Designing Stable and High-Current Density Rotor Windings of Superconducting Generator

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Abstract — A method to statistically predict quench training characteristics of a rotor windings of a superconducting generator is presented. In the method, energy of a disturbance due to a conductor motion and a quench current are statistically estimated. We apply this method to a rotor of the 70MW class Superconducting generator being developed in the Super-GM project and study the dependence of the stability on parameters of the rotor conductors, such as amount of copper stabilizer, accuracy of conductor dimensions and operating current density. To predict the stability, compliance of the rotor winding pack is a key parameter and estimated by a finite element method. In the study, it is shown that there is an optimum value of ratio of copper to superconductor to maximize the current density of the winding pack keeping necessary stability. Based on the study, a designing method for stable and high current density rotor winding is discussed.

I. INTRODUCTION

One of key issues in designing a superconducting generator is how to design high current density rotor winding whose quench current surely exceed designed operation current. However, a method to quantitatively estimate a quench current of the winding has not been developed. This paper is related to this issue. MQE (Minimum Quench Energy) is a well-known measure of the stability of superconductors but can not be a proper measure of the stability of the superconducting windings without knowledge on the size of disturbance in the windings. Therefore, it is important to know quantitatively the size of the disturbance energy to estimate the stability.

Previously, we developed a theory to statistically predict the size of the disturbance caused by a conductor motion [1]. In the theory, parameters such as mechanical properties and amount of copper stabilizer of the conductor and configuration of winding pack are taken into consideration together with the MQE. We apply this theory to 70MW class superconducting generator under development in the Super-GM project. A key

parameter of the winding pack to predict the stability is its compliance which depends on the amount of copper stabilizer of the conductor, the property of the spacer and the configuration of the winding pack. We estimated the compliance of the winding pack by the finite element method. In the paper, the validity of the theory is shown by comparing the theoretical analysis and the test results. Based on the theory, possible methods to increase the current density of the rotor winding pack keeping the necessary stability and a design method of the stability is also discussed.

II. PRINCIPLE TO STATISTICALLY ESTIMATE TRAINING CHARACTERISTICS

A Disturbance Energy and Maximum Movable Length

The rotor windings are usually wound of cable conductors composed of superconducting composite strands and we consider that a quench is most probably triggered by a motion of a strand of the conductors. The strands in the windings are mainly supported by frictional forces. The strands inevitably have irregularities in their dimensions, hence, the frictional supporting forces of the strands fluctuate because contact forces between the strands fluctuate along the strands even if uniform clamping force is applied to the windings. An abrupt strand motion occurs at a poorly supported part where the electromagnetic force to the strands exceeds the frictional supporting force, and, a quench occurs when the energy released by the strand motion at the poorly supported part is larger than the MQE of the strand. Energy released by the strand motion E_d is determined by the length of the moving part of the strand, that is, that of the poorly supported part,

$$E_d = \frac{(BI)^2(l/2)^5}{45EI_d} \quad (1)$$

where l is the length of the moving part of the strand, B is the magnetic field component perpendicular to the direction of the strand motion, I is the strand current, E is Young's modulus of the strand, and I_d is the geometrical moment of inertia of the strand, $I_d = \pi r^4 / 64$ for a round strand of the radius r . Knowing the relation between E_d and l , we can define the maximum movable length (MML), the maximum length of a part of the strand which can move without a quench. The MML is obtained from (1) by putting $E_d = MQE$ and given by

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$$MML = \left\{ \frac{1440(MQE)EI_d}{(BI)^2} \right\}^{1/5} \quad (2)$$

B. Prediction of Training Characteristics

Assuming that the random irregularity of strand dimension follows the Gaussian process, we can calculate the expected number of poorly supported parts whose lengths exceed the MML and this number is the expected number of quenches of the windings. The expected number of quenches depends on the strand current because the MQE, MML and forces to the strand depend on the strand current. We can consider that the first quench occurs at the current when the expected number of quenches becomes 1 and that the next quench follows every time at the current where the expected number of quenches increases by one. Thus training characteristics of the windings can be predicted.

III. CASE STUDY

By applying the method mention above, we estimate the training characteristics of the rotor developed by Mitsubishi Electric Co. for the 70MW class superconducting generator as a part of the Super-GM projects.

