Winding Configurations and AC Loss of Superconducting Synchronous REBCO Motors

Akifumi Kawagoe¹, Kazuma Kudou¹, Ryota Kanemaru¹, Masataka Iwakuma², Masayuki Konno³, Akira Tomioka³, Teruo Izumi⁴

1. Kagoshima University, Kagoshima 890-0065, Japan
2. Kyushu University, Fukuoka 819-0395, Japan
3. Fuji Electric Co. Ltd., Ichihara 290-8511, Japan
4. Research Institute of Advanced Industrial Science and Technology, Ibaraki 305-8564, Japan

kawagoe@eee.kagoshima-u.ac.jp

Abstract. We investigate effects of armature winding configurations on properties of fully superconducting synchronous motors using REBCO tapes. The effect of the configurations on ac losses in the winding tapes due to the changing transverse magnetic fields applied to the tapes in direction of perpendicular to the flat face of the tapes is important. In generally, it is effective to close winding factor to 1 for improvement of properties of motors. For the purpose, the shape of armature windings is better saddle-shaped winding than race-track winding. In this paper, numerical calculations on the properties of fully superconducting synchronous motors using REBCO tapes with 500 kW class were described. Operating temperature was 65 K. In order to demonstrate the feasibility of saddle-shaped winding, test coil with 5 turns were wound with YBCO tapes and then critical current measurements were carried out. The degradation of the properties has not observed.

1. Introduction

The developments of synchronous motors with REBCO tapes are ongoing [1]. The field winding without iron cores, which are wound by REBCO tapes, can produce higher magnetic flux density than the saturation magnetic flux density of iron. Therefore, it is expected that the REBCO motors can be realized lightweight and small size.

In order to improve efficiencies, however, ac losses in armature windings must be reduced. A candidate of the reduction method of the ac losses is the application of scribing processed REBCO tapes and the special winding [2–4]. Although several studies on structures and ac losses in armature windings of rotating machines were carried out [5–13], it has been not clarified optimum structures of motors applied both of multifilamentary REBCO tapes with scribing process and the special windings.

In generally, shapes of armature windings have been race-track shapes in the design of the fully superconducting motors with REBCO tapes. In the case of the race-track shape, however, it is difficult to design to be a high winding factor, because the ends of the three-phase windings interfere with each other. In contrast, the saddle-shaped winding has more flexible at the ends of the windings than that of the race-track shape. For this reason, it is possible to assemble while avoiding contact at the coil ends. Also, the angles around the axis of the winding tapes at straight parts are possible to control. So the adjusting the direction of magnetic fields applied to the tapes to parallel to its flat face in the saddle-
2. Analysis method and model
In this study, hysteresis losses in the fully synchronous motors with an output power of 500 kW were calculated on the two cases of the race-track shape windings and the saddle-shaped windings. And in order to investigate influences of the short-node winding coefficient on the loss reduction effects, ac losses in the motors on three cases of coil pitches of the armature windings were calculated. In this chapter, calculation methods of losses in the motor are explained.

2.1. The calculation method of ac losses in the armature winding
In this calculation, magnetic fields distributions in the calculated model of the motor were analysed by finite element method. The analyses were calculated by using simulation software, JMAG, which is developed by JSOL Corporation. The analyses of the magnetic field distributions were not taken the electromagnetic behaviors of superconductors into account. Therefore, the permeability of the superconducting winding area was assumed to the vacuum permeability. And eddy currents in the normal conductors were not considered. So the FEM analyses were based on $A$-method. Ac losses in the superconducting tapes in the armature winding were calculated by following. The ac losses in REBCO tapes are determined by the magnetic fields applied to the tapes in the direction of perpendicular to the tape face. The magnetic fields, which are perpendicularly applied to the tape face in each element of REBCO winding area in the numerical model, were obtained by the simulation software mentioned above. Ac losses in superconducting windings were calculated from ac losses in each element in the FEM model. Ac losses per unit volume and cycle of applied magnetic fields were calculated by the equation of Brandt [14]. And then, whole ac losses in the superconducting winding area were obtained by volume integral of ac losses in each element. Finally, the cooling penalty is taking into account.
2.2. Analysis model

Figure 2 shows the analysis of 2D models. In these analyses, the 2D infinite-long model is applied. As shown in Fig. 2, the analysis was carried out on the four-pole machine. All analysis has been carried out on the condition that the load angle is 45 degree. Table 1 shows the parameters of 2D FEM analysis. Parameters of the analysis are as follows: The output power of the motor is 500 kW. The rotating speed is 1800 rpm. Gap magnetic flux density, $B_g$, varied from 1.0 T to 2.5 T. The same model was used in

