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Experimental Study on the Characteristics of Current Distribution in Rutherford Type Cables and Parallel Strands

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Abstract---**The current distribution in a multi-stranded superconducting cable such as Rutherford type cable plays an important role in the stability. Rutherford type cables consist of many strands which are twisted and electrically contacted together. Because of this complexity, it is hard to know factors that effect to the current distribution and hence to the stability. The most important factors may be interstrand contact resistances and mutual inductances between strands mainly caused by twisting strands. To obtain the effect of contact and twisting, we compared the characteristics of Rutherford type cables with parallel strands. We have performed experimental studies on these items for parallel strands with and without insulation by heating with a spot heater. The results for insulated parallel strands show very similar behaviors to those obtained in Rutherford cables. From the fact, we conclude that the side-by-side contact resistance is very low at the edges and that large part of current movement between strands occurs at the edges. Reset of the transport current could not change the steady state current distribution. To clarify this is remained as a future research.**

I. INTRODUCTION

For a large scale superconducting devices such as particle accelerator, superconducting magnets are made by multi-stranded cables to obtain sufficient current capacity. However, the current capacity of these cables are lower than calculated values.

Besides of that, these cables can have additional problems. One of the problems is ripple in magnetic field caused by the above mentioned current distribution. Another problem is instability caused by steady state current distribution or by current re-distribution or commutation (transient state current distribution). These problems may be very serious for magnet stability.

We have performed experimental studies on the stability and current distribution of Rutherford type cables [1]-[3]. In the course of this study, we found that it was very hard to clarify the factors that affect to the current distribution and stability. It is because Rutherford type cables consist of many strands twisted together without insulation. Especially to know the effect of contact resistance and mutual inductances among the strands, the experiments on parallel strands were carried out. This paper describes the characteristics of voltage set-up in parallel strands, and the comparison between parallel strands and Rutherford type cables.

II. EXPERIMENTS

Two Rutherford type cables and three arrangements of parallel strands were prepared for the experiments. The experimental arrangement of the two Rutherford type cables with high and low interstrand resistances is described in previous papers [1], [2]. In the experiments on parallel strands, three kinds of arrangements were used; insulated two adjacent strands (INS1-2), insulated two strands with gap between them (INS1-4) and two strands without insulation (NINS1-2).

For the experimental sets of INS1-2 and INS1-4, four parallel strands with insulation were wound together on a drum shape bobbin, in a bifilar like manner to cancel the effect of winding. The four strands are attached like the character ‘s’ on the bottom disk of the drum shape bobbin. Fig. 1 shows the heater and voltage taps on the four parallel strands. For the INS1-2, strands 1 and 2 were connected to current leads, and strands 1 and 4 were connected for INS1-4.

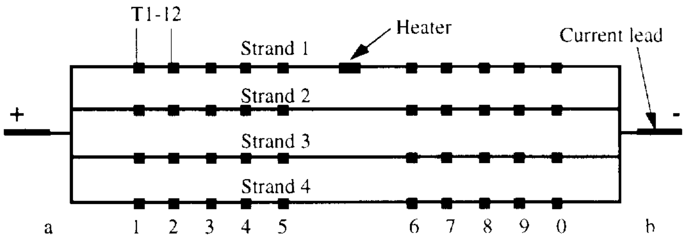

Fig. 1. Numbering voltage taps on the four strands. For example T1-12 means the voltage between tap 1 and 2 on strand 1, and T4-0b means that between tap 0 on strand 4 and negative current lead.

On the other hand, for the experimental sets of NINS1-2, two parallel strands without insulation were wound together in the same geometry as INS1-2. The specifications of the superconducting strand used for the three experimental sets are shown in Table I.

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In every experiment, the center point of the strand 1 was heated by a spot heater, that is wound around the strand using a thin resistive wire and electrically insulated from the strand. Heater voltage was used as the trigger signal for a data logger, and the voltages of all taps and total current were measured and logged.

TABLE I
SPECIFICATIONS OF THE SUPERCONDUCTING STRANDS.

Type	NbTi/Cu monolith round wire
Diameter of wire	0.486 mm
Diameter of filament	4.4 - 4.6 mm
Cu/NbTi ratio	1.80 ± 0.08
Twist pitch	23.0 ± 1.8 mm
Critical current at 5 T, 4.2K	145 - 157 A
RRR (R300/R10K, at 0 T)	35 - 50

III. RESULTS AND DISCUSSION

If the strand 1 is heated with energy larger than MQE (minimum quench energy), the voltages of strands increase and the strands will quench. Fig. 2 shows the increasing voltages in INS1-4. At first the voltage of T1-56 (between taps 5 and 6) increases, where heater is. After that the voltages of the neighboring taps increase, and voltages of all the other strands increase.

