# Multi-Strand HTS 케이블에서의 전류 불균일 분포

*배준한, **배덕권, 조전욱, 심기덕, 김해종, 성기철, **고태국
*한국전기연구원 초전도응용연구그룹
**연세대학교 전기전자공학과

# Non-Uniform Current Distribution of Multi-Strand HTS Cable

*Joon Han Bae, **Duck Kweon Bae, Jeon Wook Cho, Ki Deok Sim,
Hae Jong Kim, Ki Chul Seong, and **Tae Kuk Ko
*Applied Superconductivity Lab., Korea Electrotechnology Research Institute
**Dept. of Electrical and Electronic Eng, Yonsei Univ.
*baejh@keri.re.kr
**porthos@yonsei.ac.kr

**Abstract** - The 4-probe method with a voltage tap on terminals has been used for the measurement of the critical current of multi-strand high-Tc superconducting (HTS) cables. And the critical current of cables is obtained as the measured total current divided by the number of conductor when the terminal voltage exceeds the predetermined criterion of critical current. However, because of the non-uniform current distribution due to the different critical current, shapes, and other characteristics of each conductor, this is not applicable method to the multi-strand HTS cable. To determine the critical current of multi-strand HTS cable, the critical current of each conductor must be measured with different method. In this paper, the current distribution and the critical current of each conductor in multi-strand cable were measured with specially made pick-up coils and voltage taps. It is presented that the real critical current of multi-strand is smaller than sum of each conductors. The main cause of non-uniform current distribution is the different resistances appeared in each HTS wires.

## 1. Introduction

Bi-2223 wire, the first-generation HTS wire, was successfully commercialized and various electrical machinery and equipment are actively being developed in many countries. The HTS cables, which solve the electricity problems in load-concentration areas, have especially been installed in the substations of specific areas [1]. The HTS power cable consists of multi-layer HTS wire that is multi-stranded. The research on the current distribution of each layer by inductance or other elements has been frequently presented and the design of the HTS power cable is being implemented accordingly [2]-[4]. However, research on the current distribution of each conductor stranded on the same layer is still rare.

Superconductor maintains its superconductivity only when three critical conditions are all satisfied. If any one of them is not satisfied, the superconductivity is destroyed. Thus, from a practical point of view, the exact prediction of critical current is very important and strongly needed at the stage of cable design. It is fundamental to have important data to decide how much, within the critical current, the operating current of HTS cable should be. The commercialized HTS wire has some extra reserves in the critical current. However, as the transport current rises near the critical current, though the resistance from the HTS wire is small, the amount of the resistance cannot be ignored in each superconductor wire in the cable. Especially, when HTS wires are used to operate a system, a sudden load concentration can occur. If then, the transport current rises and resistance difference occurs in each stranded wire. When the imbalanced current occurs for the resistance difference, quench occurs in the cable, which can endanger the whole system. So, the study on this area is inevitably necessary. For this research, it is needed to measure the critical current of each HTS wire, total critical current, and the current that flows on each wire. These three elements cannot be all measured just using the 4-probe method that is usually used to measure critical current. The current distribution which flows to each strand was measured using a specially designed pick-up coil and each critical current and the values were measured by voltage taps installed on each stranded wire and common voltage taps.

## 2. Experiments

### 2.1 Preparing of the Pick-Up Coils

The pick-up coil, such as Rogowski coil or a shunt, is used to measure the current which flows in the conductor. When a shunt is used, relatively exact current can be measured. However, in the case of multi-strand cable, the shunt cannot be installed in every path and the current distribution by the resistance difference between shunts can occur so it is not appropriate for this measurement. Thus, the indirect method of firstly analyzing out the magnetic field value produced by the current and secondly converting it into current value should be introduced to measure the current of each strand. The normal pick-up coil used in the indirect current measurement is designed to be adaptable for measuring the current of the round-shape conductors. HTS wire is in the shape of thin tape so it is difficult to measure the exact current by a normal pick-up coil such Rogowski coil. To measure the current of thin-tape shaped wire, a special pick-up coil shown in Figure 1 has been designed. The special pick-up coils are installed on and below the wire and the magnetic field value was measured and converted into the current value of the conductor. Copper wire of 70m diameter was wound on the GFRP bobbin to build the pick-up coil and the total number of winding turns was 152. Figure 2 shows how the pick-up coils were mounted on each wire.

