Diagnosis of Winding Conditions in High Temperature Superconducting Coils by Applying Poynting's Vector Method

A. Kawagoe, H. Moribe, K. Kakiyama and F. Sumiyoshi

***Abstract*—We have proposed a new method for detecting unusual local conditions in a high temperature superconducting coil. In this method, two kinds of pick up coils for measuring electric fields and magnetic fields are used to obtain Poynting's vectors around the coil. This is a non-contact method using pick-up coils around the vessel for cooling the coil. The method has the following benefits: safe detection, easy handling, high sensitivity and high usability. The purpose of this paper is to clarify the relation of measured signals to the conditions of the windings. When a temperature rise has been produced locally in the Bi-2223 solenoidal coil, Poynting's vectors around the coil and the temperature of windings were measured. It was found that the measured signals rapidly decrease as the temperature of the winding achieved critical temperature, making this a reliable method to estimate the conditions in the windings.**

***Index Terms*— Poynting's vector method, superconducting coil, monitoring, diagnosis, quench**

I. Introduction

TECHONOLOGICAL DEVELOPMENT for fabrication of wires from high temperature superconductors (HTS) including Y-system and Bi-system superconductors is ongoing [1]. As the technology progresses, the need for HTS devices that employ high temperature superconducting wires is increased. On these HTS devices, stable operations are expected because the specific heat of the materials increases significantly at higher operating temperatures. If a normal transition appears, however, it is difficult to propagate the normal state, and therefore the temperature rises in a narrow area, i.e., a hotspot is likely to happen. These hot spots are difficult to be detected, and if they remain undetected the device may burn out in the worst case. Therefore, when HTS devices are operated, highly sensitive systems that can monitor the conditions of as small an area as possible in the winding area of the coil are needed.

We have proposed a new detecting method of normal transitions in windings of HTS coils, and the principle of this method has been theoretically and experimentally shown [2-6]. The method measures Poynting's vectors obtained from the cross-product of local magnetic fields and electric fields, which are measured by pick-up coils set outside of the vessel for cooling superconducting coils (Fig. 1). In this method, pick-up coils used as measuring sensors have no need to be in contact with the superconducting coils, and these pick-up coils can be mounted at room temperature. Therefore, this method has the following benefits: safe detection, easy handling, high sensitivity and high usability.

In practical use of this method for superconducting coils, however, it is important to clarify the relation of measured signals obtained by this method to the condition of the windings. The purpose of this paper is to clarify experimentally the relation of these measured signals to the temperature of the windings. This paper explains the details of experiments in which measurements of Poynting's vectors have been carried out around a solenoidal coil wound with a Bi-2223 tape when there were local abnormalities in the coil. We list the experimental results and then discuss the relation between the measured signals and the temperature of the windings.

II. Principle of the New Deteicting Method

In our detecting method for normal transitions, Poynting's vectors as electromagnetic energy flows are measured and their temporal changes are monitored. In particular, the temporal changes of a net of energy flows into the superconducting coil, i.e., loss components of the energy flows (if AC transport current is conducted, that corresponds to an active power), are observed. If temporal changes of the loss energy flow densities mentioned above can be observed, it can be diagnosed that some abnormalities have occurred in the coil winding.

In order to measure local Poynting's vectors, local electric fields and magnetic fields must be measured. In this new detecting method, only pick-up coils are used, as shown in Fig. 1. These pick-up coils are of two kinds; one type for measuring electric fields (hereafter called PC-E) and one type for magnetic fields (hereafter called PC-H). It is well known that local magnetic fields can be measured by small pick-up coils. When electromagnetic fields are axially symmetrical, a special shaped pick-up coil, PC-E, can measure local electric fields [6]. Inner and outer arcs of the PC-E are mounted on the circular lines, co-axially to the sample coil. And the outer arc is mounted on the area where the electromagnetic energy flows are small enough to be able to be ignored. Electric fields on the outer arc are almost zero. Due to axial symmetry, the

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A. Kawagoe, H. Moribe, K. Kakiyama and F. Sumiyoshi are with Kagoshima University, 1-21-40, Kohrimoto, Kagoshima City, Kagoshima 890065 Japan (phone: +81-99-285-8403; fax: +81-99-285-8413; e-mail: kawagoe@eee.kiagoshima-u.ac.jp.).

integral of the electric fields on lines connected between inner and outer arcs are canceled. Therefore, the PC-E can measure local electric fields.