A. Configurations of Rotor Winding and Conductor

The cross-sectional view of the rotor is shown in Fig. 1 and the specifications of the rotor are listed in Table I. The rotor windings are placed in the slots No.1~5. A cross-sectional view of the winding pack in the slot is illustrated in Fig. 2. Details of the rotor configuration are given in [2]. The cross-section of the conductor made of 9 strands is illustrated in Fig. 3 and the specifications of the conductor and strand are listed in Table II. The winding packs are surrounded by insulation spacers as shown in Fig. 2 and the compressive forces are applied to the packs and conductors by the clamping forces to the top insulation spacers. The rotor shaft with the windings in the slots was fitted in the rotor vessel by shrink-fit and the clamping forces were applied to the top insulation spacer by the vessel.

B. Forces to Conductor and Strand

When the rotor rotates and the windings are excited, the centrifugal forces and the electromagnetic forces are applied to the conductors in addition to the compressive force from the upper insulation spacer. The electromagnetic forces have two components of circumferential and radial directions of the rotor. The circumferential component of the electromagnetic force causes the strand motions. The distributions of the magnetic field and the electromagnetic forces to the conductors in the slots are estimated based on the analysis using the finite element method. The distribution of total forces to the conductors in the slots can be calculated by knowing the compliance of the winding pack in the radial direction.

C. Compliance of Rotor Winding

The strand of the rotor winding contain CuNi to reduce AC losses. Therefore, stress-strain characteristics of the rotor

Fig. 1. Cross-section of rotor (perpendicular to center axis, quarter of the rotor).

TABLE I
SPECIFICATIONS OF 70MW CLASS SUPERCONDUCTING GENERATOR

Rotor	
Number of pole	2
Rotating velocity	3600 rpm
Diameter	890 mm
Bearing span	4900 mm
Winding	
No. of coils	10 (5 coils/pole)
Magnetic field (maximum)	4.5 T (at 3000 A)
Conductor	9 strand compacted cable

Fig. 2. Cross-sectional view of the winding pack in the slot.

winding pack in the radial direction were calculated for different values of ratio of copper stabilizer and CuNi to NbTi by the finite element method. We call this ratio nonSc/Sc after this. In the calculation, we changed nonSc/Sc by changing the amount of outer layer copper stabilizer while fixing the amount of CuNi. The compliances were calculated for the strand of same configuration shown in Fig. 3 except nonSc/Sc. In the calculation, stress-strain data of Cu, NbTi and CuNi were used and it was assumed that the core part of the strand including NbTi filamentary region stayed in the elastic region and that stabilizing copper region went in the plastic region. The stress-strain characteristics of the insulating kapton tape given in the reference [3] were also taken into consideration. The results are shown in Fig. 4. The compressive forces to the strands fluctuate around the clamping force. Therefore, the compliance of the winding pack is determined from the slope of the stress-strain curve at the stress determined by the clamping force. Obviously from Fig. 4, the compliance increases as the nonSc/Sc increase, because the amount of soft copper stabilizer increases.

Fig. 3. Cross-sections of rotor conductor and strand.

TABLE II
SPECIFICATIONS OF CONDUCTOR AND STRAND

Conductor (compacted strand cable)	
Size in cross section	2.9 mm × 7.4 mm
No. of strands	9 strands
Critical current	5100 A (7.6 T) at 4.2 K
	4900 A (7.3 T) at 4.6 K
Strand	
Cu : CuNi : NbTi	2 : 0.7 : 1
Diameter	1.6 mm
Young's modulus	130 GPa
Geometrical moment of inertia	$3.2 \times 10^{-13} \text{ m}^4$

Fig. 4. Stress-strain curves of winding pack of different nonSc/Sc conductors.

D. Calculation of MQE and MML

We assume that a quench of the winding is initiated by a quench caused by a strand motion in the conductor, therefore, MQE of the single strand is calculated. Details of calculation of MQE are described in [4]. We assumed a point disturbance of 0.5 msec duration [5] and 2 mm spatial length to calculate MQE. The spatial length of the disturbance was determined by the observation of the conductor configuration. MQE's were calculated in the static and rotating conditions. In the calculation, the transient heat transfer of liquid helium was taken into account in the static condition. In the rotating condition, data of the steady heat transfer of the supercritical helium in high centrifugal field [6] were used, because, according to our experiment, the steady state heat transfer was established in very short time [7].

E. Calculation of Expected Number of Quenches and Training Characteristics

We assume the irregularity in the dimension of the conductor follows the Gaussian process of standard deviation σ , then the dimension irregularity of the winding pack also follows the Gaussian process whose standard deviation is $\sqrt{n}\sigma$, where n is the number of the layers of the winding pack. It can be

considered the contact forces between the conductors also follows the Gaussian process whose standard deviation is $k\sqrt{n}\sigma$ where k is the spring constant of the winding pack which can be deduced from the compliance of the winding pack calculated by the finite element method. Then, we can numerically simulate the distribution of the fluctuation of the contact force along the conductor using the method explained in [1]. We can assume that the contact forces between conductors are equal to that between the strands of the conductor. Thus, by multiplying the contact forces by the friction coefficient μ between the strands, we can estimate the distribution of the supporting force along the strand and the number of the poorly supported parts whose lengths exceed the MML for a given conductor current. This number is the expected number of quenches till the conductor current reaches the given value.

