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Improvement of Degradation Characteristics in a Large, Racetrack-shaped 2G HTS Coil for MW-class Rotating Machines

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Abstract – Degradation due to delamination occurs frequently in the high temperature superconductors (HTS) coil of rotating machines made with 2nd generation (2G) HTS wire, and the authors have observed other similar cases. Since an HTS field coil for a rotating machine is required to have stable current control and maintain a steady state, co-winding techniques for insulation material and epoxy resin for shape retention and heat transfer improvement are applied during coil fabrication. However, the most important limiting factor of this technique is delamination, which is known to be caused by the difference in thermal expansion between the epoxy resin and 2G HTS wire. Therefore, in this study, the experimental results of mixing the ratio of epoxy resin and alumina (Al_2O3) filler were applied to the fabrication of small and large test coils to solve the problem of degradation. For the verification of this scheme, eight prototypes of single pancake coils with different shapes were fabricated. They showed good results. The energization and operation maintenance tests of the stacked coils were carried out under liquid neon conditions similar to the operation temperature of an MW-class rotating machine. In conclusion, it was confirmed that the alumina powder mixed with epoxy resin in an appropriate ratio is an effective solution of de-lamination problem of 2G HTS coil.

Keywords: 2G HTS coil, Degradation, Delamination, Insulation material, Epoxy resin, Filler, Coefficient of thermal expansion.

1. Introduction

Recently, the development trend of superconducting rotating machines has mainly involved large synchronous rotating machines (such as wind turbines) with a capacity of 10 MW or more, and superconducting coils have become larger [1]. The application of superconducting technology enables the compactness and light weight of a large-capacity rotating machine. However, the superconducting coil needs to resist a high amount of stress, so a robust superconducting coil is required. For this purpose, the researchers tried to secure the robustness by applying epoxy resin to the superconducting coils in rotating machine-related studies. However, since the early use of 2G HTS wire, the degradation of HTS coils has occurred in the process of developing coils for rotating machines using epoxy resin. As a result, various experimental studies have shown that delamination occurs due to the difference in thermal expansion between the epoxy resin and the metal material composing 2G HTS wire [2], and the performance decreases as cooling and heating are repeated [3, 4]. It has also been confirmed that the cause of the problem is related to the multi-layer structure and bonding strength of 2G HTS wire [5-8]. To solve the problem of degradation, there have been various studies (examining, for example, no-insulation coil technology, polyimide coating, and the improvement of the peel-off strength of the wire), but rotating machine applications have not been confirmed yet [9-11].

In this study, to solve the thermal expansion difference of the epoxy used in the prototype production, the method of adding a filler with good electrical insulation and favorable heat transfer was selected. First, a field coil for an MW superconducting rotating machine was designed, and a coil bobbin for a prototype and test coil was fabricated. Filler specimens were prepared by mixing two kinds powder of alumina (Al_2O_3) and silica (SiO_2) with epoxy resin [12, 13] and were tested by thermal expansion coefficient measurement [14]. The mixing ratio was selected based on the test results and the viscosity suitable for the winding process; it was applied to the test coil first. The test coils were fabricated in two sizes: small and large. Each was tested for stability with a LN2 (liquid nitrogen) test. The large test coils were subjected to LNe (liquid Ne) condition conduction cooling and energization tests. The process identified from the test coils was applied to the fabrication of eight prototypes of single pancake coils (12 coils in total/pole). The prototype coils were stacked for final verification, and energization tests were conducted using the LNe condition conduction cooling tester. In order to verify the safety of laminated coils, the operating current was maintained at 125% of the design current for

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more than 2 hours and finally at 100% for more than 30 hours. From the experiments and results, we confirmed the possibility of decreasing the degradation of superconducting coils by applying an appropriate ratio of mixed filler.

2. Design of an HTS Prototype Field Coil

The field coil design is based on the assumption that the magnetomotive force is arranged considering the cross-sectional area of the superconducting wire and the dot turn ratio of the field winding. Fig. 1 shows the magnetic flux density distribution of the designed field coil, and the specifications are given in Table 1. However, the cross section of the superconducting wire used in the field winding is a tape shape, and the superconducting wire should be arranged in a step shape (as shown in Fig. 1) to make the air magnetic flux density sinusoidal.