III. Experiment

This chapter explains the results of the experiment using our proposed method to investigate the relation of the measured signals to the winding temperature of a sample coil wound into solenoidal shape with Bi-2223 multifilamentary tape.

If temperature increases of the windings are induced by a heater, in which the drive energy is electric energy, it is difficult to distinguish the loss energy flows flowing into the sample coil from those flowing into the heater, because our measuring method measures total electric energy flow. As a result, measuring errors may be produced. Accordingly, the abnormalities in the sample coils have been generated by means of blowing nitrogen gas on a part of the windings of the sample coil.

A. Experimental set up

The sample coil used in the experiment, and the method of generating the normal transitions and system to measure the normal transitions are described.

The parameters of the sample coil are shown in Table I. The winding tape is Bi-2223 multifilamentary tape whose critical current is 115 A in self fields at 77 K. The parameters of this

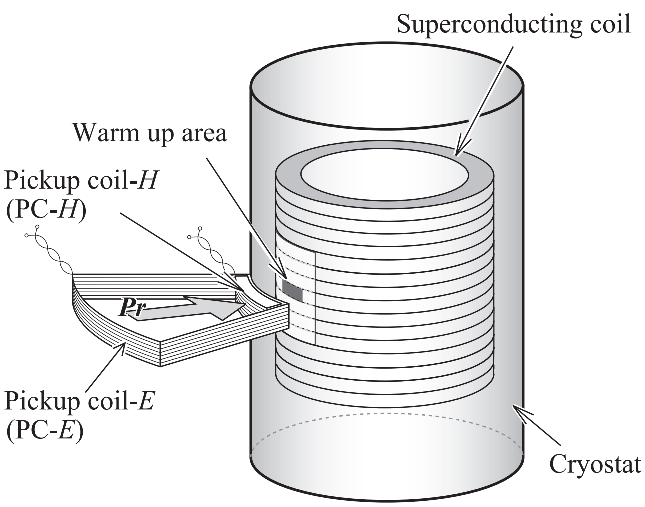

Fig. 1 Experimental set up.

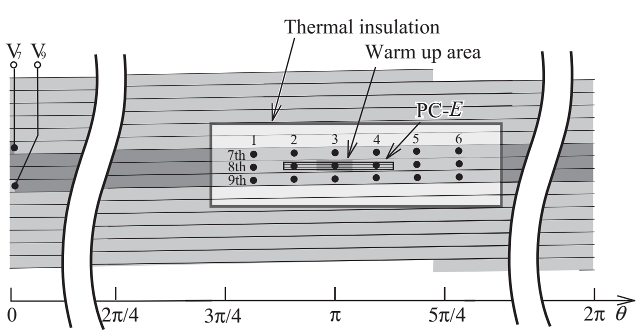

Fig. 2 Measuring sensor arrangement.

TABLE I
PARAMETERS OF SUPERCONDUCTING COILS AND TAPES

Coil	
Diameter	70 mm
Length	63.2 mm
Number of layers	1
Number of turns	15
Length of windings	3.30 m
Inductance	11.0 μH
Tape	
Filament material	Bi-2223
Number of filaments	121
Ag ratio	2.4
Width of tapes	4.2 mm
Thickness of tapes	0.22 mm
Twisting	none
Critical current at 77 K, self-field	115 A

TABLE II
PARAMETERS OF PICK-UP COILS

Pickup coil-*E*	
Turn number	24 turn
Length of inner arc	51.1 mm
Length of outer arc	130 mm
Pickup coil-*H*	
Turn number	80 turn
Length of inner arc	51.1 mm
Length of outer arc	55.0 mm

tape are also shown in Table I. For the sample coil, this tape has been closely wound into a solenoidal coil of a single layer around a bobbin made of Bakelite. The bobbin is 70 mm in diameter. The turn number of the sample coil is 15.

