3PoM02-02

Novel Strand Position Detection System Using Thermistor Array For Next Generation Large Fusion Magnet Cable-In-Conduit Conductors

S. Hoshino, N. Ishida, Y. Yagai, T. Hamajima, N. Banno, H. Utoh, and Y. Sakamoto

***Abstract*—Currently, progress is made globally to construct the ITER, to test the feasibility of fusion at a large scale. Currently cable in conduit (CIC) conductors are used for large scale magnet designs. Here the individual strand positions are a concern, due to the possibilities of non-uniform current distribution and the consequences that arise with it. Thus, knowing the position of individual strands is necessary. Many studies have been conducted in simulating the strand position. At the same time, it is necessary to physically map the positions of the strands, for confirmation and refinement of simulations.**

Our lab conducted measurements using thermal imaging by slicing a CIC conductor in sections, heating up a strand on one side and detecting the change in temperature on the other side by the thermal camera. The strand that heats up fastest should be the same one that was heated up on the other side, allowing a one-to-one matching. The results were promising, but struggled in identifying closely packed sections, due to response speed of the camera.

To improve the response speed, it was suggested to use thermistor chips, capable of detecting changes in temperature in the form of voltage with little lag. This should allow the identification of the path that a single strand takes. In this paper, an array of thermistors was tested to see the feasibility of the method, and results will be shown.

***Index Terms*—Cable-in-conduit Conductor, fusion magnet, Nb_3Sn, strand traces, cable structure.**

I. INTRODUCTION

With the progress on the ITER reactor, research and development is being made to construct a larger commercial fusion reactor, to demonstrate electricity production through fusion. However, it is yet unknown if the current magnet design can be directly applied to such a scale. Changes in the structure of the CIC showed to change multiple properties, an example being the effect that twist pitch had on the improvement of T_{CS} and increase in AC loss, estimated to be caused by the stronger contacts and lowered inter-strand resistance [1]. As such, it is yet unclear what will happen when the design is changed and scaled up. Thus, a model is needed to predict the properties of a CIC conductor from traces of strands during the designing stage. Studies about the prediction of strand position in a CIC conductor have been conducted which are an important basis for determining the positions of strands in the designing stage [2], [3]. At the same time, it is also important to be able to compare the strand positions to the performance of an actual conductor. Techniques using X-ray tomography also showed success in tracing the strands and calculating the void fraction [4], [5]. However, these studies do not measure the inter-strand resistance, one factor for AC loss and CIC performance.

Our lab aims on developing methods to trace the strands and determine the inter-strand resistance through non-disruptive techniques, to get accurate results in a shorter period and predict CIC performance. Past attempts include using resistive measurements and thermal measurements (using a thermal camera), to find the path of least resistance or the fastest heat travel with the following results. Resistive measurement required liquid helium temperature for an accurate measurement, taking 250 hours for 1422 strands. It was also recorded that there were temperature rises over 40 K, requiring cooling sessions to resume measurement, adding more time to finish each measurement. To build a model, large amount of data is needed, using multiple samples and measurements. Thus, it was deemed that a faster measurement method is required. Furthermore, it struggled to measure certain strands and the corresponding inter-strand resistivity due to the oxidation layer on the surface, outlining the limitation of resistive measurements [6].

While the thermal camera did show improvements in measuring time, it lacked in the accuracy, where the heat from one strand jumped in two or three strands to be simultaneously detected by the thermal camera. It was deemed that to do accurate thermal measurement, the detector must have a fast response speed to heat changes and need to allow data comparison between multiple points.

Given the results, thermistors were proposed as the heat detectors to replace the thermal camera. They are fast responding, allow numerical comparison of data, and can be used in an array to cover a larger area. With the strand trace data, simulations about the loads and shifts in position may be done. Furthermore, the thermistor data may reveal the information of inter-strand resistivity, an important factor in determining AC loss [1]. The methodology and results are going to be discussed in the following sections.