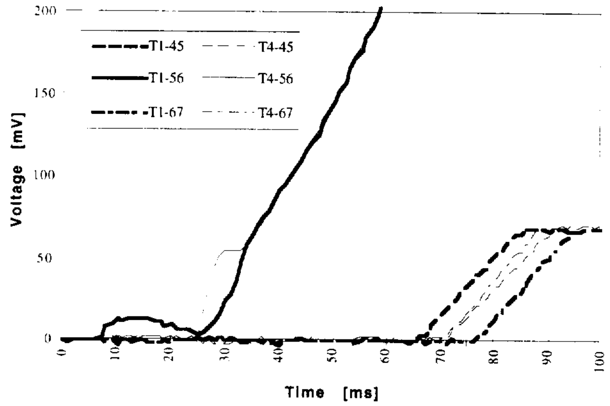

Fig. 2. Voltages measured from taps on INS1-4. Transport current is 170 A and magnetic field is 5 T. Strand 1 is heated by MQE (5.3 mJ) during 20 ms (0 - 20 ms). Voltages between tap 5 and tap 6 are larger than the other ones, because the distance between these two taps is longer than the other ones. The abbreviations in the legend are described in Fig. 1.

In this figure, it is worth to notice the behavior in the first 40 ms of T1-56 and T2-56. Heating makes normal zone in T1-56, and the voltage increases till about 13 ms. This increment means the normal zone is becoming larger. After 13 ms the voltage decreases, but it does not indicate the shrinkage of normal zone. If it were normal zone shrinkage, there is no more voltage increment and both of the strands may recovered a superconducting state.

From this we can say that the decrement of voltage after 13 ms is caused by current re-distribution; the current movement from strand 1 to strand 4. By the commutated current from strand 1, strand 4 becomes over current, and faster voltage set-up occurs in strand 4. We can see this evidence during the time between 25 ms and 35 ms. After that the current can go back to strand 1, and this current commutation can occur many times.

On the contrary, in the case of two strands without insulation (NINS1-2), the voltage wave forms do not cross each other as shown in Fig. 3. Also this figure shows that the two voltage wave forms in strands 1 and 2 have very similar behavior of proportional increment. This is because the current can commutate between two strands everywhere.

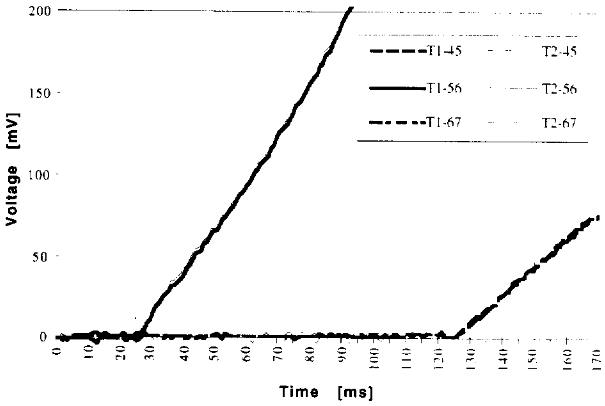

Fig. 3. Voltages measured from taps on NINS1-2. Transport current is 170 A and magnetic field is 5 T. Strand 1 is heated by MQE (15.1 mJ) during 20 ms. The waves of T1-56 and T2-56 are almost the same, and another four waves are very close.

From Figs. 2 and 3, we can see the speed of normal zone propagation in the strands without insulation is slower than that in the insulated strands, and that MQE of strands without insulation is much larger than that of the insulated strands. This result is in good agreement with Rutherford type cable (Figs. 7 and 8). In the Rutherford cables, the cable with lower contact resistance has higher MQE and slower propagation of normal zone too [1], [2].

In the case of above two samples, the normal zone spreads from the center point where the heater is, as shown in Figs. 2 and 3. However, in the case INS1-2, the sequence is T1-56, T2-a1, T1-a1, T2-56 and all the other tap voltages. It may be caused by a weak point between tap 'a' and '1' in the strand 2, or by relatively high contact resistance between strand 2 and current lead. Figs. 4 and 5 show the voltages of taps in INS1-2 and the total voltage of the two strands, respectively. The voltage at T2-a1 should be by current commutation, because this taps are distant from the T1-56. The voltage at T2-56 should be heated by conduction from heater, because there is no other voltage signal between T1-a1 and T1-56. This shows clearly the evidence that current commutation is faster than heat transfer.

The wave forms in Fig. 5 are similar to those in Fig. 2, except for the behavior of strand 2 just after heating; when the strand 1 is heated the voltage of strand 2 increases also.

Because distance between the two strands in INS1-2 is shorter than that in INS1-4, heat from the heater can reach the strand 2 in shorter time.