In order to reduce the volume of the superconducting wire and the structure supporting the superconducting wire, the end shape of the field winding was redesigned (as can be seen in Fig. 2) from a circular shape to a shape with straighter corners. As a result, the use of superconducting wire has been reduced by 4.6%, and the field winding end height in the axial direction was reduced by 28% under the same output characteristics. In addition, as the cross-sectional area of the field coil end decreased, the magnetomotive force of the field coil increased, and the maximum magnetic field on the field coil increased to 1.8 T. The coil bobbin was made of the same material as the lamination of the superconducting wire, and aluminum heat transfer plates with insulation coating were installed on the top and bottom.

Table 2 shows the specifications of the specimens for confirming the mechanical properties of the 2G HTS wire used for coil fabrication. The thickness of the superconducting wire in Table 2 was soldered on both sides of the 50 μm-thick brass stabilizer. In order to prevent the degradation of the superconducting coil, the thermal expansion property improvement test of the bonding material was performed by mixing the epoxy and the filler. The results were applied to fabricate small and large test coils, and LN2 and 30 K conduction cooling tests were performed for each case.

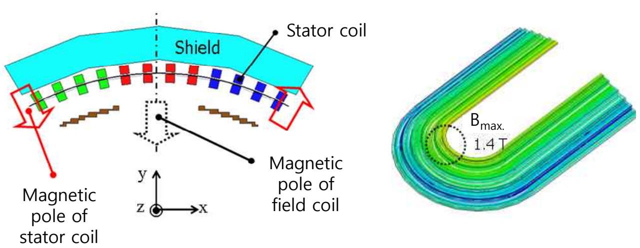


Fig. 1. Magnetic flux density distribution in the field coil

Table 1. Specifications of the HTS field coil

Major design contents	Specifications
Operating current	100 [A]
no. of turns per pole	2,335/12 coils
Straight part length of the HTS coil	1.2 [m]
Required HTS wire length in total	55.1 [km]
Max. magnetic field	1.4 [T]

Table 2. Specifications of 2G HTS wire

HTS material	Contents	Specifications
GdBCO	Wire width	4.1~4.3 [mm]
	Wire thickness	0.2~0.22 [mm]
	Lamination material	Brass
	Lamination thickness	50 [μm]

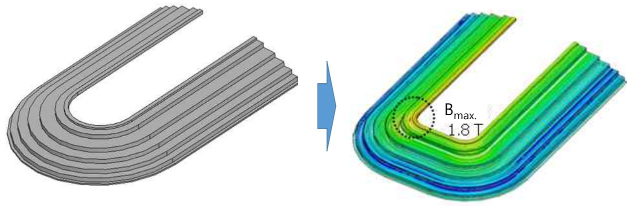


Fig. 2. Changing the shape of the coil end of the HTS field coil

3. Experimental Setup and Test Results

Fig. 3 shows the composition of the device for measuring the thermal expansion rate of bonding material when the epoxy resin and filler are mixed [13]. The filler used in this test was alumina (Al_2O_3) and silica (SiO_2). The specific particle size was selected, and the mixing ratio was varied. For the measurement of the thermal expansion coefficient, each sample was made with a length of 100 mm, a width of 10 mm, and a thickness of 1 mm, and they were tested by using the test apparatus shown in Fig. 3. The thermal contraction and the coefficient of thermal expansion (CTE) of each sample were calculated using equations 1 and 2 [14].

$$\frac{\Delta L}{L} = \frac{\Delta V_{\text{sample}} - V_{\text{ext.}}}{(CF_{@77K})(GL_{@ext.})} \quad (1)$$

$$\alpha = \frac{\Delta L / L}{\Delta T} \quad (2)$$

where $\Delta L / L$ is the thermal contraction of the sample, ΔV_{sample} corresponds to the difference in voltage reading of the sample when cooling from room temperature to 77 K, $V_{ext.}$ is the initial voltage reading of the double extensometer, $CF_{@77K}$ is the calibration factor at 77 K, $GL_{ext.}$ is the gauge length of the double extensometer, α is the CTE, and ΔT represents the temperature difference from room temperature to 77 K.