S. Hoshino, N. Ishida, Y. Yagai are with the Sophia University, Tokyo, Japan.

T. Hamajima is with the Tohoku University, Sendai, Japan.

N. Banno is with the National Institute for materials Science, Adachi, Japan.

H. Utoh and Y. Sakamoto are with the National institute for Quantum and Radiological Science and Technology, Rokkasho, Japan.

This work was supported by QST Research Collaboration for Fusion DEMO(04K067). (Corresponding author: Nobuya Banno.)

II. Method

The basis of this measurement is to find the path of fastest heat travel, by applying heat on one side and detecting the change in temperature on the other. In this experiment the heat source will be the tip of a soldering iron, and the detectors are the thermistors.

A. Setup

The CIC conductor used in this measurement is a 10 mm slice of a sample conductor for SULTAN testing of the ITER Toroidal Field (TF) coil, consisting of 900 Nb_3Sn and 522 Cu strands, whose details are shown in Table I [7]. The CIC conductor is enclosed in epoxy before sliced to prevent strand movement during the process.

TABLE I
CIC Parameters

Parameters	TF conductor
Number and material	900 Nb_3Sn / 522 Cu
Strand diameter	0.82 mm
Cabling pattern	(3 × 3 × 5 × 5+ Cu wire core) × 6
Twist pitch	81/140/186/298/420 mm
Slice thickness	10 mm
Void fraction	33%

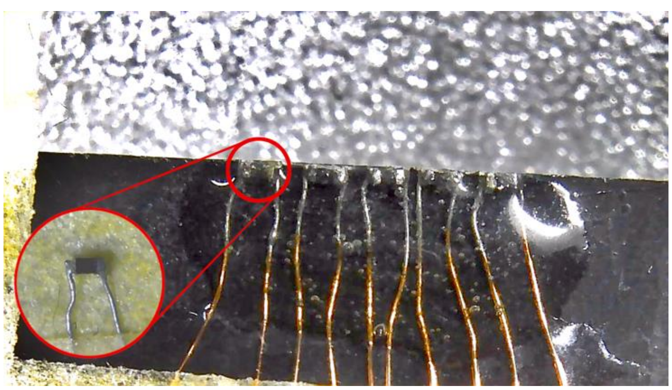

Fig. 1. Close up image of thermistor array

TABLE II
Thermistor

Parameters	TF conductor
Manufacturer	Panasonic
Type	NTC
RS number	764-0731
Manufacturer ID	ERTJZEG103FA
Resistance at 25 ˚C	10 kΩ
Dimension	0.6 × 0.3 × 0.3 mm
Max/Min working temperature	+125/-40 ˚C

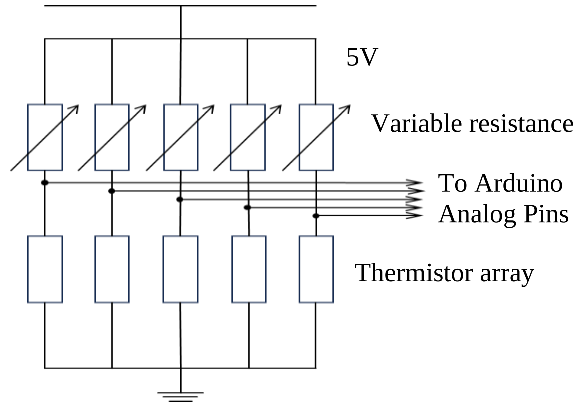

Fig. 2. Circuit diagram of the thermistor array

The thermistors used in this experiment are 10 kΩ base manufactured by Panasonic, with a dimension of 0.6 × 0.3 × 0.3 mm. They are placed as close as possible in a 5 × 1 array, superglued on a piece of plastic, and enclosed in a layer of fast hardening insulating epoxy glue, to prevent movement during measurement, as seen in Fig. 1. Fig. 2 represents the circuit diagram, where the variable resistance is present for calibration of the system, to equalize the initial voltage to facilitate measurement. To display the temperature in real time in increments of 0.01 in MATLAB, the temperature to voltage data of each thermistor was recorded using a heat table (CHP-170DF) in the range from room temperature to 65 ºC. The voltage was recorded using MATLAB and the real time temperature was recorded using Pico sensor (TC-08 with a type K tip). The 0.6 × 0.3 mm face of the thermistor was pressed to the heat table, and the temperature and voltage were recorded in three points to create a quadratic approximation.