### 2.2 Experiment Setup

2, 3, 4-strand cables are designed as shown in Figure 3 and the current distribution of each cable was measured. The upper right part of Figure 3 shows the cross-sectional view of HTS wires wound on the bobbin. In the case of 2, 4-strand cable, HTS wires were wound in a 90 gap. In the case of 3-strand cable, they were wound in a 45 gap. The ordinal numbers of each wound wire were given clockwise from zero at the top. In other words, in the case of 3-strand cable, the wound wire installed in the place of zero on the top was named as HTS1 and the rest of the wires in the 45 gap were named as HTS2, HTS3 and so forth in the clockwise direction. The pitch of the wound wire was 180mm and the length of each wire was about 90cm. The HTS wire used for this setup was reinforced wire produced by AMSC with the certified critical current of 115A(@ 77K, self-field). The specification of multi-strand cable designed for this experiment is described in Table 1.

For the experiment of current distribution, the current was supplied from a DC power supply and each of the signals was stored after they went through the filter and amplifier.

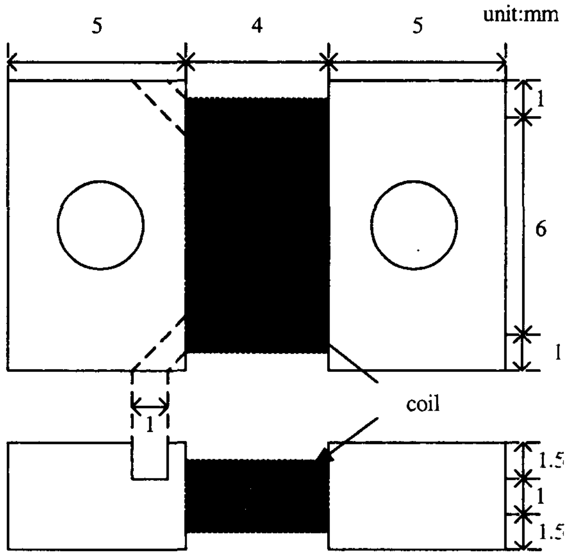

Fig. 1. Structure of pick-up coil

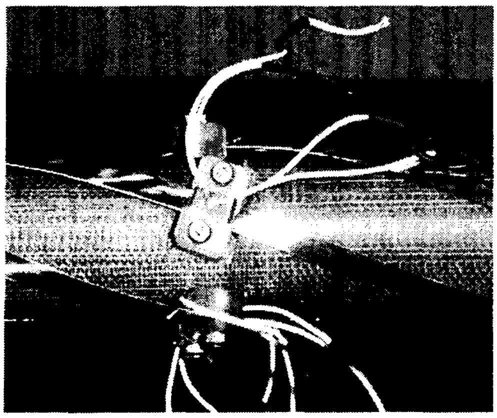

Fig. 2. Pickup coils mounted on each wire

Table 1. Specification of multi-strand cables

| Parameters | | Specification | Remarks |
|---|---|---|---|
| Pickup coil | Diameter of wire | 70μm | |
| | Number of turns | 152turns | |
| | Number of coils per strand | 2ea | |
| Bobbin | Diameter | 25.4mm | |
| | Length | 860mm | |
| | Pitch | 180mm | |
| | Length of Cu | 75mm | |
| HTS wire | Ic @ 77K, self-field | >115 A | Reinforced wire |
| | Matrix | Ag alloy | |

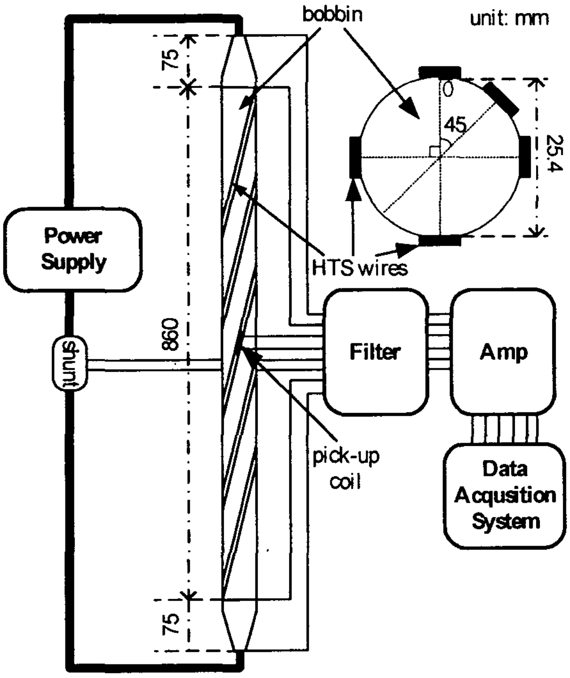

Fig. 3. Schematic of multi-strand cable and experimental setup

# 3. Results of Experiment and Discussion

## 3.1 Current Distribution of 2-Strand Cable

Figure 4 shows the current distribution of 2-strand cable whose wire was wound by 90 gap. The left side of Y-axis of Figure 4 shows the amount of current, which flows in each path. The right side shows the voltage of the taps on each HTS wire. The current has been increased to 300A with the ramping rate of 100A/s.