![Figure 2 The analysis model. (a) whole model, (b) enlarged view. The analysis was carried out on the four-pole machine. Fields windings are composed of four coils without iron cores.](image)

| Table 1 Parameters of 2D FEM analysis |
|---------------------------------------|
| Output power                          | 500kW                     |
| Number of poles                       | 4                        |
| Load angle                            | 45°                      |
| Operating temperature                 | 65K                      |
| COP@65K                               | 0.1                      |
| Outer diameter                        | 654mm                    |
| Rotor diameter                        | 370mm                    |
| Stator diameter                       | 414mm                    |
| Thickness of Vacuum heat-insulating layer | 30mm                     |
| Effective length                      | 270mm                    |
| Air gap                               | 2mm                      |

| Table 2 Ampere turns of the field and the armature winding |
|------------------------------------------------------------|
| Saddle & Racetrack type winding                            |
| Bg                        | Pitch 30° | Pitch 60° | Pitch 90° |
|----------------------------|-----------|-----------|-----------|
| 1.0[T]                    |           |           |           |
| Ampere turns of field windings | 200000A-turns | 200000A-turns | 200000A-turns |
| Ampere turns of one slot’s armature windings | 17868A-turns | 10460A-turns | 8936A-turns |
| 1.5[T]                    |           |           |           |
| Ampere turns of field windings | 300000A-turns | 300000A-turns | 300000A-turns |
| Ampere turns of one slot’s armature windings | 11926A-turns | 6992A-turns | 5964A-turns |
| 2.0[T]                    |           |           |           |
| Ampere turns of field windings | 400000A-turns | 400000A-turns | 400000A-turns |
| Ampere turns of one slot’s armature windings | 9026A-turns | 5308A-turns | 4512A-turns |
| 2.5[T]                    |           |           |           |
| Ampere turns of field windings | 500000A-turns | 500000A-turns | 500000A-turns |
| Ampere turns of one slot’s armature windings | 7458A-turns | 4400A-turns | 3730A-turns |
both cases of the race-track shape winding and saddle-shaped one. In order to check the effect of the short-node winding coefficient, the analysis was carried out on the coil pitches of the armature winding of 30, 60, 90 degrees, which correspond to short-node winding coefficients of 0.5, 0.867, 1.0, respectively. In this paper, magnetic loadings are dominant in order to suppress ac losses in armature windings. As shown in Table 2, ampere-turns of armature and fields windings are different about 10 – over 100 times. So applied magnetic fields to the armature windings are decided mainly by magnetic fields produced from the fields winding.

3. Results of analysis
In this chapter, the results of FEM analysis and ac loss calculations are explained. Firstly, perpendicular magnetic flux density applied to the flat face of the REBCO tapes in the armature windings in cases that coil pitch of 30, 60, 90 degrees are explained. Also, then ac losses in each case are shown.

3.1. Results of FEM analysis on magnetic fields distributions applied to the armature winding
Figure 3 shows distributions of perpendicular magnetic flux density applied to the REBCO tapes in the armature windings when the coil pitch of the armature windings is 90 degree, i.e., the short-node
coefficient is 1.0. In every case of $B_g$, these results clearly show that perpendicular magnetic flux density in case of the saddle-shaped windings are smaller than that in the case of race-track windings, over the whole winding area. The maximum values of perpendicular magnetic flux density in the saddle-shaped windings are half of the values in case of the race-track windings. Figure 4 shows the maximum perpendicular magnetic flux density in the armature windings. The reduction ratios are 45 – 50 %.

3.2. AC loss

Figure 5 shows the comparison of ac losses in the armature windings in case that coil pitches are 30, 60, 90 degrees, at $B_g$ is 1.0 T. Ac losses in the armature windings were calculated by using the magnetic fields distributions shown in Figure 4. The calculation methods of ac losses in the armature windings have been explained in section 2.1. It is clear that ac losses in the saddle-shaped winding are smaller than that of race-track windings. The maximum loss reduction effect is obtained in case of coil pitch of 90 degree. Because the angle between the flat face of the REBCO tapes and applied magnetic fields direction decrease as the coil pitch decrease. The larger ac losses in case of small coil pitch are estimated. This reason is that winding volume of the armature windings increase as the short-node coefficient decrease. In addition, ac losses increase as short-node coefficient decrease. This reason is that the winding volume of the armature windings increases as the short-node winding coefficient decrease.

