, the design results may be concluded to be in good agreement with the test values and, therefore, this design method has practical utility when applied to SCMs.

| Item                                      | (A) Design prediction | (B) Test result | A/B |
|-------------------------------------------|-----------------------|-----------------|-----|
| Capacity [MW]                             | 74.7                  | 74.7            | 1.0 |
| Field winding diameter [m]                | 0.580                 | 0.514           | 1.13|
| Armature winding diameter [m]             | 1.19                  | 1.14            | 1.04|
| Rotor diameter [m]                        | 0.880                 | 0.880           | 1.00|
| Stator diameter [m]                       | 2.20                  | 2.16            | 1.02|
| Stator core length [m]                    | 1500                  | 1500            | 1.00|
| Bearing span [m]                          | 4.80                  | 4.90            | 1.00|
| Magnetomotive force of the field winding [kA/pole] | 899                   | 896             | 1.00|
| Electric loading [A/cm]                   | 1390                  | 1450            | 0.96|
| Maximum experienced magnetic flux density [T] | 4.01                 | 4.05            | 0.99|
| Synchronous reactance [pu]                | 0.406                 | 0.406           | 1.00|
| Transient reactance [pu]                  | 0.30                  | 0.32            | 0.94|
| Sub-transient reactance [pu]              | 0.26                  | 0.23            | 1.13|
| Sub-sub-transient reactance [pu]          | 0.23                  | 0.22            | 1.05|
| Rotor weight [ton]                        | 16                    | 16              | 1.00|
| Generator weight [ton]                    | 81                    | 82              | 0.99|
| Generator efficiency [%]                  | 97.88                 | 97.85           | 1.00|
| Efficiency without He cooling device [%]   | 98.11                 | 98.15           | 1.00|

5. Conclusion

The primary electrical equations relating to superconducting synchronous machines were shown and a fundamental electrical design methodology using these equations has been developed. A fundamental electrical design of a 70 MW superconducting generator was carried out and it was found that the design predictions were in good agreement with the test results.