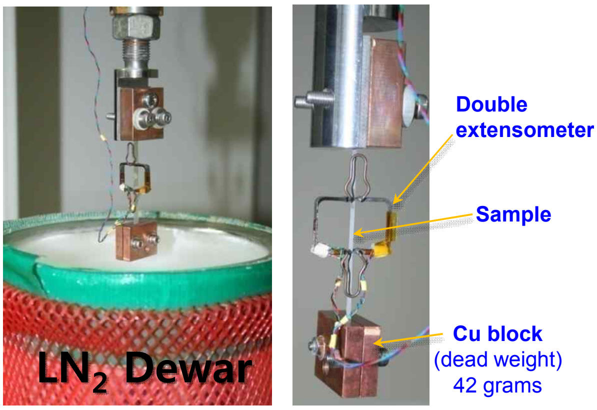


Fig. 3. Test setup for thermal strain measurement of the mixed epoxy resin and filler sample at 77 K

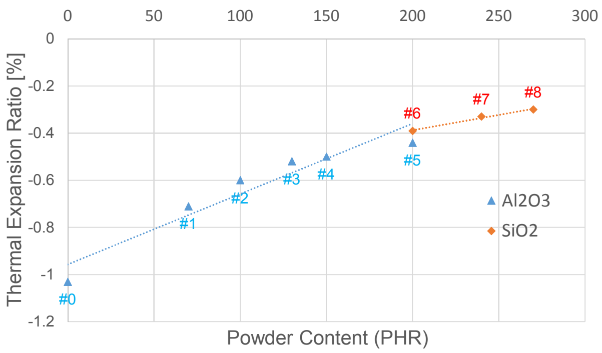


Fig. 4. Test results of the thermal expansion rate of the epoxy resin and filler sample

Fig. 4. shows the thermal expansion rate of the sample at 77 K, which is according to the filler type and mixing rate. The mixture of epoxy resin and filler was made by weight ratio. The results of sample #8 (280%) mixed with silica showed a similar thermal expansion coefficient at the liquid nitrogen temperature of the metal material used in the superconducting wire. Alumina filler-mixed specimens had a maximum thermal expansion coefficient of -0.5%. In this study, the mixing ratio corresponding to #3 (130%) specimen was selected and standard was viscosity. The higher the mixing ratio of the filler, the more similar the coefficient of thermal expansion to the metallic material, such as copper (Cu: -0.3%), of the superconducting wire. However, because of the high viscosity, the equipment and process used in this study were not capable of winding. The silica mixed sample showed a thermal expansion coefficient closer to that of the metal material than that using alumina, but was not applicable because of its high viscosity.

3.1 Small test coil

A small test coil was first fabricated and verified using the test results of the bonding material. Fig. 5 shows the external appearance of a small test coil. In the form of a

Table 3. Specifications of the small test coil

HTS Coil	Contents	Specifications
	Bobbin end radius	50 [mm],
	Bobbin length	300 [mm]
	no. of turns	100
Small test coil	Winding tension	59 [N] ± 2.9
	Winding method	Wet (with epoxy resin)
	HTS wire length	79 [m] (one piece)
	Insulation material	Polyimide, 25 [μm]

Table 4. Specifications of the large test coil

HTS Coil	Contents	Specifications
	Bobbin width	337 [mm]
	Bobbin length	1,365 [mm]
	Coil length	1,556 [mm]
Large test coil	no. of turns	291
	Winding tension	34~24.5 [N] ±2.9
	Winding method	Dry, Wet (epoxy)
	HTS wire length	1,007 [m] (5 joints)
	Insulation material	Polyimide, 25 [μm]