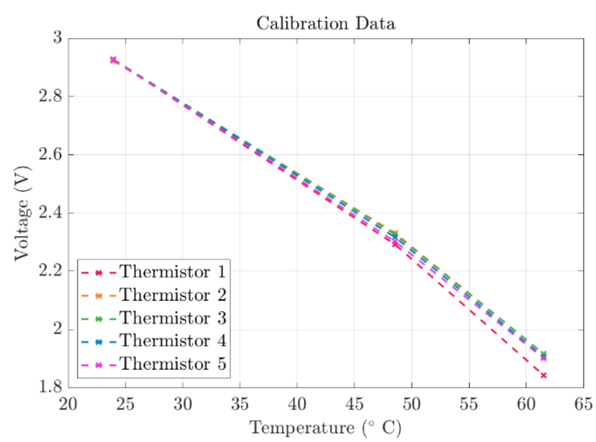

Fig. 3. Temperature to voltage curve of thermistors

This article has been accepted for publication in IEEE Transactions on Applied Superconductivity. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TASC.2024.3358267

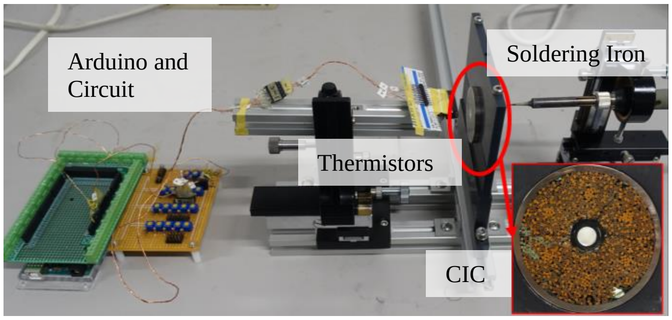

Fig. 4. Experimental setup

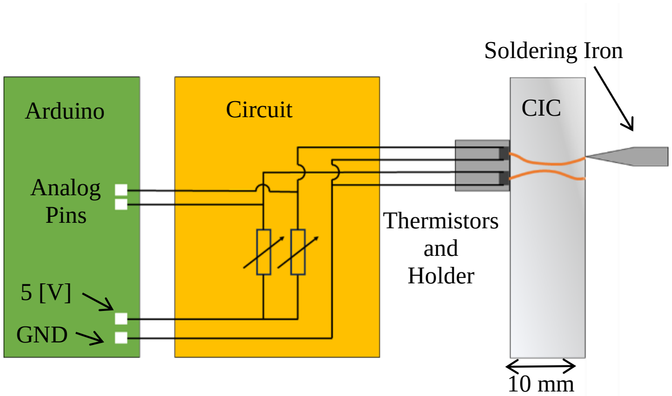

Fig. 5. Simplified diagram of the whole system

Fig. 4 shows the arm system where the components are put, allowing three-dimensional motion of the thermistor array and the heat source.

B. Test Measurement

Test of the device was conducted on a disassembled CIC, to validate the method. The array was placed so that three thermistors are in contact with three different strands, as shown in Fig. 6. Care was taken so that the centers of the thermistors and the centers of the strands would align as much as possible for the best reading.