An illustration of the experimental system is shown in Fig. 1. The sample coil has been mounted in the vessel for cooling by liquid nitrogen. The pick-up coil pair which consists of two pick-up coils is set in the area shown in this figure. One pick-up coil is to measure electric fields, PC-E, and another one is to measure magnetic fields, PC-H. The parameters of these pick-up coils are shown in Table II. These pick-up coils measure Poynting's vector near a warm up area shown by a grayed area in Fig. 1. At the warm up area, abnormalities have been generated by means of described later. Fig. 2 represents the development view of the sample coil, in which the horizontal axis is a rotation angle θ in circular direction of the sample coil. "Warm up area" shown in this figure had the nitrogen gas blown onto it. This area was at π in the 8th turn, and its size was 3 mm x 9 mm. Thermo couples with E type were used to measure winding temperatures. Measured points of temperature were represented by solid circles. In order to clarify the critical currents of the winding in the sample coil, voltage taps were attached on the 7th and 9th turn. The two taps are shown as V_7 and V_9, respectively (Fig. 2). At the warm up area, there was a 3 mm x 9 mm hole in the bobbin.

The outer side of the sample coil was covered by thermal insulation. The nitrogen gas was conducted from a room temperature area to the hole to warm up the windings and then back to the room temperature area through a Teflon tube of 3 mm inner diameter, and finally released. The control of thermal input power was carried out by means of adjusting the flow rate and pressure at the nitrogen gas cylinder.

B. Results

Firstly, critical currents in the sample coil were measured. In order to observe the local critical current of the sample coil, the voltage between V_7 and V_9 was also measured in addition to measurements of overall voltages across the terminal of the sample coil. The observed result is shown in Fig. 3. The vertical axis represents electric fields which are voltages divided by length between voltage taps. The horizontal axis represents the transport current. So criterion of critical current are defined as 100 μV/m. Open symbols represent local voltages V_{79} between V_7 and V_9, and solid symbols represent overall voltage of the sample coil. From the results, it can be seen that the critical currents of the sample coil, overall I_c, and local current near the center of the sample coil are 117 A and 121 A, respectively. A critical current of a winding near the center of the sample coil is higher than that of a short sample because applied magnetic fields in a direction perpendicular to the winding tape face are decreased due to magnetic fields produced by the transport current through neighboring turns.

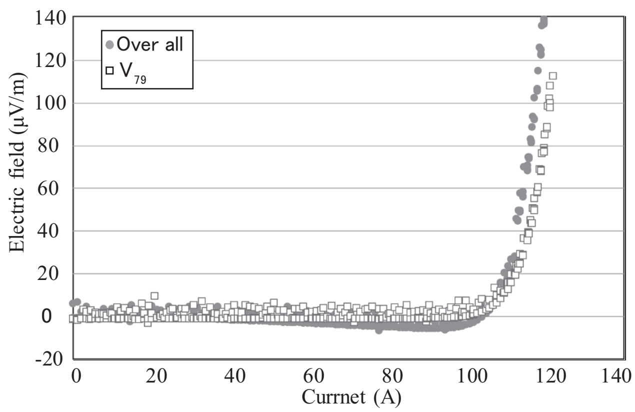

Fig. 3 I-V curves on the sample coil, solid symbols represent overall voltage of the sample coil and open symbols represent voltages at the center of the sample coil.

Next, Poynting's vector, P_r was been measured when AC currents were transported through the sample coil. Conditions of the AC transport current were as follows: Amplitudes were 50 A, 70 A and 90 A, frequency was 50 Hz. Nitrogen gas flow rates and pressures were 0.1 MPa and 0.19 L/sec. When the amplitude of AC transport currents was 50 A, temperature rise due to small AC losses in the sample coil was not observed. So the conditions of nitrogen gas were raised up 0.15 MPa and 0.21 L/sec. Figs. 4 (a), (b) and (c) represent results at amplitude for transport currents of 50 A, 70 A and 90 A, respectively. Horizontal axes are time. Vertical axes are signals measured by our measuring method and winding temperatures. Nitrogen gas is blown from 25 sec. The time corresponding to the presence of the nitrogen gas is shown by the grayed area in these figures. From the observed temperatures, it is found that the temperatures of the winding rose near the area where nitrogen gas was blown onto the point 8th-3, which is the 3rd point in the 8th turn. It is clear that the point 8th-3 has the highest temperature. Temperatures have returned to a superconducting state as the windings are cooled after the nitrogen gas stops blowing.