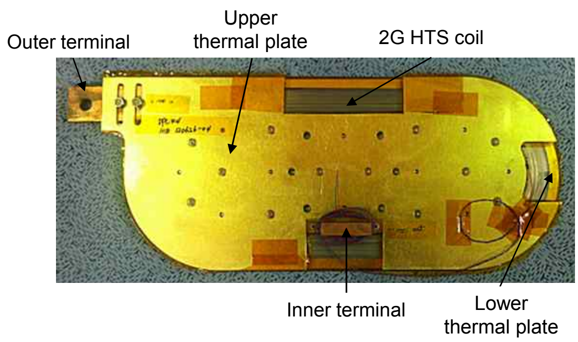


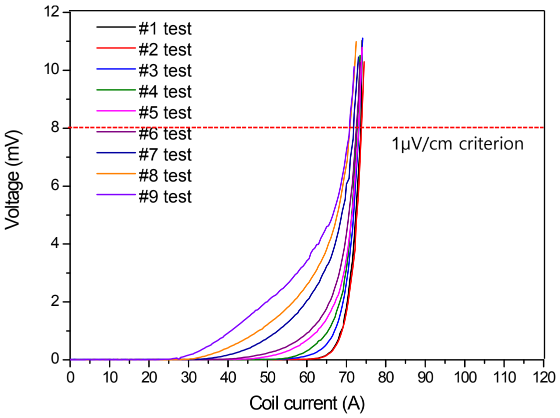
Fig. 5. Configurations of the small test coil

SP(single pancake), the current terminals are installed at the innermost turn and the outermost turn. A thermal plates were placed on the upper and lower sides of the coil, and the straight portion and the end-turn portion were cut to confirm the winding state. A voltage tap for measuring the coil voltage was installed in the end-turn. As shown in Table 3, the coil bobbin has a length of 300 mm and a curved portion of 50 mm on both sides. The wire used to make the test coil is the same as in Table 2, and 100 turns were wound with a tension of 59 N.

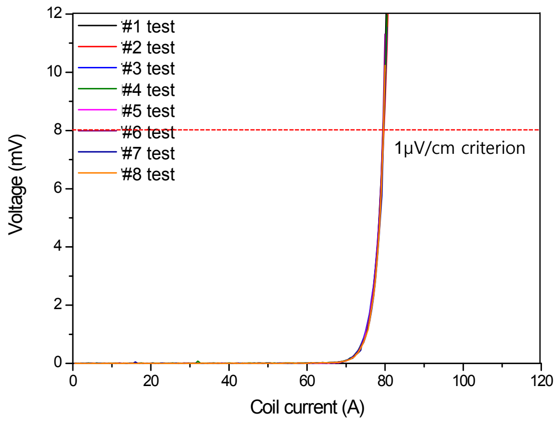
Fig. 6(a) shows the typical degradation occurring in a small test coil with a filler-free epoxy. The results were obtained by repeating the liquid nitrogen cooling and the room temperature elevation process nine times. As the repetition test progressed, the degradation of the coil's performance became worse. In contrast, Fig. 6 (b) shows the case where the mixing ratio of the epoxy and filler of sample #3 in Fig. 4 was applied, and the performance deterioration improves unlike Fig. 6(a).

3.2 Large coil test

A large test coil was fabricated based on the results obtained from the small test coil. Table 4 shows the major dimensions and specifications. The large test HTS coil was



(a) Coil with the epoxy (filler-free)



(b) Coil with the epoxy and filler

Fig. 6. Comparison of the test results with and without filler (LN2 cooled and thermal cycling test)

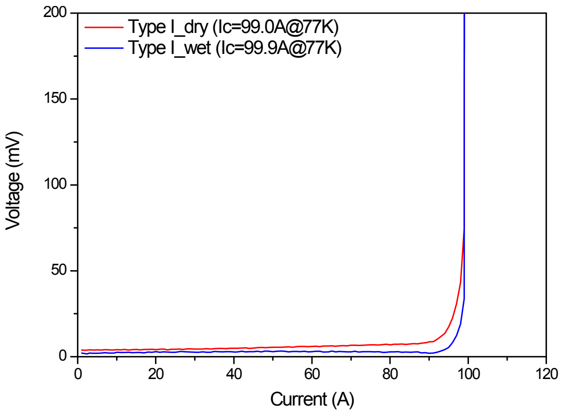


Fig. 7. Comparison of the test results between dry and wet winding conditions

also made of a SP coil, and the coil has a size of about 1.6m with 291 turns. The winding tension was decreased gradually from 34 N to 24.5 N. The LN2 cooling and energization tests were first carried out by dry winding the large test coils, and after unwinding through heating and drying processes, they were rewound using the wet-winding method with the epoxy resin. The results of the LN2 cooling and energization tests for both cases are presented in Fig. 7, which shows similar Ic values in both cases without performance degradation. In the test results, the reasons why the Ic value is slightly higher when the epoxy resin is used are that the number of windings of the coil applied by the epoxy resin is reduced by about 40 turns and the coil shape is fixed by the epoxy resin used.