At the starting of ramping-up of current, the current-increasing rate of HTS2 was higher than that of HTS1. This current concentration phenomenon becomes more and more severe but, after the critical current value, the two values become similar. Especially, the current, which flows to HTS1, was bigger after the quench. The final currents, which flow on HTS1 and HTS2, were 151.7A and 148.3A respectively. This kind of phenomenon can be analyzed in relation to the impedance generated by the transport current shown in Figure 5.

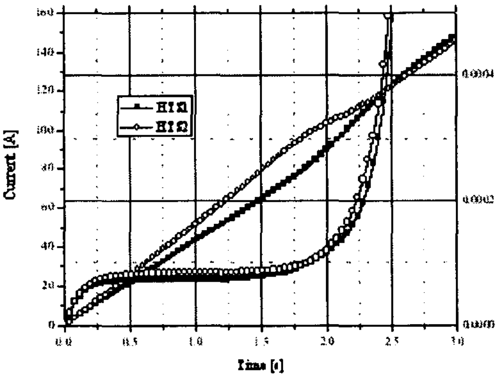

Fig. 4. Current share of 2-strand cable

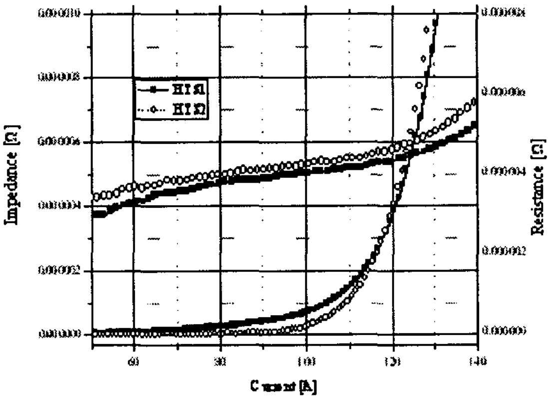

Fig. 5. Impedance and resistance of each strand

When the transport current was smaller than about 110A, bigger impedance was generated on HTS1, which is reversed after the quench so the impedance of HTS2 became bigger than that of HTS1. This phenomenon takes place because of the impedance difference generated on the wire after the quench. When the transport current was below the critical current, the impedance of HTS1 was bigger than that of HTS2.

This difference increased in proportion to the increase of transport current so the current concentration onto HTS2 became bigger. But, in the sections of transport current after the critical current, the impedance generated on HTS1 was bigger so the distribution of the currents, which flow to each strand, was changed. The wire of AMSC consists of Bi-2223 multi-filament and Ag alloy matrix. Though the same-lot-produced wires were used, the current re-distribution phenomenon by the increase of transport current was observed because of the impedance difference generated by the matrix and Bi-2223 filaments. In the section below the critical current, the difference of maximum transport current was about 17.5A. When the transport current of 300A, the maximum transport current, was transported, the difference of the transport current was 3.4A and current imbalance distribution occurred.

For this experiment, the current is more appropriately distributed by the inductance difference among each strand than by the resistance differences, such as cable contact resistance and normal-conduction parts like copper. The resistance value between the joining part of the HTS wire and the copper part at both ends of cables was shown in the right side of Y-axis of Figure 5. The resistance value of HTS2 is bigger than that of HTS1. Because the current-increasing rate of each strand below the critical current is bigger in HTS2, it is certain that what has most affect on the current distribution is not the resistance value difference like contact resistance, but the impedance difference generated by the current changes.

## 3.2 Current Distribution of 3-Strand Cable

Figure 6 shows the current distribution of 3-strand cable designed by HTS wires wound in a 45 gap and Figure 7 shows the impedance according to the transport current. Finally, the currents which flowed in HTS1, HTS2, and HTS3 were 156.7A, 143.2A, and 150.1A respectively. As shown in Figure 3, 2-strand cable and 4-strand cable are symmetrically structured in the aspect of inductance but 3-strand cable is asymmetrically structured. The inductance of each strand is determined by adding its self inductance and mutual inductance together. Each strand has the same structure so its self inductance will be same but, in the case of mutual inductance, which is proportional to the distance between windings, the mutual inductance of HTS2 will be bigger than that of HTS1 and HTS3. This is the reason for the asymmetrical structure.