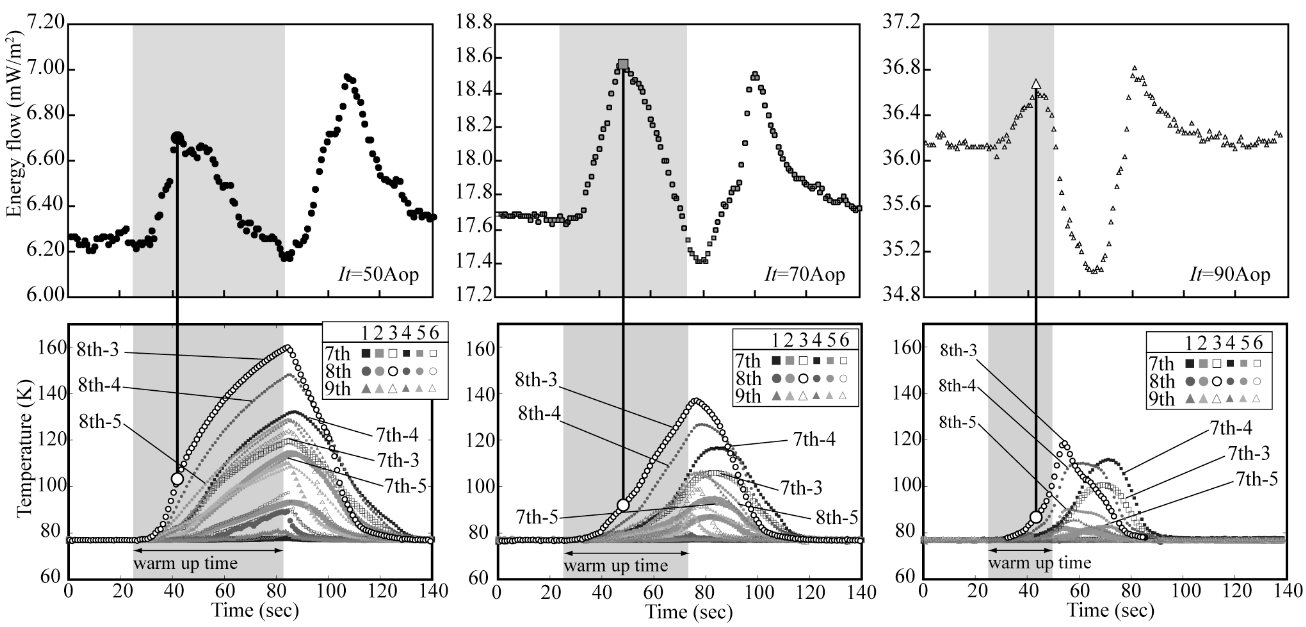

Fig. 4 Obtained relation of measured signals to winding temperature, (a), (b) and (c) represent results at amplitude of transport currents of 50 A, 70 A and 90 A, respectively. It was found that measured signals rapidly decrease when temperature rise to a threshold temperature, T_{th}

On the other hand, it is apparent that measured signals changed from rising to decreasing while the nitrogen gas continued to be blown on to the area. It can be seen that the decrease of the measured signals was observed when temperatures achieved a threshold temperature, T_{th}. The threshold temperatures, T_{th} are considered to correspond to the critical temperature of the winding, because signals measured by our method correspond to the magnitude of magnetizations of the windings. When winding temperature achieves the critical temperature, magnetizations disappear as critical current densities decrease to zero.

IV. Discussion

In order to discuss the relation of measured signals to the temperature of the winding, observed threshold temperature in the experiments above are investigated.