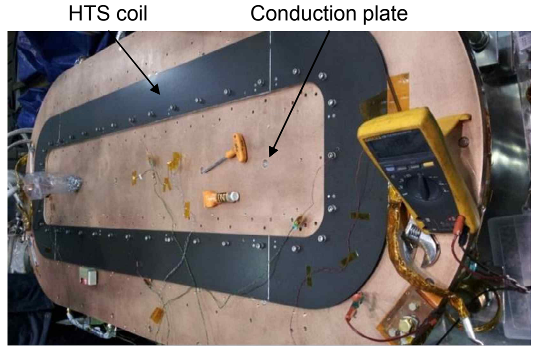


Fig. 8. A large 2G HTS test coil mounted on a conduction cooling test rig

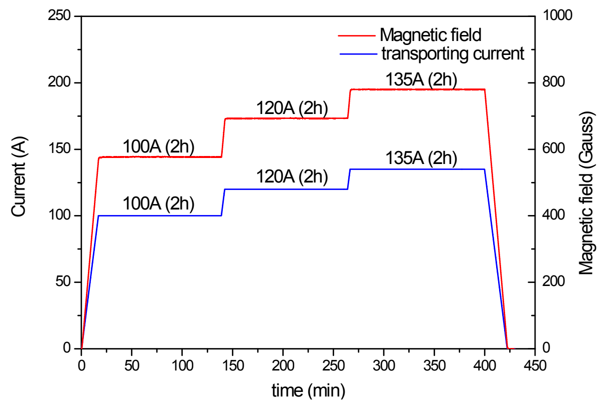


Fig. 9. Test results of the large test coil at 30 K conduction cooling

Fig. 8 shows the large test coil mounted on the conduction cooling test device. The conduction cooling test rig is capable of testing coils up to 1,000 mm in width, 2,000 mm in length, and 500 mm in end radius, and it has a maximum cooling capacity of about 150 W at the designed operating temperature (30 K). The test measurement temperature is maintained by a large heater and a heater controller installed at the bottom of the conduction cooling plate. Fig. 9 shows the results of measuring magnetic flux generation while maintaining a large test coil in a conduction cooling test apparatus and cooling to a temperature of 30 K with flowing currents of 100 A, 120 A, and 135 A for 2 hours. It can be seen that the supply current and the generated magnetic flux are linearly changed and maintained, and it was confirmed that the coil is stable through maintenance for 2 hours.

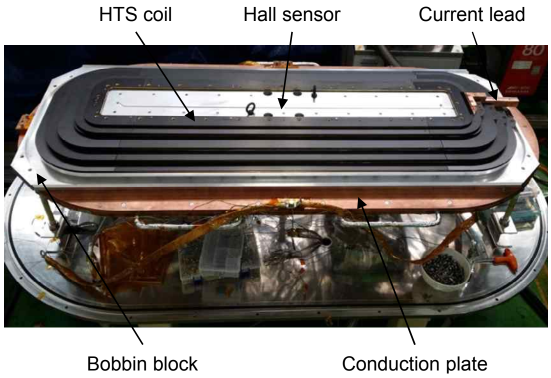


Fig. 10. Conduction cooling test rig for the assembled coil with the bobbin block

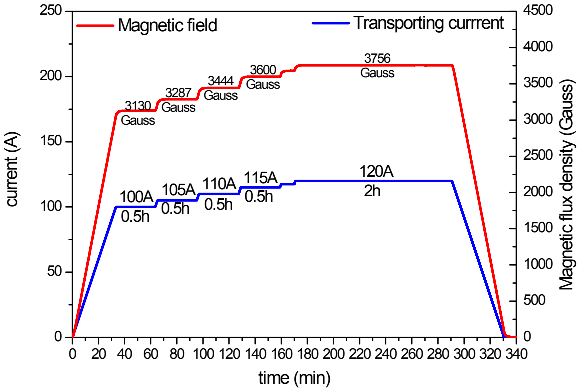
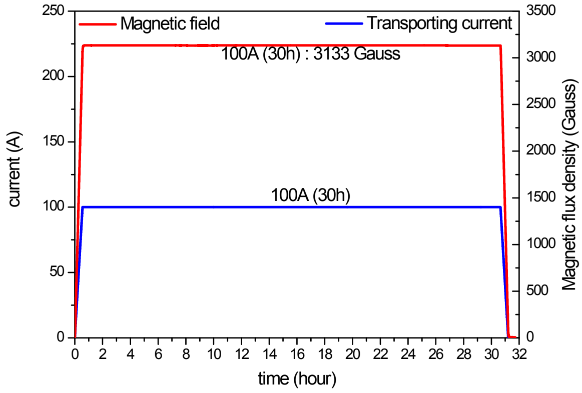