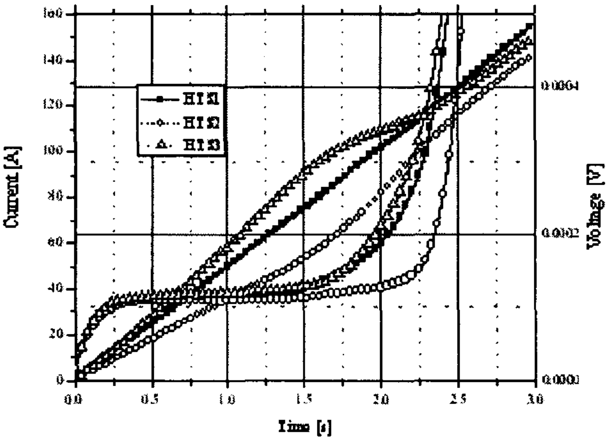

Fig. 6. Current share of 3-strand cable

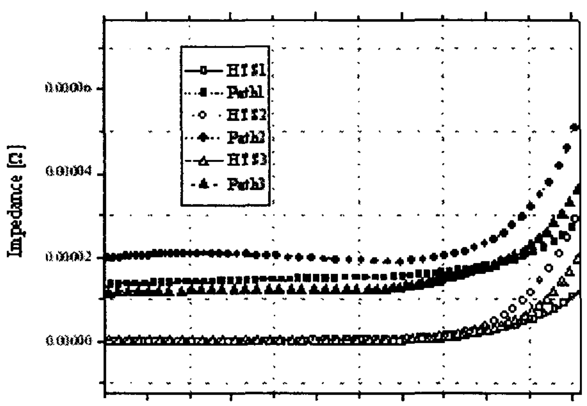

Fig. 7. Impedance of each strand

So, the current to HTS2 was expected to be the smallest. As shown in Figure 6, it was experimentally proved that the current increasing rate was lowered as the current provided from the power supply to HTS2 increased. Especially, the generated impedance was biggest in the HTS2.

The "Path" in Figure 7 means the total impedance of each strand including the normal-conduction part of current lead and "HTS" means only the impedance of HTS wire.

In Figure 6, one second after the power source turned on, the currents were distributed to HTS1, HTS2, and HTS3 by about 52A, 38A, and 60A respectively. When they are compared with the amount of impedance quantity produced by the current, the impedance in Path 1, 2, and 3 was 14.2, 18.7, and 12μΩ, respectively. so the current increasing rate in 3-strand cable was also determined in inverse proportion to the impedance value. Especially, in HTS2, though the smallest current flowed, the impedance was biggest, which is thought to be because of the mutual inductance difference.

## 3.3 Current Distribution of 4-Strand Cable

Figure 8 and 9 show the current distribution of 4-strand cable and the impedance distribution. 4-strand cable was designed by arranging wire by 90 degrees. In other words, it has a structure whose mutual inductance between each wound material is symmetrical. The current increasing rate of power supply was 250 A/s and was increased up to 600 A. In the current distribution before the quench, the current flowed the most in HTS3 and resistance occurred first in it. However, the generation tendency was different from other strands. In other words, it showed not the typical V-I curve of superconductor but the V-I curve of normal-conduction part co-existing in superconductor. This is because the flux creep that occurred in HTS3 was earlier than the others. It was observed that the current increase rate of HTS3 was decreased by the generated resistance and that of other strands was increased.