The dependencies of the threshold temperatures on transport currents are shown in Fig. 5. The horizontal axis represents the amplitude of the transport currents divided by the local critical current. Open circles represent measured data. For measured data, the local critical current is that of the center winding of the sample coil, at 121 A. A solid line represents the linear approximated line of transport current dependencies of the critical temperature of the short sample. It can be seen that the measured threshold temperatures correspond to the critical temperature. It is observed that differences between measured data and the approximated line increase with transport current decrease. The differences can be explained as follows: in the case of low currents, the distributions of temperatures were broad. Therefore, it is considered that the measured signals of energy flows cannot be decided by the temperature at a single point.

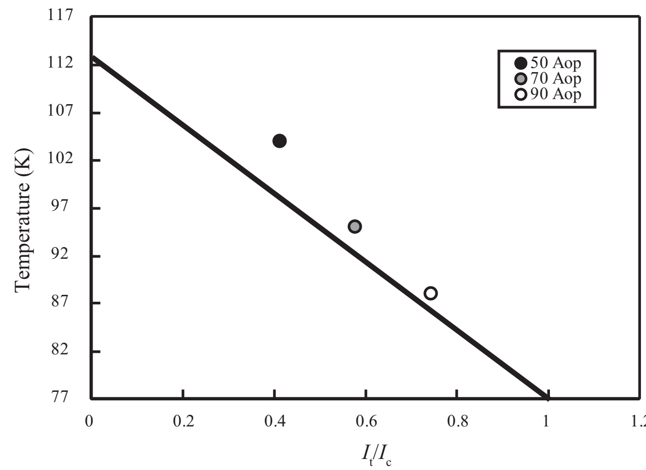

Fig. 5 Transport current dependences on threshold temperatures.

V. Conclusions

For practical use of superconducting coils, it must to be possible to detect normal transitions locally. In addition, diagnosing the conditions of windings is also required. In order for our local detecting method of normal transitions to be used for the purpose, it is important to clarify the relations of signals measured by this detecting method to health of windings of the coils. In order to clarify the relation of measured signals by our new detecting method, and therefore measurements of Poynting's vectors and the temperature of windings were carried out. It was found that the measured signal rapidly decreases as the winding temperature rises to threshold temperature. In addition, the threshold temperatures corresponded to the critical temperature. These results show that this method can be used to estimate the conditions of the windings and that it is one method of judging whether or not the coil should be kept in operation.

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References

[1] Y. Shiohara, et al. "Japanese efforts on coated conductor prcessing and its power applications: New 5 year project for materical and power applications of coated conductors (M-PACC)", *Physica C*, **469**, pp. 863-867, 2009.

[2] F. Sumiyoshi, K. Fukushige, M. Nakagami, H. Hayashi, "AC losses in Bi-2223 multifilamentary tapes" *Inst Phys Conf Ser*, 167, pp. 935-938, 1999 (Proc. of EUCAS, Spain, September);

[3] H. Kasahara, F. Sumiyoshi, A. Kawagoe, K. Kubota, S. Akita, "AC losses in long Bi-2223 tapes wound into a solenoidal-coil" *IEEE Trans Appl Supercond*, vol. 14, no. 2, pp. 1078-1081, 2004.

[4] F. Sumiyoshi, A. Kawagoe, M. Tokuda, S. Kaminohara, "A quench monitoring system of superconducting coils by using the Poynting vector method" *IEEE Trans Appl Supercond,* vol. 19, no. 3, pp. 2341-2344, 2009.

[5] K. Habu, S. Kaminohara, T. Kimoto, A. Kawagoe, F. Sumiyoshi, H. Okamoto, "The contactless detection of local normal transitions in superconducting coils by using Poynting's vector method" *Physica C*, 470, pp. 1860-1864, 2010.

[6] A. Kawagoe, et al., "Non-contact Detection of Normal Transitions in Superconducting Coils –Proposal of a New Measuring Method by Using Pick-up Coils Out side a Vessel –", *TEION KOGAKU*, vol. 46, no. 8, pp. 481-488, 2011 (in Japanese)