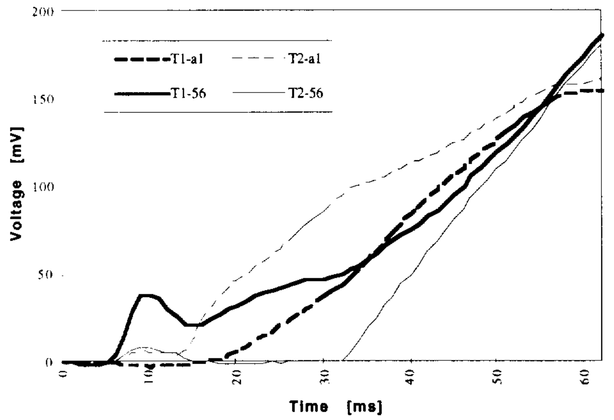

Fig. 4. Voltages measured from four tap pairs on INS1-2. Transport current is 170 A and magnetic field is 5 T. Strand 1 is heated by MQE (4.7 mJ) during 20 ms.

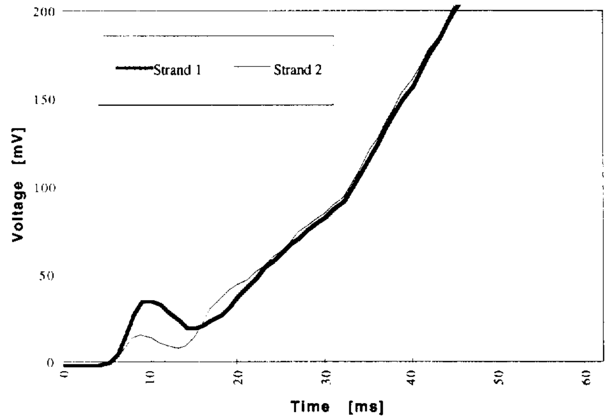

Fig. 5. The total voltages of the two INS1-2. This figure is to compare Rutherford type cables and parallel strands.

In the comparison of INS1-2 and INS1-4, it was impossible to obtain the effect of mutual inductance. Probably the current commutation is affected by the mutual inductance especially in the case of insulated strands, but the effect of heat was too large to expose the effect of mutual inductance.

The results of the parallel strands were compared with those of Rutherford type cables. Fig. 6 shows the positions of two voltage tap pairs related to a spot heater on a Rutherford type cable. The tap pair 1 and the heater are on the same strand and this strand is identified as strand 1.

Figs. 7 and 8 show voltage wave forms measured from the two tap pairs on Rutherford type cables with and without CuMn barrier, respectively. The characteristics of the two kinds of cables are the same except that the interstrand contact resistance of the cable with barrier is larger than that without barrier by two orders of magnitude [1], [2].

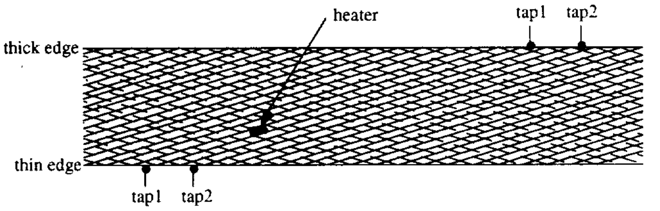

Fig. 6. Positions of two voltage tap pairs and a spot heater on a Rutherford type cable. The spot heater and the tap 1 are on the same strand which is identified as strand 1.

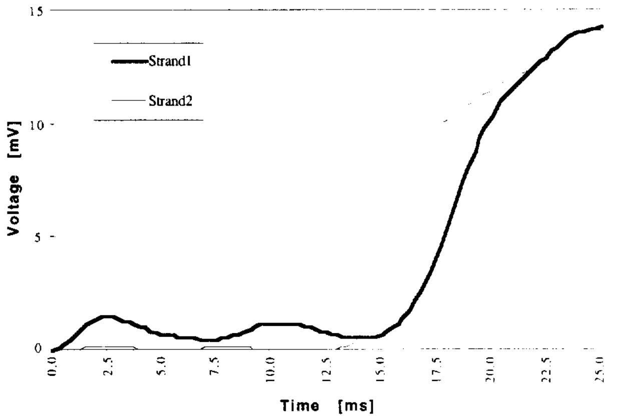

Fig. 7. Voltages measured from tap pairs on two strands in Rutherford type cable with higher interstrand resistance (with CuMn barrier), after heating by a spot heater attached on the strand 1. Transport current is 5 kA and magnetic field is 7 T. Heating energy is MQE (6.2 mJ), and heating time is 10 ms.

Fig. 7 shows voltage wave forms of the cable with the CuMn barrier. In this figure, we can easily see the similarity between this cable and insulated parallel strands whose voltage wave forms are shown in Figs. 2, 4 and 5. For the two strands in Rutherford type cables in parallel position, this similarity suggests that the side-by-side contact resistance is relatively low at the both edges, and that this resistance at the edge is low in comparison with cross-over resistance [1]-[3].