F. Comparison of Predicted Training Characteristics with Experimental Result

The quench test of the rotor winding which is case-studied here was performed in the static condition. nonSc/Sc of the strand is 2.7. The validity of the prediction method can be checked by comparing the predicted training characteristics with the experimental result. Using the parameters listed in Table III, the accumulation of the expected number of the quenches until the conductor current reached I was calculated for the nonSc/Sc=2.7 for the static conditions. $\sigma=33 \mu\text{m}$ was determined based on the specified dimension allowance of the conductors and $\mu=1.0$ was determined based on experimental value of the copper vs. copper friction [8]. Fig. 5 shows the estimated training characteristics. As seen in the figure, the first quench current is 4.4 kA for the static condition. It is also seen that the first quench is followed by many successive quenches.

Result of the quench test in the static condition is shown in Fig. 6. The current at the first quench is 4.3kA and many quenches follows as is seen in the calculation result in Fig. 5. Based on this comparison, we can assume that the method to predict the training characteristics is valid.

G. Dependence of Stability on Amount of Copper Stabilizer

As nonSc/Sc increases, the spring constant k of the winding pack decreases and the standard deviation of the contact forces between the strands decreases. Therefore, the number of the poorly supported parts whose lengths exceed the MML decreases and the conductor current reaches its critical value with smaller number of the training quenches. However, high nonSc/Sc sacrifices the current density. On the other hand, low nonSc/Sc strand causes large winding pack spring constant and severe training effect.

From the standpoint of designing the rotor winding, it is important that the first quench current is high. Obviously from the discussion above, there is an optimum value of nonSc/Sc to make the first quench current maximum for given clamping force to the winding pack and σ . Fig. 7 shows the dependence of the first quench current on the nonSc/Sc. The dependence is estimated for a conductor of same dimensions shown in Fig. 3 for different values of σ by the method described above. The parameters for the calculation are same as in Table III except σ . The critical current of the conductor I_c on the load line, depending on the nonSc/Sc, is also shown in

TABLE III
PARAMETERS ON CALCULATION OF EXPECTED NUMBER OF QUENCH

σ	33 μm
μ	1.0
Spring constant of winding pack (nonSc/Sc=2.7)	5.5×10^7 [N/m/strand]/m (static condition) 3.7×10^7 [N/m/strand]/m (rotating condition)
Clamping force to the windings	5.2×10^4 N/m/conductor (static condition) 6.2×10^4 N/m/conductor (rotating condition)

Fig. 5. Prediction of training quenches of the winding in the static condition.

Fig. 6. Result of training quench test.

Fig. 7. For the case of $\sigma=33\mu\text{m}$, the first quench current becomes maximum at nonSc/Sc=3.7 and is 4.6kA which is I_c at the point. For nonSc/Sc higher than 3.7, the conductor current reaches I_c without quench but current capacity of the conductor becomes lower.

To obtain higher first quench current, it is necessary to decrease σ for a conductor of lower nonSc/Sc to reach the maximum first quench current. The maximum values are 4.9kA for $\sigma=25\mu\text{m}$ at nonSc/Sc=2.7 and 5.1kA for $\sigma=20\mu\text{m}$ at nonSc/Sc=2.1. The first quench can be also increased by increase of the clamping force to the winding but too high clamping force deteriorates the conductor performance damaging the conductor.

IV. CONCLUDING REMARKS - DESIGNING STABLE AND HIGH CURRENT DENSITY WINDING

Summarizing the study above, the following conclusions are obtained.

1. Quantitative estimation of the first quench and design of the stability of the winding are possible by the method described in the paper.
2. For a given value of σ and clamping force to the

Fig. 7. Dependence of first quench current on nonSc/Sc for different values of σ .

winding, there is an optimum value of nonSc/Sc to make the first quench current maximum. Low value of nonSc/Sc, that is, high I_c does not necessarily make the current density of the winding high. Increase of nonSc/Sc contributes to the reduction of the conductor cost by reducing the amount of NbTi.

3. Data of the compliance of the winding pack are key of our stability estimation method, we need more knowledge and data on the compliance of the winding.

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