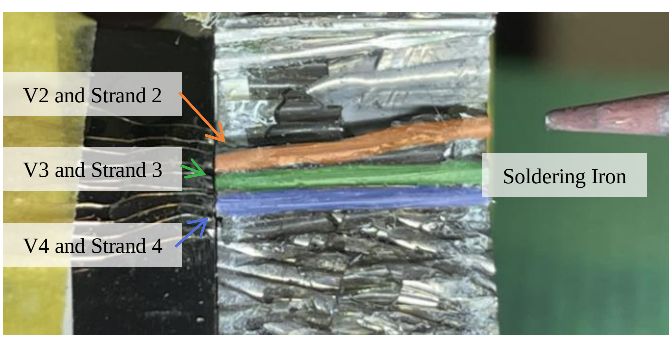

Fig. 6. Strand traces of the disassembled CIC for test measurement

The soldering iron was pressed on one strand until a noticeable voltage/temperature change was detected by the thermistor. Once this change is detected, the tip is released to cool down the CIC. The data recorded by the thermistors during the test measurement is recorded in Fig. 7.

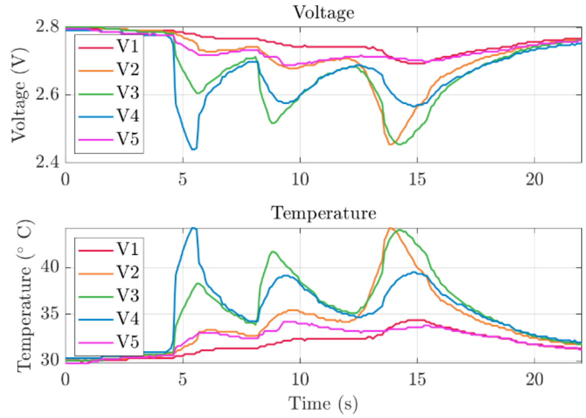

Fig. 7. Measurement data from test measurement

The result was in line with expectations, with thermistors showing a rise in temperatures when the corresponding strands were heated up. The only anomaly seen in the thermistor 2, can be explained by the small misalignment it is off center from the strand. During the measurement it is difficult to perfectly align individual thermistors to the centers of strands. In the case of the test measurement thermistors 3 and 4 were perfectly centered to strands 3 and 4, while thermistor 2 was slightly misaligned from the center of strand. This effect can be seen from the shape of the third peak, with the heat moving from strand 2 to 3 being detected by thermistor 3, just after thermistor 2 reached its maximum reading. This effect was negated by doing multiple measurements using different thermistors. At the end, it was concluded that the system is adequate in detecting strand traces.

III. Result

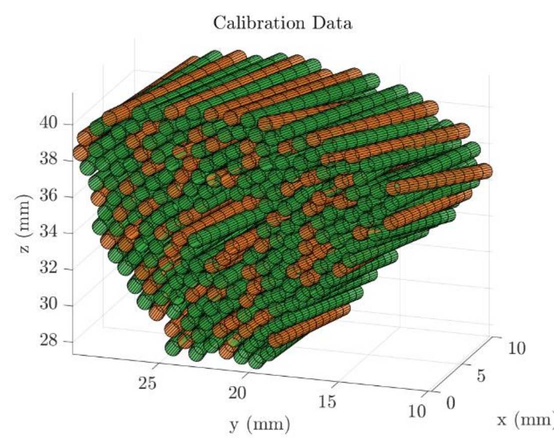

Fig. 8. Reconstruction of strand traces based on measurement

In Fig. 8, the result of the measurement is shown as a 3D representation, where the green strands are the Nb_3Sn strands and orange ones are the Cu strands. In total 150 Nb_3Sn and 75 Cu strands were measured in a span of 24 hours. The system was able to detect traces of strands that are strongly in contact with each other, causing a quasi-simultaneous temperature rise, which thermal imaging was not capable of distinguishing. Most of the strands required multiple measurements using different thermistors, while 10 to 15 showed clear responses as seen in the test measurement.

It also has been observed that some strand traces overlap with each other such as the Cu strand in Fig. 9. At the time of measurement, three possible reasons can be given. One is that some of the measurements was erroneous and there are mismatched strand pairs. The second one is an interpolation error, due to the system forced to use line interpolation, instead of spline interpolation. The last possibility is where the traces are correct, and strands are simply pressing on each other causing a dent.