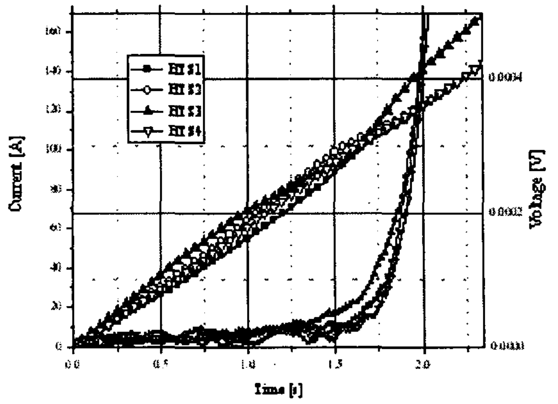

Fig. 8. Current share of 4-strand cable

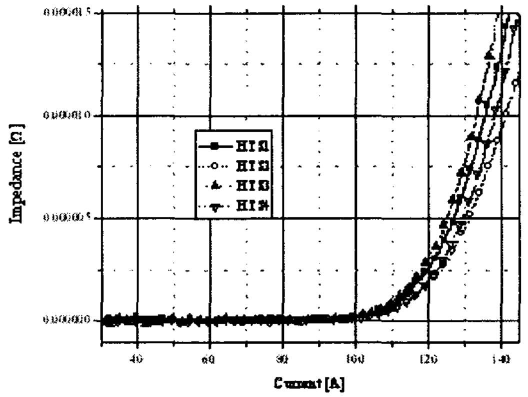

Fig. 9. Impedance of each strand

But, the result after the quench showed a somewhat strange pattern. In the voltage value of the voltage tap shown on the right of Figure 8, HTS3 was quenched first. As the quench was achieved, the current increase rate of HTS3 was reduced but increased again after the quench of whole wires. Finally, the biggest current was concentrated on HTS3. The currents which flowed through HTS1, 2, 3, and 4 were 143.5, 143.4, 168.9, 144.2A, respectively. In the symmetry structure, theoretically, the current should be distributed 25% in each but, according to the experiment result, the current distribution rate of HTS3, on which the biggest current was concentrated, was 28.15%, which is about 3% bigger than expected. This experiment output shows the possibility of the existence of an affecting element to the current distribution besides the resistance generated by the main part after the quench. However, the reason for that should be further studied.

### 3.4 Critical Current of Multi-Strand Cable

Table 2 shows the critical current values measured on each strand with regards to three kinds of multi-strand cables in this study and on each total multi-strand cable. The critical current of multi-strand cables was smaller than the total sum of each strand. In the case of 3-strand cable, total sum of the critical current in each strand can be said to be nearly same with that of the cable but, in other cases, all the critical current values were measured 4-5% below. This phenomenon takes place mainly because the characteristics of each wire are not identical. Therefore, the resistance generated in Bi-2223 wire is different according to the transport current, so the current to each strand was not divided equally. This is the biggest reason why the critical current of multi-cable was measured so low. Especially, it was noticed by this experiment result, that when impedance is generated a lot and/or some strands have a small value of critical current, current re-distribution occurred easily.

Table 2. Critical currents of multi-strand cable

| | | Critical current [A] | Whole critical current/ Sum of each critical current |
|---|---|---|---|
| 2-strand cable | HTS1 | 103.6 | 212.3/203.7= 0.95 |
| | HTS2 | 108.7 | |
| | Whole | 203.7 | |
| 3-strand cable | HTS1 | 103.6 | 318.6/317.6= 0.997 |
| | HTS2 | 106.3 | |
| | HTS3 | 108.7 | |
| | Whole | 317.6 | |
| 4-strand cable | HTS1 | 109.4 | 443.5/420.7= 0.949 |
| | HTS2 | 112.4 | |
| | HTS3 | 109.1 | |
| | HTS4 | 112.6 | |
| | Whole | 420.7 | |

### Acknowledgment

This research was supported by a grant from Center for Applied Superconductivity Technology of the 21st Century Frontier R&D Program funded by the Ministry of Science and Technology, Republic of Korea.

## 4. Conclusions

Experimental non-uniform current distribution of multi-strand HTS cable was studied and the result is as follows.

1. The biggest reason of non-uniform current distribution of multi-strand cable is the difference of impedance generated by the transport current.

2. The critical current of the whole multi-strand cable decreases because of the difference of the characteristics and the critical currents among strands. The highest decrease rate confirmed by this experiment was about 5%.

3. When there is an imbalance on the mutual inductance among strands, the non-uniform current distribution became severe but the decrease rate of total critical current was the smallest in this experiment.

4. Current re-distribution phenomenon among strands also takes place according to the difference of impedance occurrence rate as the current rises in the symmetry multi-strand structure.

### [References]

[1] N.J. Kelley, C. Wakefield, M. Nassi, P. Corsaro, S. Spreafico, D. W. Von Dollen and J. Jipping. IEEE Trans. on Applied Superconductivity 2001;1:2461

[2] S. Kruger Olsen, C Traholt, O. Tonnesen, M. Daumling and J. Ostergard. IEEE Trans. on Applied Superconductivity 1999;2:833

[3] M. Daumling. Cryogenics 1999;39:759

[4] C. Traholt, Kruger Olsen, O. Tonnesen, M. Daumling, F. Hansen, C.N. Rasmussen and D. Wilen. Physica C 2002;372:1567