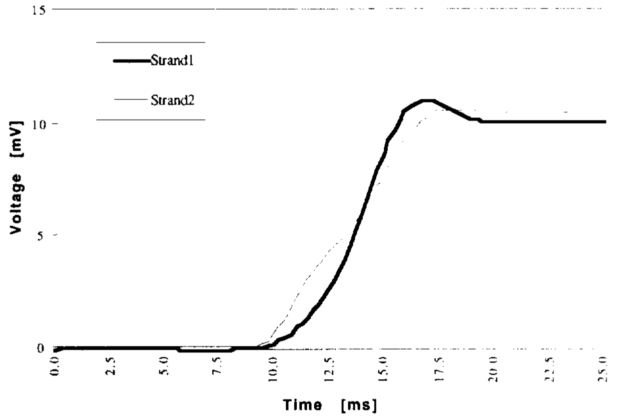

Fig. 8. Voltages measured from taps on two strands in Rutherford type cable with lower interstrand resistance, after heating by spot heater attached on the strand 1. Transport current is 5 kA and magnetic field is 7 T. Heating energy is MQE (7.6 mJ), and heating time is 10 ms.

Fig. 8 shows the voltage wave forms of Rutherford cable without barrier and then having low interstrand contact resistance. The wave forms of this cable are similar to the wave forms of NINS1-2. However, these voltage wave forms also have a similar behavior to the insulated parallel strands. Though the first increment in strand 1 is small, there are crossings of voltage wave forms. Also this depicts relatively low contact resistance at the edge.

From this small edge resistance, it is expected that large part of the commutating current flows at edges in Rutherford cables.

In Figs. 2 and 4, it is shown that there is current commutation between two insulated strands after heating one strand, and Fig. 9 is another good evidence of current commutation. This figure shows the voltage wave forms of T1-56 in INS1-4 when heated several times by energy a little bit lower than MQE. The interval between heating is approximately 5 minutes.

At the first heating the peak voltage is about 13.5 mV, but from the second heating this peak voltage becomes lower than 2 mV. This means almost all of the current in strand 1 moves to the other strand by the first heating.

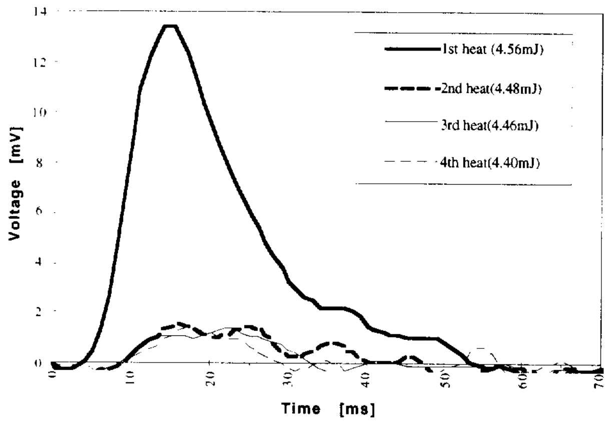

Fig. 9. Voltages measured from T15-6 of INS1-4 in continuous heating without quench. The MQE of this arrangement is 5.3 mJ. Transport current is 170 A and magnetic field is 5 T.

In the experiments, we found an interesting phenomenon. For example the MQE of INS1-4 is approximately 5.3 mJ. If we heat one strand with more energy than 5.3 mJ, the strands quench. However after heating with a little bit less energy than the MQE, we cannot quench the strands with the MQE. More energy is needed to quench the strands in this condition. We called this energy as "pre-heated MQE." This is because the current in the strand heated by less energy than MQE moves to the other strand [1].

We heated one strand with less energy than MQE, and heated by energy between the MQE and pre-heated MQE several times without quench. After that we decreased the transport current of the strands to zero and increased it again, and heated with energy between the two MQE's, expecting quench. However, this could not make quench. This means that reset of the transport current cannot make the steady state current distribution to a virgin state.

We could see this phenomena in all the combinations of parallel strands and even in Rutherford type cables, but the reason is not clear yet.

IV. CONCLUSIONS

In the result of insulated two strands, we could see the current commutation and heat transfer. The current commutation was faster than heat transfer.

It was impossible to detect effect of the mutual inductance because the effect of heat transfer was relatively large. Comparison between two parallel strands and two twisted strands can be suggested to enhance the effect of mutual inductance.

The wave form of two strands in a Rutherford type cable is similar to that in the insulated two parallel strands, and this means that the side-by-side contact resistance at the edge is relatively low in Rutherford cables.

Reset of the transport current could not make the steady state current distribution clear. To clarify the reason is remained as a future research.

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