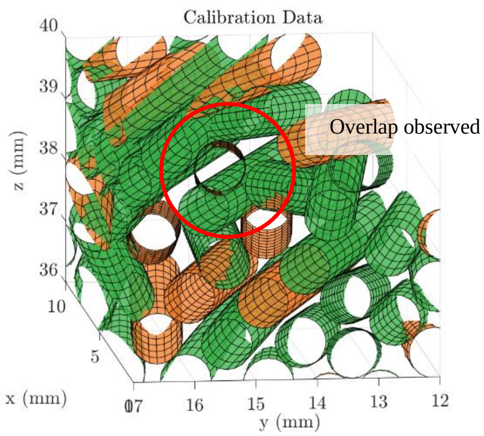

Fig. 9. Magnification of overlapping strand

Nevertheless, it is necessary to measure the remaining strands and the adjacent CIC slices to determine the cause for this result. We are also looking to calculate the inter-strand resistance from the heat conductivity based on the temperature changes, an aspect that current methods such as X-ray tomography struggle to achieve, and we hope it will give more insight to the relation between strand traces and CIC performance.

Further testing is also needed to decide the measurement conditions and environment such as the pressure applied to the thermistors, the temperature to conductor the experiment, and how to cool the CIC after heating. Validation of the method to other types of CIC conductors is also necessary, to see if the system will work on different materials and designs.

IV. Conclusion

In this paper, a novel method of strands position detection system is presented, using an array of thermistors. The results showed that the method is capable of mapping strand traces, which previous methods struggled in a short period of time. Although further experimentation using adjacent CIC slices and improvements to the measurement system and method is required, the system shows promising results, which can be used for further analysis of CIC performance.

References

[1] Y. Nabara *et al.*, "Impact of Cable Twist Pitch on T_{CS} -Degradation and AC Loss in Nb_3Sn Conductors for ITER Central Solenoids," in *IEEE Transactions on Applied Superconductivity*, vol. 24, no. 3, pp. 1-5, June 2014, Art no. 4200705, doi: 10.1109/TASC.2013.2284193.

[2] D. Miyagi *et al.*, "Analysis of 3-D Locations of All Strands in CIC Conductor," in *IEEE Transactions on Applied Superconductivity*, vol. 22, no. 3, pp. 4802104-4802104, June 2012, Art no. 4802104, doi: 10.1109/TASC.2011.2177509.

[3] T. Sasaki, T. Nishiura, S. Nishijima and T. Satow, "Monte Carlo simulation of strand motion in CIC conductor," in *IEEE Transactions on Applied Superconductivity*, vol. 10, no. 1, pp. 1094-1097, March 2000, doi: 10.1109/77.828423.

[4] M. S. Commisso, E. Maire, J. -Y. Buffiere and D. Ciazynski, "Nondestructive Analysis of Nb3Sn CICC and Strand by X-Ray Tomography," in *IEEE Transactions on Applied Superconductivity*, vol. 26, no. 3, pp. 1-5, April 2016, Art no. 4800205, doi: 10.1109/TASC.2015.2509939.

[5] I. Tisenau *et al.*, "Multi-scale 3D modelling of a DEMO prototype cable from strand to full-size conductor based on X-ray tomography and image analysis," in *Fusion Engineering and Design*, vol. 146, part A, pp. 568-573, September 2019, doi: 10.1016/j.fusengdes.2019.01.025.

[6] T. Yagai *et al.*, "Irregular Loops With Long Time Constants in CIC Conductor," in *IEEE Transactions on Applied Superconductivity*, vol. 16, no. 2, pp. 835-838, June 2006, doi: 10.1109/TASC.2006.871277.

[7] H. Kajitani *et al.*, "Results of All ITER TF Full-Size Joint Sample Tests in Japan," in *IEEE Transactions on Applied Superconductivity*, vol. 31, no. 5, pp. 1-5, Aug. 2021, Art no. 4201905, doi: 10.1109/TASC.2021.3064004.