Figure 4 The maximum perpendicular magnetic flux density in case of the coil pitch of 90 degree.

Figure 5 Ac losses in the armature windings with the coil pitches of 30, 60, 90 degrees under $B_g$ of 1.0 T. The loss reduction effect is larger in case of large coil pitch.
4. Conclusions
Numerical calculations on the properties of fully superconducting synchronous motors using REBCO tapes with 500 kW class were carried out. The transverse magnetic fields applied to the tapes in the armature windings on two winding shapes, race-track shape windings and saddle-shaped windings and ac losses in their windings were investigated. Results show as follows: The perpendicular magnetic fields applied to the flat face of the winding tapes smaller in the saddle-shaped windings than race-track shape. As a result, ac losses in saddle-shaped windings are smaller than that of race-track windings. The loss reduction effects increase as short-node winding coefficient increase.

5. References
[1] Iwakuma M, et al., “Development of a 15 kW Motor With a Fixed YBCO Superconducting Field Winding,” IEEE Trans. Appl. Supercond., Vol. 17, No. 2, June 2017, pp. 1607-1610.
[2] Okamoto H, et al., “AC loss properties in YBCO model coils for loss reduction,” Physica C, Vol. 468, 2008, pp. 1731-1733.
[3] Iwakuma M, et al., “Development of REBCO superconducting power transformers in Japan,” Physica C, Vol. 469, 2009, pp. 1726-1732.
[4] Iwakuma M, et al., “Development of a 3φ-66/6.9kV-2MVA REBCO Superconducting Transformer,” IEEE Trans. Appl. Supercond., Vol. 25, 2015, Art. No. 6935085.
[5] Advanced Low Carbon Technology Research and Development Program supported by Japan Science and Technology Agency, “Development of REBCO fully superconducting motors,” from 2014
[6] Iwakuma M, et al., “Feasibility Study on a 400 kW–3600 rpm REBCO Fully Superconducting Motor,” IEEE Trans. Appl. Supercond., Vol. 22, No. 2, 2012, Art. No. 5201204.
[7] Tamura K, et al., “Study on the Optimum Arrangement of the Field Winding for a 20-kW Fully Superconducting Motor,” IEEE Trans. Appl. Supercond., Vol. 26, No. 4, 2016, Art. No. 5206905.
[8] Zhang M, et al., “AC Loss Estimation of HTS Armature Windings for Electric Machines,” IEEE Trans. Appl. Supercond., Vol. 23, No. 3, 2013, Art. No. 500604.
[9] Zhang M, et al., “Design and Modelling of 2G HTS Armature Winding for Electric Aircraft Propulsion Applications,” IEEE Trans. Appl. Supercond., Vol. 26, No. 3, Apr. 2016, Art. No. 5205705.
[10] Li Y, et al., “Numerical Study on AC Loss Characteristics of REBCO Armature Windings in a 15-kW Class Fully HTS Generator,” IEEE Trans. Appl. Supercond., Vol. 27, No. 4, Jun. 2017, Art. No. 5200206.
[11] Qu T, et al., “Development and Testing of A 2.5 kW Synchronous Generator with A High Temperature Superconducting Stator and Permanent Magnet Rotor,” Supercond. Sci. Technol., Vol. 27, No. 4, 2014, p. 044026.
[12] Kawagoe A, et al., “Numerical Analyses on Influences of Armature Winding Shape and Yoke Arrangements on Total Losses in Fully Superconducting Synchronous Motors Using REBCO Tapes,” IEEE Trans. Appl. Supercond., Vol. 28, No. 6, 2018, Art. No. 5208104.
[13] Fukuda S, et al., “Design Study of 2-MW Fully Superconducting Synchronous Motors,” IEEE Transactions on Applied Superconductivity, Vol. 28, No. 2, Apr. 2018, Art. No. 5207006.
[14] Brandt E H and Indenbom M: “Type-II superconductor strip with current in a perpendicular magnetic field,” Phys. Rev. B. 48 (1993) 12893-12906.

Acknowledgments
This work was supported in part by the Japan Society for the Promotion of Science (JSPS): Grant-in-Aid for Scientific Research JP18H03783 and JP19K14964), Japan Science and Technology Agency (JST): Advanced Low Carbon Technology Research and Development Program (ALCA), the New Energy and Industrial Technology Development Organization (NEDO),