Fig. 11. Trend plot of the transporting current and magnetic field (at 30 K)

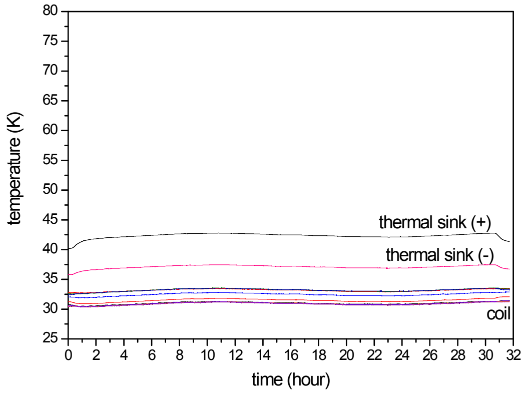
3.3 Prototype coil test

Fig. 10 shows that the eight fabricated coils are equipped with a conduction cooling test rig. The eight coils were fabricated by applying a process, which was confirmed through the fabrication and testing of large test coils; the Ic characteristics and coil integrity were confirmed individually through LN2 cooling tests. For the setup in the conduction cooling test system, an aluminum bobbin block was installed, and each coil was installed in the shape of a bobbin block embossed to match the internal shape. As shown in Fig. 10, a hall sensor was installed in the middle of the bobbin block to measure the generated magnetic field, and the magnetic field analysis value and the measured value were found to have an error of about 3.2% based on the operation current. In addition, a 120% energization and 2-hour maintenance test of the operating current was carried out, and the linear relationship with the generated magnetic field is shown in Fig. 11.

Fig. 11 shows the results of the operating current at 100% of the design value for 30 hours after energization. The test results show that the current and flux remain stable and that the temperature rises about 2.5 K higher than the initial temperature at the thermal sink of the current lead though it stabilizes over time. As a result, it



(a) Trend plot of the transporting current and magnetic field



(b) Temperature variation of the HTS coil

Fig. 12. Test results for 30 hours of current transporting

can be seen that the minute changes in the temperature are due to the change of the radiation heat invasion, which is caused by the external temperature change around the test apparatus. In other words, the temperature of the coil was judged to be completely stabilized.

4. Conclusions and Discussions

The degradation of the coils was confirmed through the small coil test. In order to solve this problem, an epoxy with an appropriate thermal expansion rate and a viscosity suitable for the process was selected and applied; it was mixed with alumina and silica as a filler. The degradation of the small and large test coils was clearly improved. The results can be summarized as follows:

1) It was confirmed that the proper mixing of the epoxy and mixed filler has similar properties to the thermal expansion rate of 2G HTS wire. It is expected that degradation will decrease as the difference in thermal expansion rates becomes smaller.
2) As the ratio of the mixed filler increases, the difference in the thermal expansion coefficient becomes smaller, but since the viscosity becomes high and it becomes

unsuitable in view of workability, a proper balance between the thermal expansion coefficient and workability is needed.
3) The small and large test coils were fabricated by using the mixed material filler in the proper ratio, and cooling and energizing tests were performed under LN2 and 30 K conditions through which stable results have been confirmed.
4) As in the case of the actual rotating machine, eight coils were stacked and subjected to the cooling energization test at 30 K. As a result, stable flux generation of up to 120% of the designed operating current was confirmed.
5) The laminated coil assembly was confirmed to be in a stable state by energizing and maintaining 100% current for 30 hours, and it was confirmed that the generated magnetic field was in good agreement with the results of the analysis.
6) From the above results, the possibility of decreasing the degradation of 2G HTS coils by applying an appropriate ratio of the mixed filler was demonstrated.

Future studies will ensure the stability of large 2G HTS coils for MW-class rotating machines.

References

[1] J. Lloberas, A. Sumper, M. Sanmarti, X. Granados, “A review of high temperature superconductors for offshore wind power synchronous generators,” *Renewable and Sustainable Energy Reviews*, vol. 38, pp. 404-414, 2014.

[2] C. Barth, N. Bagrets, K-P. Weiss, C. M. Bayer and T. Bast, “Degradation free epoxy impregnation of REBCO coils and cables,” *Superconductor Science and Technology*, vol. 26, no. 5, 2013.

[3] M. Oomen, W. Herkert, D. Bayer, P. Kummeth, T. Arndt, “Manufacturing and test of 2G-HTS coils for rotating machines: Challenges, conductor requirements, realization,” *Physica C: Superconductivity and Its Applications*, vol. 482, pp.111-118, 2012.

[4] Y. Zhang, D.W. Hazelton, A.R. Knoll, J.M. Duval, P. Brownsey, S. Repnoy, S. Soloveichik, A. Sundaram, R.B. McClure, G. Majkic, V. Selvamanickam, “Adhesion strength study of IBAD-MOCVD-based 2G HTS wire using a peel test,” *Physica C*, vol. 473, pp. 41-47, 2012.

[5] T. Takematsu, R. Hu, T. Takao, Y. Yanagisawa, H. Nakagome, D. Uglietti, T. Kiyoshi, M. Takahashi, H. Maeda, “Degradation of the performance of a YBCO-coated conductor double pancake coil due to epoxy impregnation,” *Physica C*, vol. 470, pp. 674-677, 2010.

[6] Y. Zhang, D.W. Hazelton, A.R. Knoll, J.M. Duval, V. Selvamanickam, “Adhesion strength study of IBAD-MOCVD-based 2G HTS wire using a peel test,” *Physica C: Superconductivity*, vol. 473, pp. 41-47, 2012.

[7] A. Gorospe, A. Nisay, J.R. Dizon, H.S. Shin, “Delamination behaviour of GdBCO coated conductor tapes under transverse tension,” *Physica C: Superconductivity*, vol. 494, pp. 163-167, 2013.

[8] H.S. Shin and M.J. Dedicatoria, “Variation of the strain effect on the critical current due to external lamination in REBCO coated conductors,” *Superconductor Science and Technology*, vol. 25, no. 5, p. 054013, 2012.

[9] H. Park, A. Kim, S. Kim, M. Park, K. Kim, T. Park, “Mechanical and electric characteristics of vacuum impregnated no-insulation HTS coil,” *Physica C*, vol. 504, pp.138-143, 2014.

[10] Y. Yanagisawa, K. Sato, T. Matsuda, T. Nagato, H. Kamibayashi, H. Nakagome, X. Jin, M. Takahashi, H. Maeda, “An ultra-thin polyimide insulation coating on REBCO conductors by electrodeposition produces a maximum overall current density for REBCO coils,” *Physica C: Superconductivity*, vol. 495, pp. 15-18, 2013.

[11] M. Yoshizumi, N. Sakai, T. Izumi, “Improvement of delamination strength of REBCO coated conductors,” *Physics Procedia*, vol. 58, pp. 150-153, 2014.

[12] S.H. Jeong, J.B. Song, Y.H. Choi, S.G. Kim, B.S. Go, M. Park, H. Lee, “Effect of micro-ceramic fillers in epoxy composites on thermal and electrical stabilities of GdBCO coils,” *Composites: Part B*, vol. 94, pp. 190-196, 2016.

[13] L. Ren, K. Pashayi, H.R. Fard, S.P. Kotha, T. Borca-Tasciuc, R. Ozisik, “Engineering the coefficient of thermal expansion and thermal conductivity of polymers filled with high aspect ratio silica nanofibers,” *Composites: Part B*, vol. 58, pp. 228-234, 2014.

[14] Marlon J. Dedicatoria, John Ryan C. Dizon, Hyung-Seop Shin and Ki-Duk Sim, “Establishment of CTE Measurement Procedure for PPLP at 77K HTS Power Cables using Double Extensometers,” *Superconductivity and Cryogenics*, vol. 14, no. 4, pp. 24-27, 2012.

[15] A.R. Nisay and H.S. Shin, “Mechanical and electromechanical analysis in differently stabilized GdBCO coated conductor tapes with stainless steel substrate,” *Progress in Superconductivity and Cryogenics*, vol. 15, no. 2, pp. 29-33, 2013.

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